Biomass and Bioenergy 112 (2018) 73–84

Contents lists available at ScienceDirect

Biomass and Bioenergy

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

Research paper

Fluidized bed co-combustion of rice husk pellets and moisturized rice husk: The effects of co-combustion methods on gaseous emissions

Pichet Ninduangdee[a], Vladimir I. Kuprianov[b,*]

[a] Division of Mechanical Engineering, Faculty of Engineering and Industrial Technology, Phetchaburi Rajabhat University, Phetchaburi, 76000, Thailand
[b] School of Manufacturing Systems and Mechanical Engineering, Sirindhorn International Institute of Technology, Thammasat University, P.O. Box 22, Thammasat Rangsit Post Office, Pathum Thani, 12121, Thailand

ARTICLE INFO

Keywords:
Rice husk
Fluidized-bed combustor
Co-firing techniques
Co-firing optimization
NO emission reduction

ABSTRACT

This work explores the potential of three co-combustion methods for reducing NO_x in a fluidized-bed combustor. Pelletized rice husk (base fuel) was co-fired with moisturized rice husk (secondary fuel) in this reactor using silica sand as the bed material. Four groups of experiments for (1) conventional combustion of rice husk pellets, (2) co-firing pre-mixed fuels, (3) co-firing using fuel staging with bottom air injection, and (4) co-firing using a reburning method combining fuel staging and air staging, were performed at a 200 kW heat input to the reactor. In the test series, the energy fraction of the secondary fuel in the total fuel supply (EF_2) was within 0–0.25, with excess air (EA) varying from 20% to 80% at given EF_2. During the reburning tests, the secondary-to-total air ratio (SA/TA) ranged from 0.1 to 0.4, at each EA. The findings revealed that the effects of EF_2, EA, and SA/TA on the combustion and emission characteristics of the reactor were substantial. An optimization analysis was performed to determine the optimal EF_2, EA, and SA/TA, leading to minimal emission costs of the applied co-firing techniques. Under optimal operating conditions, the combustor ensures high (~99%) combustion efficiency with minimum emission costs and reduced NO emission: by about 13% when co-firing pre-mixed fuels, by 37% for the fuel-staged co-combustion, and by 53% when using reburning, as compared to 167–176 $cm^3\ m^{-1}$ from burning the base fuel alone. However, some increase in the CO and C_xH_y emissions was observed when using the proposed co-firing techniques.

1. Introduction

In Thailand, rice husk is an important biomass energy resource, showing an energy potential of 93 PJ per year, mainly because of great availability and the relatively high calorific value of this agricultural residue [1]. Due to some advantages over grate firing and pulverized fuel firing techniques, bubbling, circulating, vortexing, and swirling fluidized-bed combustion systems (combustors/furnaces) are effective for converting rice husk into energy, mainly because of excellent solid – gas mixing, temperature homogeneity and effective emission control [2–6]. However, pioneering studies on these combustion systems have reported difficulties in achieving high combustion efficiency and controlling CO and NO_x emissions, mainly because of elevated fuel-N and fuel-ash contents. In spite of moderate bed temperatures (typically, below 850 °C), the NO_x emissions from the above-listed fluidized-bed combustors were elevated, up to about 200 $cm^3\ m^{-3}$, while the CO emission was within 800 $cm^3\ m^{-3}$ (both at 6% O_2 on a dry gas basis). The combustion efficiency of properly designed and operated fluidized-bed combustion systems was 96–98%. Some studies on circulating, vortexing, and swirling fluidized-bed combustors showed weak effects of air staging on NO_x and CO emissions when burning rice husk [4–6]. However, the use of flue gas recirculation in the vortexing fluidized-bed combustor resulted in relatively low NO_x emissions, 65–83 $cm^3\ m^{-3}$ (at 11% O_2 on a dry gas basis), mainly because of the lowered bed temperature (about 700 °C) and dilution effects from the recycled flue gas [7].

A cyclonic fluidized-bed combustor, ensuring biomass oxidation in a strongly swirled flow, has been developed for firing rice husk [8]. High, over 99%, combustion efficiency was achieved with this technique when burning rice husk under optimal operating conditions, mainly due to the reduced CO emission, below 400 $cm^3\ m^{-3}$ (at 6% O_2 on a dry gas basis). However, the NO_x emissions from the cyclonic fluidized-bed combustor were high, 350–425 $cm^3\ m^{-3}$, likely because of the high combustion intensity (or heat release rate per unit combustor volume) and elevated excess air, as compared to other fluidized-bed combustion systems.

Co-firing (or co-combustion) of two or more fuels with different properties is one of the most effective ways of improving the emission

* Corresponding author.
E-mail address: ivlaanov@siit.tu.ac.th (V.I. Kuprianov).

https://doi.org/10.1016/j.biombioe.2018.02.016
Received 2 August 2017; Received in revised form 5 January 2018; Accepted 19 February 2018
0961-9534/

performance of a combustion system, while maintaining its combustion efficiency at a relatively high level. Some related studies on grate-firing, pulverized fuel-firing, cyclone-firing, and fluidized-bed combustion systems revealed that the co-firing is flexible for fuel type (coal, biomass, RDF, combustible wastes, etc.) and combustion method [9–12]. However, the combustion and emission performance of a combustion system was affected by the method of fuel injection into the combustor/furnace.

A large number of studies on the co-firing of coal and biomass, commonly used as blended fuels in modified pulverized coal-fired boilers, have reported a reduced (net) production of CO_2, as well as a noticeable reduction in NO_x and SO_2 emissions, compared to burning coal on its own [11–16]. Limited knowledge, regarding the co-firing of biomass with another biomass in a single fluidized-bed combustion system, is reported in the literature. However, some pilot studies revealed that biomass–biomass co-firing systems can effectively utilize problematic fuels (e.g., with unacceptable emission characteristics and/or very low calorific value) with lower emissions of NO_x, compared to burning the base fuel alone [17,18].

Fuel-staged combustion methods, such as fuel biasing and reburning, have been proposed to reduce NO_x in various combustion systems (co-)fired with coal/biomass. When using fuel biasing (a type of fuel staging), the base fuel is injected into the main (or primary) combustion zone together with combustion air, whereas the rest of the fuel or another fuel is added downstream of the primary zone with no air supply [19]. As a result, chemical reactions occurring in the secondary zone generate precursors (radicals) to participate in the reduction of NO_x, previously formed in the primary zone. A recent study on the co-firing of palm kernel shell (primary fuel) and high-moisture empty fruit bunch (secondary fuel) in a fluidized-bed combustor has revealed a 35% NO emission reduction that was achieved via the use of fuel-staged combustion with bottom air injection. However, the NO_x reduction level was found to depend on the mass/energy share of the secondary fuel and excess air used [20].

A reburning method has been suggested as one of the most effective solutions to reduce NO_x emissions from different combustion systems. This method is, in fact, a combination of fuel staging and air staging [10]. The relevant processes occur within three sequent zones of the reactor: (i) primary zone where primary (main) fuel burns, (ii) reburn zone where the reburn (secondary) fuel is injected into the reactor to create fuel-rich conditions, resulting in a reduction of NO_x formed in the preceding zone, and (iii) burnout zone, where the burnout (secondary) air is introduced for achieving complete combustion [21,22]. The reburning method has been extensively studied on large-scale pulverized coal-fired boilers and grate-fired biomass-fueled systems, with different types of reburn fuel. Some pioneering studies have reported that up to 70% NO_x reduction can be achieved with this method, with no adverse effects on the operation of a combustion system [21–24]. However, very limited information on applications of both fuel staging and reburning in fluidized-bed systems co-firing different types of biomass has been reported in the literature.

The main purpose of this work was to explore the potential of three co-firing methods: (i) burning pre-mixed fuels, (ii) using fuel staging with bottom air injection, and (iii) using reburning, with the aim to reduce the NO_x emissions of a fluidized-bed combustor co-fired with pelletized rice husk (PRH) and moisturized rice husk (MRH). Effects of operating conditions on the behavior of major pollutants (CO, C_xH_y, and NO) in different reactor regions, as well as on the emissions and combustion efficiency of the combustor, were compared for the proposed co-combustion methods. Special attention was given to the optimization of operating parameters, minimizing the emission costs of the co-firing techniques. The novelty of this work is knowledge on the influence of the selected co-combustion methods on the extent of NO emission reduction, as well as practical guidelines on optimal operating conditions, during biomass – biomass co-firing in fluidized-bed combustion systems.

2. Materials and methods

2.1. Experimental setup

A fluidized-bed combustor with a cone-shaped bed (referred to as a 'conical FBC') was used in this study. The experimental setup, including the conical FBC and auxiliary equipment (two air blowers, two screw-type fuel feeders, a cyclone for collecting particulate matter, and a diesel-fired start up burner), is shown in Fig. 1. The combustor consisted of two steel sections assembled coaxially: (1) a conical section of 0.9 m height with 40° cone angle and 0.25 m inner diameter at the bottom plane, and (2) a cylindrical section of 2.5 m height and 0.9 m inner diameter. A more detailed description of the combustor's configuration has been provided in previous studies on individual firing of biomass with this combustion technique [25,26].

In the current work, during the test runs for individual firing PRH and co-firing pre-mixed PRH and MRH, the base fuel and the biomass mixtures were supplied into the reactor by using a single fuel feeder located at level $Z = 0.6$ m above the air distributor, whereas the combustion air was injected into the bottom (conical) section of the conical FBC by an 18.7 kW air blower through the air distributor at the reactor bottom. The air distributor, comprising nineteen bubble-cap standpipes (closely arranged on the distributor plate), induced fluidization of the bed material in the conical section. Each stand pipe had 64 holes of 2 mm in diameter, evenly arranged over the pipe outer surface, and six vertical slots (15 mm × 3 mm in sizes) at the top of the pipe. The proposed design of the air distributor ensured quite uniform distribution of airflow over the bed (i.e., avoiding bed spouting) with an insignificant pressure drop across the device [26].

To perform co-firing tests for fuel staging and reburning methods, the combustor was additionally equipped with a secondary fuel feeder and a secondary air system (the latter was used in reburning tests). During the tests of these two groups, primary and secondary fuels were delivered separately into the reactor by the two screw-type fuel feeders, as shown in Fig. 1. The primary fuel was injected into the fluidized bed at $Z = 0.6$ m above the air distributor, whereas the secondary fuel was introduced into the cylindrical section of the combustor, at $Z = 1.15$ m, by a secondary fuel feeder. Primary (or fluidizing) air was injected into the bed by the above-mentioned 18.7 kW air blower through the air distributor, whereas in reburning tests, the secondary air (SA) was tangentially introduced into the reactor at $Z = 1.65$ m by a secondary 3.7 kW blower.

2.2. Fuels and bed material

As shown in previous studies on fuel-staged biomass co-combustion with bottom air supply, a substantial reduction of the NO_x emissions can be achieved when primary and secondary biomass fuels comply with two major requirements [20,27]. Firstly, the calorific value of a primary fuel should be noticeably higher than that of the secondary fuel, mainly due to substantial moisture content in the secondary fuel. This requirement ensures stable and high-efficiency combustion in the primary combustion zone, avoiding a high temperature peak inside the reactor. Secondly, it is desirable (but not compulsory) to use a secondary fuel with the fuel-N content lower than that in the primary fuel, to prevent intensive NO formation in the secondary combustion zone. With the use of reburning, the NO_x reduction is expected to be more significant, as compared with the fuel-staged co-combustion, mainly due to the more active mitigation of NO formation reactions and strengthening of secondary (NO reduction) reactions in the primary and reburn zones.

In this work, pelletized rice husk (PRH) was used as the base (primary) fuel, while low-calorific moisturized rice husk (MRH) was selected to be the secondary fuel. PRH was supplied by a local company manufacturing pelletized biomass fuels. Prior to the pelleting process that used a flat-die fuel pellet machine, "as-received" rice husk was