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Experimental investigation on an entrained flow type biomass gasification system using coconut coir dust as powdery biomass feedstock

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HIGHLIGHTS

- An entrained flow gasifier has been successfully tried with coconut coir dusts.
- The gasifier could attain temperatures in the range of 976–1100 °C.
- The gas yield and tar content were influenced by introduction of steam and preheat.
- The LHV and peak CGE of 7.86 MJ/Nm^3 and 87.6% respectively were obtained.

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ABSTRACT

Based on an entrained flow concept, a prototype atmospheric gasification system has been designed and developed in the laboratory for gasification of powdery biomass feedstock such as rice husks, coconut coir dust, saw dust etc. The reactor was developed by adopting L/D (height to diameter) ratio of 10, residence time of about 2 s and a turn down ratio (TDR) of 1.5. The experimental investigation was carried out using coconut coir dust as biomass feedstock with a mean operating feed rate of 40 kg/h The effects of equivalence ratio in the range of 0.21–0.3, steam feed at a fixed flow rate of 12 kg/h, preheat on reactor temperature, product gas yield and tar content were investigated. The gasifier could able to attain high temperatures in the range of 976–1100 °C with gas lower heating value (LHV) and peak cold gas efficiency (CGE) of 7.86 MJ/Nm^3 and 87.6% respectively.

1. Introduction

Biomass is the collective form for all forms of plant materials including forest and agro-residues. It has environmental benefits, offer fuel flexibility and can be used as supplemental low cost fuel, especially residues, for use in combustion systems, i.e. gas turbine, gas engines and gas burners. Gasification of biomass is a thermochemical process and has the potential to convert lignocellulosic biomass into a gas or liquid intermediate suitable for further refining to valuable products. It is a less developed technology than biomass combustion. Because of this reason, there is an increased risk associated with the commercialization of gasification technology. Several studies indicate that the available biomass potential in India can be used for energetic and chemical processes very efficiently via gasification.

Several types of biomass gasifiers have been developed over the years including fixed bed, bubbling fluidized bed and circulating fluid bed gasifiers for solid biomass (McKendry, 2002; Dasappa et al., 2004; Corella et al., 2005; Sharma, 2008; MNRE Newsletter, 2008; Barman et al., 2012; Balu and Chung, 2012). These gasifiers operate at pressures ranging from atmospheric to 2.4 MPa and with typical operating temperatures in the range of 250–900 °C. The content of impurities in terms of tar and particulate matter in the raw product gas necessitates cleaning activity in order to meet both utility and environmental emission limits (Lin et al., 2011). The effect of bed temperature and steam flow rate on product gas yield in a fixed bed biomass gasifier was studied by Yan et al. (2010). It has also been reported in literature that introduction of steam could able to generate nitrogen free hydrogen-rich product gas with higher heating values in fluidized and steam-oxygen blown circulating fluidized bed gasifiers with a medium range heating values (Peng-mei et al., 2003; Kempegowda et al., 2010; Karmakar et al., 2011; Meng et al.,2011). A few studies on design, developmental and modeling aspects of cyclone type biomass gasifiers have been reported in literature (Gabra et al., 2001; Syred et al., 2004; Guo et al., 2009; Sun et al., 2009).

Fletcher et al. (2000) carried out CFD modeling of entrained flow gasification of biomass which may be considered useful in designing such systems. Henrich and Weirich (2004) have

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conducted studies on a pressurized entrained flow biomass gasifier reactor with straw as biomass feedstocks. The pyrolysis condensate and pulverized pyrolysis char in the form of dense slurry were pumped into a slagging entrained flow gasifier at high operating temperature and pressure for production of syn-gas. Zhao et al. (2009) have developed a kinetic model for gasification of rice husk in an entrained flow reactor with a residence time of less than 1.5 s and emphasized on the requirement of higher temperature in the order of 900–1000 °C for optimal producer gas yield. Some investigators have indicated that the particle size, residence time and pyrolysis pretreatment temperatures significantly affect the performance of an entrained flow gasification system (Hernandez et al., 2010a; Xiao et al., 2010). Qin et al. (2011) have investigated in a laboratory scale atmospheric pressure entrained flow gasifier using wood and straw as biomass feed stock. The addition of steam indicated an improvement in producer gas yield and at the largest supply of steam addition (H_2O/C) a molar ratio of H_2/O equals to 1 was achieved. Cheng et al. (2012) have developed an allothermal biomass gasification system using biomass micron fuel (BMF) as external heat source. Heat was supplied to the gasifier by combustion of BMF. The system energy efficiency was comparatively low (around 44%) due to high cost of energy required for preparation of BMF.

At present, India produces more than 200 million tons of agro-wastes per annum in the form of powdery biomass from various agro-processing industries such as rice mills, coir industries, saw mills etc. The energy values of these huge wastes can be extracted through advanced gasification technology for various thermal applications such as in large scale agro and food processing industries, ceramic and glass industries, metallurgical industries. This paper describes the construction of a 30 kWe biomass gasifier with various system elements based on the entrained-flow technology and it's testing with coir dust as biomass feedstock. A series of gasification trials were conducted to investigate the effect of equivalence ratio, reactor temperature, preheat and steam feeding on the performance of the gasifier. Reaction conditions were discussed for achieving optimum gas yield with high cold gas efficiency (CGE).

2. Methods

2.1. Experimental materials and analyses

The coconut coir dusts used for the study were collected from a local coir industry in Puri district of Orissa situated in the eastern coastal region of India. The moisture content of the samples were determined by using Moisture Analyzer Instrument ((Make: Denver Instruments, Germany, Model: IR 60, Accuracy: 0.01%). The calorific value of the samples were measured with digital bomb calorimeter (Make: Parr, Model: 6100 Isoperibol Calorimeter, Precision classification: 0.2% Class) and was found to be 17.79 MJ/kg. It has been cited in the literature that the coir dust has more than 97.1% combustible components (Volatiles: 70.3 wt.%, Fixed Carbon: 26.8 wt.%) and a very low ash content of around 3 wt.% on dry air basis (Ganesh, 2006). The ultimate analysis of coir dust indicated C, H and O wt.% of 50.3, 5.1 and 39.6% respectively (Gaur and Reed, 1998). Abad et al. (2002) determined the content of fiber constituents in some Indian coconut coir dusts and the cellulose, hemi-cellulose and lignin contents were found to be 32.4 wt.%, 8.4 wt.% and 43.1 wt.% respectively. The particle size distribution was determined by rehydrating and air drying coir dust samples. After the samples were dried, particle sizes were separated by sieving 100 g sample on a CSC Scientific (Fairfax, va) rotating shaker for 10 min using screens with pore diameter of 8, 6.3, 4.0, 2.0, 1.0, 0.5 and 0.25 mm. The weight of the material collected in each screen was determined. The weight distribution of the coir dust samples indicated that 68% of the particles were in the range of 0.5–2 mm in diameter and 27.6% of the particles were in the size range of 2–8 mm in diameter. The amount of very fine (<0.5 mm) and very coarse (>8 mm) particles were determined to be 3.6% and 0.8% respectively.

2.2. System elements of the entrained flow reactor

A schematic diagram of the entrained flow biomass gasification system is shown in Fig. 1. The system mainly consists of an entrained flow reactor, oil ignition and pre-heating unit, fuel feeding arrangements, air and steam injection units and a gas sampler.

The reactor is made up of 5 mm thick outer mild steel shell lined inside with high alumina (70%) refractory castables of 100 mm thick to withstand high temperatures in the range of 1000–1500 °C and to provide an adequate insulation for minimizing heat loss. A L/D (height to diameter) ratio of 10 has been adopted in the reactor geometry to provide not only adequate residence time for maximizing char gasification but also to improvise the mixed flow and plug flow characteristics for the reactor. These characteristics are quite essential for entrained flow gasification systems to enhance the energy density of the end product gas as cited in the literature (Fletcher et al., 2000). Based on simple plug flow calculation a gas residence time of about two second has been adopted for the gasifier.

The oil ignition and pre-heating unit comprises of an oil storage tank of 0.3 m^3 capacity, fuel oil-air injection with atomizing nozzles, oil pumps (one in operation and other standby), a 2.2 kW blower with air regulating valve to supply air for atomization and combustion. The biomass feeding arrangements consist of a novel type air jet biomass feeder, biomass bin, feeder pipes. Due to sticky characteristics of biomass particles and to avoid possible chocking at the bin outlet, a vibratory mechanism has been provided to ensure continuous supply of powdery biomass to the gasifier through the air jet feeder.

The vibrating mechanism attached to the feeding bin consists of motorized pulley, an eccentric mounted over a rotating shaft, a connecting rod and leaf springs. The rotational speed of the eccentric provides gentle oscillatory to and fro motion to the bin by means of reduction motor-pulley arrangements. The biomass flow rates are controlled by means of a sliding gate with rack and pinion type linear actuator provided at the outlet of the bin. The steam injection unit consists of a steam generator having a steam output capacity of 20 kg/h at a pressure of 3 kg/cm^2. Mountings such as main steam stop valves, air vent valve, single port spring loaded safety valve, blow down valve, non-return valve on feed water line, isolating needle valves for indicating instruments etc. are provided in the steam generator. For instrument control and safety steam pressure indicator, steam pressure switches for heat on/off, water level controller for auto on–off of the feed pump, audiovisual alarm for low water safety lockout and gauge glass assembly are also provided. The steam flow rates are measured by means of a steam flow meter installed in the steam feeding pipe line of the reactor. A secondary combustor provided at the outlet of the gasifier burns the product gas fully before leaving it to the atmosphere. The flue gas after combustion was cooled to a temperature of 250–300 °C in a dilution chamber and then left to atmosphere through an exhaust chimney.

A gas sampler fabricated in the laboratory was installed near the top end of the gasifier reactor. A number of gas sampling ports. The gas sampler consists of a 20 liter capacity stainless steel tank with fiber filter, air vent valve and sample gas inlet and outlet valves. A pulley with wire rope arrangement provides up and down movement of the water tank for collecting the gas samples by water displacement method. The hot product gas after passing