Journal of the Energy Institute xxx (2015) 1–8

Contents lists available at ScienceDirect

Journal of the Energy Institute

journal homepage: http://www.journals.elsevier.com/journal-of-the-energy-institute

Effects of air staging on emission characteristics in a conical fluidized-bed combustor firing with sunflower shells

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A R T I C L E I N F O

Article history:
Received 25 August 2015
Received in revised form
28 November 2015
Accepted 1 December 2015
Available online xxx

Keywords:
Air-staged combustion
Fluidized-bed combustor
Sunflower shells

A B S T R A C T

This paper presents experimental results investigated from combustion of sunflower shells in a conical fluidized-bed combustor at feed rate 45 kg/h. Effects of operating parameters, such as excess air (EA) and secondary air to total air ratio (S/T) on combustion performance and emission characteristics of CO, C_xH_y and NO as well as combustion efficiency (η_c) were studied. Temperature and gas concentrations were measured along the combustor and at the outlet. The secondary air was tangential injected to the combustor at 0.5 m above the fuel feeding system and it was supplied at S/T = 0–0.4 for EA of 20–80%. The high combustion rates were found into two different zones of the combustor; in the bed region with the primary air and in freeboard region which were evidenced by two peaks of C_xH_y and CO concentrations. According to Thailand emission standard, the optimum operating condition to control CO and NO emissions at the quite high combustion efficiency (~99%) seems to be EA at 40–60% and S/T = 0.3. Compared with conventional combustion, air staged combustion can reduced the NO emission by 27% when the combustor was operated at EA = 40% and S/T = 0.3. However, CO and C_xH_y emissions were apparently high.

1. Introduction

In Asian countries, the non-plant biomass fuels from agricultural residues and manufacturing waste were widely used for energy and power generations. As reported by Food and Agriculture Organization of the United Nation in 2012 [1], about 5.75 million tons of sunflower seeds are produced in Asia (or about 15% of world crop), the main suppliers being China 2.37 million tons and Turkey 1.37 million tons. Based on the availability and calorific values of sunflower shells (assessed as 17 MJ/kg), the energy potential of this biomass fuel is annually estimated to be about 15.3 PJ.

Thailand is an agricultural country which also produces various types of agricultural wastes such as rice husk, bagasse, corncob, peanut shells and sunflower shell. By using the appropriate technology, Thailand has the ability to replace old-fashion fossil fuel with biomass fuel. Sunflower shells are one of the alternative biomass fuels due to their moderate availability, cheap price and high heating value. Basically, sunflower shells are easy to accumulate as compared with the other unconventional biomass fuels such as: cassava root, rice straw and corn stalk because they are produced from the sunflower oil refinery process at about 26,000 t annually [2].

The three primary routes in combustion control for the reduction of NO emission in the fluidized combustion systems were reported to be i) lower the combustion temperature, ii) create a fuel rich condition in the bed region, and iii) lower the residence time which enhanced NO formation reactions [3–5]. Air staged combustion is widely considered to be one of the most effective technique for NO reduction [6]. By introducing the secondary air (SA) to the post-combustion zone (freeboard region), reaction rate of fuel particles with oxygen in the bed zone decreased and leaded to the low local gas temperature which retarded the intermediate reactions involving in NO formation [3,7]. Moreover, the greater quantities of unburned hydrocarbons (CO and C_xH_y) escaped to the freeboard and the higher carbon-char of biomass particles also enhanced the NO reduction reactions [6,8–10].

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http://dx.doi.org/10.1016/j.joei.2015.12.001
1743-9671/

A large number of research studies have conducted the experimental study to investigate the impact of the air staged combustion on NO emission for firing biomass in various laboratory scale fluidized-bed combustor (FBC) such as a pilot-scale bubbling FBC [10–12], a short combustion chamber FBC [13], a laboratory-scale swirling FBC [8,9], a pilot scale vortexing FBC [6,14] and circulating FBC [15,16].

In the vortexing FBC, Chyang et al. [6] conducted the experimental tests for firing corncob and found that, the NO emission could be reduced up to 15% by air staging technique when compared with direct combustion mode. From the experimental results, the trend of CO emission was inconsistent when the secondary to total air ratio (S/T) increased. CO emission significantly increased from about 10 to 100 ppm at increasing of S/T from 0 to 0.375 while it was decreased from about 100 to 60 ppm for the higher range of S/T (0.375–0.5). Meanwhile, NO emission gradually decreased from about 115 ppm to 55 ppm for increase of S/T. The effect of S/T on NO emission was also supported by the studies conducted by Kuprianov et al. [8]. However, the effects of SA injection on NO emissions seemed to be small in their experimental tests which conducted in the range of secondary to primary air ratio (S/P) 0.26–0.75 and EA 40% when firing rice husk.

In the bubbling FBC, the effect of SA injection on the temperature and gas composition profiles as well as emissions were investigated by Tarelho et al. [10], Okasha F. [11] and Varol and Atimtay [12] for firing biomass waste, rice straw, and olive cake respectively. The experimental results from Ref. [12] showed the significant effects of SA on temperature profiles, CO and C_xH_y emissions meanwhile NO emissions were almost independent from the SA injection. CO and C_xH_y emissions decreased with the increasing of SA at the fixed excess air because of the higher temperature and more amount of available air in the freeboard which contrasted with the experimental results reported by Ref. [11]. With increasing secondary air, the reactions of NO with CO and C_xH_y as well as the lower bed and freeboard temperature were responsible for NO reduction. While the bed temperature was variable in the experimental tests of Ref. [12], it was fixed at 750 and 800 °C in the experimental study conducted by Ref. [10]. In the tests the secondary to primary air ratio was maintained at 20:80 while the total excess air was varied from 10 to 100%. From the experimental procedure, the decrease of CO and NO concentrations was found between the bed surface (splash region) and the location near the SA injection. The reduction of CO could be explained by the conversion of CO to CO_2 and dilution effect, and the major reason for NO reduction was dilution effect.

As revealed from the literature, no effect of SA on the combustion and emission performances for firing sunflower shells in a FBC was investigated. Therefore, this study was aimed to study the effects of operating conditions (secondary to total air ratio and excess air) on combustion characteristics and emission performance of the conical FBC. Gas temperature and detail measurements of local O_2, CO, C_xH_y and NO concentrations were gathered along the combustor height as well as at the cyclone outlet. The combustion efficiency was also focused in this study.

2. Materials and methods

2.1. Experiment set-up

Fig. 1 shows the schematic diagram of an experimental set-up with the conical fluidized-bed combustor, a cyclone system for ash collector, a screw-type fuel feeder, a 25-hp primary air blower and a 5-hp secondary air blower. The combustor consisted of a conical module with 0.9 m height, 0.25 m inner diameter and 40° cone angle at the bottom part, and five cylindrical modules of 0.5 m height and 0.9 m inner diameter at the top part. The combustor was completely insulated to avoid the convection and radiation heat losses. A 19-bubbling-cap air distributor was located at the lower part of the combustor to supply primary air for fluidizing bed particles in the conical section.

The biomass fuel was fed to the combustor at 0.65 m above the air distributor. For secondary air injection, the ambient air was supplied through two tangential connected pipes with 0.04 m inner diameter at level of 1.12 m above the air distributor. The temperatures were measured with the seven stationary K-type thermocouples along the combustor height, at 0.2 m, 0.6 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m and 3.0 m above the air distributor. The gas samples were taken from the seven sampling ports located at nearly the same levels as temperature and another one at the flue gas outlet (see Fig. 1). The U-tube manometers connected to the upstream and downstream sides of orifice plates were used to measure volume flow rates of primary and secondary air supply to the combustor. A cyclone was used to separate fly ash particles from the flue gas for analyzing carbon content. Finally, the percent of carbon content in fly ash was used to determine heat loss due to unburned carbon.

2.2. Fuel and bed characteristics

Empty sunflower seed shell has the teardrop shape and the dimensions of around 3 mm width and 10 mm length. The characteristics of sunflower shells are shown in Table 1. The proximate analysis is shown on as-received basis meanwhile the ultimate and structural analyses are presented on dry and ash-free basis. As any other biomass fuels, the value of volatile matter (VM) was significant at 71.1% and the fixed carbon (FC) was moderate at 17.4%. The solid density of sunflower shell was $\approx 600 \pm 15$ kg/m^3. From the structural analysis, the sunflower shells were composed of hemicellulose (15.7 wt.%), cellulose (45.8 wt.%), lignin (24.5 wt.%) and some minor extractives.

Table 2 shows the composition of sunflower shell ash (as wt.% of oxide). As seen in the table, the major components of sunflower shell ash were potassium oxide and some significant amount of calcium oxide, followed by magnesium oxide and sulfur oxide. Aluminum, silicon, iron, chlorine and phosphorus were represented by substantially lower percentages of their oxides.

When using the silica sand as bed material, the fractions of K in fuel ash composition were reported to have the significant role on bed agglomeration and led to the defluidization of biomass combustion in FBC system [17]. However, this fuel ash also contained the significant amounts of calcium and magnesium, which was reported to increase the ash and ash/bed melting temperatures and to reduce the risk of bed agglomeration problem [18,19]. Silica sand ($SiO_2 = 99.5$ wt%) with solid density ≈ 2500 kg/m^3 and particle size 0.3–0.5 mm was used as bed material at the static bed height of 30 cm and to avoid the bed agglomeration, it was replaced every 18 h of use.

2.3. Experimental planning

To compare the emission performance of the combustor when performing air staged combustion, the normal combustion with no SA was also investigated at the same excess air and fuel feed rate. The sunflower shells were burned at the fixed feed rate (FR), 45 kg/h, excess air