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Co-combustion of rice husk with coal in a cyclonic fluidized-bed combustor (ψ-FBC)

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ABSTRACT

Thailand is well-endowed with renewable energy resources. In Thailand, rice husk, a by-product of the rice-milling process and one of the most potentially sustainable cultivated biomasses, has an annual energy equivalent of 6.6×10^7 GJ. Using rice husk alone, however, can be problematic, particularly if there is a deficit during the off-season. Coal, the most abundant fossil fuel, has thus been considered an appropriate supplementary fuel. This paper describes the combustion characteristics of co-firing rice husk with bituminous coal in a 120 kW_{th}-capacity cyclonic fluidized-bed combustor (ψ-FBC), and how excess air ratios and fuel blends impacted emissions and combustion efficiency (E_c). Overall, excess air and blending ratios did not have tremendous effects on E_c, easily achieving >97%. Radial temperature profiles revealed that vortex combustion prevailed along the combustor walls. Concurring with axial temperature profiles, axial O_2 profiles suggested that the combustion was confined chiefly to regions under the vortex ring. Despite massive CO production in the lower section, CO emissions were satisfactory (range 60–260 ppm, at 6% O_2). Due to the high bed temperatures, NO_x appeared rather high (260–416 ppm, at 6% O_2). Not only were NO_x emissions affected by coal ratio, it were also highly reliable on the operating conditions. SO_2 emissions varied directly, but not proportionally, with the sulfur content of the fuel mixture.

1. Introduction

Rice is one of the most important agricultural crops in Asia, i.e. Thailand, China, Indonesia, the Philippines, and Vietnam. The annual quantity of rice husk, a by-product from rice mills, is very high. In Thailand alone, it is about 4.4 million tons, with an annual energy equivalent of 6.6×10^7 GJ, or 3300 GWh/year, corresponding to a heating value of 15 MJ/kg. Rice husk is therefore becoming increasingly attractive for heat and power generation in Thailand. Combustion is one thermochemical conversion technology (i.e. combustion, gasification, and pyrolysis), and is the most effective technology nowadays for biomass utilization [1]. Among the combustion technologies, bubbling fluidized-bed and circulating fluidized-bed systems have proven efficient for burning biomass, particularly rice husk [2–6]. Because of the CO_2-neutrality and low sulfur content of sustainable cultivated biomass, co-firing biomass with coal has recently intensified, to reduce the negative environmental impacts of coal combustion. Besides awareness of the environmental impacts of power generation using fossil fuels (mainly coal) [7–12], the disposal of municipal solid waste [13–14] and energy recovery from industrial waste [15–18] strengthen the case for utilizing biomass via co-firing with fossil fuel. Apart from reducing CO_2, co-firing biofuels with coal is a proven technique for reducing SO_2 and NO_x emissions from burning coal [12–15,17,19]. However, many studies [8,18–19] have shown that the decrease in NO_x, by increasing the biomass fraction, depended on the reduction reactions of volatiles released from the biomass (mainly as NH_3), rather than the nitrogen fuel content. Details of these chemical reactions have been reported elsewhere [1,20]. In a previous work by Madhiyanon et al. [21] a novel combustor, named a "cyclonic fluidized-bed combustor" (ψ-FBC) was developed and evaluated, and succeeded in integrating gas-solid vortex and fluidized-bed combustion regimes into a unique combustor.

However, the use of rice husk alone, as a fuel to generate heat and power, can be problematic, because rice is a seasonal crop and rice-mill operations vary depending on the availability of rice. Despite its negative impacts on the environment, coal is considered suitable for firing with rice husk, especially during a deficit seasonal because it is the most abundant fossil fuel and will remain an important energy resource into the future. This study extensively investigated the feasibility and performance of the ψ-FBC, using various rice-husk-coal mixtures. The objectives of this study were (a) to evaluate the combustion characteristics of rice-husk/coal firing in the ψ-FBC, and (b) to correlate the emissions and combustion efficiency with various ratios of excess air and fuel blends.

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2. Experiment set-up

2.1. Apparatus

The cyclonic fluidized-bed combustor (ψ-FBC) used in this study was developed by Madhiyanon et al. [21], to combine the distinctive characteristics of cyclonic and fluidized-bed combustion. A schematic of the ψ-FBC, with a capacity of 120 kW_{th}, is shown in Fig. 1. The system includes a combustor, a high efficiency cyclone, and a fuel-feed system. Ash is carried out by the gaseous combustion products and discharged into an exhaust pipe connected to the cyclone. The combustor is made of stainless steel and insulated inside with refractory and on the outside surface with ceramic fiber. The ψ-FBC comprises two main parts: (1) a cylindrical combustor, 0.40 m ID, 0.90 m high, and (2) a conical base 0.10 m ID, truncated-apex cone 0.25 m high, designed to contain a bed of coarse char and ash particles. The cylindrical part has a circular ring, named a 'vortex ring', made of refractory with 0.24 m opening diameter, located 0.75 m above the air distributor. The vortex ring divides the combustor into upper and lower combustion chambers, and is used to trap the entrained particulates in the combustion gases impinging upon its bottom side.

Primary combustion air is introduced tangentially at the top of the ψ-FBC and used to establish a vortex flow (or swirl flow) along the combustor wall, and simultaneously convey rice husk into the combustor. Primary air is supplied by a 2.2 kW blower. Secondary air (fluidizing air) is provided by a 2.2 kW blower and injected vertically at the bottom of the conical base through an air distributor to promote fluidization and well-mixed conditions in the lower part. Coal (bituminous) was fed separately into the combustor via tertiary air tangentially introduced into the combustor at 0.65 m height. Primary and tertiary air was supplied by the same 2.2 kW blower, while secondary air was provided by another 2.2 kW blower. Rice husk and coal were fed separately into the combustor via two screw feeders, each equipped with a variable-speed drive to regulate fuel-feed rate. No bed material was mixed into the fuel mixture to create fluidization; instead, the generated char and rice-husk ash during combustion behave as a secondary solid in the bed, thus contributing to favorable mixing and stable conditions [21].

2.2. Measurement

The desired feed rate was regulated with a variable-speed drive. Air-flow rates were adjusted by Venturi flow meters linked to manual valves and differential pressure transmitters. The temperature profiles inside the combustor were monitored using a data logger with an accuracy of ±1 °C, connected to type-K thermocouples at vertically spaced elevations of 0.10, 0.35, 0.60, 0.85, and 1.65 m (exit) above the air-distributor plate. In the same cross-sectional plane, temperatures were measured radially outward from the combustor center, approximately 2 cm apart. Gas emissions were monitored using a multigas analyzer (Testo 350XL). The measuring principle was based on electrochemical cells for CO, O_2, NO, NO_2, and SO_2. CO_2 is not measured directly. Instead, based on a built-in algorithm in the instrument, CO_2 is derived from the measured O_2 concentration. A Leco C-H-N-S analyzer was used to analyze unburned carbon content.

2.3. Fuel and ash characteristics

The rice husk, a derivative of the milling process, formed the primary fuel, while bituminous coal was employed as the supplementary fuel in the co-combustion experiments. The proximate, ultimate, and ash analyses of fuels are shown in Table 1. Coal particles ranged between <0.25 and 1.2 mm in size.

2.4. Experimental procedure

The ψ-FBC was heated first by igniting rice-husk loaded in advance into the combustor. Rice husk stored in a hopper was then fed gradually into the combustor. Combustion continued until the bed temperature accomplished about 800°C; thereafter, bituminous coal was injected separately into the combustor via tertiary air. The duration of each run was about 6 h, of which 1.5 h were used to reach steady state. Thereafter, gas emissions were monitored every 2 min for 2 h, and averaged over the measurement period. To analyze unburned carbon content, the values of which were used to determine combustion efficiency, ash was collected regularly from the cyclone outlet (every 15 min). During testing, axial and radial temperature profiles inside the combustor, and concentrations of O_2, CO_2, CO, NO_x, and SO_2, along the combus-

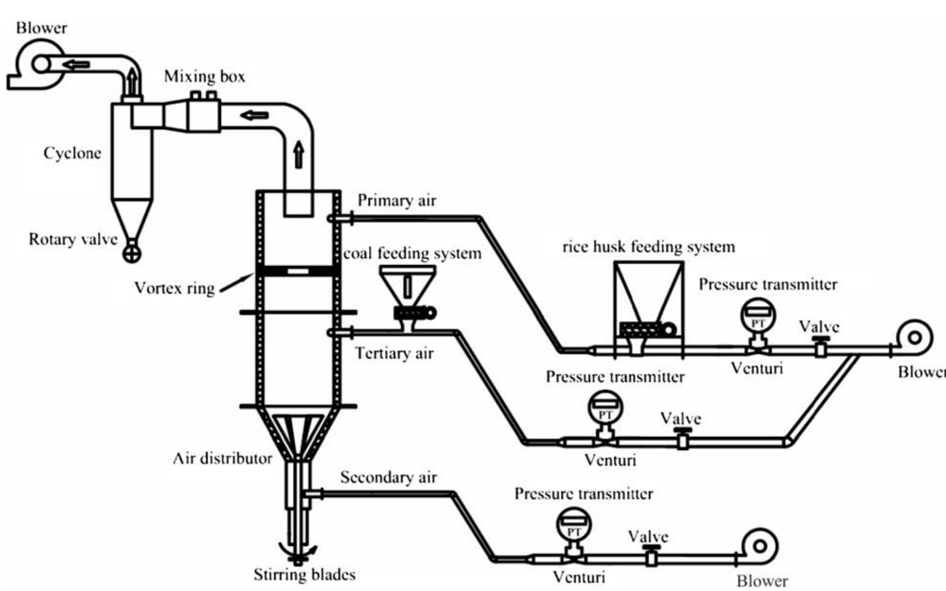

Fig. 1. Schematic diagram of the ψ-FBC testing facilities.