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Co-combustion of coal and biomass in a circulating fluidized bed combustor

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Abstract−In this research, co-combustion of coal and rice husk was studied in a circulating fluidized bed combustor (CFBC). The effects of mixed fuel ratios, primary air and secondary air flow rates on temperature and gas concentration profiles along riser (0.1 m inside diameter and 3.0 m height) were studied. The average particle size of coal from Maetah used in this work was 1,128 mm and bed material was sand. The range of primary air flow rates was 480-920 *l*/min corresponding to U_g of 1.0-2.0 m/s for coal feed rate at 5.8 kg/h. The recirculation rate through L-valve was 100 kg/hr. It was found that the temperatures along the riser were rather steady at about 800-1,000 degrees Celsius. The introduction of secondary air improved combustion and temperature gradient at the bottom of the riser, particularly at a primary air flow rate below 1.5 m/s. Blending of coal with biomass, rice husk, did improve the combustion efficiency of coal itself even at low concentration of rice husk of 3.5 wt%. In addition, the presence of rice husk in the feed stocks reduced the emission of both NO_x and SO_2.

Key words: Circulating Fluidized Bed, Biomass, Coal, Co-combustion

INTRODUCTION

Circulating fluidized bed (CFB), which is a technology for combustion of solid fuels, was first used for combustion of coal due to its unique ability to handle low quality, high sulfur content coals. Nowadays this technology is being widely used in boilers with solid fuels. In October 1998 the 200 MWe Tonghae thermal power plant CFB boiler was the largest boiler to fire a Korean anthracite coal for generation of electricity [1]. The size of the largest boilers has increased, based on the experience gained, and is now about 300 MWe [2]. A combustion efficiency as high as 98% when burning coal in a CFBC was reported in 1984 [3]. Recently, circulating fluidized bed combustion (CFBC) has increased its market share of biomass combustion. The principal reasons are high burnout of the fuel, wide fuel span, high combustion efficiency, and low emissions of polluted gases. Co-combustion with coal can be applicable to utilization of waste materials that otherwise would be landfilled or inefficiently incinerated alone. The performance of the CFBC for different alternative fuels has been extensively investigated.

CFBC seems to be a suitable technology for converting a wide range of agricultural wastes to energy. It takes advantage of the excellent mixing and high reaction rates of gas-solid mixtures [4]. The CFBC consists of a riser containing a bed of inert particles such as sand, and fuel, supported by a distributor plate. Air is passed through the distributor plate and its velocity is increased so as to lift the entire bed. Beyond a certain air velocity, the bed is said to be fluidized, and it exhibits fluid-like properties. The combustion takes place in the riser starting from bottom to top (free board) of the riser. The unburned fuels are recovered by a cyclone and move back through the downcomer or standpipe and a recycling system, e.g., L-valve, J-valve, Loop seal etc., into the riser. These complete the circulation loop of CFBC. Uniform temperatures and high heating capacities of sand permit a wide range of low grade fuels of even non-uniform size and various moisture contents to be combusted efficiently.

Rice husk is the most abundant agricultural waste in quantity, amounting to 43% of the total wastes [5]. Rice is cultivated in more than 75 countries in the world. In Thailand, approximately 5.6 million tonnes of rice husk are produced every year [6]. However, there are some problems with rice husk utilization because of the huge volume of waste and low density. The main characteristics of rice husk are as follows: about 16 MJ/kg heating value, a volatile matter content of 74% and medium ash of about 16-23%. Its ash contains more than 95% silica that gives rigid skeleton-like structure to the ash [4]. The CFBC offers some advantages due to its unique operating characteristics. The high turbulence in the bed can break the rigid ash skeleton to let the trapped carbon available for combustion. The ash can easily be removed from the bed by entrainment in the gas stream, from which it can be separated by a particle separating system such as a cyclone. Furthermore, the bed temperature can be kept below the ash slagging temperature by properly controlling its operating conditions, and localized combustion can be restricted as long as the isothermal bed temperature can be maintained by ensuring uniform fluidization.

The objective of this work was to study the feasibility of co-firing between coal and rice husk in the CFBC. The variables are the mixture of coal-rice husk blends, velocities of primary air and secondary air. The fuels used were lignite-rank coal, from Mae-tha, Lampang province in the northern Thailand and rice husk collected from various rice mills around Bangkok.

1. Fuel Characteristics

Table 1 shows the proximate and ultimate analyses, the heating values and the bulk densities of coal and rice husk used in these studies. It also shows that the rice husk has high volatile matter content (66.92%) and medium ash content (15.59%). Both parameters

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Table 1. Analyses of coal and rice husk

	Coal	Rice husk
Proximate analysis (wt%, as received)		
Fixed carbon	19.24	6.87
Volatile matter	37.68	66.92
Moisture	17.38	10.62
Ash	25.70	15.59
Ultimate analysis (wt%, daf)		
C	58.44	39.48
H	5.16	5.01
O	33.85	52.44
N	0.69	0.92
S	1.87	nil
Gross calorific value, MJ kg^{-1}	22.42	15.19
Sauter mean diameter, μm	1,128	-
Bulk density, kg m^{-3}	858.7	129.6

have an influence on the fluidized bed combustion characteristics. The rice husk is easier to ignite and to burn than coal, due to the high volatile matter. Its ignition temperature was experimentally found to be about 340 °C [7]. The high volatile matter content is also expected to affect the combustion process and temperature distribution in the riser. Moreover, the low density of rice husk complicates its processing, transportation, storage and firing. Nevertheless, medium content of ash in rice husk will slightly reduce the ash from the combustion. In addition, no sulfur content of the rice husk is very important since it will help reducing polluted gas emissions.

EXPERIMENTAL

Fig. 1 shows a schematic diagram of the CFBC used in this work. The inside diameter of the riser is 0.1 m and the total height of 3 m. The lower part of the riser (2 m) was refractory-lined with a thickness of 0.05 m and the downcomer (0.2 m I.D. and 1.6 m height)

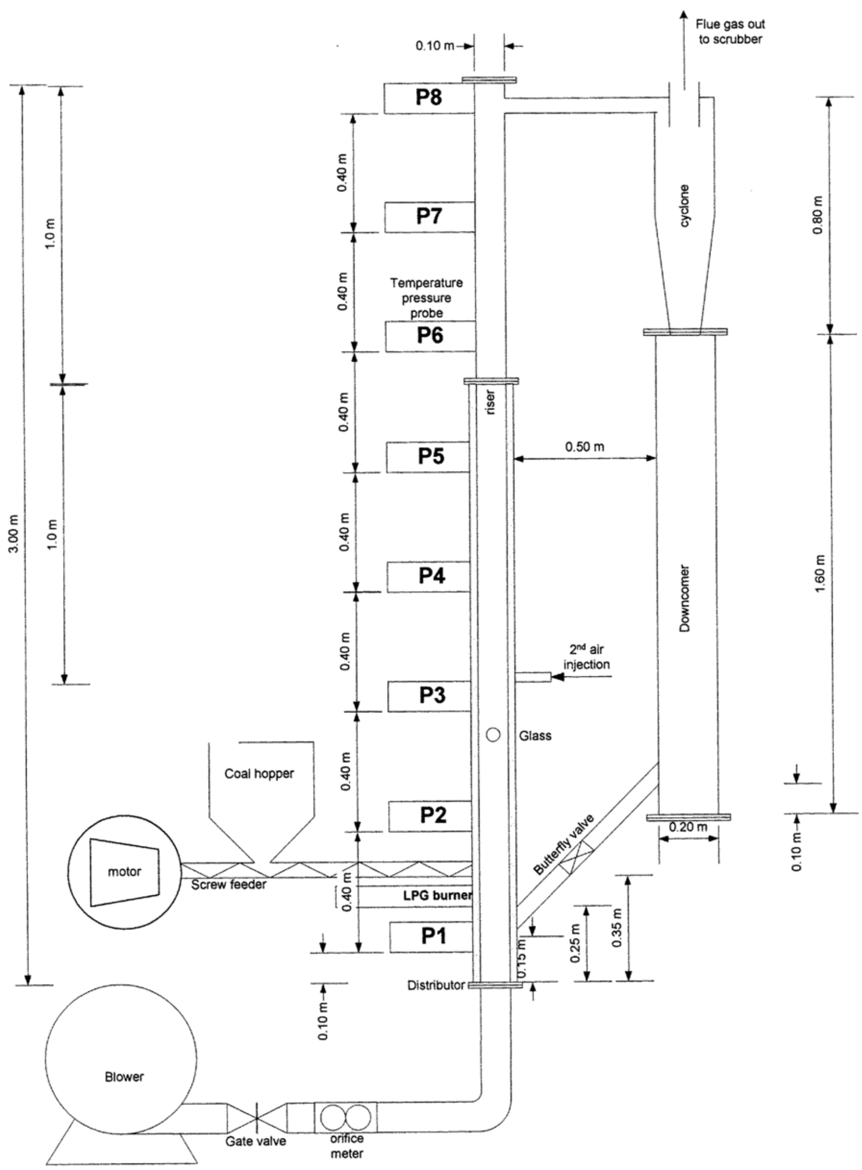

Fig. 1. Schematic diagram of the CFBC system.

was insulated with asbestos on its outer surface and covered externally by 1 mm thick galvanized steel. The primary air was preheated by an LPG burner during the start up operation. After the operation of CFBC reached steady state, the air preheated system was turned off. Coal was used as the primary fuel in all experiments. All coal particles were crushed and sieved to 1,128 um as average particle size. The primary air velocity in the riser varied from 1.0-2.0 m s^{-1}. The secondary air was introduced at 1 m above the distributor plate and the flow rates were varied from 0 to 5.51×10^{-3} m^3 s^{-1}. The bed material was sand with an average particle size of 275 μm and its inventory was 20 kg. In every run, the mixed fuel was fed at a fixed rate of 5.8 kg h^{-1} through a screw feeder located at 0.35 m above the air distributor plate. Three ratios of coal to rice husk mixtures, namely 100 : 0, 80 : 20 and 65 : 35 by volume, were studied. Most solid particles, bed material and unburned fuel entrained by combustion gases from the riser, were collected by the cyclone. The gases from the cyclone were fed to a water scrubber. The particles were returned to the riser through an L-valve controlled by a butterfly valve at 50% opening. Temperatures along the riser were measured using thermocouples (Type-K) installed at different heights as shown in Fig. 1. Point no. 1 in the figure was located at 0.10 m above the air distributor, while the remaining points were located at 0.40 m apart. Exhaust gas was sampled and its composition (O_2, NO, NO_x, CO, SO_2 and NO_2) was analyzed by the flue gas analyzer (TESTO 350) on a dry basis.

RESULTS AND DISCUSSION

In a series of trials, it was observed experimentally that the operation of the CFBC was stable for fast fluidization at primary air velocity starting from 1.0 m s^{-1}. As a consequence, all experiments were carried out at three primary air velocities of 1.0, 1.5 and 2.0 m s^{-1} , respectively.

1. Temperature Profiles Along the Riser for Coal Combustion

Fig. 2 shows the temperature profile along the riser for primary air velocity of 1.0 m s^{-1} with different secondary air flow rates. It can be seen that the temperatures below secondary air injection position were almost uniform at about 750 to 775 °C. A study of the temperature profiles shows that when there is no secondary air injection the temperatures decrease slowly or remain constant until a height of 1.7 m is reached. Above this level, the temperature starts to decrease gradually. This temperature profile indicates that the primary air was used up for partially combusting coal from the beginning region of the riser between 0.5 and 1.7 m height. The released heat from combustion might be used for devolatilization in this region. When secondary air was injected, the remaining fuels as well as the combustible volatile were further combusted and liberated large amount of heat causing a substantial increment of temperature. It was observed that a higher flow rate of the secondary air produced a higher average temperature above the injecting position. This is attributable to an abundance of fuel or combustible matters. The statement was confirmed later by the plot of CO profile depicted in Fig. 5. With different flow rates of secondary air, the maximum temperatures obtained in each case were somewhat noticed at the same position of 1.5 to 1.7 m. Above this height, the temperatures were gradually reduced, indicating that stable combustion could not be attained. There are two reasons for this ob-

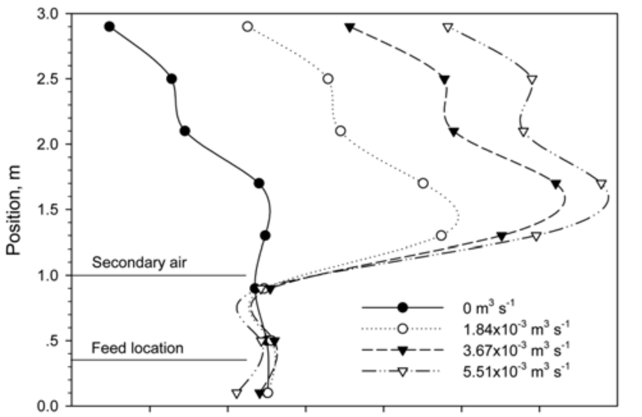

Fig. 2. Temperature profiles along the riser for primary air velocity of 1.0 m s^{-1} at different secondary air flow rates.

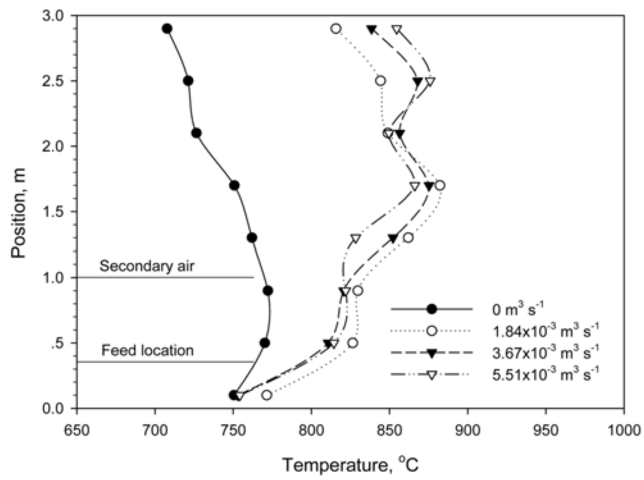

Fig. 3. Temperature profiles along the riser for primary air velocity of 1.5 m s^{-1} at different secondary air flow rates.

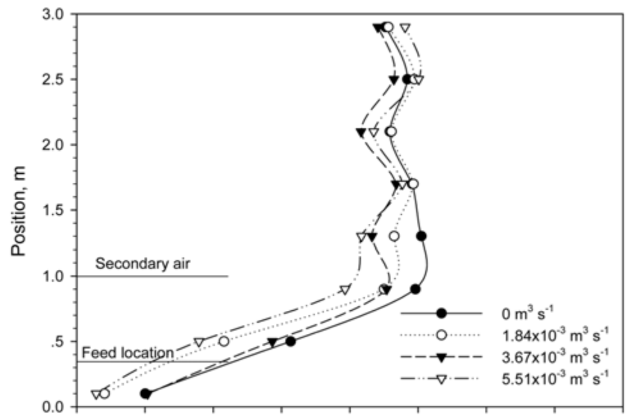

Fig. 4. Temperature profiles along the riser for primary air velocity of 2.0 m s^{-1} at different secondary air flow rates.

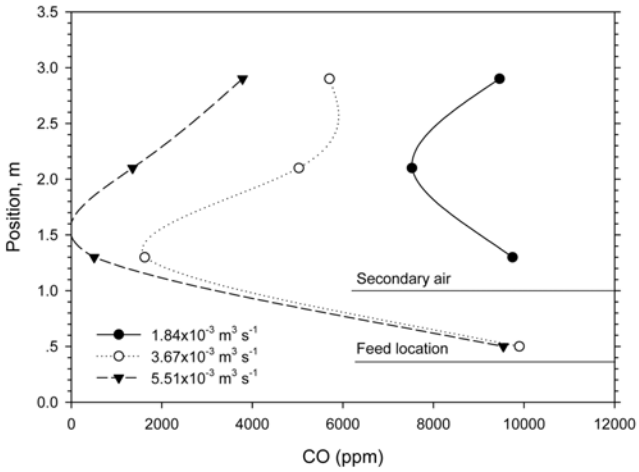

Fig. 5. CO profiles along the riser for primary air velocity of 1.0 m s^{-1} at different secondary air flow rates.

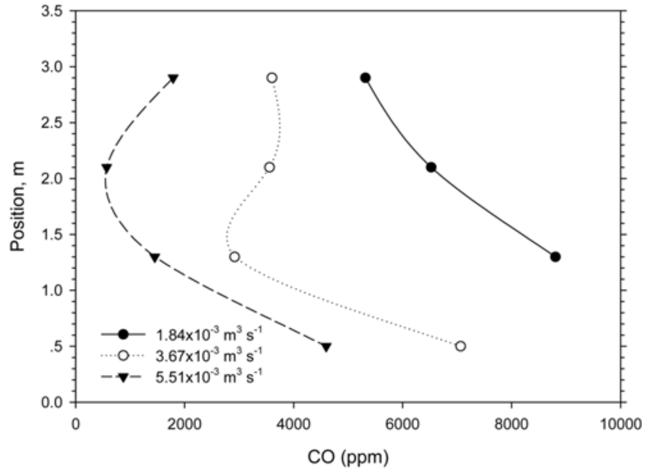

Fig. 6. CO profiles along the riser for primary air velocity of 1.5 m s^{-1} at different secondary air flow rates.

servation. First, heat loss from the combustor was probably taking place, due to imperfection of insulation. The loss might be dominant at such a region in which the temperature difference between the combustor surface and the ambient is very large. Second, the presence of CO_2 due to combustion in this zone induces the Boudouard reaction:

$$C+CO_2 \rightarrow 2CO \qquad \Delta H=+172 \text{ MJ/kmol}$$

As can be seen, the drop in temperature in Fig. 2 would be due to the endothermic behavior of this reaction. This is emphasized by higher concentration of CO, which is shown later in Fig. 5.

Fig. 3 shows the temperature profiles along the riser for primary air velocity of 1.5 m s^{-1}. In case of no secondary air, the temperature was increased slightly and started decreasing along the riser when the height was beyond 0.9 m. This is because of the lack of oxygen in air left for combustion at the higher zone. On the other hand, when secondary air was applied, it promoted the further combustion of fuel in the vicinity of the injection point both upward and downward, causing the temperature in the riser to increase accordingly. Beyond the injection point of secondary air, the temperature profile seems to be quite steady. This somewhat differs from the results obtained for the primary air velocity of 1.0 m s^{-1}. A temperature gradient below the injection point of secondary air was observed. This is attributable to more uniform solid holdup at this primary air velocity, leading to more effective heat and mass transfer along this region. In contrast, the gradient was not observed when no secondary air was introduced. A reason would be the insufficient oxygen for combustion reactions along the riser. An evidence for this could be the lower CO when the secondary air was introduced, as depicted in Fig. 6.

Fig. 4 shows the variation of temperatures along the riser when the flow rate of primary air was increased to 2.0 m s^{-1}. The pattern of profile is rather the same as that shown in Fig. 3. A rapid increase of temperature from the bottom of the riser to the point where the secondary was injected could be observed. After that the temperature was approximately constant, which is typical for normal CFBC operations, resulting from a good solid mixing. The increase in temperature even at no secondary air injection indicates that this primary air flow rate can provide enough oxygen (air) for combustion. This can be confirmed by the constant low concentration of CO, as shown later in Fig. 7.

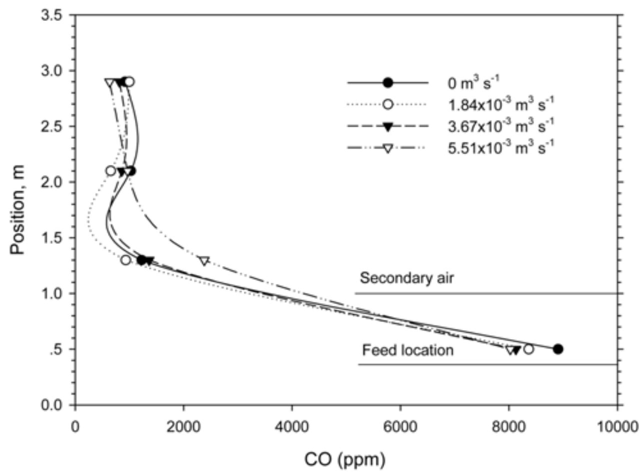

Fig. 7. CO profiles along the riser for primary air velocity of 2.0 m s^{-1} at different secondary air flow rates.

2. Emissions During Coal Combustion

2-1. CO Emissions

Fig. 5 shows the concentration profiles of CO along the height of the riser at three different secondary air flow rates. As can be seen, the higher value obtained at the bottom of the riser indicates that incomplete (partial) combustion took place at the region. Above the secondary air injection point CO concentration decreased considerably since there was more air for combustion, especially burning with combustible gas, e.g. CO. Above this zone, the CO concentration increases again. As mentioned above, this might be due to the Boudouard reaction. This finding was expected since in this zone a temperature drop of about 100 °C was observed, as depicted in Fig. 2. When the primary air velocity was increased to 1.5 and 2.0 m s^{-1}, the resulting CO concentration profiles were different as shown in Figs. 6 and 7. The concentration of CO above the turning point at the height of about 1.5 likely became constant when the primary air velocity was increased. This indicates that the Boudouard reaction was competed with the combustion reaction due to the excess oxygen at these conditions. It corresponds to the temperature profile that seems constant as shown in Figs. 3 and 4. Based on the equilibrium, the combustion reaction takes place rather than the Boudouard reaction at lower temperature. This could explain the gradual decrease in CO concentration observed in Fig. 6. In Fig. 7, the CO concentration is decreased along the riser and is not increased again as observed in Fig. 5. The average CO concentration is 1,000 ppm in the zone above the secondary air injection port. This observation, on the other hand, demonstrates that the supplied air as primary air at this high flow rate, i.e. 2 m s^{-1}, provides enough oxygen for combustion.

2-2. SO_2 Emissions

Fig. 8 illustrates SO_2 emissions as a function of positions along the riser at a primary air velocity of 2.0 m s^{-1}. SO_2 concentrations tend to increase to the top of the riser. Values of about 400 to 600 ppm were obtained. The combustion in the riser was taking place with volatile matter in coal first. Then, the solid part of the coal would be burned because of the sulfur component in it. Thus, the longer the coal stayed in the riser, more sulfur would be burned. Studies have been made by many investigators to reduce SO_2 emissions by using limestone or dolomite [8,9].

2-3. NO_x Emissions

The concentration profile of NO_x along the riser is shown in Fig. 9. These values were related with the riser temperatures. When there was no secondary air supplied, the riser temperature was highest (see Fig. 4) and so was the NO_x concentration. The concentration varies in the range from 50 to 150 ppm in most experiments. However, these values are much less than the values reported for conventional fluidized bed combustion [9]. The reasons are due to lower bed temperature and the introduction of secondary air.

3. Temperature Profiles Along the Riser for Coal and Rice Husk Combustion

Experiments were also conducted using coal and rice husk blends. The concentrations of rice husk used are 0, 3.5 and 7 wt%, respectively. From the previous section of coal combustion, it can be noticed that with a primary air velocity of 2.0 m s^{-1} the addition of secondary air has no profound effect on the temperature distribution. Thus, from this point onward the results to be presented for combusting coal/rice husk blends would be based on the primary air flow rate of 2.0 m s^{-1} with no secondary air injection.

Fig. 10 shows the temperature profiles along the height of the riser in the combustion test runs with coal and rice husk blends. The effect of rice husk in the mixtures on the temperature profiles is significant. The larger amount of rice husk in the fuel mixture induces an increase in average temperature, particularly at the top section (zone above feed inlet). This means the addition of biomass helps improve the combustion efficiency of coal along the riser by lowering the ignition temperature [7]. The high reactivity of the rice husk compared to that of coal results in a rapid burn-out of rice husk particles [1]. According to the computation, heat released from additional biomass of 0.20 kg h^{-1} (3.5% biomass) coincides with an increase in the column temperature of approximately 90 degrees Celsius. This heat would somewhat be lost to the surroundings. Therefore, the temperature rise in Fig. 10 was only 50 degree Celsius.

4. Emissions during Coal and Rice Husk Combustion

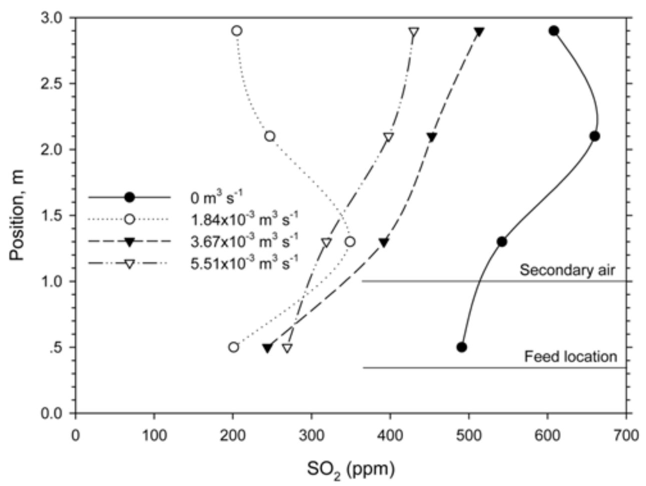

Fig. 8. SO_2 profiles along the riser for primary air velocity of 2.0 m s^{-1} at different secondary air flow rates.

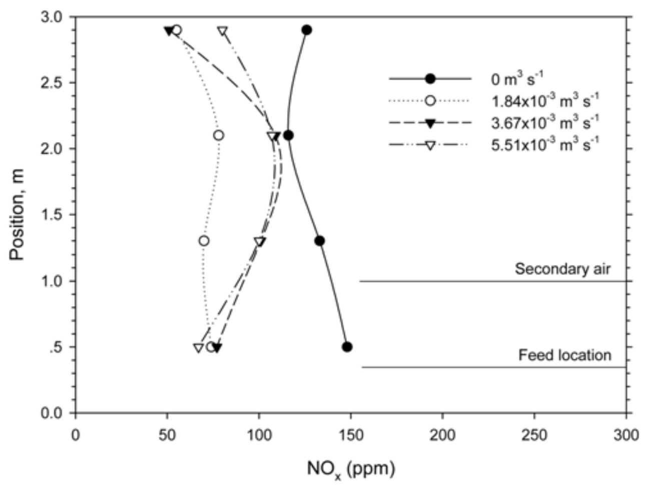

Fig. 9. NO_x profiles along the riser for primary air velocity of 2.0 m s^{-1} at different secondary air flow rates.

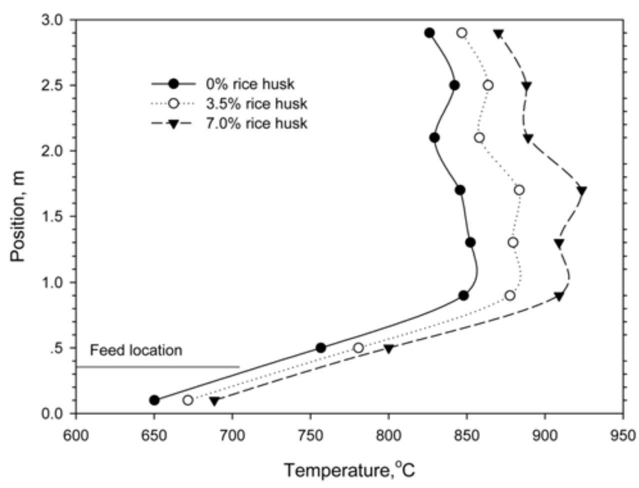

Fig. 10. Temperature profiles along the riser for primary air velocity of 2.0 m s^{-1} at different rice husk concentrations.

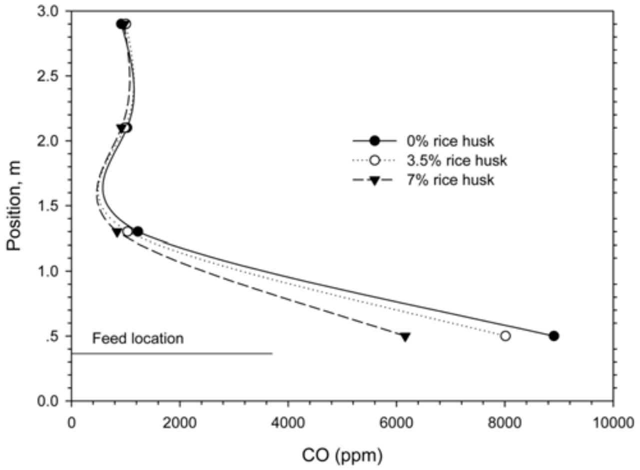

Fig. 11. CO profiles along the riser for primary air velocity of 2.0 m s^{-1} at different rice husk concentrations.

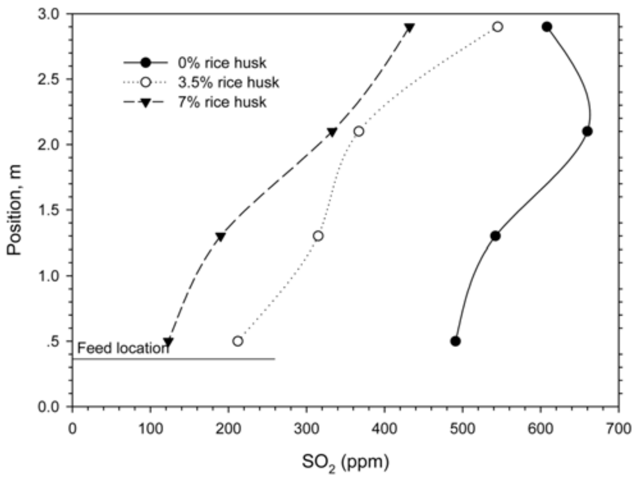

Fig. 12. SO_2 profiles along the riser for primary air velocity of 2.0 m s^{-1} at different rice husk concentrations.

4-1. CO Emissions

Fig. 11 illustrates CO emissions in the test runs carried out with primary air velocity of 2.0 m s^{-1}. The profile is quite the same as that shown in Fig. 6. CO emissions reduced remarkably from the bottom of the riser and reached a rather constant value of about 1,000 ppm at the height 1.3 m and above. Rice husk does not seem to affect the CO concentration profile in the riser. This result shows an agreement with the temperature profile. The lower CO indicates more complete combustion, in turn increasing the bed temperature.

4-2. SO_2 Emissions

Fig. 12 shows SO_2 emissions during co-combustion of coal and rice husk. It can be seen that increasing rice husk content results in decreasing SO_2 emissions. This is due to the fact that the rice husk has lower sulfur content in comparison to coal. The SO_2 was observed to drop significantly, i.e., more than a half, even though only 3.5% rice husk was added. This is attributable to the synergetic effect of the biomass ash in terms of reducing SO_2 emission [10,11].

4-3. NO_x Emissions

The variation of NO_x concentrations along the riser is shown in

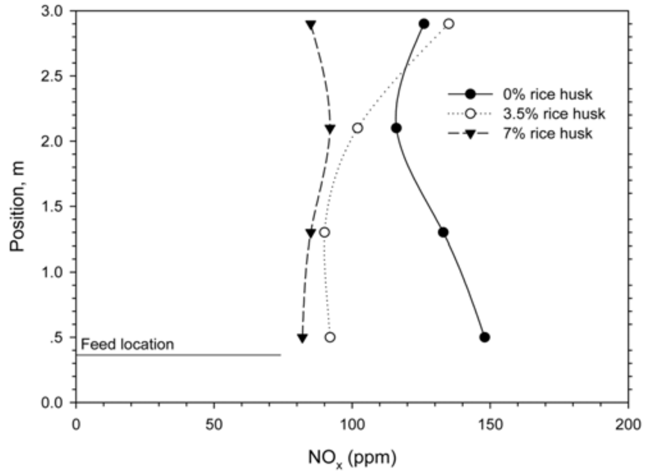

Fig. 13. NO_x profiles along the riser for primary air velocity of 2.0 m s^{-1} at different rice husk concentrations.

Fig. 13. NO_x emission decreases dramatically when only 3.5% rice husk is present. As the concentration of rice husk is increased, the NO_x concentration declines slightly. In general, during low temperature combustion NO_x is produced from the nitrogenous species in biomass released with the volatiles rather than from the nitrogen in the air (thermal NO_x) [11]. Rice husk was found to have higher nitrogen contents than coal. Hence, the drop in NO_x emission as increasing amount of rice husk might be due to the effects of nascent char from the rice husk and volatile matter on the reduction of NO_x [11, 12]. The NO_x emissions during the combustion are between 80 and 150 ppm.

CONCLUSIONS

In this paper, a circulating fluidized bed combustor was constructed for the combustion of local materials, which are coal and rice husk. The combustion was conducted and its characteristics were investigated. The temperature and gas emission along the riser were observed when coal was combusted alone. The secondary air has an influence on the temperature profile along the riser when primary air is in deficit. However, when the primary air reaches the excess air condition, the effect vanishes. The addition of rice husk helps improve combustion efficiency of coal and increases the average bed temperature. The emissions of NO_x and SO_2 are also reduced in the co-combustion condition.

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