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Comparison of the thermal behaviors and pollutant emissions of pelletized bamboo combustion in a fluidized bed combustor at different secondary gas injection modes

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A B S T R A C T

Staged combustion significantly affects the complete combustion of biomass and reduces pollutant emissions. This study primarily aimed to compare the thermal behaviors and pollutant emissions of different secondary gas injection modes in a pilot-scale fluidized bed combustor (FBC). Pelletized thorny bamboo was used as the fuel, and silica sand was used as the bed material. Flue gas recirculation (FGR) was employed. The experimental results demonstrate that the secondary gas injection modes in the FBC affected the combustion characteristics. The temperature of pelletized bamboo combustion with tangential injection mode (T mode) was lower than that of centripetal injection mode (C mode); however, T mode produced lower CO and NOx emissions than C mode because of the well-swirling effect. The secondary gas velocity and airflow distribution uniformity in the secondary gas layers jointly affect combustion, while T mode with four nozzles or C mode with two nozzles is optimal to reduce emissions. Furthermore, increasing the elevation of secondary air further reduces NOx emissions in C mode but does not significantly affect emissions in T mode.

1. Introduction

Biomass is considered a promising renewable energy that is carbon neutral and contains low levels of sulfur [1–3]. Bamboo is an important biomass source for energy that is renewable and can be stored and transported easily. According to the statistics from the Food and Agriculture Organization of the United Nations (FAOSTAT) reported in 2010, the total cultivated area of bamboo is over 2200 million ha, and Asian bamboo comprises approximately 85% of the world's production. Thorny bamboo is the main type of bamboo cultivated in southern China, and bamboo is a highly promising source of energy that has been explored in numerous recent studies. These studies have primarily investigated bamboo gasification [4], pyrolysis [5], and torrefaction [6]. Bamboo-producing countries enjoy environmental and economic benefits from the utilization of bamboo as a source of renewable energy.

Fluidized bed combustion has been adapted as a reliable combustion technology for biomass combustion. The direct combustion of bamboo is recognized as one of the most promising bamboo-related technologies, but the combustion behavior and pollutant emissions resulting from bamboo combustion in an FBC have not been thoroughly investigated. Specifically, staged combustion, in which the secondary gas is injected into the freeboard zone, has been used in fluidized bed combustors to improve the combustion efficiency and decrease the pollutant emissions. Studies of secondary injection have examined the effects of the injecting angle, layers of injection, and the ratio of injected secondary air on the combustion behavior.

Varol et al. [7] used woodchips and low-calorie lignite coal with a high sulfur content for co-combustion in a laboratory CFBC with an inner diameter of 108 mm and height of 6 m. Secondary air was injected 142 cm, 233 cm, 324 cm, and 415 cm above the distributor plate, and the secondary air ratio ranged from 10 to 30%. The results show that CO emission inversely correlates with the layer of secondary air injection for all fuels. In addition, the secondary air injection layer did not significantly affect NO and SO_2 emissions, but Saikaew et al. [8] found that increasing the secondary air injection elevation further reduces NOx and N_2O emissions. Varol and Atimtay [9] co-combusted coal and olive cake in a 900-mm high, 102-mm inner diameter bubbling fluidized bed with a secondary

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air injection layer 330 mm above the distributor plate. They found that CO, CxHy, and NOx emissions were reduced, whereas the secondary air flow rate and freeboard temperature were increased. Furthermore, the high secondary air flow rate inversely correlated with the freeboard temperature and CO emissions for a cooling effect. The experimental result presented by Madhiyanon et al. [10] showed that the secondary air flow rate can be optimized. Specifically, they found that the combustion efficiency directly correlates with the secondary air flow rate for burning biomass, which corroborates the results reported by Atimtay and Varol [11]. However, the secondary air flow rate did not significantly affect SO_2 emissions. Arromdee and Kuprianov [12] burned sunflower shells in a swirl bubbling fluidized bed combustor (BFBC). The secondary air injection level was 0.5 m above the distributor plate. The results show that increasing the secondary air ratio reduces the temperature and O_2 distribution. Moreover, Okasha reported that the CO emissions directly correlated with the secondary air ratio [13], whereas Chyang et al. [14] showed that CO emissions first increased and then decreased as the secondary air ratio increased. Nevertheless, both studies showed that CxHy emissions increased and NO emissions decreased as the secondary air ratio increased. Kuprianov et al. showed that the secondary air significantly affected the combustion efficiency [15]. Moreover, Arromdee and Kuprianov [12] and Okasha [13] showed that the optimum secondary air ratio maximizes the combustion efficiency. Razuan et al. [16] conducted their experiment in a pilot-scale fluidized bed reactor with a height of 2.3 m and inner diameter of 46 mm; the secondary air was injected 1.6 m above the distributor plate. In this reactor, injecting secondary air reduced the freeboard temperature. Tarelho et al. [17] conducted their experiments in a 3-m-high BFBC with an inner diameter of 0.25 m, and the secondary air was injected 0.43 m above the distributor plate. The secondary air primary affected gaseous pollutant via the dilution effect. The injection of secondary air further oxidizes CO to CO_2. They found that the combustion efficiency was approximately 97.2–99.3%. The dilution effect of injecting secondary air on NO was greater than that of the destruction reaction. Youssef et al. [18] use wheat straw, sawdust-wood, cottonseed burs, and corncobs as the fuel to study their combustion behavior in a pilot-scale CFB with a height of 2 m and an inner diameter of 145 mm. Secondary air was injected 0.3 m and 0.8 m above the distributor plate. The effect of excess air on the temperature profile was not significant, and CO and NOx emissions were minimized at 24% excess air. Specifically, temperature sharply decreased, and CO and NOx emissions slightly decreased when secondary air was injected at a higher level. Rao and Reddy [19] conducted their experiments in an FBC with a height of 1000 mm and inner diameter of 150 mm. They installed a disengagement section 1000 mm above the distributor, and secondary air was injected 1.15 m above the distributor plate, i.e., in the disengagement. They found that the temperature distribution was uniform and carbon loss was reduced when secondary air was injected into the combustor. In other words, the combustion efficiency was improved by injecting secondary air. Duan et al. [20] found that CO emissions inversely correlate with the excess oxygen ratio and secondary gas flow rate, whereas NOx emissions directly correlated with these parameters for peanut shells combusted in a fluidized bed.

Besides, Krzywanski J. et al. [21,22] also setup a generalized model to interpret the combustion performance and pollutant emissions in a circulating fluidized bed combustor under staged combustion mode. However, the most commonly reported secondary air injection mode in the published literature is centripetal injection mode from one nozzle. A vortexing fluidized-bed combustor (VFBC) was used to create a swirling flow by injecting air tangentially into the freeboard to increase combustion efficiency, and this approach has been employed in coal and biomass combustion studies for several years [23–25]. Moreover, smaller particles and lower biomass weights result in a higher combustion fraction in the freeboard zone compared to fossil fuels. Therefore, secondary gas injection significantly affects complete combustion and lowers pollutant emissions. However, the combustion behaviors and pollutant emissions resulting from different secondary gas injection modes in the same FBC have not yet been compared.

Therefore, this study primarily aimed to compare combustion behaviors and pollutant emissions for different secondary gas injection modes in a pilot scale fluidized bed combustor. The following parameters were examined: centripetal mode or tangential mode, number of secondary gas nozzles, and secondary gas layout. Pelletized thorny bamboo was used as the combustion material, and recirculating flue gas (FGR) was employed to maintain a constant total oxygen content in the primary gas for a certain total gas flow rate or superficial velocity [14,26].

2. Experimental

2.1. Fuel and bed material

Because blocking problems are common in the feeder, the thorny bamboo was first crushed and then treated with a roller compaction granulator to produce cylindrical pelletized thorny bamboo. A small amount of composite-modified starch was added during the compaction process to help to shape the bamboo into pellets that were 5 mm in diameter and 15 mm long on average. This pelletized thorny bamboo was used as the fuel in this study. Proximate and ultimate analyses, a metal analysis and the heating value of pelletized thorny bamboo are given in Table 1. Silica sand (99.5% SiO_2) with a mean diameter of 0.576 mm and apparent density of 2600 kg/m^3 was used as the inert bed material in this study. Table 2 presents the particle distribution of silica sand.

2.2. Experimental apparatus

Fig. 1 shows a schematic of the VFBC system, which was introduced in our previous studies [25,27]. FGR was also employed. The primary gas consisted of the primary air and FGR. The primary air was supplied by a 11.2 kW Roots blower, and the FGR was supplied

Table 1
Proximate and ultimate analyses, metal analysis and heating value of pelletized thorny bamboo.

Fuel	Symbol	Pelletized thorny bamboo
Proximately analysis (wt. %, as-received)		
Moisture	M	7.94
Volatile	V	72.09
Fixed carbon	FC	16.02
Ash	A	3.95
Ultimately analysis (wt. %, dry and ash free)		
Carbon	C	48.40
Hydrogen	H	6.64
Oxygen (by difference)	O	44.21
Nitrogen	N	0.41
Sulfur	S	0.34
Metal analysis (mg/kg, dry basis)		
Na		116
K		18,300
Ca		514
Mg		884
P		404
Heating value (MJ/kg)		
HHV (DB)		18.96
LHV (WB)		15.90