Impacts of Air Staging on NO Emission from a Conical Fluidized-bed Combustor Firing Sunflower Shells

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Abstract

In this experimental study, a conical fluidized-bed combustor (conical FBC) of 0.9 m inner diameter and 3.4 m height was used to fire sunflower shell at 45 kg/h, excess air about 60% at the secondary to total air ratio (S/T) 20, 40 and 60% for two different locations of secondary air injection: 1.6 and 2.6 m above the air distributor. The axial temperature as well as O_2, CO and C_xH_y concentrations profiles in the reactor as well as at the combustor outlet were investigated. In the air-staged combustion, flue gas temperature was found to be at maximum in the vicinity of fuel injection into the combustor, nevertheless, reduced to the minimum in the upper region (close to a level of secondary air injection). Due to the reduced concentration of O_2 in the bed region during the air-staged combustion of sunflower shells, CO showed significant values in this region, however, drastically reduced in the combustor freeboard above the secondary air nozzles. As revealed by the experimental data, the percentage of secondary air as well as the location of which secondary air is injected showed significant effects on the axial O_2, and CO concentration profile, whereas, the axial C_xH_y and NO_x concentration profile exhibited rather weak effects of this operating variable. Taking into account the emission characteristics, the percentage of secondary air of 20-40% and the injection level of 2.6 m (above the primary air distributor) seems to be the optimum option for the effective mitigating of NO_x emissions. In the range of these operating conditions, NO_x emissions quantify at minimum value, ~220−227 ppm at the rather low CO emission in the flue gas.

Keywords: air-staged combustion, fluidized-bed combustor, sunflower shells.

Introduction

Thailand is one of the agricultural-based countries, many biomass fuels such as rice husk, bagasse and energy crops are available for heat and power generations. While the conventional biomass were traditional utilized in the rice mill, sugar industrial and biomass-fuelled power plant, the processed waste such as tamarind shells, peanut shells, palm stalks, cotton stalk apricot and date stones, corncob and rice straw were growing attention as the biomass fuels in the past decade. A large number of the research studies have been mainly focused on the combustion efficiency and emission performance of the fluidized-bed combustion system firing biomass fuels. The burning of some uncon-ventional biomass fuels (olive cake, peach and apricot stones) reported to have the high fuel-ash content, big particle size and high fuel-moisture content, the CO, C_xH_y emissions and the unburned carbon associated with fly ash showed the elevated values leading to the lower combustion efficiency [1-2]. While the CO emissions and unburned carbon in Ref. [2-6] are generally controlled by the optimal operating conditions: excess air, combustion temperature and fuel feed rate. The NO emission from fluidized-bed combustor appear to be strongly influenced by the nitrogen content of the biomass fuels, however, some studies reported the signficant effects of excess air and air-staged combustion on NO emission [2, 7-9].

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In this research study was aimed at studying the effects of air staging on NO emission when firing the sunflower shells in the conical fluidized bed combustor. The axial temperature, O_2, CO and NO concentrations along the combustor height as well as at the cyclone outlet were investigated for various secondary to total air ratio at different locations at which secondary air is supplied.
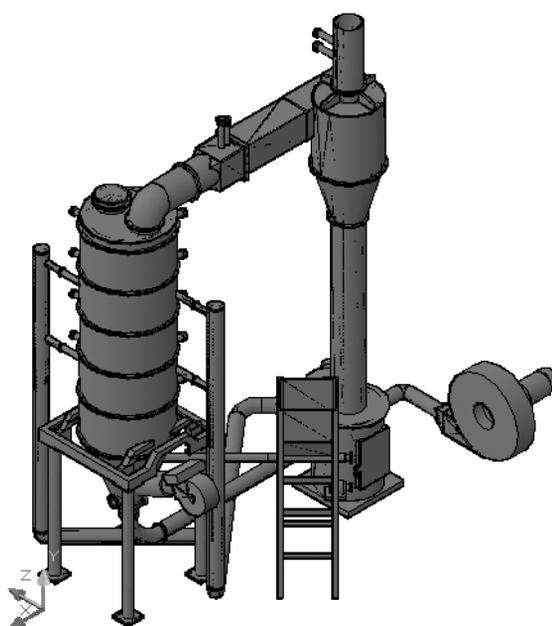
Experimental

Experimental Set-up

Fig. 1 shows the schematic diagram of an experimental set-up with the conical FBC with the cone angle of 40° and inner diameter of 0.25 m at the bottom plane and 0.9 m inner diameter of at the upper part. The total height of the combustor was 3.4 m consisted of a conical (bottom) section with 1.9 m height and a cylindrical (upper) section with 2.5 m height.

The primary air (or fluidizing air) was supplied through the 13-bubbling-cap air distributor at the bottom part of the combustor by a 25-hp blower. The secondary air was tangentially supplied through a 0.04-m inner diameter pipes at each level of 1.6 and 2.6-m above the air distributor by 5-hp blower. The schematic diagram of the air staging system is also shown in Fig. 1.

A screw-type feeder delivered the tested biomass fuel over the bed at 0.6 m above the air distributor.

Figure 1 Schematic diagram of the experimental set-up with the conical fluidized-bed combustor.

Table 1   Ultimate and proximate analyses and lower heating value (LHV) of Sunflower shells used in experimental studies on the conical FBC

Biomass fuel	Ultimate analysis (wt.%, as-received basis)					Proximate analysis (wt.%, as-received basis)				
	C	H	O	N	S	W	A	VM	FC	LHV (MJ/kg)
Sunflower shells	50.1	7.1	39.3	1.0	0.13	9.1	2.4	71.1	17.4	19.6

Silica sand with particle sizes of 0.3-0.5 mm at the static height of 30 cm was used as the bed material in this study. To avoid the bed agglomeration, it was replaced every 18 hours of use [4].

The combustor had gas sampling ports, as well as stationary Chromel-Alumel thermocouples (of type K) for measuring the temperatures in the axial direction inside the rector during the experimental tests. To quantify the gaseous concentrations (O_2, CO and NO) along the combustor and at the cyclone exit, a model "Testo-350XL" gas analyzer (Testo, Germany) was used to monitor the temperature and gas concentrations.

Fuel Characteristics

Table 1 shows the ultimate and proximate analyses as well as the lower heating value (LHV) of the sunflower shells used in this work. It can be seen in Table 1 that sunflower shells were characterized by a significant amount of volatile matter (VM), a moderate proportion of fixed carbon (FC), and relatively low contents of fuel-moisture (W) and fuel-ash (A) in the proximate analysis, which resulted in a substantial LHV. Note that the sunflower shells contained proportion of fuel-N (1.0 wt.%) and fuel-S (0.1 wt.%), therefore, the SO_2 was not addressed in this study.

2.3 Experimental Planning

In the experimental tests, the sunflower shells were burned at the fixed feed rate (FR), 45 kg/h, excess air (EA) about 60% at the secondary to total air ratio (S/T) 20, 40 and 60% for different locations of which secondary air (Z) were supplied: 1.6 and 2.6 m above the air distributor. For the comparative study with the air-staged combustion, the conventional combustion of sunflower shells without secondary air injection was also conducted at the fuel feed rate of 45 kg/h and excess air about 60%.

Results and Discussions

Combustion Characteristics

Fig. 2 shows the effects of air staging and the the location of secondary air injection on the axial temperature and O_2 concentration profiles. As seen in the figure, the location of secondary air injection has shown the significant effects on both axial temperature and O_2 concentration profiles.

(a)

(b)
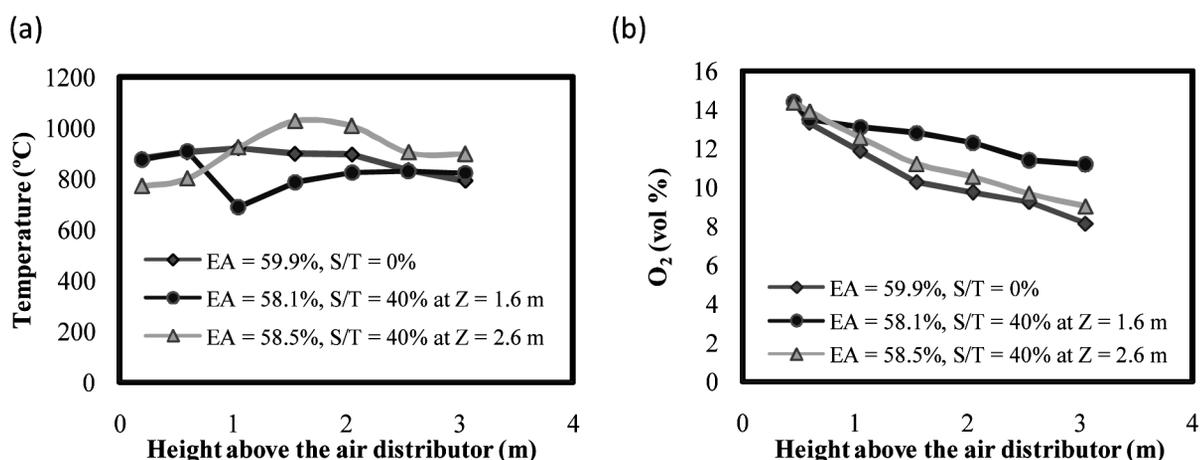
Figure 2 Effect of secondary air injection level on the axial temperature (a) and O_2 concentration (b) profiles along the conical FBC when firing Sunflower shells at EA ≅ 60% and S/T = 40%.

The maximum combustion temperature $1027^{\circ}C$ was found at level 1.6 m above the air distributor when the secondary air was injected to the combustor at Z = 2.6 m. The minimum flue gas temperature $688^{\circ}C$ and the low oxygen consumption was found when secondary air was supplied at Z = 1.6 m. While the injection at the higher level seems to enhance the good mixing between bed material and the selected biomass fuel (char particles), vice versa, it retarded the oxidation of fuel when the secondary air was injected into the combustor at the lower level. Due to the vortexing flow of secondary air in the reactor, it was found that the maximum temperature occurred at the level below the secondary air injection for both case studies.

Emissions Characteristics

Fig. 3 shows the effects of air staging and the location of secondary air injection on the axial CO NO and $C_x H_y$ (as CH_4) concentration profiles. The maximum CO concentrations in every test were observed in the bed region near the location of fuel injection (at 0.6 m about the air distributor).

The highest CO concentration was found in the combustion test with air staging at Z = 1.6 m, mainly because of the lower combustion temperature, the higher devolatilization (of volatile hydrocarbon to CO) and the less oxygen consumption (see Fig. 2b) in this region. However, the high CO oxidation occurred in the freeboard region in the vicinity of secondary air injection into the combustor.

Comparing with the air-staged combustion, the CO concentrations in the conventional combustion were significantly lower, particularly in the bed region, because of the higher rate of char-C oxidation.

In contrast to the axial CO concentration profiles, the axial NO concentrations seems to independent from the location at which secondary air was injected. For every experimental test, the highest NO concentrations observed at the same level ~0.8 m above the air distributor.

In the upper region of the combustor (at Z > 2 m), the NO reduction rates in the air-staged combustion tests were found to be higher due to the greater catalytic reduction of NO by CO (on the char surface).

As seen in Fig. 3c, the highest $C_x H_y$ concentrations in flue gas were also found in the bed region at the level in vicinity of the fuel injection. However, the $C_x H_y$ were effectively mitigated by secondary air, to relative small value in the freeboard region (at Z > 2 m), thus leading to the apparently lower than the $C_x H_y$ concentrations in the air staging tests.

Major Emissions in Flue Gas

Fig. 4 depicts the CO, $C_x H_y$ (as CH_4) and NO emissions (all presented on dry gas basis and at 6% O_2) from the conical FBC fired with sunflower shells at 45 kg/h, excess air about 60% at the secondary to total air ratio (S/T) 20, 40 and 60% for two different locations of secondary air injection: 1.6 and 2.6 m above the air distributor.

Whereas the location of which secondary air is injected presented significant effected on the CO emissions as seen in Fig.4a, it showed slightly effect on the NO emissions. While $C_x H_y$ emissions seemed to independent from this operating variable.
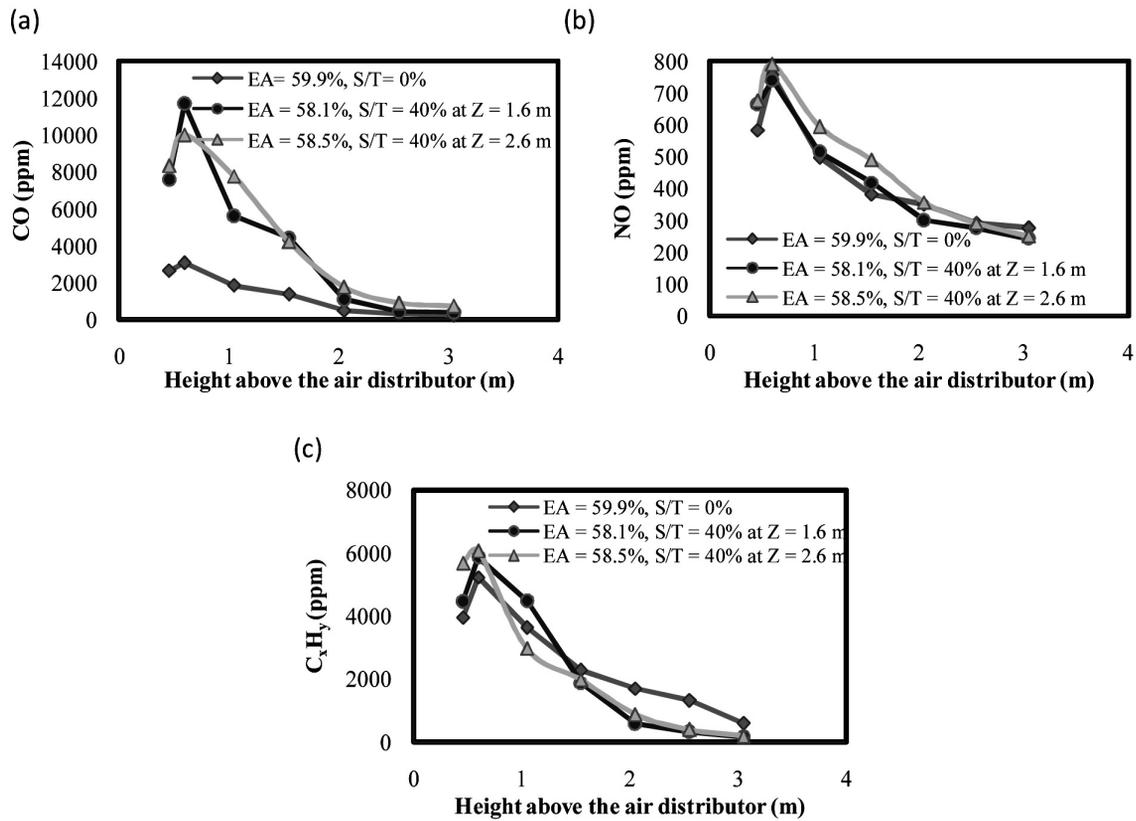
Figure 3 Effect of secondary air injection level on the axial CO, C_xH_y and NO concentration profiles inside the conical FBC firing Sunflower shells at EA $\cong$ 60% and S/T = 40%.

Due to the higher residence time for C-char oxidation in the conventional combustion (firing without secondary air injection), the CO emissions was found at rather low value (at 232 ppm) compared with the tests with air staging.

In air-staged combustions, the CO emission seems to be greater when the secondary air was injected at Z = 2.6 m, and the maximum value was 800 ppm at S/T = 40%. In contrast to the CO emissions, NO emissions was found to be reduced to the satisfaction value (220 ppm) for the same operating conditions.

From CO, C_xH_y and NO emissions in the range of experimental tests, it can be clearly seen that the main chemical reactions responsible for NO reduction is the catalytic reduction of NO by CO when firing the sunflower shells in the proposed fluidized-bed combustor.

Conclusion

As revealed by the experimental data, the percentage of secondary air showed significant effects on the axial O_2, CO and C_xH_y concentration profile, whereas the axial NO_x concentration profile exhibited rather weak effects of this operating variable.

(a)

(b)

(c)
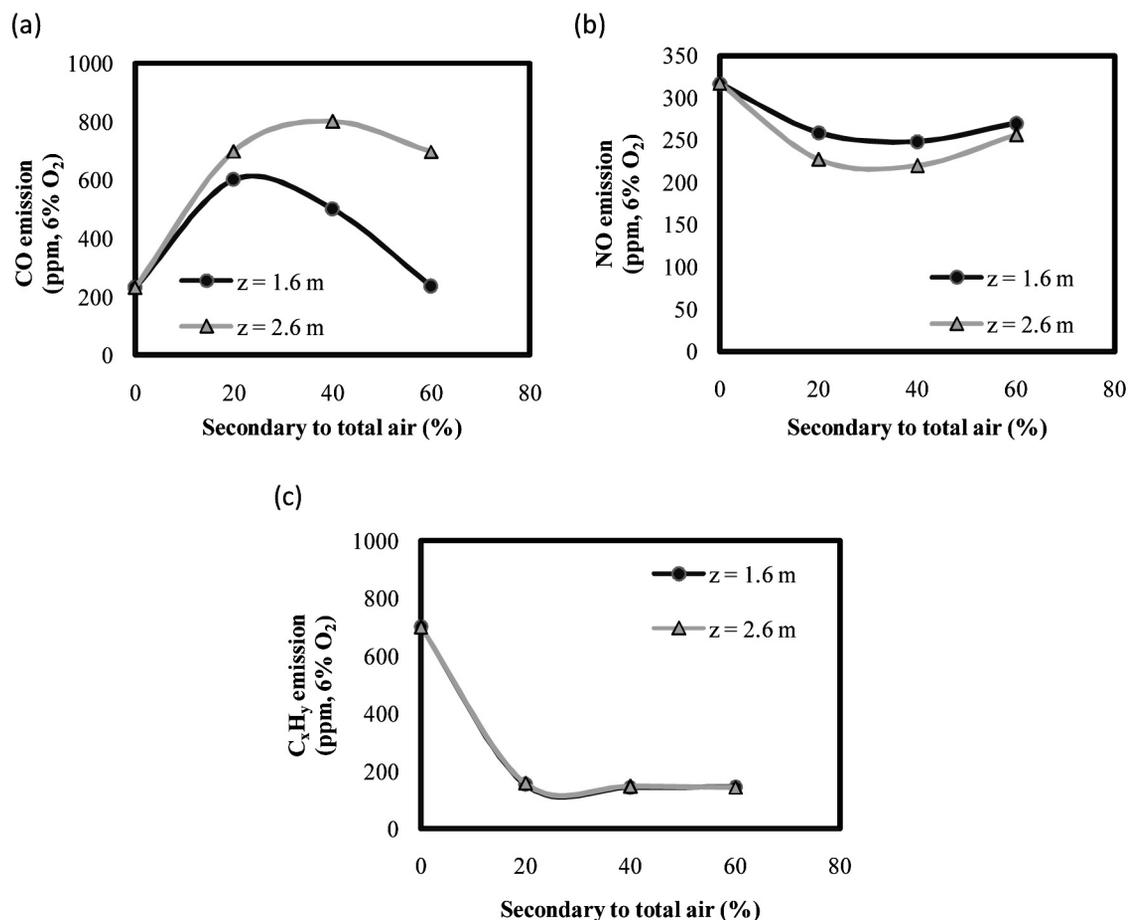
Figure 4 Effects of air staging on the emission of CO, C_xH_y (as CH_4) and NO from the conical FBC fired with sunflower shells.

The percentage of secondary air of 20–40% and the injection level of 2.6 m (above the primary air distributor) seems to be the optimum option for effective mitigation of NO_x emissions in the conical FBC.

Under these operating conditions, the NO_x emissions can be controlled at a minimum value, about 220 ppm (on a dry gas basis and at 6% O_2), whereas the CO emissions was in the acceptable value, about 800 ppm.

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