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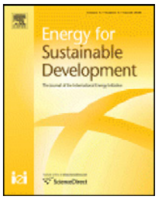

Influence of surface area to volume ratio of fuel particles on gasification process in a fixed bed

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ABSTRACT

The paper addresses the effect of particle size on tar generation in a fixed bed gasification system. Pyrolysis, a diffusion limited process, depends on the heating rate and the surface area of the particle influencing the release of the volatile fraction leaving behind residual char. The flaming time has been estimated for different biomass samples. It is found that the flaming time for wood flakes is almost one fourth than that of coconut shells for same equivalent diameter fuel samples. The particle density of the coconut shell is more than twice that of wood spheres, and almost four times compared with wood flakes; having a significant influence on the flaming time. The ratio of the particle surface area to that of an equivalent diameter is nearly two times higher for flakes compared with wood pieces. Accounting for the density effect, on normalizing with density of the particle, the flaming rate is double in the case of wood flakes or coconut shells compared with the wood sphere for an equivalent diameter. This is due to increased surface area per unit volume of the particle. Experiments are conducted on estimation of tar content in the raw gas for wood flakes and standard wood pieces. It is observed that the tar level in the raw gas is about 80% higher in the case of wood flakes compared with wood pieces. The analysis suggests that the time for pyrolysis is lower with a higher surface area particle and is subjected to fast pyrolysis process resulting in higher tar fraction with low char yield. Increased residence time with staged air flow has a better control on residence time and lower tar in the raw gas.

Introduction

Biomass gasification as a thermo-chemical conversion process is being addressed by various researchers from Second World War times (SERI, 1979). The technology has been revisited by various groups from the early eighties and more so in the recent time as a mitigation option for climate change and energy access to the remote areas (Dasappa et al., 2011; Kaupp and Goss, 1994; Knoef, 2012; SERI, 1979). Gasification process became a promising approach to convert biomass into useful combustible gaseous products. However, the raw product gas contains both gaseous and particulate impurities and has to be cleaned to meet the requirements for different applications (Zhang et al., 2012). Different reactor configurations of the gasification process are being practiced for power generation, and the downdraft process is generally accepted to generate reasonably clean raw gas that need to be further conditioned for use in reciprocating engines. Biomass gasification yields essentially three different products: gases, condensable tars, and solids (char and ash) (Kinoshita et al., 1994). Tars are loosely defined as organic condensable (at room temperature) compounds formed in thermo-chemical reactions; the major tar species derived from biomass gasification range from single-ring to five-ring aromatic hydrocarbons (Kinoshita et al., 1994). Tar formation in the final gas output is one of the major problems to deal with biomass gasification systems. Tar condenses at reduced temperature, thus blocking the process equipments such as engines, turbines and burners (Devi et al., 2003).

Kinoshita et al. have done detailed parametric tests on tar formation at varying temperatures, equivalence ratio and residence time on a fluidized bed gasifier (Kinoshita et al., 1994). This study concludes that the temperature and equivalence ratio has significant effects on tar yield and tar composition. Tar yield decreases with the increase in temperature or equivalence ratio. While this is true, but actual concentrations of the particulate and tar in the gas depend upon the reactor design, properties of the feed stock and operating conditions. Hence, to obtain the best quality gas output, the gasifier performance needs to be optimized by its design and operation practices (Devi et al., 2003). To achieve a high carbon conversion of biomass and low tar content in the resultant product gas, a high operating temperature (above 1073 K (800 °C)) in the gasifier is preferred to crack the higher molecular weight compounds (Devi et al., 2003).

Most of the gasification systems are designed to operate with wood as fuel; very little work is carried out to use agro residues as fuel. Particle size of fuel for use in gasifier as referred in SERI was linked to the throat diameter (SERI, 1979; Shrinivasa and Mukunda, 1984). It is necessary to

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understand the scientific implications of the influence of particle size on the gas quality. Hernández et al. (2010) reported that the fuel conversion increases (57.5% for 8 mm diameter particles) when reducing the fuel particle size, reaching a value as high as 91.4% for 0.5 mm diameter in an entrained gasification system. The smaller the fuel particle size, the more effective the mass and heat transfer since the particle external surface area/volume is higher, and the char fraction formed during pyrolysis is expected to be lower and more porous owing to a higher volatile release, which concluded that a lower time is required for the completion of pyrolysis when the particle size decreases (Babu and Chaurasia, 2003). However, this study has not addressed the effect of particle size on tar and particulate matter generation. Yin et al. (2012) concluded that as the particle size increases, the gas yield increases while the tar and dust contents decrease. Feng et al.'s (2011) study also showed that with the increase in particle size, gas production increases. The authors stated that the reason for this is that as the particle size increases, biomass feeding rate reduces. Hence, the residence time for gases has increased which translates the complete gasification process (Feng et al., 2011). However, in a packed bed with the increase in particle size, the pressure drop decreases, resulting in an increase in gas flow rate, while the gas production rate depends on the surface area exposed per unit volume in a packed bed reactor. The similar argument has been given in Luo et al.'s (2010) study. In this study, the authors reported that the particle size and the temperature had integrated effects on product yield and composition in steam gasification process at a fixed bed reactor. This study concludes that higher temperature resulted in higher gas yield with less tar and char, and, at the same temperature, dry gas yield increased with a decrease in particle size, and char and tar yield also decreased (Luo et al., 2010).

The dry gas yield and the production of char and tar are primarily influenced by the operating temperature. Dasappa and Paul (2001) have done a detailed study on a packed bed; where two crucial processes take place (i) the heterogeneous reactions between the particle and the reacting ambient resulting in the gaseous species and (ii) gas-phase interaction in the bed resulting in the final products of gasification. Pérez et al.'s (2012) experimental studies concluded that the higher process temperatures lead to volatile reforming reactions with higher reaction rates, which in turn results in the lower tar production rates. This study also concludes that as the equivalence air/fuel ratio increased, the thermo-chemical process moved from gasification (fuel rich) to combustion (fuel lean) zone. With increases of equivalence ratio, the amount of tar in the exit gas decreases (Phuphuakrat et al., 2010). However, it is also found that tar cannot be entirely eliminated by the influence of air supply. Light tar could be minimized, but it would increase heavy tar yield. Therefore, the gas cleaning system is still necessary to remove condensable tar before the producer gas is being supplied to the engine (Phuphuakrat et al., 2010).

Various reactor configurations are used for converting biomass to gaseous fuel. The typical designs are updraft, fluidized bed and the downdraft gasification systems. The processes taking place in an updraft is more a result of the pyrolysis product with a large amount of tar. In the case of the fluidized bed, even though the temperature profile is uniform across the reactor section, with limited contact between the char and the products of pyrolysis combustion results in high tar content in the gas (Knoef, 2012). The advantage of downdraft is the low tar content in the gaseous fuel as a result of sequential pyrolysis, oxidation and reducing process that occur in the packed bed. For engine applications, with low tar content in the gas reduces the complexity in the gas cooling system. Hence, the preferred reactor configuration is a fixed bed downdraft configuration for engine applications (SERI, 1979).

Pyrolysis, a primary process has been extensively researched for combustion, gasification and other process involving the thermochemical conversion. Flaming and glowing combustion has been studied with the aim to establish the limited conditions of operation. It has been established that the d^2 law (d_0 is the initial diameter of the particle) prevails both in the flaming and glowing combustion regimes (Dasappa et al., 1994; Mukunda et al., 1984; Murthy, 1972). Depending upon the heating rate, the pyrolysis processes are classified as slow and fast pyrolysis, with the major difference being the yield of gas and residual char. Hence, the size of the fuel is crucial to achieve better conversion rate with acceptable quality of gas in the case of downdraft gasification systems. The diffusion limited condition has a significant effect on the conversion time scale, which depends on the particle size; with time for conversion $\sim d_0^2$. This parameter in particular assumes significance while addressing a closed top downdraft reactor with a choke plate or throat. In the case of an open top gasifier due to the flame propagation front moving towards the reactor top, the combustion zone is extended and hence effectively increasing the residence time for the gas. This has an important influence on the reduction of higher molecular weight compounds. Some of these features are addressed by tracking the particle temperature along the length of the reactor (Dasappa et al., 2004).

Particulates and tar components in the producer gas create operational issues for use of the gas in an internal combustion engine. Apart from choking, the ducts are used for transporting the gas and the components like the gas carburetor, valves, turbo-charger, after cooler. The gas quality for successful internal combustion engine operation has been found as below 50 mg/m^3 for the particulates and less than 100 mg/m^3 for the tars in the case of naturally aspirated engines (Hasler and Nussbaumer, 2000). The sampling methods for particulates and tar need to be based on long term measurements for its high validity for the plant characterization under actual operating condition. Ueki et al. (2011) reported that the amounts of tar generated in the continuous running mode under updraft and downdraft conditions were 132.4 and 32.3 g/m^3, respectively. Tar compounds in syngas under downdraft conditions are smaller than those under updraft conditions. This is because tars are cracked during the passage through char conversion section at high temperature. The gasification which is a sub-stoichiometric combustion process follows the following reaction.

$$CH_nO_m + p\,(O_2 + 3.76\ N_2) = aCH_4 + bCO + cCO_2 + dH_2 + eH_2O + fN_2.$$

The sole objective of gasification is to enhance the mole fraction of combustibles in the product with lower molecular weight compounds. Based on experimental evidences, typical gas composition at the exit of the gasifier has been found to be CH_4: 1.5–2.2%, CO: 18–20%, CO_2:10–12%, H_2:18–20%, H_2O: 8–10% and the rest is N_2 (Dasappa et al., 2004). Depending upon the mole fractions of the product distribution, the air to fuel ratio varies. As the process transforms from gasification to combustion regimes, the product distribution reaches the stable form of oxides i.e., CO_2 and H_2O and transforms all the energy into the sensible heat. Experimental observation on the air-to-fuel ratio for gasification for long duration operation has been found in the range of 1.5 to 1.8 for high gasification efficiency (Mukunda et al., 1994). This ratio is constant irrespective of the type of gasification process (both fixed and fluidized bed) adapted. This arises from the fact that the elements have to be conserved. Based on this air fuel ratio; every kg of biomass say wood produces about 2.5 to 2.8 kg of producer gas, as cited in most of the literature (Mukunda et al., 1994). Further even in a given reactor geometry, based on the turndown ratio (operation range either side from its rated capacity), the air to fuel ratio is found to be consistent over the load range.

It is necessary to note that pre-processing of fuel for gasification is an essential activity. Wood chipping is an established and efficient process for different applications. Fuels having different physical properties like size, density etc. have an effect on pyrolysis and heterogeneous char reaction process. There are many gasification systems that use wood chips as a fuel and are having extensive cooling and cleaning system to generate engine acceptable gas. The current research study presents results from experiments and analysis of fuel properties like particle size, density on tar and particulates in a fixed bed downdraft gasification systems.

Methodology

Typically biomass gasification technology package consists of a reactor, gas cooling and cleaning system. The gasifier system configuration for end use application is shown in Fig. 1. The 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. Further a blower is employed to provide necessary draft for the gasifier operation.

In the present study, a downdraft gasification system was used for the analysis. The measurement scheme includes, biomass consumption rate, ash/char extraction rate, pressure drop across the reactor outlet, cyclone outlet, scrubbers, reactor exit gas temperature, gas flow rate and gas composition measurement using online gas analyzer (SICK Maihak: S715 Extractive gas analyzers) at periodic time intervals. In this study, the sampling method has been used as reported by Hasler and Nussbaumer (2000). Tar and particulates are measured by passing 0.5 m^3/h of gas from the main gas output line and bubbled through distilled water, and a solvent to extract dust and tar separately as shown in Fig. 2.

The gas sampling consists of a nozzle, gas bubblers, thimble filter, vacuum pump followed by a gas flow meter and a burner in the isokinetic setup. The gas bubbles pass through a bottle containing distilled water and move to an empty bottle to remove the moisture or water droplet if any carried over from the previous system. The next three bottles contain a solvent, namely anisole (methoxybenzene) followed by an empty bottle as a trap. All the bottles are placed in an ice and salt bath. The gas finally passes through a thimble filter. The thimble filter must be large enough to ensure that the fine dust collection does not pose any serious pressure drop on the suction pump. The gas after being pumped out of the system passes to a swirl burner. The burner introduced in the circuit has two important features, one is to ensure that the gas is burnt, and secondly to ensure that gas burns in a diffusion mode. If there is any air leakage in the sampling train, it will be evident in the burner apart from measuring the oxygen fraction in the gas. After the sampling, the equipment is cleaned by washing with water and appropriate solvents. Soxhlet extraction process was used to ensure that all the tars are extracted from the filter paper used in the capturing of the tar and particulate. The liquids generated are thereof analyzed in the laboratory. Experiments were conducted on wood spheres, wood flakes and coconut shells for obtaining the flaming time; a reflection of the pyrolysis process. The fuel used in the testing was wood flakes from the eucalyptus tree which had an average particle size of 25 mm × 22 mm × 4 mm. The average density of the wood flake was found to be 357 ± 17 kg/m^3. Similarly, the wood spheres are also used for this study. Table 1 presents the various fuel samples which are used in the study.

Results and discussion

In order to understand the influence of fuel properties like size, density on the gas quality, the present study consists of two aspects: (a) fundamental studies on the flaming and glowing combustion and (b) gasification studies towards measuring the tar and particulate.

Studies on fuel particle combustion

Wood spheres, wood flakes and coconut shells are used as fuel to establish some of the combustion characteristics of the fuel relevant for gasification. Pyrolysis and char combustion are the principal processes of any thermo-chemical conversion. In this study, the experiments have been conducted to measure the flaming and glowing times for the fuel species, to have a better understanding of the above two processes. Typical biomass contains about 75% volatiles and 25% fixed carbon on a moisture and ash free basis. During the flaming mode on heating, biomass de-volatilizes followed by combustion of volatiles with the air available in the surroundings. The products of combustion of volatiles contain mainly CO, CO_2, H_2, H_2O, CH_4 and some higher hydrocarbons (tars). The process of devolatization is called pyrolysis — either with inert or reactive environment (Fig. 3). Flaming time is defined as the time taken for all the pyrolysis products to be released, i.e., time after ignition of the sample and quenching of the flame surrounding the sample. Fig. 4 represents a typical thermo gravimetric analysis of the biomass sample where the biomass is subjected to heating during which weight loss is recorded. From the TGA profile, it is evident that in the temperature range of 300 to 500 °C, the biomass loses all its volatiles and this is clear from the weight loss profile. This process, identified as pyrolysis occurs in the flaming period which further undergoes combustion with air towards establishing a flame surrounding the sample. On release of volatiles, the biomass sample has residual char, i.e., after flaming period, where char undergoes heterogeneous combustion with air consuming the carbon from basically CO_2 and CO in oxidizer starved conditions. The carbon consumption leads to residual ash. The time taking for complete conversion of left over char to ash is known as glowing time and this process is known as char combustion.

The experimental setup is simple, consisting of a stand with pin holder to hold the sample as shown in Fig. 5. The stand along with the sample has been placed on a weighing electronic balance for determining the mass loss with time. The fuel is ignited by using a lamp with wick. The ignition source is removed immediately after the fuel has ignited, and the yellow flame is observed enveloping the fuel sample. The duration (flaming time) is noted from the moment the ignition has started till the flame ends for flaming and further (glowing time) till the char is reduced to ash after the glowing combustion.

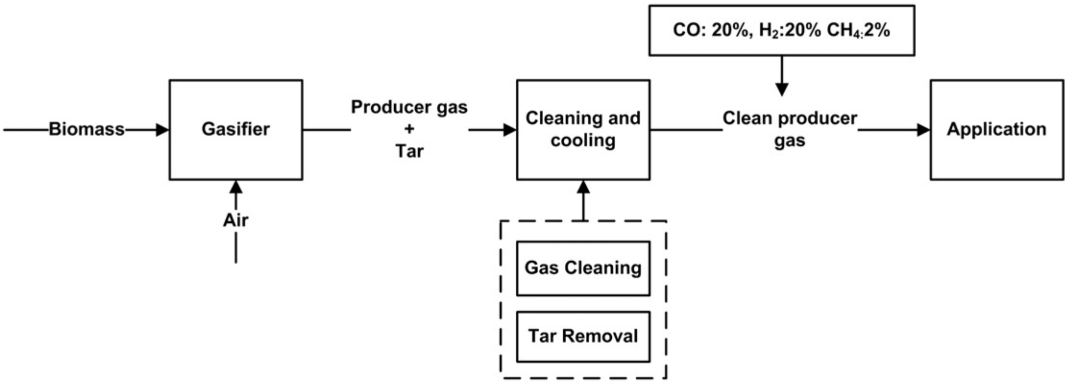

Fig. 1. Block diagram of a typical gasification system.

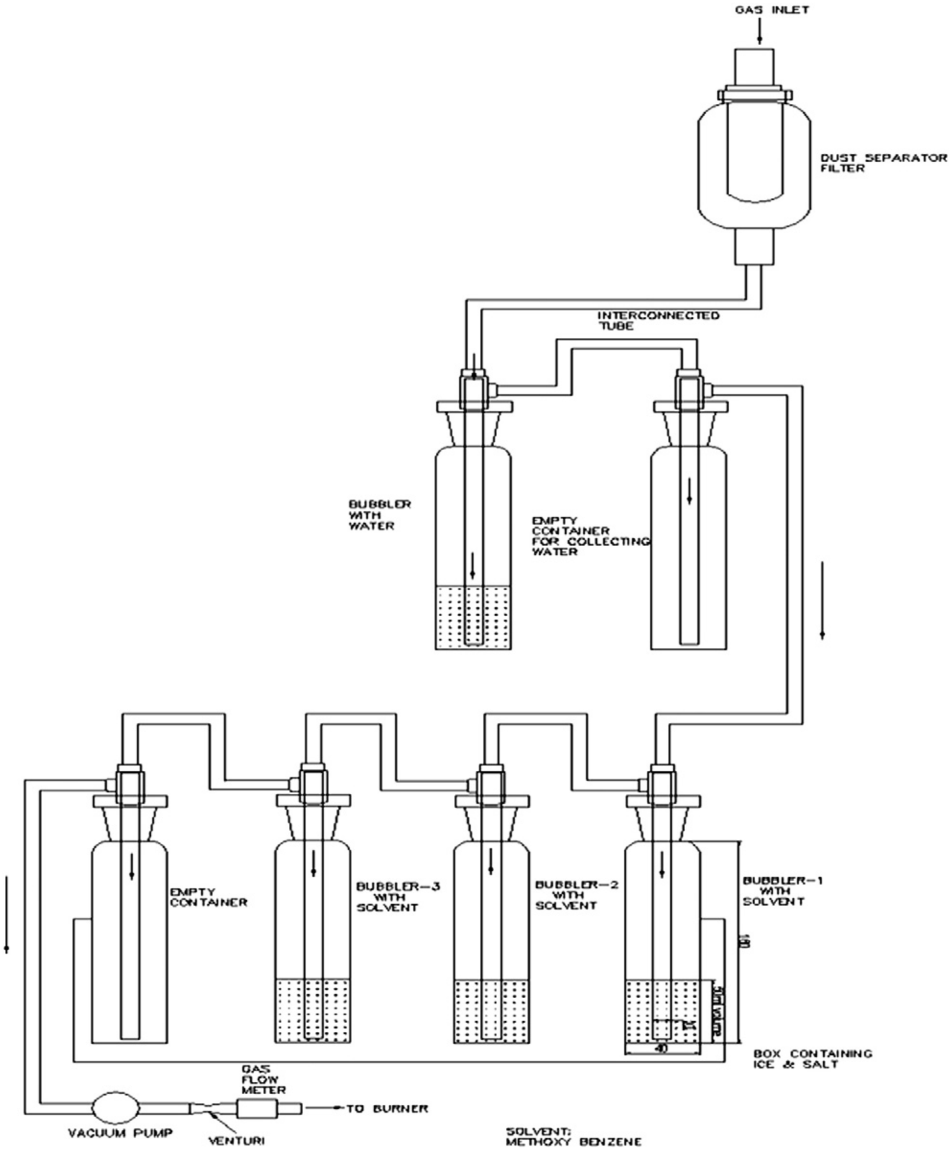

Fig. 2. Tar and particulate measuring system.

Simultaneously, the weight of the fuel sample is noted after the flame is off. This is done for the estimation of the weight loss during the flaming time, a process where the volatiles are driven away from the fuel.

The process of combustion of the fuel consists of two phases. In the first phase, a flame envelopes the sample (flaming) and in the second phase there is no gaseous flame and char combustion started (glowing). During the char combustion, it is observed that particle size decreases in size with a coating of ash on the outer surface. In the first phase, an inward movement of pyrolysis front with pyrolysis gases issuing out from the surface and combustion of volatiles takes place in the gas phase. As

Table 1
Fuel sample details.

Fuel sample details	Wood flakes	Coconut shells	Wood sphere
Photograph			
Dimension of fuel sample	25 mm × 22 mm × 4 mm	25 mm × 22 mm × 4 mm	10 mm
Particle density (kg/m^3)	357 ± 17	1352 ± 17	600
Bulk density (kg/m^3)	200 ± 20	650 ± 20	462 ± 20
Moisture content (%)	8–9	8–9	8–9
Ash content (%)	1.0–1.5	<1	<1

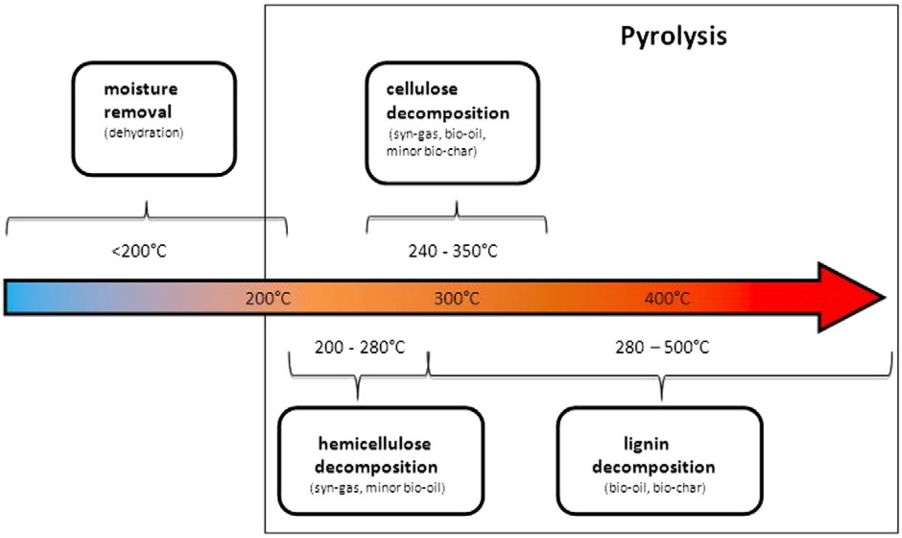

Fig. 3. Pyrolysis process in a biomass sample.

soon as the pyrolysis front has reached the center, 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 the wood combustion process cited in the literature (Mukunda et al., 1984; Murthy, 1972). Gas phase reactions are faster compared to solid phase reactions. Table 2 presents the experimental results of the wood sphere of various sizes. It can be observed from Table 2 that the glowing time is about 3.5 to 4.2 times higher than the flaming time in the case of the wood sphere.

It is noticed during the experiments that the char particle with the smallest mechanical disturbance used to break up into small pieces. Hence, necessary care has been taken during the experiment to make sure to minimize these problems. It is found that the volatile content is in the range of 75–80%. Table 3 summarizes the results from the experiments using the wood flake and coconut shells influenced by the particle size, flaming time, density, equivalent diameter and exposed surface area (surface area per unit volume). The pyrolysis rate process increases with the increase in the effective exposed surface area per unit volume of the bed. In order to understand this phenomenon, the flaming time is compared to fuels with different physical properties. The flaming time for various fuel samples used in the present study is presented in Table 4.

It is observed from Table 4 that the flaming time for wood flakes is almost one fourth that of coconut shells for the same equivalent diameter fuel samples and one-third that of the standard wood sphere. The comparison of time for flaming normalized with respect to the density is also presented in Table 4 where the effect of particle density is addressed. For a fuel sample with 15 mm equivalent diameter of the wood sphere with density of 600 kg/m^3, the flaming time is 120 s. Comparing with the wood sphere, the normalized value is nearly one half for the wood flakes and coconut shells. It must be observed that the density of the coconut shells is more than two times that of the wood spheres. It is clear from the above findings that the flaming rate which is an indication of pyrolysis rate is double in the case of flakes compared with the wood sphere.

It is also observed from Table 4, that the ratio of the surface area to equivalent diameter in comparison to wood sphere is nearly double in the case of flakes and also the coconut shell. This is reflected in the data on the flaming thus increasing the pyrolysis rate in a given packed bed reaction volume. The normalized flaming time in both cases has reduced by half while the surface area ratio is increased twice compared with the wood sphere. Increased rate of pyrolysis enhances volatiles' release, which further increases the gas volume fraction thus reducing the residence time in a given packed bed reactor geometry. The increase of gas yield can be attributed mainly to the higher pyrolysis rate.

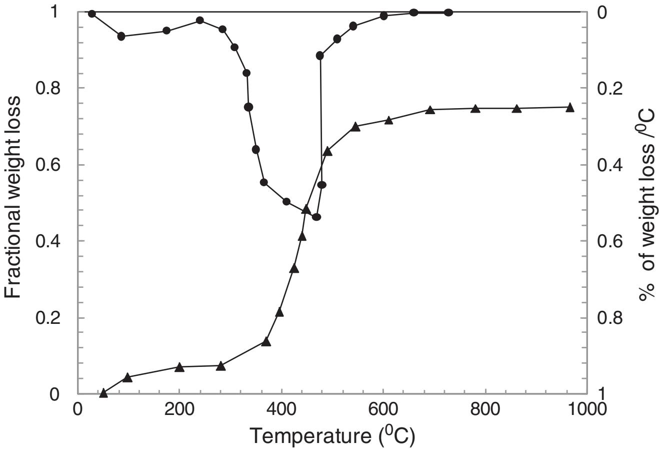

Fig. 4. Thermo gravimetric analysis of biomass sample.

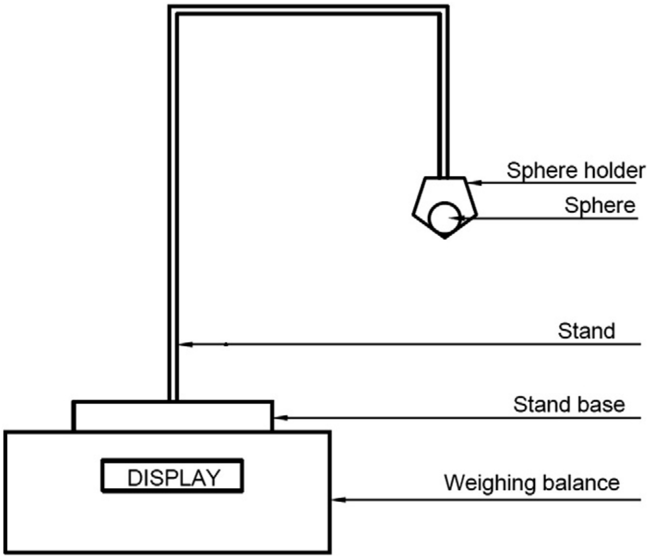

Fig. 5. Experimental setup for glowing and flaming time measurement.

Table 2
Flaming and glowing time of wood sphere.

Wood sphere diameter (mm)	Flaming time (s)	Char glowing time (s)
10	60 ± 5	220 ± 8
15	120 ± 6	500 ± 10
20	200 ± 6	750 ± 13
25	270 ± 8	950 ± 15

Table 4
Analysis of flaming time for different fuels.

Fuel	Particle density (kg/m^3)	Flaming time (s)	Flaming time/ particle density (s/kg-m^{-3})	Ratio of surface area to equivalent diameter in compare to wood sphere
Wood sphere	600	120	0.200	1
Wood flakes	357	38	0.106	1.88
Coconut shells	1352	166	0.123	1.97

Further, it is also important to note that at higher operating temperatures of the reactor, fast pyrolysis can also predominate based on the energy flux received on the small size particles resulting in higher fractions of long chain hydrocarbon in the pyrolysis gases. With the reduction in residence time, cracking of the higher molecular weight compounds is significantly affected. These factors increase the tar fraction in the producer gas.

Tar and particulate measurements

Experiments are conducted in a downdraft gasifier using wood chips and flakes to measure the tar and particulates in the exit gas. Standard wood chips of sizes 30 × 30 × 30 mm, which can be treated as a sphere, suggest an equivalent diameter of 37 mm. Tar and particulate sampling was carried out using the wet method (Ueki et al., 2011). The gasification system was operated at 45 kg/h for both the fuels and the gas-sampling rate was 0.5 m^3/h. Iso-kinetic samples were drawn and analyzed to obtain the tar and particulate content in the hot gas. Table 5 presents the tar and particulate measurements in the gas for wood flakes and standard wood chips.

It is clear from Table 5 that the amount of tar is in the range of 336 to 416 mg/m^3 in the case of wood flakes, and for wood chips, the measurements indicate a range of 43 to 77 mg/m^3, which is lower by about 400% compared with the wood flakes. In typical downdraft gasifiers with air as gasifying medium, the tar content in the raw gas is in the range of 500–3000 mg/m^3 which strongly depends on the reactor design, feedstock, moisture content in the feedstock and also the operating load conditions (Knoef, 2012). In the case of fluidized bed gasification system, the reported value of tar in the raw gas is in the range of 100 g/m^3. The strong dependence of type of biomass is evident from the data on field evaluated values of tar with rice husk which is about 40 times that of wood (Knoef, 2012). It is shown in the study that as the equivalence ratio increased from 0.30 to 0.32, and the temperature slightly increased from 995 to 1014 °C, the tar content in the syngas decreased sharply from 11,800 to 6560 mg/m^3 at the exit of reactor (before cleaning) in a downdraft fixed bed gasification systems (Phuphuakrat et al., 2010). However, it is also observed that the tar content reduced to 14–36% (by weight) at the exit of the scrubbers and sawdust adsorbers, respectively (Phuphuakrat et al., 2010). Dogru et al. study reported that the tar and dust contents are in the range of 6370–8380 mg/m^3 in a throat type downdraft gasifier, whereas the throat less type downdraft gasifier produced the highest tar yield of 13,000 mg/m^3 (Dogru et al., 2002). The particulate matter in the gas is slightly higher in the case of flake owing to smaller fuel size probably resulting in higher dust loading in the gas. Based on the above finding, it is evident that particles with the higher surface area are subjected to higher pyrolysis rate and also yielding fast pyrolysis products. It is also clear from the literature that fast pyrolysis products also yield higher molecular weight compounds, used in bio-oil (liquid fuel) generation. Larger particles contain greater heat transfer resistance, and hence the actual temperature inside the particle is lower, which leads to the occurrence of non-complete devolatilization process. Subsequently, incomplete pyrolysis results in a large fraction of residue containing volatile fraction. Ahmed and Gupta also reported that decrease in the char particle radius decreases the resistance due to gasifying agent diffusion which consequently decreases the time duration for the conversion (Ahmed and Gupta, 2011). This is attributed to the fact that reduction in diffusion resistance gets limited as the particle gets smaller. The other possible reason could be that the pyrolysis process of smaller particle is mainly controlled by reaction kinetics; as the particle size increases, the process is mainly controlled by gas diffusion, since the resultant product gas inside the particle has to diffuse out (Luo et al., 2010; Ueki et al., 2011). Majority of the heat transfer process in the bed is by radiation and has been elaborated in Dasappa and Paul (2001).

Simple numerical analysis suggests that for a heat flux of 20 kW/m^2, the heating rate is about 3 K/s for a 30 mm wood particle, compared with a wood flake thickness of about 4 mm, it is about 12 K/s. Depending upon the particle size, the net heating rate increases with an increase in the surface area of the particle. Thus, the volatile generation rate increases with the reduction in particle size. For a given reactor geometry, the residence time is designed to meet throughput of fuel gas generation. Hence, with the change in the pyrolysis rate, both the quantity of pyrolysis and the quality of products vary and have a

Table 3
Equivalent diameter and flaming time of wood flakes and coconut shells.

Length (mm)	Width (mm)	Depth (mm)	Volume (mm^3)	Equivalent diameter (mm)	Particle density (kg/m^3)	Flaming time (s)	Surface area/volume (mm^{-1})
Wood flakes							
24	21	4	2016	15.7	358	36	0.68
23	22	4	2024	15.7	341	33	0.68
27	24	4	2592	17.0	347	40	0.66
24	22	4	2112	15.9	368	37	0.67
26	22	4	2288	16.4	372	39	0.67
25	20	4	2000	15.6	355	35	0.68
26	24	4	2496	16.8	356	43	0.66
Coconut shells							
24	21	4	2016	15.7	1347	158	0.68
23	22	4	2024	15.7	1353	160	0.68
27	24	4	2592	17.0	1346	179	0.66
24	22	4	2112	15.9	1372	166	0.67
26	22	4	2288	16.4	1356	169	0.67
25	20	4	2000	15.6	1367	155	0.68
26	24	4	2496	16.8	1320	173	0.66

Table 5
Tar and particulate tests data for wood flakes and standard wood chips.

Total gas flow (m^3)	Time duration (h)	Total particulates (mg/m^3)	Total tar (mg/m^3)
Wood flakes			
0.469	1	1103	351
0.417	1	929	376
0.410	1	1054	336
0.883	2	1516	416
Standard wood chips			
0.965	2	875	77
0.904	2	638	43

Table 6
Effect of increase in residence time on tar and particulate.

Case	Nozzle air flow to total air flow ratio	Particulates (mg/m^3)	Tar (mg/m^3)
1	0.986	1850	1058
2	0.690	1260	217
3	0.506	895	49
4	0.353	743	47

significant influence on the quality of the gas generated. It is in this connection that particle size was notionally fixed as a multiple of throat diameter to have a certain designed pyrolysis rate process, in the case of the downdraft fixed bed gasification system (SERI, 1979). In the case of fluidized bed gasification systems, where particle sizes are small, the gas quality reported is with higher tar fractions in the hot gas, partly attributed to the above reasons along with very little char and gas interactions. In the case of coconut shell as a fuel, field data suggests that the closed top gasification system has a relatively high amount of hot tar than the open top gasification system. This is related to the smaller reduction zone in the throated reactor resulting in lowering the residence time for the gases to help in tar cracking. In the case of open top the propagation front moves upward which helps in increasing the residence time, thus reducing the tar fraction in the hot gas (Shrinivasa and Mukunda, 1984).

Experiments were carried out to improve the residence time of the gas in the reduction zone. This was carried out using an extended reducing zone by providing air at varying locations and also varying air flows at the nozzle (Fig. 6). Table 6 presents the details on the downdraft system operated with a different ratio of air between the nozzles at the bottom and from the top. It can be observed from Table 6 that with the decrease in the fraction of air flow from the nozzle, the tar level at hot gas reduces.

This is due to the consequence of increasing the residence time of the gas in the high temperature zone. The introduction of air above the air nozzles helps in increasing the combustion zone length, allowing pyrolysis to occur above the air nozzle with reference to case 1 as in Table 6. In cases 3 and 4, increasing the air fraction at 600 mm above the air nozzle, the combustion and the reduction zone have extended, thus resulting in an increased residence time. With the superficial velocity at 0.42 m/s in the reactor calculated at 1000 K, the additional increase in residence time of the gas is about 1000 ms from case 1 to case 4. The actual velocity through the bed depends on the porosity which is a strong function of particle sizes and fragmentation occurring during the pyrolysis process.

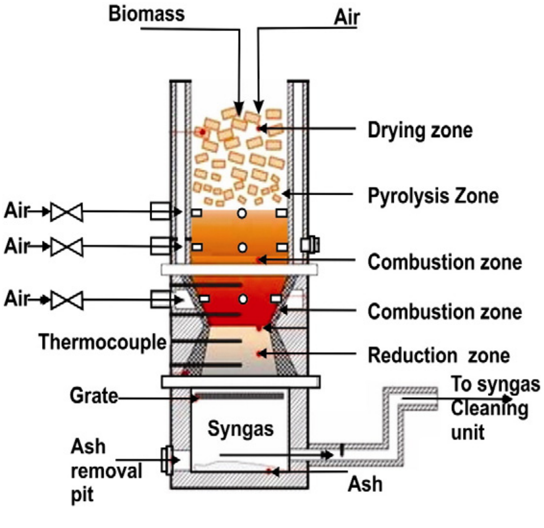

Fig. 6. Reactor with multiple air entry.

In the case of the multi nozzle downdraft configuration used in the present study, the analysis based on the air flow rates from the top and nozzle and the pressure drop across the bed reveal that the air flow through the nozzle has been high compared with the standard wood configuration. In the case of wood flakes, the bed resistance is about 3 times higher than that of wood pieces resulting in an increased air flow from the nozzle compared with the wood pieces. This affects the propagation rate and reduces the effective reactive bed height. This has an influence on the residence time of the gas in the hot bed which influences the cracking process.

Conclusions

It can be concluded that the flaming time for wood flakes is almost one fourth that of coconut shells for the same equivalent diameter fuel samples. The flaming rate which is an indication of pyrolysis rate is higher as the surface area per unit volume has increased. Particles with higher surface area per volume are subjected to higher pyrolysis rate resulting in fast pyrolysis products. It is also important to note that at higher operating temperatures of the reactor, fast pyrolysis can also predominate based on the energy flux received on the small size particles resulting in higher fractions of long chain hydrocarbon in the pyrolysis gases. With the reduction in residence time, cracking of the higher molecular weight compounds is greatly affected. These factors increase the tar fraction in the producer gas. The experiments and analysis provide a scientific basis for the generation of high tar in fixed bed gasification system for small size wood pieces. The quality and quantity of tar generated depend on the heat flux the particle is exposed. Increasing the residence time helps in reducing the hot tar.

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