Experimental Study on Firing of Some Viable Thai Biomass Fuels in a Conical Fluidized-bed Combustor

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Abstract: This paper presents the results of an experimental study on conventional combustion of distinct Thai biomass fuels (sawdust, rice husk and pre-dried sugar cane bagasse) in a conical fluidized-bed combustor (FBC) using silica sand as the inert bed material. Experimental tests were carried out with the aim of characterization of the combustion efficiency and environmental performance of the proposed device. The FBC design concept and procedure are discussed. The minimum fluidization velocity (an important input parameter for the combustor design) was estimated with the use of Ergun's equation. Selection of the proper cone angle for the conical part of the reactor was made using data from "cold" experimental tests on sand fluidization in different conical models (prototypes). Axial temperature as well as CO, NO and O_2 concentration profiles were compared for the studied biomass fuels. The effects of fuel properties and operating conditions (combustor load and excess air) on these emission characteristics were investigated. The axial profiles of the major gaseous pollutants, CO and NO, were found to have the maximums (CO_{max} and NO_{max}, respectively) which were strongly affected by the fuel properties and operating conditions. Using experimental data on CO emission and unburned carbon content in fly ash, the combustion efficiency of the conical FBC was quantified for the selected biomass fuels fired under different operating conditions. For the maximum combustor load (of some 70–80 kg/h), a combustion efficiency of over 99% was achievable when firing sawdust and pre-dried bagasse at excess air of 50–100%. Meanwhile, because of the elevated unburned carbon content in fly ash, the combustion efficiency for firing rice husk was essentially lower, of 81–86%. Of the studied Thai biomass residues, sawdust is the most environmentally friendly fuel whereas the firing of rice husk is accompanied by noticeable environmental impacts.

Keywords: Temperature, Gas Concentrations, Axial Profiles, Combustor Load, Excess Air, Emissions.

Introduction

Biomass is one of the major primary energy sources in Thailand, accounting for about 28 % of the total energy consumption by the main industrial sectors of the country [1]. Residues and wastes collected on a large scale from the agricultural and forest-related activities such as rice, sugar, wood and palm oil industries are used as biomass fuels for heat and electricity production. The overall power generation potential in Thailand from the viable biomass fuels is estimated to be over 2 GW [2], which significantly exceeds the currently installed capacities. Development of the highly efficient and environmentally friendly technologies for the utilization of the above biomass fuels is the problem of paramount importance for this country. The growing substitution of combustible biomass for fossil fuels (particularly, fuel oil and natural gas), could undoubtedly contribute to energy conservation as well as to mitigation of harmful emissions in the power sector of the Thai economy.The main thermochemical biomass conversion technologies have been reviewed in Refs.[3–5]. Among the proven combustion technologies (such as grate-fired systems, suspension-fired systems, fluidized bed systems), the fluidized bed technology is reported to be the most efficient and suitable for converting agricultural and wood residues into energy.

The emissions from biomass combustion systems, including products of complete (CO_2) and incomplete combustion (CO, char particles, tar, polycyclic aromatic hydrocarbons and other organic compounds), as well as NO_x, SO_2, HCl and ash particles, are affected by the combustion method as well as by operating conditions and fuel properties [3,6–8]. In order to control the emissions effectively (especially, to minimize emissions of incomplete combustion products), one has to know the effects of the above variables/factors on the particular emission.

This paper deals with the experimental study of combustion of distinct biomass fuels (namely, sawdust, rice husk and sugar cane bagasse) in a conical fluidized-bed combustor (FBC) using silica sand as inert material. Compared with cylindrical and prismatic fluidized-bed combustors, the proposed device is characterized by a lower pressure drop over the bed, shorter start-up time and uniform cross-sectional (i.e. radial) profiles of combustion characteristics [9,10]. The main objectives of this work were: (1) to study formation and reduction of the major gaseous pollutants (CO and NO) in the conical FBC when firing selected biomass fuels, and (2) to determine the combustion efficiency of the device fired with these fuels for different operating conditions.

Experimental Set-Up

Experimental investigations on firing distinct Thai biomass fuels were carried out on the conical FBC using silica sand as the inert bed material [10]. The experimental set-up included the major element, the conical FBC, and the auxiliary equipment such as the blower, fuel feeder, pilot burner and cyclone (used as the ash collecting device) as well as the facilities for measuring, collecting and treatment of variables (parameters) of interest.

The combustor consisted of a series of the modular components made of 4.5-mm-thick steel and connected by flanges. Four cylindrical sections of 0.9-m inner diameter formed a 2-m-height cylindrical part of the reactor, whereas a 1-m-height conical (bottom) section with the cone angle of 40o was made as a single part. An air distributor was flanged to the lowest combustor component.

The outer combustor wall was insulated with a 50-mm ceramic-fiber material covered externally by 1-mm-thick galvanized steel in order to minimize the heat losses across combustor walls. For providing the temperature and gas concentration measurements, combustor body had the holes arranged at different levels along the combustor height.
The details on the designing (sizing) of the conical FBC, are discussed below.
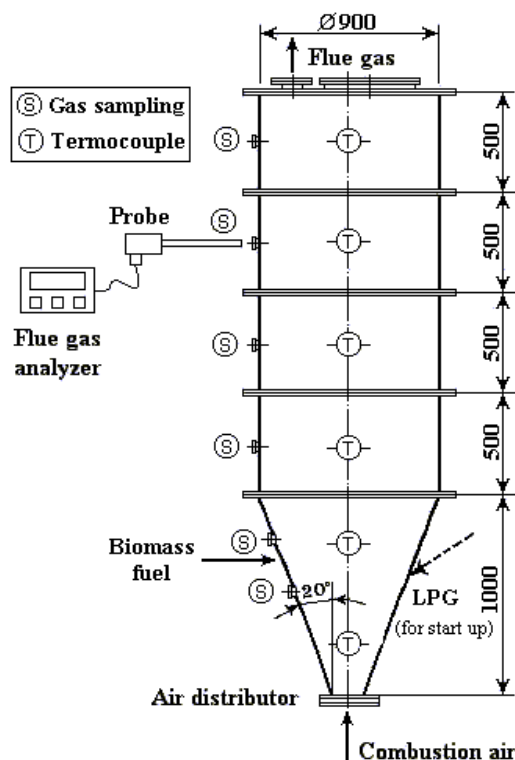

Fig. 1 Schematic diagram of the conical fluidized-bed combustor.

Minimum fluidization velocity

As mentioned above, silica sand of "round" shape, of 300–500   m in mean diameter, was selected as the bed material. The average particle diameter 400   m was therefore used in these design calculations.

The Ergun's equation [11] was used in this work for determining the minimum fluidization velocity, U_{mf}, an important input parameter for the combustor designing. In order to obtain the solution, the Reynolds number was preliminary calculated based on the pre-estimated U_{mf}: Re = 7.5. With the use of relevant properties of the bed material and air the U_{mf} was then estimated to be 0.23 m/s.

Operational velocity

For providing the sustainable fluidization mode and also for avoiding the carryover of the solid particles, the operational velocity was selected to be $6U_{mf}$ (or 1.4 m/s). This assumption allowed quite significant reduction in the combustor load as well as in the excess air ratio. On the other hand, the above value of the operating velocity secured avoiding the terminal velocity at which the bed material particles could be carried away from the combustor.

Diameter of the air distributor plate

Sustainable bubbling fluidization of the bed material was expected for wide ranges of operating variables (e.g. 30–100% for the combustor load and 20–120% for excess air). For the maximum *EA* of 120%, the air volume flow rate of $0.216 m^3/s$ was required for firing the "design" fuel at a feed rate of 100 kg/h (the main input variable). Hence, for ensuring the above value of the operational velocity (1.4 m/s), the cross-sectional area related to the mid-level of the expanded sand bed was quantified to be $0.154 m^2$. Based on this area, the mean diameter of the conical bed was estimated to be 0.44 m.

When fluidizing, the bed may expand to some 150–200% of the initial (static) bed height depending on the operating velocity. For the static bed height *BH* = 40 cm, the cone bed of the above mean diameter of 44 cm was expected to vary in the diameter (along the bed height) from about 25 cm (for the lower base) to 60–80 cm (for the upper base). Based on the above consideration, the diameter of the lower base of the conical part, or that of the air distributor plate (D_O) was selected to be 25 cm.

Cone angle

As known, the cone angle affects the fluidization mode [12]. Three conical devices (models of the combustor conical part) with the cone angles of 30°, 44° and 60°, respectively, were designed and preliminarily tested under "cold" operating conditions. Sand of the secured size of 300–500 μm diameters was used in these tests.

The cone-shaped models (or prototypes) were made of galvanized steel sheet of 2-mm- thickness. Diameters of bottom and top bases were fixed for all three models at 0.25 and 0.9 m, respectively. The heights of the conical models were, therefore, different: of 126, 82 and 56 cm for the cone angles of 30°, 44° and 60°, respectively. Each conical part was equipped with a glass window for observation of the fluidization process during the tests. Meanwhile, a number of small holes along the height were arranged in each device for measuring the pressure drop between two desired points in the conical bed.

The test results showed that the cone angles of 30° and 44° secured the bubbling fluidized bed mode whereas an increase in the angle value to 60° had led to the spouting fluidization in the bed of sand. Based on this conclusion, the conical part with the 40°-cone angle was selected as the bottom element for this conical FBC.

The combustor

The diameter and height of the cylindrical part are the key geometrical characteristics affecting the combustion efficiency because their influence on the residence time of the fuel particles carried by the flue gas. In this research, the diameter of the cylindrical part (D_c) of the conical FBC 90 cm was selected based on the above consideration. Meanwhile, the height of the cylindrical part was selected to be 2 m. with the use of D_o, D_c and selected cone angle, the height of the conical part could be readily estimated to be 1 m. The conical FBC is shown in Fig. 1 with the geometrical combustor characteristics.

The Fuels

Three Thai biomass fuels (sawdust, rice husk and sugar cane bagasse) delivered from different Thai mill companies were used in the experimental tests.

The supplied sawdust was in effect the mixture of residuals (sawdust) of various local woods (Teng, Maka, Rang, Pradu and some others). The average particle size of the sawdust was about 0.8 × 0.8 mm. The individual particles of rice husk were much greater in size (of 2.4 × 8 mm on average). However, this fact did not involve any problem in feeding the fuel into the combustor because of relatively low fuel moisture (W = 10.3%).

Attempts to burn "as-received" bagasse failed   in preliminary tests because of the high moisture content in this raw biomass fuel (W = 48.8%). The fuel was, therefore, preliminarily dried to the moisture content of about 14.4% under room conditions (i.e. by natural ventilation) for a few days.

Table 1 shows ultimate and proximate analyses as well as the lower heating values (*LHV*) of the fuels used in this work.

Table 1 Properties of biomass fuels used in the experimental tests

Fuel	Ultimate analysis (wt.%, *daf*)					Proximate analysis (wt.%)		LHV (MJ/kg)
	C	H	O	N	S	W	A	
Sawdust	45.43	6.71	47.65	0.19	0.02	15.9	0.61	13.9
Rice husk	48.45	6.16	44.62	0.55	0.22	10.3	19.54	12.3
Bagasse [a] (sugar cane)	42.00	6.58	51.00	0.26	0.16	14.4	1.84	12.6

[a] Pre-dried under room conditions from W = 48.8% (as-delivered) to W = 14.4%.
W = moisture, A = ash," *daf*" = dry and ash-free basis
LHV = fuel lower heating value (proximate analysis)   .

Experimental Procedures

The concentrations of major gaseous pollutants (CO and NO) in flue gas were measured in the experimental tests along the combustor height above the air distributor when firing the selected biomass fuels. In addition, O_2 concentrations as well as temperatures were detected along the combustor height and in the flue gas at the cyclone outlet (see Fig.1). For each test run, the value of excess air in the flue gas was determined using the O_2 and CO concentrations at the cyclone outlet.

Flue gas was sampled through seven holes arranged at different locations along the flue gas path. For measuring the gas concentrations, the "Testo-350" gas analyzer was employed. The relative measurement errors were of 5% for CO and NO and about 1% for O_2. Seven chromel-alumel thermocouples (of type K) were fixed at different levels along the combustor height and at the cyclone outlet to monitor the temperatures (in relative error of about 1%) in the flue gas.

The unburned carbon concentrations in fly ash were detected (in relative error of 15% for sawdust and bagasse and 5% for rice husk) in the fuel laboratory in order to assess an associated heat loss.
Two parameters were chosen in this work as independent variables: fuel feed rate (*FR*) and percent excess air (*EA*). For each selected fuel, the conical FBC was tested at two different fuel feed rates and the required feed rate was provided by the corresponding

rotational speed of the feeder screw.   For maximum combustor loading, the screw feeder provided 81.5 kg/h, 82.4 kg/h and 70.0 kg/h when firing sawdust, rice husk and bagasse, respectively; in the tests with minimum fuel supply, the feed rates were 35.0 kg/h, 37.3 kg/h and 31.0 kg/h, respectively. For the maximum fuel feed rates, the combustor was run at five *EA* (of about 20, 40, 60, 80 and 100%), whereas in operation with the minimum loads the fuels were fired at three *EA* (of about 20, 60 and 100%).

Results and Discussion

Based on the measured temperatures and gas concentrations (averaged over time), the corresponding axial profiles along the height above the air distributor were plotted for the fuels of interest fired in the conical FBC under different operating conditions. In the following sections, the profiles of the above variables, as well as other relevant characteristics obtained for these fuels, are compared for some operating conditions.

Axial temperature profiles
The axial temperature profiles for maximum and minimum loads, i.e. for different *FR*s, of the conical FBC firing the fuels at similar *EA* (of about 60%) are shown in Fig.2. These profiles seem to be rather uniform and characterized by small temperature   gradients along the height above the air distribution: positive in the bed region (for heights up 0.8–1.5 m), and negative in the freeboard region.

For quasi-identical   operating   conditions,   the   highest temperatures in the combustor were observed for sawdust. Despite the LHV for bagasse being greater than that for rice husk, all of the temperature profiles for bagasse were lower because of the higher moisture content and smaller feed rate for this fuel.

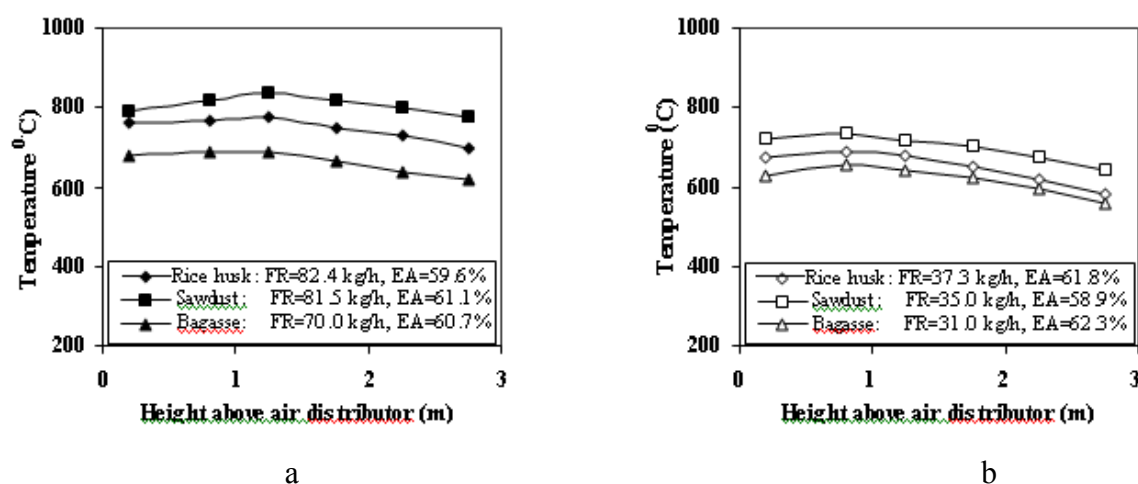With variation in *EA* for the fixed combustor load, the bed

| a | b |

Fig. 2 Axial temperature profiles in the conical FBC for three distinct biomass fuels fired under different operating conditions.

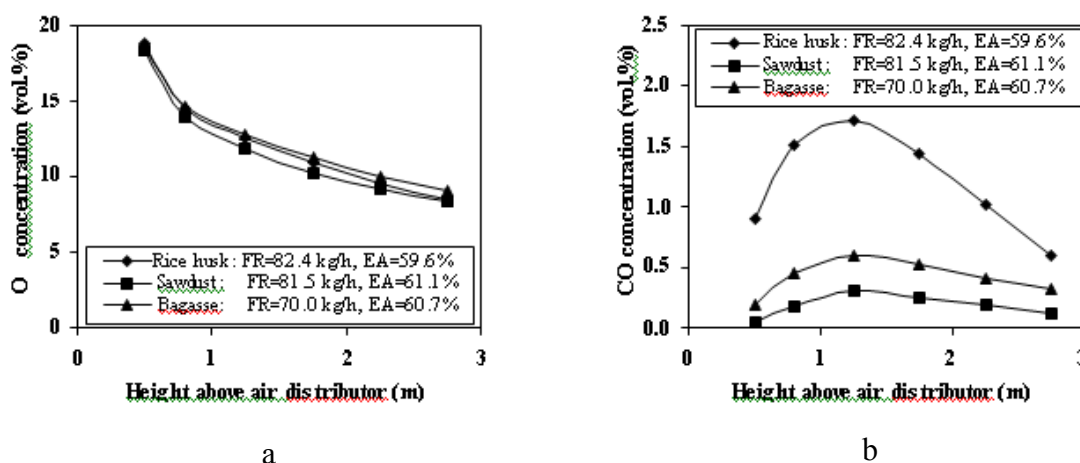a   b

Fig. 3 Axial O_2 and CO concentration profiles in the conical FBC for three distinct biomass fuels fired under different operating conditions at the maximum combustor loading.

temperatures remained to be almost unchanged. However, in the freeboard region the temperatures were found to have a tendency to increase for higher *EA*. for example, when *EA* varied from about 20% to 100% in the tests with maximum *FR*, the temperature at the combustor top (2.75-m height) increased by 60–80°C for firing rice husk and bagasse, whereas it increased by 160°C for firing sawdust. This tendency, but of a lesser degree, remained for the reduced combustor loads.

As seen in Fig. 2, at fixed *EA*, the load reduction of more than 2 times led to some decrease in the temperatures. In particular, for *EA* of about 60%, the bed temperature dropped by some 90°C for rice husk, 70°C for sawdust and 50°C for bagasse, remaining, nevertheless, at a evel sufficient for stable fuel ignition and combustion. This confirmed the high sustainability of the combustion process of the selected biomass fuels in the conical FBC operating in wide ranges of the combustor load and excess air.

Axial O_2 and CO profiles

The axial O_2 concentration profiles for firing the selected biomass fuels at maximum combustor loading are shown in Fig. 3a. For particular excess air, the rate of oxygen consumption along the combustor height was almost independent of either nature of biomass fuel or combustor load; at the same sampling point, the differences in oxygen concentrations for the fuels of interest did not exceed 1.5% O_2. The maximum rates of oxygen consumption were observed in the bed region for all the fuels.

It appears that, with variation in *EA*, the oxygen concentration gradient (along the height above the air distributor) is changed. Meanwhile, in a combustion test at the particular value of EA, the axial oxygen profiles for distinct fuels were found to hold the above tendencies.

The axial CO concentration for firing the selected biomass fuels at maximum combustor loading are shown in Fig. 3b. In all the tests, the axial CO concentration profiles were found to have an extreme (maximum), CO_{max}, at approximately the same locations (or heights above the air distributor) which were detected for the maximum temperatures

for corresponding operating variables. Hence, the combustor volume could be conventionally divided into formation (lower) and reduction (upper) regions with regard to the location of CO_{max} in the combustor.

As seen in Fig. 3b, the rate of CO formation for rice husk was much greater than that for sawdust and bagasse. This could be explained by higher fuel-ash concentration and coarser char particles for rice husk: up to 200 μm, against 5 μm for sawdust and 10 μm for bagasse, as follows from fly ash analyses. These factors result in higher char holdup in the bed region and, consequently, led to higher values of CO_{max} for rice husk in comparison with sawdust and bagasse. For the same reasons, and because of the lower temperatures, the rate of CO formation for bagasse was higher than that for sawdust.

For formation rate of CO in the bed region with EA < 50%, CO formation drastically increases with lowering excess air. In the region with *EA* > 50%, the CO_{max} were gradually reduced (but with quite low rates) whilst *EA* was increased. Thus, emission of this pollutant could be controlled by proper air supply.

The apparent difference in the axial CO concentration profiles for the selected biomass fuels confirms a significant role of heterogeneous reactions (on the char surface), of char-carbon with CO_2 and water vapor, at temperatures typical for fluidized bed combustion [13]. These reactions are basically followed by fuel in-bed devolatilization and further oxidation of the carbon-based components, released from the fuel particles with volatiles, to CO [3]. In addition to the effect of the char particle size, the above reactions explain an elevated rate of CO formation in the bed region for the case of firing high-ash rice husk.

In the reduction region, the CO is basically oxidized in the chain termination reaction with OH radicals as well as by oxygen directly [13]. For the selected biomass fuels, the rates of CO reduction were found to be in an apparent correlation with the CO concentrations in the freeboard region; accordingly, the highest rates were determined for the rice husk. Reduction in combustor loading at fixed *EA* led to a significant diminishing of both formation and reduction rates of CO when firing rice husk, whereas the effect of the load on these processes was relatively weak for firing sawdust and bagasse.

NO formation and reduction in the conical FBC

A comparison of the axial NO concentration profiles is shown in Fig. 4. Similar to CO, all the axial NO concentration profiles possesses a maximum, NO_{max}, the locations of which coincide with those for CO_{max} for corresponding operating

(a)   (b)
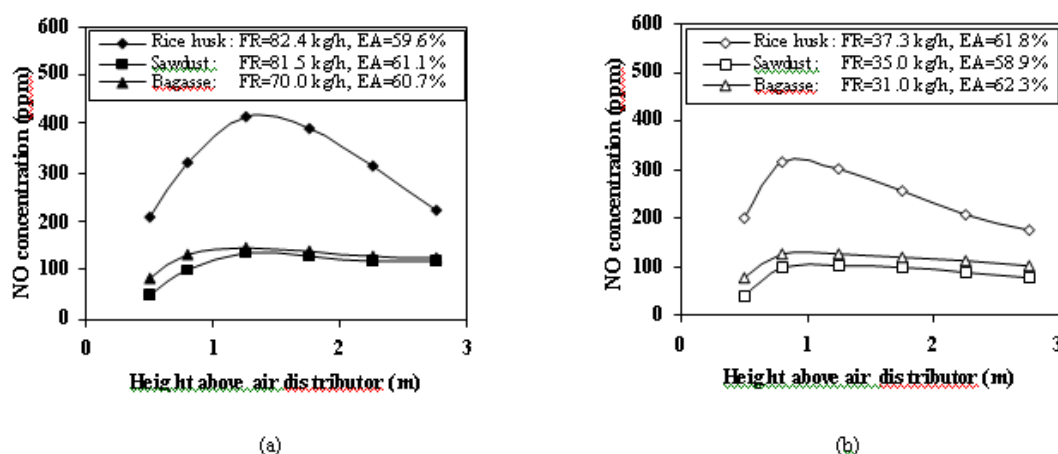
Fig. 4. Comparison of axial NO concentration profiles in the conical FBC for three distinct biomass fuels fired under different operating conditions.

For the temperatures provided in Fig. 2, NO would be expected to originate from the fuel-N [3, 8, 14]. Basically, fuel-NO can be formed through: 1) combustion of the nitrogenous species released with volatile matter (such as HCN, NH3), and 2) oxidation of the nitrogen retained in the char. These reactions, resulting in rapid formation of NO, are most likely to proceed in the bed region of this FBC with the bottom air injection.

Meanwhile, in zones with volume O_2 concentrations lower than 10–12%, the NH_3 concentration is probably elevated due to the rapid formation of NH3 from HCN [8] as well as because of the emission of NH_3 released with volatiles from fuel particles present in these zones. In the upper combustor region (with lower O_2 concentrations, as seen in Fig. 3a) this may lead to NO reduction through its reaction with NH3, followed by formation of nitrogen gas and water vapor, i.e. neutral products. The alternative mechanisms of NO reduction in the upper region of the fluidized bed combustor involve reactions of NO with carbon and CO on the char surface [3, 8] which are highly probable when firing high- ash fuels.

It is the high fuel-N and ash contents as well as the large size of particulates (char and ash) that explain the high rates of NO formation (in the bed region) and reduction (in the freeboard region) in the case of firing rice husk. Apparently, the fuel-N has a strong effect on NO formation, as follows from comparison of experimental results depicted in Fig. 4a. With reduction in the combustor load, the rate of NO formation (or NO_{max}, respectively) becomes somewhat lower, as seen in Fig. 4b, corresponding to the diminished bed temperatures. The above facts confirm the fuel-NO mechanism of the NO_X formation in combustion of the selected fuels.

The nitric oxide represents, in effect, the overall NO_x emissions from a biomass combustion system. In this study, the NO_2 concentrations were found to be 0–1 ppm for all of the tests. The N_2O formation in biomass combustion is reported to be relatively small or negligible; moreover, even though N_2O has been formed, it may be rapidly destroyed in the flame by active radicals and molecules [3].

As seen in Fig. 4, the NO_{max} were slightly greater for higher *EA,* which was typical for the fuel-NO formation route, in spite of the dilution effects caused by excess air. Hence, for the fuels fired at maximum combustor loads, the values of excess air of 50–60% seemed to be optimal for minimizing the environmental impact of the conical FBC fired with the selected fuels, unless the flue gas is not utilized in other combustion systems. For the minimum loads, the optimum values of *EA* were somewhat lower (because of lowering in CO formation) and could be selected in the range of 40–50%.

Table 2 Heat losses and combustion efficiency (% *LHV*) for the conical FBC firing distinct biomass fuels at the maximum fuel feed rate and different values of excess air

Biomass fuel fired	Fuel feed rate (kg/h)	Excess air (vol.%)	Heat loss owing to incomplete combustion (%)	Heat loss owing to unburned carbon (%)	Combustion efficiency (%)
Sawdust	81.5	16.9	3.51	0.01	96.48
	81.5	61.1	0.39	0.02	99.59
	81.5	99.8	0.16	0.02	99.82
Rice husk	82.4	16.3	4.29	12.47	83.24
	82.4	59.6	0.53	13.15	86.32
	82.4	100.7	0.34	18.35	81.31
Bagasse	70.0	17.3	3.72	0.02	96.26
	70.0	60.7	0.81	0.03	99.16
	70.0	101.1	0.53	0.06	99.41

Combustion efficiency

For estimation of the combustion efficiency (as percentage of the *LHV*), the heat losses owing to incomplete combustion (accounting the CO emission) and unburned carbon contained in particulate matter (fly ash) were determined by Ref. [15].Table 2 shows these heat losses along with combustion efficiencies for the selected fuels fired at maximum combustor loads for different *EA*.

The highly efficient combustion, over 99%, of sawdust and bagasse in the conical FBC is achieved for *EA* > 50%. Taking into consideration the above discussion, *EA* of 50–60% seems to be sufficient to secure the highly efficient combustion of these fuels with minimized environmental impacts.

The combustion efficiency for rice husk was found to be much lower than that for other fuels because of higher heat loss associated with unburned carbon which was affected by both the high ash content and elevated concentration of unburned carbon in particulate matter collected from the cyclone. Owing to the opposite effect of EA on the above heat losses, the total heat loss for rice husk possessed a minimum at *EA* of 50–60% corresponding to the maximum combustion efficiency, as seen in Table 2. Thus, the above recommendation regarding the optimal *EA* proposed for sawdust and bagasse is also applicable to the firing of rice husk in the conical FBC.

Conclusion

An efficient and sustainable operation of the conical FBC was performed when firing sawdust, rice husk and pre-dried sugar cane bagasse in wide ranges of *FR* and *EA*. The axial temperature profiles in the conical FBC were fairly uniform for all the fuels and weakly affected by fuel analysis and operating conditions. For particular excess air, the rate of oxygen consumption along the combustor height was almost independent of either the nature of the fuel or *FR*.

Both CO and NO axial profiles possessed a maximum whose location divided conventionally the combustor volume into formation (lower) and reduction (upper) regions for these pollutants. CO formation rates, and consequently CO_{max}, for rice husk were much greater than those for sawdust and bagasse for similar operating conditions because of coarser char particles and higher ash concentration leading to higher char hold up in the bed region and significant contribution of char-carbon to CO formation. The CO_{max} for distinct fuels were rapidly diminished with an increase in excess air of up to 50–60% demonstrating however a weak dependence on excess air in the region of 60–100%. The rates of CO reduction for distinct biomass fuels were found to be in an apparent correlation with CO concentrations in the freeboard region; accordingly, the highest rates were determined for the rice husk.

The NO_{max} was strongly affected by fuel-nitrogen and weakly dependent on the operating conditions confirming a fuel-NO formation mechanism for all the fuels. The rate of NO reduction for rice husk was much greater than those for sawdust and bagasse due to the significant role of heterogeneous reactions (on the char surface) in the freeboard region and ash collecting device (cyclone). Of the studied fuels, sawdust is the most environmentally friendly biomass fuel whereas the firing of rice husk is accompanied by noticeable environmental impacts.

For the maximum combustor load and excess air of 50–100%, a combustion efficiency of over 99% could be achieved when firing sawdust and bagasse. For the case of firing rice husk at the maximum load, the combustion efficiency was lower because of higher losses owing tounburned carbon. The maximum combustion efficiency of 86% for firing rice husk was obtained for excess air of about 60%; an increase in excess air of up to 100% resulted in a deterioration of the combustion efficiency (to 81%).

Acknowledgement

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