Combustion of some Thai agricultural and wood residues in a pilot swirling fluidized-bed combustor

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Abstract: This paper reports a comparative study of burning Thai rice husk, sunflower shells and fine rubberwood sawdust as well as co-firing of the sawdust and shredded eucalyptus bark in the swirling fluidized-bed combustor (SFBC). All experiments for firing individual fuels were performed for the combustor heat input of ~300 kW_{th}. However, in the co-firing tests, the fuel mixture was delivered at a fixed feedrate, while ranging mass fraction of the blended fuels. For each fuel option, excess air was varied from 20% to 80%, while a flowrate of secondary air was constant. Temperature and gas concentrations (O_2, CO and NO) were measured in axial directions in the reactor, as well as at stack. Axial profiles of these variables were compared between the fuel options for selected operating conditions. The axial temperature profiles were weakly dependent on operating conditions, whereas the axial gas concentration profiles were apparently affected by fuel properties, excess air and secondary air injection. The behavior of CO and NO indicated the occurrence of three (or four) specific regions along the combustor height. As revealed by the experimental results, CO and NO emissions from the combustor can be controlled meeting the national emission standard, via maintaining excess air at ~55%, for all the fuel options. At this excess air, high, 99.1–99.9%, combustion efficiency is achievable when burning these fuels in the SFBC. However, the best combustion and emission performance for the co-firing of rubberwood sawdust and eucalyptus bark can be ensured at 85% sawdust contribution to the combustor heat input.

Keywords: *Biomass Residues, Swirling Fluidized-Bed Combustor, Emissions, Combustion Efficiency*

1. Introduction

Biomass is an important source of energy in Thailand. Some agricultural and forest-related residues collected on a large scale (such as rice husk, sugar cane bagasse, wood sawdust and chips) are widely used in this country as biomass fuels for heat and power generation. However, the domestic agricultural and industrial sectors generate a variety of residues and/or byproducts potentially considered as fuels due to their excellent combustion properties.

The fluidized bed-combustion technology is proven to be effective for conversion of energy from biomass. A large number of studies have been devoted to bubbling, vortexing and circulating fluidized-bed combustion systems firing conventional biomass fuels [1–4]. Some authors pointed out difficulties in achieving high combustion efficiency when firing high-ash biomass fuels [1,2], while the others highlighted ash-related operational problems caused by alkali-based compounds in biomass ashes [1,5]. These studies revealed that the combustion of most conventional biomass fuels is accompanied by substantial gaseous emissions [1–4].

During the past decade, a growing attention has been paid to the feasibility of effective utilization of various unconventional biomass fuels (from fibrous fuels to fruit stones and shells), basically, through their burning in bubbling and circulating fluidized-bed combustion systems. As shown in relevant pioneering works, combustion efficiency of these systems firing unconventional fuels is comparatively low and strongly affected by fuel properties, whereas gaseous emissions can be controlled at levels typical for conventional fuels [6–8].

Due to some specific hydrodynamic features, an innovative swirling fluidized-bed combustor (SFBC) with a cone-shaped bed seems to be a promising multi-fuel combustion technique for effective firing of various biomass fuels with significantly different fuel properties and characteristics. A swirling gas–solid fluidized bed is reported to ensure the flexibility in fuel particle size and shape, and, also, prevent the growth of large bubbles in the bed [9].

This work was aimed at comparing the combustion and emission performance of the SFBC between different fuel options: (1) individual burning of Thai rice husk, sunflower shells and fine rubberwood sawdust, and (2) co-firing of the sawdust and eucalyptus bark. Effects of fuel properties and operating conditions on major (CO and NO) emissions, as well as on combustion efficiency of the SFBC, were the main focus of this study.

2. Materials and Methods

2.1. Experimental set-up

Fig. 1 depicts the schematic diagram of an experimental set-up with the SFBC. The combustor consisted of six refractory-lined steel modules: a conical section with a 40° cone angle and an inner diameter of d_0 = 0.25 m at the bottom plane, and five cylindrical sections of 0.5 m height and 0.9 m inner diameter. Quartz sand of 0.5–0.6 mm particle size and 30 cm static bed height was used as the inert bed material to ensure stable swirling fluidized-bed regime [9].

An annular spiral air distributor arranged at the bottom of the conical section was used as the swirler of the bed. A 25-horsepower blower delivered primary air to the combustor. For firing

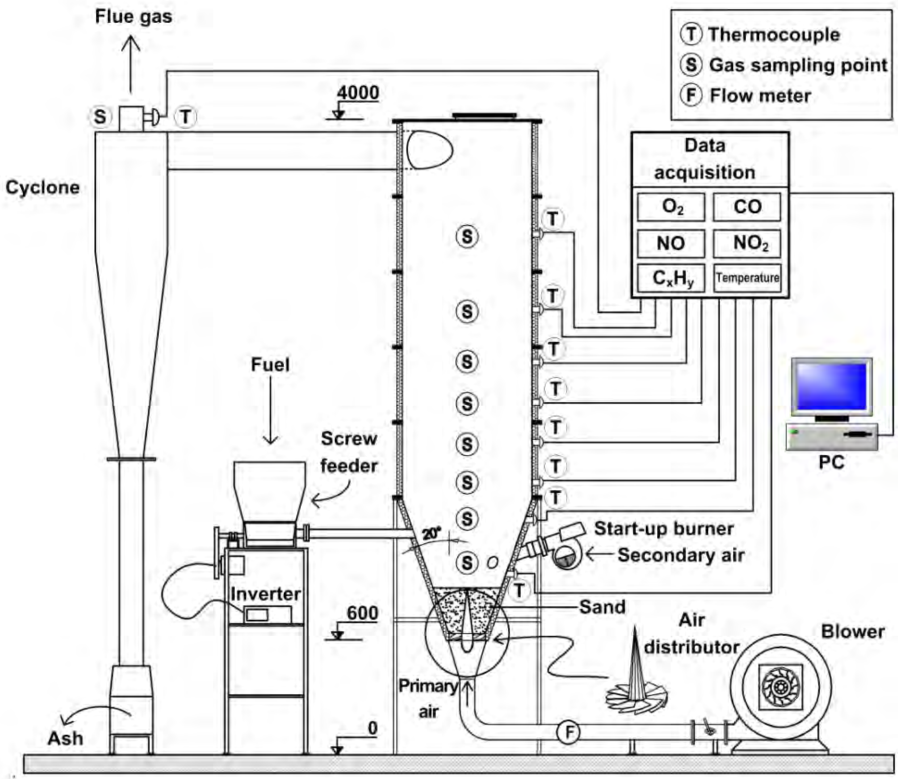

Fig. 1. Schematic diagram of the experimental set-up with the swirling fluidized-bed combustor.

rice husk and sunflower shells, the air distributor was made up of 11 straight steel vanes, each vane being with a length of L = 0.09 m and a swirl angle of β = 76° (or 14° to the horizontal). However, for the (co-)firing tests with rubberwood sawdust, the SFBC was equipped with a 22-vane air distributor assembled from the straight steel vanes with L = 0.085 m and β = 79°. The swirl number of both axial-flow swirlers used in this study was estimated by Ref. [10]:

$$S = \frac{2}{3}\left[\frac{1-(d_{\mathrm{h}}/d_0)^3}{1-(d_{\mathrm{h}}/d_0)^2}\right]\tan\beta \tag{1}$$

where d_{h} is the hub diameter of the swirler: $d_{\mathrm{h}} = d_0 - 2L$.

A diesel-fired burner (model "Press G24" from Riello Burners Co.) was used to preheat sand during the combustor start-up. This start-up burner was fixed at a 0.5 m level above the air distributor and inclined at a –30° angle to the horizon. When the bed temperature attained ~700 °C, a diesel pump of the burner was turned off, and the combustor load was sustained by feeding biomass fuel. A screw-type feeder delivered the fuel over the bed at a 0.6 m level above the air distributor. During the combustion tests, the burner fan remained to operate injecting secondary air tangentially into the bed splash zone at a constant flowrate of Q_{ba} = 0.024 $\mathrm{Nm^3/s}$ required to protect the burner head against overheating and impacts from solids.

A "Testo-350XL" gas analyzer was used to measure temperature and gas concentrations (O_2, CO and NO) along the axial direction (Z) in the reactor space, as well as at the cyclone exit.

2.2. The fuels

Table 1 shows the ultimate and proximate analyses as well as lower heating value (LHV) of rice husk, sunflower shells, rubberwood sawdust and eucalyptus bark used in this study. Except eucalyptus bark with its high moisture content (W), the biomass residues were, in effect, high-volatile (VM), low-S fuels. Meanwhile, rice husk included an elevated proportion of fuel ash (A) affecting LHV and fuel devolatilization rate. The average dimensions of rice husk particles were (on average) 2 mm wide, 0.5 mm thick and 10 mm long. On the contrary, sunflower shells were characterized by rather low fuel-ash but medium fuel-N contents, and individual particles of this biomass fuel were a width of 6 mm, a thickness of 0.7 mm, and a length of 10 mm (on average). The main features of rubberwood sawdust were elevated fuel-N but rather low fuel-ash, as well as small particle size (of ~200 μm dominant size). Eucalyptus bark had significant fuel moisture but rather low contents of fixed carbon (FC), fuel-N, fuel-S and fuel-ash. Note that the large size and hard structure of eucalyptus bark particles caused significant problems with fuel feeding when using the above screw-type feeder. It was therefore decided to burn the bark as shredded fuel co-fired with fine rubberwood sawdust.

Table 1. Properties of biomass fuels used in the combustion tests

Biomass fuel	Ultimate analysis (wt.%, as-received basis)					Proximate analysis (wt.%, as-received basis)				
	C	H	O	N	S	W	A	VM	FC	LHV (kJ/kg)
Rice husk	40.5	4.1	28.7	0.3	0.03	8.4	18.0	58.0	15.6	14,620
Sunflower shells	52.2	5.6	29.7	0.6	0.10	9.1	2.7	65.6	22.6	17,150
Rubberwood sawdust	46.7	5.7	33.5	1.8	0.04	6.6	5.7	61.5	26.2	17,070
Eucalyptus bark	25.8	2.9	19.2	0.2	0.02	47.5	4.4	41.5	6.6	8 320

2.3. Experimental planning

Two test series were carried out on the conical SFBC: (1) for firing rice husk and sunflower shells using an 11-vane swirler, and (2) for firing rubberwood sawdust, and also its co-firing with eucalyptus bark using a 22-vane swirler. In the first test series, to ensure similar heat inputs to the combustor (~300 kW_{th}), the fuel feedrate was different: 80 kg/h for firing rice husk, and 60 kg/h for firing sunflower shells. For these two fuel options, axial temperature and gas concentration profiles were compared between two values of excess air (EA): 40% and 80%. However, in the second test series, when a priority was given to the effects of fuel properties, the axial profiles were compared between the energy fractions of the sawdust in the fuel blend (EF_{sd}), while maintaining the fuel feedrate and excess air to be constant: 60 kg/h and 40%, respectively. The trials of the second test series were therefore performed for three sawdust energy fractions: EF_{sd} = 1 (firing pure sawdust at heat input of ~300 kW_{th}), EF_{sd} = 0.85 and EF_{sd} = 0.75.

For all the fuel options, CO and NO emissions and combustion efficiency of the SFBC were quantified for four values of EA: 20%, 40%, 60% and 80%. For each test run, excess air and heat losses (due to unburned carbon and incomplete combustion) were predicted together with combustion efficiency by Ref. [10]. The unburned carbon content in fly ash was determined by laboratory analysis with the aim to estimate associated heat loss (when it was sensible).

3. Results and Discussion

3.1. Axial temperature and gas concentration profiles in the SFBC

Fig. 2 shows the axial temperature as well as O_2, CO and NO concentration profiles in the SFBC firing rice husk and sunflower shells for two EA values: ~ 40% and ~80%. The

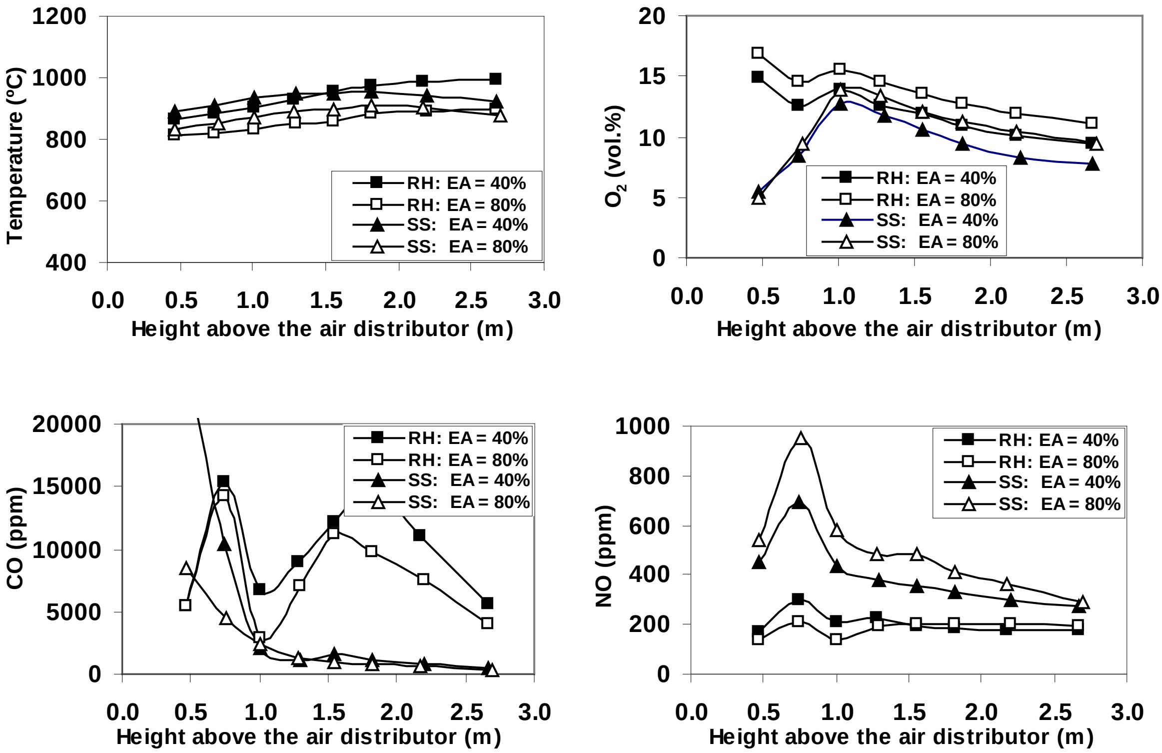

Fig. 2. Effects of excess air on the axial temperature as well as O_2, CO and NO concentration profiles in the conical SFBC firing rice husk (RH) and sunflower shells (SS) at similar heat inputs of ~300 kW_{th}.

temperature profiles were rather uniform, indicating the highly intensive heat-and-mass transfer in the reactor. For both fuels fired at similar EA, the temperatures at different points in the reactor were nearly the same due to similar heat inputs. An increase in EA resulted in some reduction of temperature at any given point, mainly, because of the air dilution effects. However, the axial gas concentration profiles in Fig. 2 exhibit strong effects of fuel properties and secondary air injection as well as the noticeable influence of excess air. In the dense bed region ($0 < Z < 0.5$ m), the rate of O_2 consumption for firing sunflower shells was significantly greater than that for rice husk, mainly, due to the coarser particles, higher VM and lower ash content in sunflower shells. In the next region (up to $Z = 1$ m), O_2 increased along the reactor centerline due to the injection of secondary air. In the combustor freeboard ($Z > 1$ m), O_2 gradually diminished along the centerline showing an apparent influence of excess air.

Like O_2, the CO behavior along the combustor height was quite different in various regions. When firing high-ash rice husk, CO formation in the dense bed occurred at a moderate rate, since some amounts of fuel-C and VM retained in the chars were carried over from this region. However, for firing sunflower shells with higher VM and substantially lower fuel-ash contents, CO formed in the dense bed at a quite significant rate, resulting in higher CO at all points along the reactor axis. In the upper region, up to $Z = 1$ m, CO was characterized by a significant negative gradient along the axial distance caused by the secondary air injection. When burning rice husk, due to the carryover of char-C and VM, CO exhibited a substantial axial increase in the region of $1.0 \text{ m} < Z < 1.8$ m due to oxidation of combustibles, followed by rapid decomposition of CO at the reactor top. However, CO was much lower at all locations in the freeboard when firing sunflower shells for the range of EA (see Fig. 2).

The axial NO concentration profiles in the combustor were found to exhibit four regions. At the combustor bottom, the rate of NO formation from nitrogenous volatile species (mainly, NH_3 [1]) prevailed the rate of NO decomposition. At $Z \approx 0.8$ m, NO attained the maximum, which was quite different for rice husk and sunflower shells, and affected by EA. Due to higher fuel-N, the NO maximum for firing sunflower shells was substantially greater than that for burning rice husk at similar EA. At $0.8 \text{ m} < Z < 1$ m, due to (i) catalytic reduction of NO by CO and (ii) reactions of NO with NH_3 and C_xH_y [1], NO exhibited some reduction in the axial direction. In the freeboard, the rates of NO formation and decomposition were quite low. For firing rice husk, these rates were nearly the same, resulting in rather stable values of NO along the centerline. However, for burning sunflower shells, the NO decomposition rate at the combustor top was greater than that of NO formation, which led to diminishing of NO along the combustor height. Effects of EA on the behavior of NO in the axial direction were rather weak for firing rice husk; however, the effects were substantial for burning sunflower shells.

Attempts to burn fine rubberwood sawdust in this combustor with the 11-vane air distributor, characterized by a swirl number of $S = 2.9$ (as estimated by Eq. (1)), failed in preliminary tests because of the dramatic carryover of light fuel/char particles from the combustor into the cyclone. To increase the residence time of the sawdust char particles in the reactor space, the SFBC was equipped with the 22-vane air distributor with a greater swirl number, $S = 3.6$.

Fig. 3 depicts the axial temperature as well as O_2, CO and NO concentration profiles in the SFBC for (co-)firing fine rubberwood sawdust and eucalyptus bark at different energy fractions of sawdust in the fuel blend at similar EA (of ~40%). Despite the substantial difference in S, the profiles in Fig. 3 exhibit the behaviors and trends similar to those of respective dependencies in Fig. 2. Thus, the axial temperatures for firing sawdust seen to be nearly the same as those for firing rice husk and sunflower shells, and this fact can be explained by similar heat inputs to the

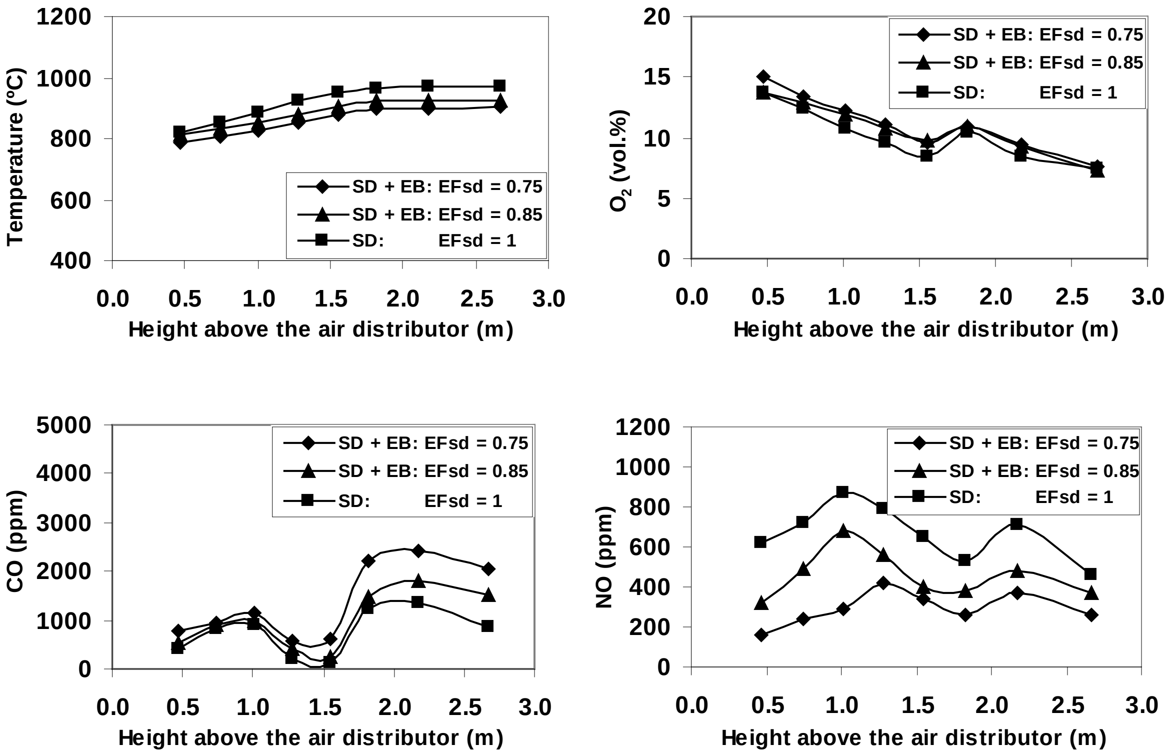

Fig. 3. Effects of the sawdust energy fraction in the fuel mixture on the axial temperature as well as O_2, CO and NO concentration profiles in the conical SFBC firing fine rubberwood sawdust (SD) or co-firing its mixture with eucalyptus bark (SD + EB) at similar excess air value of ~40%.

combustor. However, for the co-firing tests at EF_{sd} = 0.85 (corresponding to the sawdust mass fraction of $MF_{sd} \approx 0.73$) and EF_{sd} = 0.75 (at $MF_{sd} \approx 0.60$), the temperatures at all locations in the combustor volume where somewhat lower, mainly, due to increased moisture content in the blend. It can be seen in Fig. 3 that the effects of secondary air on the axial gas concentration profiles were shifted upward, as compared to the results for firing rice husk and sunflower shells. The carryover of light fuel/char particles of sawdust (or fuel blend) led to the elevated CO and NO concentrations in the freeboard, exhibiting secondary peaks of CO and NO at $Z \approx 2.2$ m. In the meantime, an increase in the mass fraction of eucalyptus bark in the mixture resulted in the higher concentration of CO at all locations along the centerline, mainly, due to the enhanced rate of carbon-C “wet” oxidation despite the reduction in temperature. Elevated CO, together with the reduction in fuel-N and combustion temperature, led to the lower NO concentrations with increasing the mass/energy fraction of eucalyptus bark in the fuel blend.

3.2. Emissions

Fig. 4 shows the CO and NO emissions from the SFBC firing rice husk and sunflower shells for the range of EA compared in the graphs with the Thai emission standards for biomass-fuelled industrial applications [11], all on 6% O_2 dry gas basis. As seen in Fig. 4, at EA of ~20%, the CO emission from the combustor was very high: ~4200 ppm for rice husk, and ~2700 ppm for sunflower shells. By increasing EA, the CO emission can be significantly reduced to a quite low level. However, with higher excess air, the NO emission was found to be increased, thus, indicating the fuel-NO formation mechanism [1]. An excess air of ~55% seems to be the best option at which both CO and NO emissions from this SFBC firing rice husk and sunflower shells comply with the corresponding national emission standards. Fig. 5

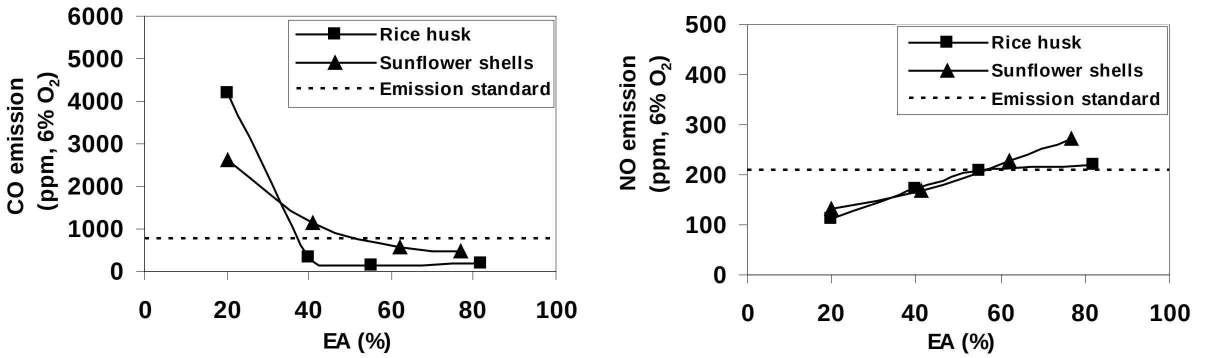

Fig. 4. Effects of excess air on the CO and NO emissions from the conical SFBC firing rice husk and sunflower shells at similar heat inputs of ~300 kW_{th}.

depicts the CO and NO emissions versus EA for (co-)firing rubberwood sawdust and eucalyptus bark for variable EF_{sd}. As seen in Fig. 5, to meet the emission standards, the SFBC should be fired at $EF_{sd} \approx 0.85$ (or SD/EB ≈ 73/27, by weight) maintaining excess air at ~55%.

3.3. Combustion efficiency

For all the fuel options, heat loss due to unburned carbon was found to be weakly dependent on EA and estimated as quite low (0.49–0.74% for firing rice husk, and ~0.15% for firing sunflower shells) or negligible (for firing rubberwood sawdust or its co-firing with eucalyptus bark). In the meantime, heat loss due to incomplete combustion was at a rather low level as well (<1%, for excess air of 40–80%). As the result, at 40–80% excess air values, the total combustion heat losses were estimated to be below 1%, which resulted in the high magnitudes of combustion efficiency, 99.1–99.9%, for all the fuels used. At excess air of ~55% ensuring best emission performance of the SFBC, the combustion efficiency was: 99.4% for rice husk, 99.5% for sunflower shells, 99.9% for rubberwood sawdust, 99.6% for the sawdust–bark mixture at $EF_{sd} = 0.85$, and 99.1% for the sawdust–bark mixture at $EF_{sd} = 0.75$.

4. Conclusions

In this comparative study, a swirling fluidized-bed combustor have been successfully tested for different fuel options: firing rice husk, sunflower shells and fine rubberwood sawdust, as

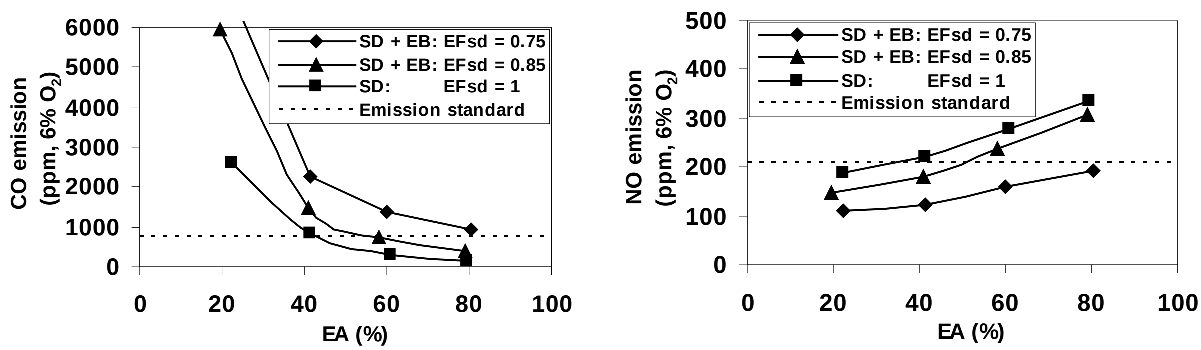

Fig. 5. Effects of excess air and sawdust energy fraction on the CO and NO emissions from the SFBC firing fine rubberwood sawdust (SD) or co-firing its mixture with eucalyptus bark (SD + EB).

well as co-firing the sawdust and eucalyptus bark at variable energy fraction of sawdust in the fuel blend. Substantial differences in properties of the selected fuels/blends (especially, in volatile matter, fuel-N and fuel-ash contents), as well as in the fuel particle size, affect significantly formation and decomposition of CO and NO in various regions of the combustor. For all the fuel options, CO emission can be effectively controlled by tangential injection of secondary air into the bed splash zone of the reactor. With higher excess air, NO emission from the combustor increases substantially in accordance with the fuel-NO formation mechanism. Through co-firing of rubberwood sawdust and high-moisture eucalyptus bark, NO emission from the combustor can be noticeably reduced, which is, however, accompanied by an increase in CO emission. Excess air of ~55% seems to be an optimal value ensuring high, 99.1–99.9%, combustion efficiency for the fuel range. At this excess air, CO and NO emissions can be controlled meeting corresponding national emission standards. For the co-firing, the best result is achievable when the sawdust energy fraction in the fuel blend is ~0.85.

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