Effects of (co-)combustion techniques and operating conditions on the performance and NO emission reduction in a biomass-fueled twin-cyclone fluidized-bed combustor

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Keywords: rice husk (co-)firing, air staging, flue gas recirculation, NO emission reduction.
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1. Introduction

For many years, rice husk has been an important energy resource in Thailand. Due to significant availability and excellent combustion properties, rice husk shows its high energy potential and suitability as a fuel for heat and power generation. Fluidized-bed furnaces/combustors are reported to be high-efficiency and environmentally friendly combustion systems for energy conversion from biomass. However, burning rice husk in conventional fluidized-bed systems is commonly accompanied by elevated NO emission.

From the literature review, a substantial reduction of NO emission can be achieved through co-firing coal and biomass in pulverized coal-fired boilers, particularly when using air/fuel staging techniques. Besides, a number of research works have shown the effectiveness of flue gas recirculation (FGR) as a NO-controlling tool in fossil fuel-fired boilers. However, there is a lack of knowledge on: (i) biomass–biomass co-combustion in fluidized-bed systems using air staging and (ii) the effects of FGR during fluidized-bed combustion of a single biomass fuel, both exhibiting the potential for NO emission reduction.

This experimental work was performed on a novel twin-cyclone combustor with a swirling fluidized bed, to explore the potential of different (co-)combustion techniques for the reduction of NO emission from the biomass-fueled combustor. Along with a test series for burning pure rice husk at conventional (bottom) air injection, two groups of experiments aimed at reducing NO emission were conducted in this work: (1) co-firing rice husk pre-mixed with sugar cane bagasse using air staging, and (2) burning pure rice husk at bottom air injection using FGR. The effects of operating parameters (excess air, secondary-to-total air ratio, and proportion of FGR) on the behavior of major gaseous pollutants (CO, C_xH_y, and NO) in different reactor regions, as well as on the combustion and emission performance of the proposed twin-cyclone fluidized-bed combustor, were compared between the selcted techniques. A special attention was given to an optimization of the operating parameters ensuring the minimal "external" (or emission) costs of each technique.

2. Materials and Methods

2.1. Experimental

Fig. 1 shows the schematic diagram of an experimental setup with the twin-cyclone fluidized-bed combustor. The combustor comprises two cyclonic chambers with identical configurations arranged co-axially.

In this work, rice husk with LHV = 12.3 MJ/kg was used as a base fuel, whereas high-moisture sugarcane bagasse with LHV = 4.7 MJ/kg served as a secondary fuel in co-firing tests. Silica sand with 0.3–0.5 mm particle sizes was employed as the bed material in the lower chamber. This combustion chamber was generally aimed at intensive burning of a base fuel (or biomass–biomass mixture during co-firing tests) in a swirling fluidized bed of the sand induced by an axial-type swirler, whereas the upper chamber was used to ensure complete combustion.

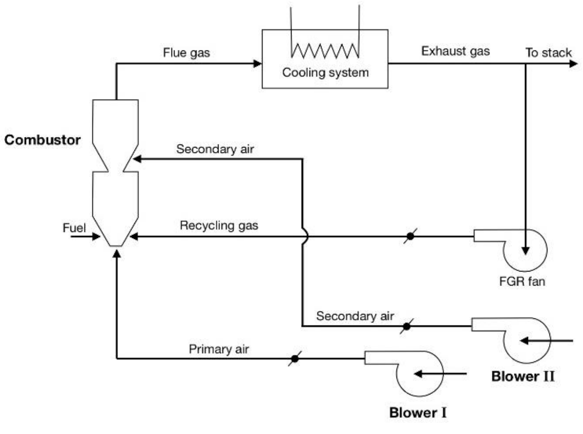

Fig. 1. Experimental set-up for (co-)combustion tests using air staging and flue gas recirculation.

2.2. Methods for (co-)firing tests

For comparability, all three test series were conducted with a 100 kW_{th} heat input, at excess air (EA) of 30%, 40%, 50%, and 60%. In the tests for burning pure RH, all air was injected into the bed through the swirler. The co-firing tests with air staging were performed at 15% energy fraction of sugarcane bagasse, when ranging the secondary-to-total air ratio (SA/TA) from 0.1 to 0.3 for each EA. During the tests, no FGR was applied, whereas the secondary air was tangentially injected into the upper chamber through nozzles to sustain swirling flow. In the test series with FGR (at bottom air supply), the recycled flue gas was tangentially introduced into the lower chamber in the vicinity of fuel injection, at the FGR proportion varied from 5% to 20% for each specified EA.

Temperature and gas concentrations (O_2, CO, C_xH_y, and NO) were measured in the axial direction inside the reactor and at stack, using a "Testo-350" gas analyzer, to investigate the combustion and emission characteristics, particularly focusing on the NO emission reduction. For each test run, the combustion-related heat losses and combustion efficiency were predicted by taking into account the O_2, CO, and C_xH_y (as CH_4) concentrations at stack.

2.3. Optimizing operating parameters

For the techniques using air staging and FGR, the operating parameters (EA, SA/TA, and FGR) were optimized using an objective function aimed at minimizing "external" costs of the combustor, as given below:

$$J_{\mathrm{ec}} = \mathrm{Min}(P_{\mathrm{NOx}}\dot{m}_{\mathrm{NOx}} + P_{\mathrm{CO}}\dot{m}_{\mathrm{CO}} + P_{\mathrm{CxHy}}\dot{m}_{\mathrm{CxHy}})$$

where $\dot{m}_i$ are emission rates of the pollutants, and P_{NOx}, P_{CO}, and P_{CxHy} are respective "external" emission costs.

3. Results and Discussion

Compared to burning the base fuel alone, co-firing of rice husk and high-moisture sugarcane bagasse using air staging created a favorable condition for NO reduction in the lower chamber of the combustor, mainly due to the decreased O_2 and elevated CO and C_xH_y, enhancing NO reduction reactions in this chamber (despite an increase in the bed temperature). As a result, with lowering EA and increasing SA/TA (within the ranges), the CO and C_xH_y emissions increased, leading to a noticeable reduction of the NO emission from the reactor.

Recycling some part of the flue gas into the reactor (at bottom air injection) led to the lower bed temperature and higher CO and C_xH_y in the lower chamber, compared to burning rice husk on its own. Along with decreasing the actual concentration of reactants in the lower chamber (caused by FGR), these factors resulted in a decrease of a (net) rate of NO formation in the zone of fuel devolatilization. The experimental results revealed that with a greater proportion of FGR within the range (at fixed EA), the NO emission can be noticeable reduced (~2 times). With increasing EA (at fixed FGR), the NO emission increased according to the fuel-NO formation mechanism.

Note that an increase in the CO and C_xH_y emissions led to an insignificant reduction of the combustion efficiency (by < 1%) in the two NO-controlling test series, compared to burning the base fuel at similar excess air.

Fig. 2 illustrates the optimization tool aimed at determining the optimal EA, SA/TA, and FGR for the NO reducing techniques applied in this work. From Fig. 2a, EA = 50% and SA/TA = 0.2 are optimal for co-firing RH and SB using air staging, whereas EA = 45% and FGR = 17% are the most suitable for burning pure rice husk using flue gas recirculation (as seen in Fig. 2b). Under optimal operating conditions, the combustor ensures high (~99%) combustion efficiency at minimal "external" costs and reduced NO emission: by 35% when co-firing RH and SB with air staging, and by 38% for burning RH using FGR, as compared to 165–180 ppm from the conventional combustion of RH.

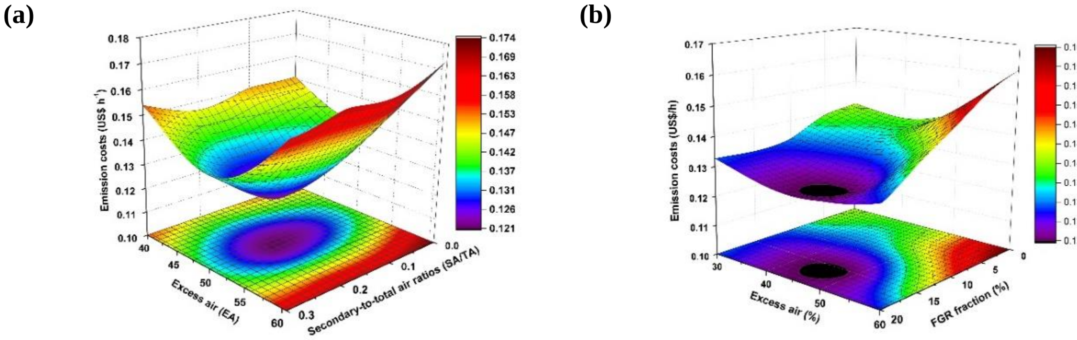

Fig. 2. "External" costs of the twin-cyclone fluidized-bed combustor when (a) co-firing rice husk and sugarcane bagasse using air staging, and (b) burning pure rice husk using flue gas recirculation.

4. Conclusions

A novel twin-cyclone fluidized-bed combustor has been successfully tested using two NO-reducing techniques: (i) co-firing rice husk with high-moisture sugarcane bagasse using air staging and (ii) burning rice husk alone using flue gas recirculation. The proposed techniques and operating parameters have noticeable effects on the major gaseous emissions and combustion efficiency of the combustor. Both techniques create the NO reducing conditions in the lower combustion chamber, resulting in a noticeable reduction of the NO emission from the combustor (by 35–38%), as compared to burning the base fuel alone) at high (~99%) combustion efficiency.