Fuel 112 (2013) 494–501

Contents lists available at SciVerse ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Experimental results of gasification of cotton stalk and hazelnut shell in a bubbling fluidized bed gasifier under air and steam atmospheres

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HIGHLIGHTS

- The quality of the product gas increases with decreasing ER.
- The LHV–ER correlations are developed.
- Hazelnut shell is more sensitive to the variation in ER than cotton stalk.
- Steam to fuel ratio hardly changes the LHV.
- Steam consumption can be kept at the lowest.

ARTICLE INFO

Article history:
Received 22 February 2013
Received in revised form 26 March 2013
Accepted 11 April 2013
Available online 25 April 2013

Keywords:
Gasification
Fluidized bed
Biomass
Cotton stalk
Hazelnut shell

ABSTRACT

Gasification converts solid fuel into product gas which can be used in various applications. The product gas can be combusted to generate heat and electricity. It can also be used as a feedstock for the production of synthesis gas, liquid fuel and chemicals. This paper presents the experimental results of gasification of cotton stalk (C.S.) and hazelnut shell (H.S.) in a laboratory scale bubbling fluidized bed gasifier under air and steam atmospheres. The effects of equivalence ratio (ER) and steam to fuel ratio on the quality of the product gas are investigated for the air and steam atmospheres, respectively. Identical tests are conducted to investigate the repeatability of experimental results. The composition of the product gas is determined with an online gas analyzer which measures CO, CO_2, CH_4, H_2 and O_2 components. The lower heating value (LHV) of the product gas is calculated by using the gas composition measurements. The LHV is obtained in the range of 2.49–11.28 MJ/Nm^3. In the case of air gasification, the ER is varied in the range of 0.71–0.36 and 0.68–0.25 for the cotton stalk and hazelnut shell cases, respectively. The ER significantly affects the LHV for hazelnut shell. In the case of steam gasification, the steam to fuel ratio is changed in the range of 1.69–0.52 and 2.26–0.33 for the cotton stalk and hazelnut shell cases, respectively. The steam feeding rate can be maintained at minimum because it slightly changes the LHV.

1. Introduction

Gasification process is used to obtain a product gas from a solid fuel such as coal or biomass. The product gas is mainly composed of CO, CO_2, CH_4, H_2, O_2 and N_2 gases. The product gas also contains particulates, tar, ammonia and hydrogen sulfide in minor amounts. Since these compounds cause blockage and corrosion problems, they should be eliminated in-bed (in situ) or post-bed (downstream). After being subjected to an appropriate cleaning process, the product gas can be used to generate electrical energy by using a fuel cell, gas turbine or gas engine. Apart from the energy production, the product gas can also be used to produce a liquid fuel through a synthesis process.

Bubbling fluidized bed is one of the most widely used technologies for moderate capacities with low investment costs. It operates at lower temperatures than entrained bed. It has lower agglomeration and corrosion potentials than circulating fluidized bed. It provides good air and fuel mixing, produces less tar and is more tolerant to fuel type than fixed bed. In addition, bubbling fluidized bed has high heat transfer characteristics and high scale-up potential.

Gasification of biomass for the generation of product gas has attracted many researchers because biomass is abundant, widely available, carbon neutral and renewable. In general, three types of biomass resources were taken into consideration: Forestry, agricultural and fruit residues.

Kar and Tekeli [1] reported that Turkey's annual biomass energy potential was 32 Mtoe (million tons of oil equivalent). They also reported that the available annual cotton stalk and hazelnut shell productions were 1,512,169 and 453,150 tons in 2003,

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http://dx.doi.org/10.1016/j.fuel.2013.04.025

respectively. Therefore, Turkey's cotton stalk and hazelnut shell residues can be considered as potential biomass resources for gasification.

Many researchers investigated the gasification of forestry residues in fluidized bed. Several of them used air as a gasification agent. Narvaez et al. [2] gasified sawdust under air atmosphere by using silica sand as a bed material. They changed the equivalence ratio from 0.28 to 0.47. Kaewluan and Pipatmanomai [3] gasified rubber wood chip under air atmosphere. They used silica sand and varied the ER between 0.32 and 0.43. Campoy et al. [4] performed gasification experiments on wood under air atmosphere by using ofite as a bed material. They kept the ER at 0.35. Hanping et al. [5] studied gasification of sawdust with air for the ER range of 0.15–0.35.

Some other researchers used either steam or air and steam mixture as a gasification agent. Turn et al. [6] gasified sawdust under steam atmosphere by using alumina as a bed material. They varied the steam to fuel ratio between 1.1 and 4.7. Cui et al. [7] gasified leucaena under steam atmosphere. They used alumina and kept the steam to fuel ratio at 2.0. Lv et al. [8] and Pinto et al. [9] gasified sawdust and pine, respectively, and used air and steam mixture as a gasification agent and utilized silica sand as a bed material.

Much research has also been done on agricultural residues. Boateng et al. [10] gasified rice hull under steam atmosphere by using the mixture of 75% of silica sand and 25% of limestone as a bed material. Sun et al. [11] and Sun et al. [12] investigated the combustion of Chinese cotton stalk in circulating and fluidized bed combustors, respectively. They [11,12] reported that cotton stalk could be a potential biomass fuel in energy production. Chen et al. [13] performed thermogravimetric analysis (TGA) of Chinese cotton stalk with a carbon content of 42.49%. Putun et al. [14] investigated the pyrolysis of Turkish cotton stalk having a carbon content of 48.89%, on dry basis, in a fixed bed Heinze reactor. They also conducted thermogravimetric (TG) and derivative thermogravimetric (DTG) analyses under nitrogen atmosphere. In conclusion, no one investigated the gasification of Turkish cotton stalk in a fluidized bed under air and steam atmospheres.

Few researchers investigated the gasification of fruit residues. Mohammed et al. [15] gasified empty fruit bunch of oil palm in fluidized bed under air atmosphere. They used silica sand as a bed material and varied the ER from 0.15 to 0.35. Rapagna et al. [16] conducted gasification experiments on almond shell in fluidized bed under steam atmosphere. They used silica sand and kept the steam to fuel ratio at 1.0. Dogru et al. [17] investigated the gasification of Turkish hazelnut shell having a carbon content of 46.76%, on dry basis, in a downdraft fixed bed gasifier under air atmosphere.

Although many researchers studied the gasification of various forestry, agricultural and fruit biomass samples, the published work on gasification of cotton stalk and hazelnut shell in fluidized bed is scarce. This work aims to fill this void in the literature. Hence, the present study investigates the gasification of cotton stalk and hazelnut shell in a bubbling fluidized bed gasifier under air and steam atmospheres by using silica sand as a bed material. This work focuses on the effects of equivalence ratio (ER) and steam to fuel ratio on the quality of the product gas for the air and steam cases, respectively.

2. Experimental set-up

The gasification experiments were performed in an atmospheric pressure bubbling fluidized bed gasifier [18]. Fig. 1 shows the schematic drawing of the experimental facility. The gasification reactor had a thermal capacity of 20 kW, a height of 2.29 m and an inner diameter of 82 mm. The reactor was made of stainless steel AISI 310S. Four thermocouples, T/C-1, T/C-2, T/C-3 and T/C-4, were installed to measure the temperature at the axis of the reactor. The thermocouples were type K, NiCr–Ni. Two electrical furnaces were used to heat the reactor. The furnaces circumferentially wrapped the reactor pipe, and were controlled by using the thermocouples, T/C-2 and T/C-3, and the PID control units.

Two screw feeders, positioned one on top of the other, were used to feed the biomass fuel to the reactor. The bottom screw feeder was passed through the hopper in which the biomass sample was stored. The fuel feeding rate was controlled by changing the revolution speed of the top screw feeder. Meanwhile, the bottom screw feeder was turned at a constant rate. Both motors had their own speed controller units. The nitrogen was used to facilitate the biomass feeding and supplied from a cylinder. A rotameter with a measurement range of 0–150 (slpm) was used to measure the nitrogen flow.

In this work, two different gasification agents were used: Air and steam. The air was supplied from an air compressor and fed into the reactor at ambient temperature. The flow rate of air was measured by using a rotameter. The measurement range of the rotameter was 0–150 (slpm). The steam was supplied from a steam generator which produces saturated steam. Therefore, in addition to the generator, an electrical heater was used to obtain superheated steam. The thermocouple T/C-5, positioned at the end of the steam supply line, and a temperature controller were used to control the steam temperature. The mass flow rate of the steam was determined by using a precision weight scale and a chronometer to measure the discharged mass and time, respectively. Before fed to the reactor, the gasification agent was passed through a wind box and a distributor plate. The wind box was used to straighten the flow. The distributor plate has 180 holes with a diameter of 2 mm. The holes were arranged in a circular pattern.

When the product gas leaves the gasifier, it flows into the cyclone where the solid particles in the product gas are captured. A T-junction and a valve were set at the cyclone outlet pipe. An ancillary flow line was connected to this junction. The flow of product gas to the gas analyzer was performed with a vacuum pump. The gas sample was passed through first a perlite column, then a silica gel bed and finally a glass wool bed. The last two filters were filled into the arms of a U glass tube, which is immersed into a cooling tank, to cool the gas. The cooling tank was cooled by means of a water cooling bath. A commercial gas analyzer is used to measure the CO, CO_2, CH_4, H_2 and O_2 gases in volume fraction. The gas analyzer uses a non-dispersive infrared absorption technique to measure the concentrations of the CO, CO_2 and CH_4. The analyzer performs a thermal conductivity measurement to obtain the H_2. The analyzer measures the O_2 on the basis of the specific paramagnetic behavior of oxygen. The N_2 component of the product gas is calculated by subtracting the sum of the CO, CO_2, CH_4, H_2 and O_2 from 100.

3. Experimental methodology

In the present study, two different types of Turkish biomass feedstocks were gasified: Cotton stalk and hazelnut shell. These biomass samples were commercial products of local companies. Table 1 shows the proximate analysis, ultimate analysis and calorific value of the cotton stalk and hazelnut shell samples on dry basis.

Table 2 shows the matrix of experiments. Silica sand, which is composed of SiO_2, Al_2O_3 and Na_2O of 99.2%, 0.5% and 0.1%, respectively, was used as a bed material. The bed material had a mean particle size of 450 μm, a weight of 1082 g and a static height of 152 mm. The particle sizes of the cotton stalk and the hazelnut shell were 0.5–2.0 and 0.2–2.0 mm, respectively. The fuel feeding