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Experimental study on rice husk combustion in a vortexing fluidized-bed with flue gas recirculation (FGR)

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HIGHLIGHTS

- ▶ The combustion behavior of rice husk in a vortexing fluidized-bed combustor (VFBC) is studied.
- ▶ Under optimal operation condition, the combustion efficiency of rice husk can reach 99%.
- ▶ Effect of FGR can be attributed to the dilute effects, thermal effects, and chemical effects of CO_2.
- ▶ There is an inverse dependency between the NOx and CO concentrations at the exit of VFBC.

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ABSTRACT

Vortexing fluidized-bed combustor (VFBC) has been proven to be an effective equipment in converting biomass wastes into clean energy. This study conducted experiments on rice husk combustion in a VFBC with FGR. The effect of FGR on combustion characteristics is investigated. In addition, the effect of operating variables such as excess oxygen ratio, and in-bed stoichiometric oxygen ratio on the temperature distributions, pollutants emissions, and combustion efficiency are also studied. The results show that the combustion efficiency of rice husk can reach 99% at optimal operation condition. CO emission increases with the in-bed stoichiometric oxygen ratio, but decreases with excess oxygen ratio. NOx emissions show inverse trend, and it can be effectively reduced by using FGR in the VFBC.

1. Introduction

The global energy demand has been continuously rising due to the population growth and the improved living standards in developing countries, especially in China. In addition, the major pollutant emissions released from the combustion of fossil fuels have forced people to find cleaner and renewable energy sources. Biomass such as rice husk, abundant in rice-growing countries, is considered to be an ideal alternative energy.

Rice is one of the world's most important staple crops. Its production is ranked third among the major agricultural crops. China produces about one third of rice in the world. According to the statistical data from FAOSTAT, China's annual yield of rice in 2010 reached more than 200 million tons. Rice husk and straw are the largest agricultural residues in quantity, and China's annual yield of rice husk is about 60 million tons. However, rice husk with high ash content and small particle sizes is not suitable for the traditional combustion methods.

Fluidized bed combustion (FBC) is recognized as one of the most promising technologies in dealing with rice husk combustion. Many experimental studies have been carried out to understand the combustion behavior and pollutant emissions of rice husk combustion in FBC. Fang et al. (2004), Armesto et al. (2002) studied the combustion characteristics of rice husk in a FBC. They concluded that the gas velocity and staged air inputs have great effect

Abbreviations: VFBC, vortexing fluidized bed combustor; FGR, flue gas recirculation; LHV, lower heating value; FBC, fluidized bed combustor; CFB, circulating fluidized bed; ID fan, induced draft fan; E_o, excess oxygen ratio (%); S_b, in-bed stoichiometric oxygen ratio (%); V_{1st}, volumetric flow rate of primary air (N m^3 min^{-1}); V_{FGR}, volumetric flow rate of FGR (N m^3 min^{-1}); C_{FGR}, oxygen concentration of FGR at the outlet of ID fan (%); V_{PRI}, volumetric flow rate of primary gas (N m^3 min^{-1}); V_{2nd}, volumetric flow of secondary gas (N m^3 min^{-1}); V_T, volumetric flow rate of total gas (N m^3 min^{-1}); V_{TO}, volumetric flow rate of oxygen in the primary gas (N m^3 min^{-1}); T_b, bed temperature (°C), E_F, rate of energy input as carbon in the fuel (kg h^{-1}); E_{loss}, rate of energy loss as carbon in the ash from the baghouse (kg h^{-1}); E_{fg}, rate of energy loss as carbon monoxide in the flue gas (kg h^{-1}).

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on rice husk combustion. Kuprianov et al. (2010) investigated the effect of moisture content on the pollutant emissions. Their study showed that the increasing rice husk moisture content can reduce the concentration of NO emission. Ghani et al. (2009), Madhiyanon et al. (2009, 2011, 2010) presented that the co-combustion of a mixture of rice husk and coal in a FBC designed for coal combustion increased combustion efficiency by up to 20% depending upon excess air levels. They also found that CO, NOx, SO_2 emission concentrations decrease with the increase in rice husk mixing ratio.

In addition, some modified FBCs were introduced to improve fluidized bed rice husk combustion. Permchart and Kouprianov (2004) studied the combustion behavior in a conical fluidized-bed combustor. The main benefits of the cone-shaped fluidized bed are: (i) reduced start-up time and (ii) a smaller pressure drop across the bed (Kaewklum and Kuprianov, 2008; Sathitruangsak et al., 2009). Janvijitsakul and Kuprianov (2008), Kaewklum and Kuprianov (2010), Martínez et al. (2011) Madhiyanon et al. (2009) develop a swirling fluidized bed which created vortexing effect in the bottom part of the reactor. This can increase the combustion efficiency by preventing the growth of large bubbles. Albina (2006) investigated the emissions of CO and CO_2 using rice husks as the fuel in different configurations of spout-fluidized beds, namely, multiple-spouted and spout-fluid fluidized bed.

From the results of these studies, CO and NOx are the major pollutants emitted from rice husk combustion. Compared with other combustors, FBC has lower NOx emissions; this can be attributed to lower operating temperatures (700–900 °C) which significantly reduce the emission of thermal NOx and prompt NOx. When burning rice husk in FBC systems, NOx in the flue gas mainly comes from the conversion of fuel-N via homogeneous oxidation of the dominant nitrogenous volatile species to fuel-NOx (Abelha et al., 2008; Kilpinen and Hupa, 1991; Kuprianov et al., 2011; Werther et al., 2000; Winter et al., 1999). CO emission is a function of operating variables, such as excess oxygen ratio, bed temperature, and secondary gas ratio (Permchart and Kouprianov, 2004).

The concept of VFBC is introduced to create a vortex by injecting a secondary gas tangentially into the freeboard to increase the combustion intensity. This system improved the combustion performance of FBC (Chyang et al., 2012, 2008). VFBC has been used for coal combustion studies for many years, but few have focused on its application in rice husk combustion.

Flue gas recirculation (FGR) has been widely accepted as an effective solution for reducing NOx emissions. Some studies focused on the reduction of NOx emissions by FGR in the cases of coal combustion (Hayashi et al., 2002; Hosoda et al., 1998; Okazaki and Ando, 1997). However, reports of biomass FBC with FGR are few. The main purpose of this study is to investigate the combustion behavior and pollutant emissions of rice husk combustion in a VFBC with FGR. The effect of variables such as excess oxygen ratio, and in-bed stoichiometric oxygen ratio on the temperature distributions, pollutants emissions, and combustion efficiency are also studied.

2. Methods

2.1. Materials

Silica sand (99.5% SiO_2) was employed as the inert bed material. The mean particle size of the silica sand was 0.59 mm. Rice husk was used as the fuel. The feeding rate was kept at 40 kg/h in this study. The proximate analysis data such as moisture, volatile, fixed carbon and ash are 10.40%, 63.34%, 15.54%, and 10.72%, respectively. The ultimate analysis data of rice husk such as C, H, O, N, S, and Ash are 41.28%, 5.84%, 41.63%, 0.34%, and 0.19%, respectively. The higher heating value is 18,083 kJ/kg.

2.2. VFBC test facility

All the experiments were conducted in a VFBC test facility. A process flowchart of the VFBC system consists of a combustor with a windbox, a feeding system, heat convection sections, an air supply system and a flue gas treatment system as shown in Fig. 1. Fig. 2 shows the configuration of the VFBC. The VFBC with a cross section of $0.8 \times 0.4\ m^2$, a freeboard with an inner diameter of 750 mm, and 4.6 m in total height is fabricated of SS41 steel. Refractory bricks and ceramic fibers were used for thermal insulation. Four equally spaced secondary gas injection nozzles of 30 mm in diameter are installed tangentially at the level of 2.05 m above the air distributor. The secondary gas is preheated to about 200 °C with exhaust heat from the combustor before entering the windbox. After preheating, the secondary gas expands, resulting in higher gas velocity in the freeboard, which is helpful in promoting the gas mixing and solid retention.

FGR is used in this study. The primary gas is composed of the primary air and recirculated flue gas (FGR), and is injected into the combustor from the windbox. The primary air is supplied by a 15 hp Root's blower, and FGR is pumped by a 7.5 hp turbo blower. The secondary gas is made up of a mixture of air and pure nitrogen (from high-pressured nitrogen cylinders), and is pumped by a 7.5 hp Root's blower.

A Novatech oxygen analyzer 1632 (the precision is 1%) continuously measures the oxygen concentration of flue gas at the outlet of the ID fan. The temperature of flue gas pumped from ID fan ranges between 40 and 50 °C. The flow rate of FGR is controlled by the primary gas control system.

The temperatures in the VFBC are measured with K-type thermocouples installed in the combustor. As seen in Fig. 2, the bed temperature is controlled by an adjustable heat-transfer tube immersed in the bed, and its value is the average of the values taken from the four lateral distribution thermocouples located 0.45 m above the air distributor. The freeboard temperature is the average of the values from the three axial distribution thermocouples located 2.55, 2.80, and 3.00 m above the air distributor, respectively. The temperature of the combustor outlet is measured with a thermocouple located 4.5 m above the air distributor.

The flue gas was sampled at 0.85 and 4.5 m above the air distributor. The components of the flue gas, such as CO, CO_2, O_2, and NOx were analyzed by Anapol EU5000 gas analyzer. The values of the concentrations in this study are all corrected to 11% residual oxygen on a dry basis. The measurement accuracies of the gas analyzer with O_2, CO, CO_2 and NOx are 0.4%, 6%, 0.5%, and 1%, respectively.

2.3. Methods

The S_b is changed by changing the ratio of FGR in the flue gas. The following definitions were used:

$$S_b = \frac{Q_{TO}}{\text{Stoichiometric Oxygen}} = \frac{Q_{1st} \cdot 21\% + Q_{FGR} \cdot C_{FGR}}{\text{Stoichiometric Oxygen}} \tag{1}$$

To limit the cross effect of operation parameters, all of the experiments are conducted at a fixed primary gas flow rate of 3 Nm^3/min and a fixed secondary gas flow rate of 2 Nm^3/min, respectively. The oxygen concentration data of the flue gas at the outlet of induced draft fan were transmitted to the primary gas control system for adjusting the mixing ratio of the primary air and FGR to maintain the oxygen content in the primary gas at a set value. The flow rate of FGR can be calculated by the following equations:

$$V_{1st} + V_{FGR} = V_{PRI} \tag{2}$$

$$Q_{1st} \cdot 21\% + Q_{FGR} \cdot C_{FGR} = Q_{TO} \tag{3}$$