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Effect of Air Velocity, Type and Size of Biomass on Performance of Downdraft Gasifier

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ABSTRACT

Investigation on thermal gasification of different biomass materials viz., Pigeon pea stalk (*Cajanus cajan*), Cotton stalk (*Gossypium hirsutum*) and Vilaytee babool (*Prosopis juliflora*) in a downdraft gasifier (1 kW capacity) was conducted to study the effect of air velocity, type and particle size of biomass. The influence of three different particle sizes viz. 25-50, 50-75, 75-100 mm, at three different air velocities viz., 2.4, 7.4 and 12.4 m s^{-1} on biomass consumption rate, gas flow rate and gasification yield was investigated. With the increase in particle size, the reduction in biomass consumption rate was observed, whereas the increase in air velocity increased the biomass consumption rate. Similar trend was observed in gas flow rate and gasification yield respectively. Under the experiment conditions, the biomass consumption rate, gas flow rate and gasification yield of selected biomass material varied in the range of 3.80 to 7.76 kg h^{-1}, 6.13 to 14.40 Nm^3 h^{-1} and 1.40 to 2.30 Nm^3 kg^{-1}, respectively. The experimental results showed that the gasification performance was better for Vilaytee babool (*Prosopis juliflora*) biomass with 25-50 mm size at 7.4 m s^{-1} air velocity.

Key words : *Biomass consumption rate, Bulk density, Calorific value, Gas flow rate, Gasification yield*

Introduction

Biomass is an organic matter produced by plants (both terrestrial and aquatic), animal and human waste and biomass is considered as a renewable source of energy, because it is renewable in nature unlike fossil fuel like coal, oil and natural gas. Biomass can be converted into solid, liquid and gaseous fuel depending on their physical availability and conversion process technology. When this biomass is used in various applications like home, industries for energy production then they release CO_2 to atmosphere and at the same time it is balanced by capturing CO_2 for the growth of plant and trees.

Biomass such as agricultural, forest and organic processing residues can be converted to commercial products via either biological or thermo-chemical processes. Biological conversion of low value ligno-cellulosic biomass still faces challenges in low economy and efficiency. Combustion, pyrolysis and gasification are three main thermo-chemical conversion methods.

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Gasification is a thermo-chemical partial oxidation process in which carbonaceous substances (biomass, coal, and plastics) are converted into gas in the presence of gasifying agents (air, steam, O_2, CO_2 or mixture of these). The gas generated, commonly referred to as producer gas or syngas (synthesis gas), consists mainly H_2, CO, CO_2, N_2, small particles of char (solid carbonaceous residue), ash, tars and oils (Ruiz *et al.*, 2013).

The versatility of gasification is that it can be used for producing syngas, H_2 or other liquid fuels, and can thereby meet the demand of electricity or thermal energy. Furthermore, the resulted fuel can be transported with high energy densities, enabling the generation of electricity to be centralized based on disperse gasification system. Among deferent types of gasifiers like fluidised bed type and fixed type (updraft, downdraft and cross flow) gasifiers, the updraft gasifier show the highest tar content, while downdraft show the lowest, while that of fluidized bed its intermediate tar production. For large scale applications, it is favorable to use entrained flow gasifiers, where as small scale application requires downdraft gasifiers. Downdraft gasifier is widely used for gasification of agricultural residues and forest wastes (Ruiz *et al.*, 2013).

A downdraft gasifier is a co-current flow reactor where biomass is fed at the top and the air intake also enters the top or the side of the reactor and flow in the same direction as that of biomass. The product gas flows downward and leaves through a bed of hot ash. Due to gas passes through a high- temperature zone, this enables cracking of tar during the gasification process. For this reason, the advantage of downdraft gasifier was higher conversion efficiency with a low tar and particulate matter generations (Nisamaneenate *et al.*, 2015). An exhaustive research work is reported on the gasification of wood, fuel cane bagasse, olive industry wastes, oil palm waste, hazelnut, sugarcane leaf, rise husk, paper industry wastes, cashew nut shells and MSW (municipal solid waste) in downdraft gasifier (Sheth and Babu, 2009).

In India, northern Karnataka region, the major agricultural crop residues namely pigeon pea stalk (*Cajanus cajan*) and cotton stalk (*Gossypuim hirsutum*) are available after harvest of the crops. Presently majority of the biomass burnt is in the field only. The forest species like Vilaytee babool (*Prosopis juliflora)* is grown naturally, freely and abundantly available and at present this is used as a rural domestic fuel purpose, which is less efficient and also leads to emission of GHG (greenhouse gases). Instead of burning, these residues can be used as feedstock for biomass gasification for the production of producer gas, further converting it into energy for power generation by using the gasifier-generator system.

Studies have shown that size and type of biomass, air velocity affect the performance of the gasifier in terms of biomass consumption, gas flow rate and gasification yield (Chaves *et al.*, 2016). Rao *et al.* (2004) analysed chemical properties of biomass material for counter current fixed-bed gasification. The results showed that volatile matter content, ash content and fixed carbon content of wood chips were 83.20, 1.30 and 15.50 per cent, respectively. Chaves *et al.* (2016) evaluated the small scale power generation in downdraft gasifier coupled to engine generator set. The parameter related to biomass consumption rate of 5.6 kg h^{-1}, gas flow rate of 14.30 $Nm^3 h^{-1}$ and gasification yield of 2.5 Nm^3 kg.

By keeping the above points in view present investigation was conducted to study the effect of size, type of biomass and air velocity on performance of downdraft gasifier.

Materials and Methods

Biomass feedstock

The required size of cotton stalk, pigeon pea stalk and Vilaytee babool woods were collected from the Main Agricultural Research Station (MARS), Raichur. These biomass materials had higher length and diameter. Hence, there was a need to reduce the length of cotton stalk, pigeon pea stalk and Vilaytee babool wood. The experiments were carried out with three different particle sizes viz., 25-50, 50-75 and 75-100 mm of length.

Since these biomass materials used for entire study was collected once from only single site and all the samples with different size were stored in plastic container for experiments, composition and properties were assumed same for all particle sizes.

Physico-chemical and thermal properties

The physical, chemical and thermal properties of agricultural and forest biomass material viz., moisture content, bulk density, volatile matter content, ash content and fixed carbon content was determined using Hot air oven, Muffle furnace apparatus by using the ASTM D3173-11 and ASTM D/3175-11 standard test procedure. The calorific value of the different biomass material was measured by digital bomb calorimeter according Indian standards (IS: 1359; 1959).

Experimental study

The experimental set-up consists of throat type, fixed bed, 1 kWe downdraft gasifier, operating on selected biomass materials, gas conditioning system, and flow measuring device (Fig. 1). The biomass gasification system was selected based on the type of biomass used and their properties, for the different types of gasifier in which downdraft gasifier was best suitable for adapting the agricultural and forest residues (Ruiz *et al.*, 2013). The technical specifications of downdraft gasifier power generation system are presented (Table 1).

Charging of the gasifier

The different selected biomass material viz., cotton stalk, pigeon pea stalk and Vilaytee babool were fed into the gasifier. The biomass feedstock charging door lid was opened by lifting it until fuel hopper is full and closed the door by putting back and water was filled in the annular space around the lid. Then the flaring pipe cap was opened to see that the wa- the ignited torch was inserted and the plug for all surroundings was screwed.

The flaring pipe cap was closed and the water was filled in the annular space surrounding and look for smoke coming out of the flaring pipe. If smoke does not come continuously, the torch was burning or not checked. If the torch was extinguished, then the fire was re-ignited. The ignition was continued for about 5 to 10 minutes, within this time, the fire zone of the gasifier would normally attain temperatures high enough to convert wood into gas. Gas production was checked by applying a lighted torch to the gas coming out of the flaring pipe of gasifier. Sometimes, the flame of the gas did not stabilize even after 30 minutes, in such case the blower was stopped and the gasifier was checked for any trouble shouting. If the gas burns with a stable flame, gas was diverted to the engine by opening the engine valve. The gas flaring pipe cap was closed and the water was filled in the water seal (in the annular space).

Producer gas was allowed to pass into different chambers like; scrubber, primary and secondary filters, heat exchanger, flow meter, inlet of engine and generator and finally it was exhausted. During the experiment biomass consumption rate, gas flow rate

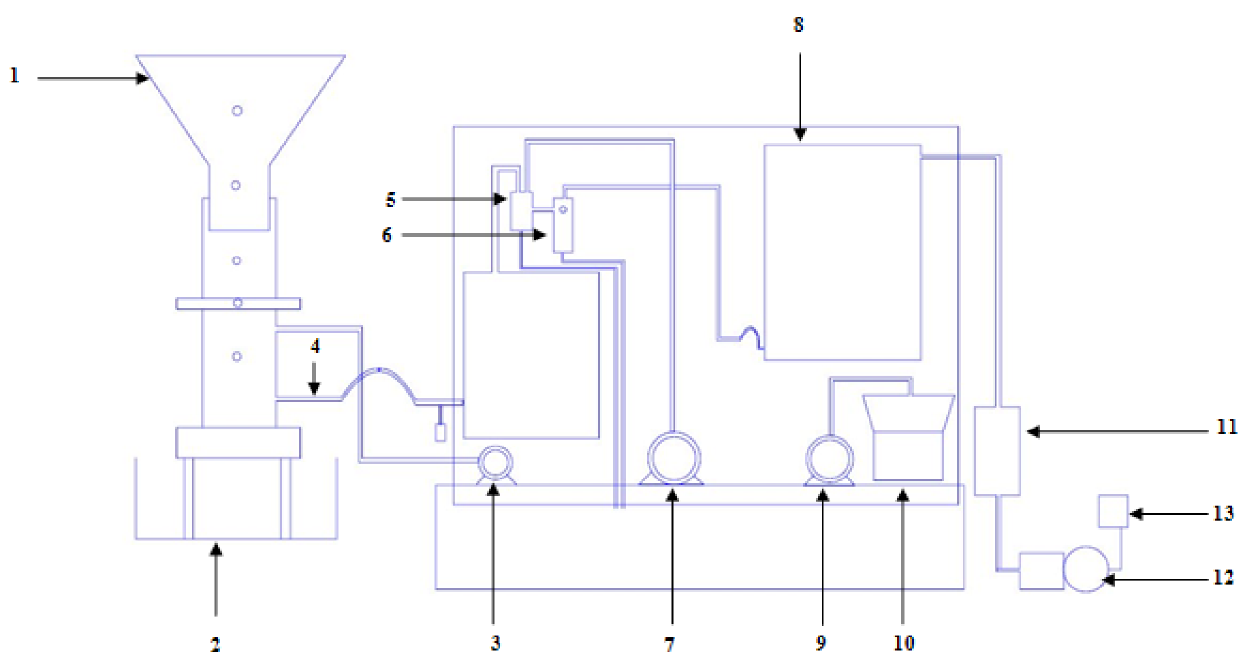


Fig. 1. Block diagram of the gasification unit

1. Hopper 2. Grate 3. Blower 4. Outlet of Gasifier 5. Primary filter 6. Secondary filter 7. Pump 8. Heat exchanger 9. Pump 10. Water filter 11. Gas flow meter 12. Engine 13. Generator

Table 1. Technical specifications of gasifier-power generation system

Model	Downdraft throat type, with insulated reaction zone with ash removal water seal
Rated capacity	50,000 kcal h^{-1}
Hopper Capacity	60 kg firewood
Rated gas Output	25 Nm^3 h^{-1}
Fuel	Wood chips, Bulk density> 250 kg m^{-3}, Moisture content < 10 per cent, Ash < 2 per cent
Biomass Consumption at rated load	Size : 25 -100 mm, 8-10 kg h^{-1}
Calorific value of gas	1000-1200 kcal Nm^{-3}
Gas composition	CO : 18-22 per cent, CH_4: 1-4 per cent N_2 : 45-55 per cent, H_2 : 13-20 per cent CO_2: 9-12 per cent
Biomass to gas conversion efficiency	70-75 per cent
Biomass feeding interval Period of continuous operation Initial	Batch time and depending up on work load
Starting time	Not more than 10 minutes
Auxiliary electrical load	0.5 hp, single Phase
Ash removal interval (main duct)	60 hours of operation
Ash removal system	Manual ash removal system
Type of Air blower	Centrifugal
Capacity	40 m^3 h^{-1}
Pressure	100 mm of WG (to overcome pressure drops in gasifier and pipeline
Area required	3×1.2 m^2

Biomass consumption rate

After initial charging of the gasifier, a known weight of material was added in the reactor. Gas flow rate was set to the desired value. When the flame reached to the top of the material layer, a known weight of material was added. The starting time was noted and towards the end of the run, when the fire reached top layer of feed material, the time required to burn the feed material was noted. The difference in time were recorded gave the operating time. The biomass gasification rate was determined by the ratio of quantity of biomass material consumed per unit time and is calculated by the following formula.

$$\text{Biomass consumption rate (kg h}^{-1}\text{)} = \frac{\text{Weight of biomass consumed (kg)}}{\text{Operating time (h)}}$$

Gas flow rate

The size of biomass materials were fed to the gasifier in a batch of 8 to 10 kg. The quantity of gas produced and the duration of test run for combustion of biomass material were measured using a wet type gas flow meter (Make; Optima Tech Solutions, Bangalore) attached to the delivery pipe and a hand held stop watch, respectively. The gas flow rate was measured by using gas flow meter and calculated by the following formula (Chaves *et al.*, 2016).

$$\text{Gas flow rate (Nm}^3\text{h}^{-1}\text{)} = \frac{\text{Quantuty of gas produced (Nm}^3\text{)}}{\text{Time of duration (h}^{-1}\text{)}}$$

Gasification yield

In the gasification process, the ratio of quantity of producer gas (syngas) coming out of the downdraft gasifier to the quantity of biomass material consumed during the operation for converting into volume of gas produced from the gasifier was determined by using following formula (Chaves *et al.*, 2016).

$$\text{Gasification yield (Nm}^3\text{h}^{-1}\text{)} = \frac{\text{Gas flow rate (Nm}^3\text{ h}^{-1}\text{)}}{\text{Biomass consumption rate (kg h}^{-1}\text{)}}$$

Results and Discussion

Physico-chemical and thermal properties of selected biomass material

The physical properties of selected biomass material were presented in Table 2. The moisture content of

Table 2. Physical properties of biomass material selcted for the study

Sl. No.	Types of biomass material	Size of biomass material (mm)	Diameter (mm)	Moisture content (per cent)	Total solids (per cent)	Bulk density (kg m^{-3})
1	Pigeon pea stalk	25-50	6-10	3.28	96.72	501
		50-75	6-14			
		75-100	6-18			
2	Cotton stalk	25-50	5-10	6.98	93.02	465
		50-75	6-13			
		75-100	6-16			
3	Vilaytee babool	25-50	11-18	9.45	90.55	556
		50-75	18-26			
		75-100	18-46			

selected biomass material ranged from 3.28 to 9.45 per cent and the maximum bulk density of 556 kg m^{-3} was observed for Vilaytee babool and a minimum of 465 kg m^{-3} for cotton stalk. The chemical and thermal properties of selected biomass material were presented in Table 3. The maximum volatile matter content of 80.81 per cent was observed for Vilaytee babool and a minimum of 80.20 per cent for cotton stalk. The ash content of selected biomass material ranged from 1.39 to 1.83 per cent and the maximum calorific value was observed for Vilaytee babool (17.49 MJ kg^{-1}) and a minimum of 16.05 MJ kg^{-1} for cotton stalk.

Biomass consumption rate

Biomass consumption rate of different biomass materials was increased with the increase in air velocity as shown in Fig. 2 (a), (b) and (c). Biomass consumption rate was maximum at air velocity of 12.4 m s^{-1} whereas minimum was observed at 2.4 m s^{-1} for all the biomass. The biomass consumption rate trend obtained in this work is in line with the results reported in the literature (Patel *et al.,* 2014). The increase in biomass consumption rate with the increase in air velocity might be due to the effective surface area increased for smaller particle sizes which in turn increase the reactivity of fuel. The increase in the air flow rate provides more oxygen to oxidize and higher amount of biomass would get combusted. The energy released will increase the rate of drying and pyrolysis. Biomass consumption rate increased not only due to a higher combustion rate, but also due to the enhanced pyrolysis and drying rate.

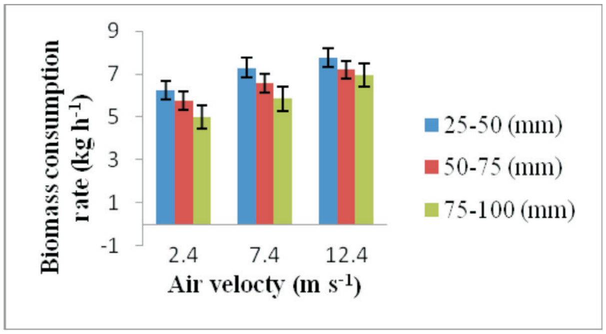
Biomass consumption rate was maximum for 25-50 mm size of biomass material whereas it was minimum for 75-100 mm (Fig. 2). It was observed that the biomass consumption rate decreased with increase in size of biomass, because of larger particle sizes have lower rate of combustion due to slow rate of diffusion within the particles and also due to fact that the smaller size of biomass burns quickly as compared to larger size, which reduces the feeding rate. These are agreement with the findings of (Patel *et al.,* 2014). Same trends were observed for all types of biomass. Biomass consumption rate was maximum for pigeon pea stalk whereas minimum for Vilaytee babool because of higher heating value of biomass material (Zhang *et al.,* 2012).

Gas flow rate

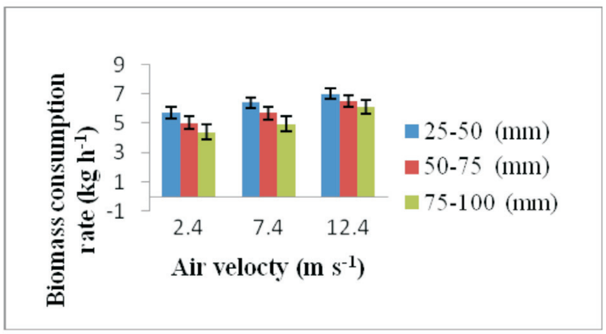
Gas flow rate of different biomass materials was increased with the increase in air velocity as shown in Fig. 3 (a), (b) and (c). Gas flow rate was maximum at air velocity of 12.4 m s^{-1} whereas minimum gas flow rate was observed at 2.4 m s^{-1} for all the biomass.

Table 3. Chemical and thermal properties of biomass material selcted for the study

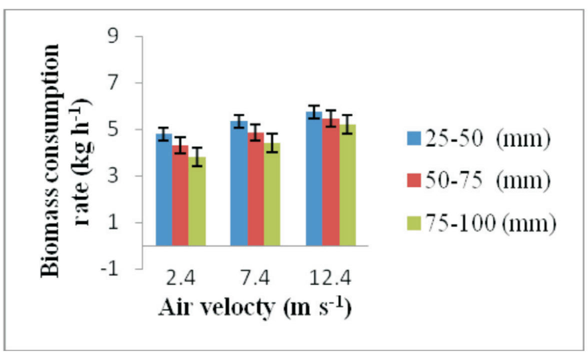
Sl. No.	Types of biomass material	Size of biomass material (mm)	Volatile matter (per cent)	Ashcontent (per cent)	Total carbon content (per cent)	Calorific value (MJ kg^{-1})
1	Pigeon pea stalk	25-100	80.67	1.39	17.94	16.44
2	Cotton stalk	25-100	80.20	1.43	18.37	16.05
3	Vilaytee babool	25-100	80.81	1.83	17.36	17.49



(a) Pigeon pea stalk

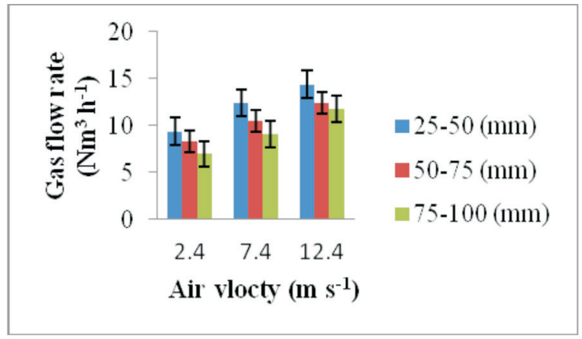


(b) Cotton stalk

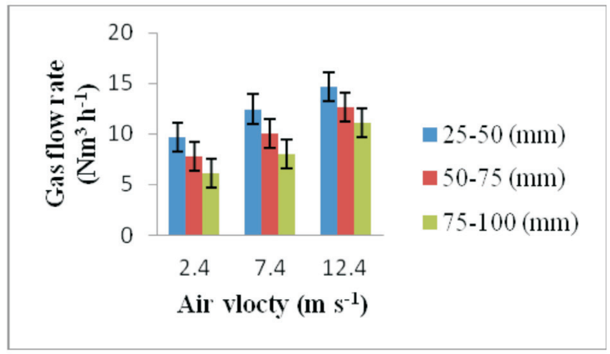


(c) Vilaytee babool

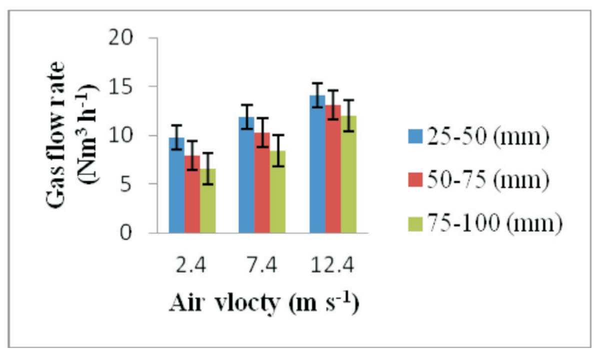
Fig. 2. Effect of air velocity with different lengths of biomass on biomass consumption rate



(a) Pigeon pea stalk



(b) Cotton stalk



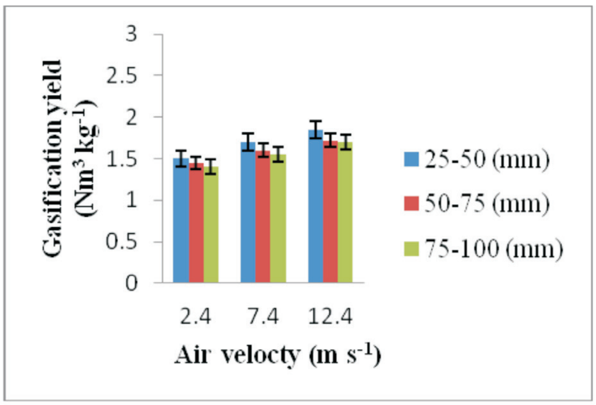
(c) Vilaytee babool

Fig. 3. Effect of air velocity with different lengths of biomass on gas flow rate

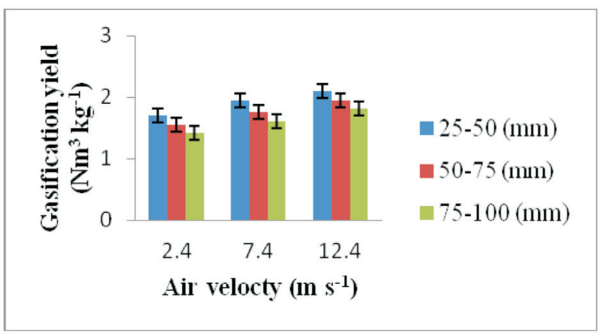
The increase in gas flow rate with the increase in air velocity might be due to more oxygen supply in combustion zone for burning of biomass material and this leads more gas production rate. Gas flow rate was maximum at 25-50 mm size of biomass material whereas it was minimum at 75-100 mm (Fig. 3). It was observed that the gas flow rate decreased with increase in size of biomass, due to larger particle sizes takes more time needed for combustion with high resistance to heat. These findings are similar to the findings of Kumar and Kumar (2013). Gas flow rate was maximum for cotton stalk whereas minimum for Vilaytee babool. It was observed that the cotton stalk having more fibrous in nature and quickly burning of biomass takes place in the gasifier system, due to this more gas production occurs in cotton stalk. These similar results were reported (Chaves *et al*, 2016).

Gasification yield

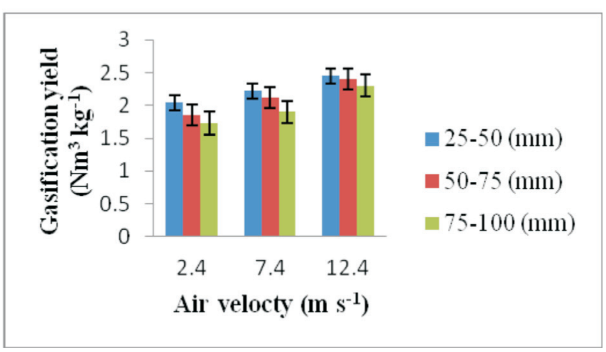
Gasification yield of different biomass materials was increased with the increase in air velocity as shown in Fig. 4 (a), (b) and (c). Gasification yield was maximum at air velocity of 12.4 m s^{-1} whereas minimum gasification yield was observed at 2.4 m s^{-1} for all the biomass. The increase in gasification yield with the increase in air velocity might be due to faster rate of consumption of biomass and gas flow rate. Gasification yield was maximum for 25-50 mm size of biomass material whereas it was minimum for 75-100 mm (Fig. 4). It was observed that the gasification yield decreased with increase in size of biomass due to fact that the larger particle sizes contribute less surface area, which intern produce less light gases and more char. These findings were closely agreement with results of Chaves *et al* (2016). Gasification yield was maximum (2.45 Nm^3 kg^{-1}) for Vilaytee babool whereas minimum for pigeon pea stalk (1.40 Nm^3 kg^{-1}). It was showed that the Vilaytee babool having higher heating value compared with pigeon pea stalk. The gasification yields were varied from 1.40 to 2.30 Nm^3 kg^{-1} was reported by Kumar and Vivekanandan (2016).



(a) Pigeon pea stalk



(b) Cotton stalk



(c) Vilaytee babool

Fig. 4. Effect of air velocity with different length of biomass on gasification yield

Conclusion

The effect of air velocity, size of biomass material on the performance of gasifier was experimentally investigated in a 1 kW downdraft gasifier and the follwong conclusions were drawn:

- The bulk density was maximum (556 kg m^{-3}) for Vilaytee babool and a minimum (465 kg m^{-3}) for cotton stalk.
- The volatile matter content was maximum (80.81 per cent) for Vilaytee babool and a minimum (80.20 per cent) for cotton stalk.
- Biomass consumption rate was maximum for pigeon pea stalk with 25-50 mm size of biomass at air velocity of 12.4 m s^{-1} whereas it was minimum for Vilaytee babool at 2.4 m s^{-1} with 75-100 mm size biomass.
- Gas flow rate was maximum for cotton stalk with 25-50 mm size of biomass material at air velocity of 12.4 m s^{-1} whereas it was minimum Vilaytee babool at 2.4 m s^{-1} with 75-100 mm.
- Gasification yield was maximum for for Vilaytee babool with 25-50 mm size of biomass material at air velocity of 12.4 m s^{-1} whereas it was minimum for pigeon pea stalk at 2.4 m s^{-1} with 75-100 mm.

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