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EFFECTS OF FUEL MOISTURE ON COMBUSTION EFFICIENCY AND EMISSION PERFORMANCE OF A FLUIDIZED-BED COMBUSTOR FIRING RICE HUSK

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ABSTRACT
This work presents the results of experimental study on firing Thai rice husk in a conical fluidized-bed combustor (FBC) at different fuel qualities secured by variable fuel moisture. For the particular fuel analysis, the conical FBC was operated at the 82.5–82.8 kg/h fuel feed rate for various percentages of excess air (about 40, 60, 80 and 100%). The test runs at the fuel moisture greater than 40% failed because of the combustion instability and disruption. The axial temperature profiles in the conical FBC were found to be rather uniform and independent of excess air but noticeably affected by the fuel moisture. With higher fuel moisture, due to diminishing the bed temperature, CO formation in the conical bed was enhanced, whereas NO formation was mitigated when firing the fuel at constant excess air. Similar trends were observed for CO and NO emissions, respectively. Firing rice husk at the above fuel moistures resulted in the sustainable combustion in the reactor at the 91−96% efficiency. By adding water into rice husk, both NO emission and ash related problems could be mitigated in the fluidized bed combustion system due to reduction in the bed temperature.

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

1. INTRODUCTION

In Thailand, rice husk represents one of the viable biomass fuels. Despite extensive utilization of rice husk for heat and power production, a significant amount of this biomass fuel is being unused and eventually lost. Annual loss of rice husk in this country is reported to be 2.3–3.7 million tons. Taking into account the fuel lower heating value, the aggregate power generation potential from the unused rice husk is estimated to be 234–375 MW [1]. Development of efficient and environmentally friendly technologies for energy conversion from rice husk and other biomass fuels is therefore the problem of paramount importance for the Thai energy sector.

The fluidized-bed technology is reported to be the most efficient and suitable technology for converting biomass fuel into energy [2–4]. A number of research works have been recently carried out on the fluidized bed combustion of rice husk. Literature sources point at a wide range (81–99%) of variation in the rice husk combustion efficiency, depending upon fuel properties and operating conditions in the combustion system. Meanwhile, the combustion of rice husk is accompanied by noticeable environmental impacts, mostly being done by NO_x and CO pollutants [5−8]. Because of elevated nitrogen in the rice husk ultimate analysis, NO_x emissions from conventional fluidized-bed system are of about 100 to 180 ppm when burning this biomass fuel at the excess air values of some 20 to 100%, respectively. At low excess air (less than 40%), the CO emission from the rice combustion is very high (especially, for high-ash rice husks), basically greater than 5000 ppm, and strongly dependent on excess air. On the other hand, at excess air above 60%, the CO emission from the combustor is reduced to 600−1100 ppm and almost independent of the operating variable [5−9]

Another two problems related to the fluidized bed combustion of rice husk in combustors and boilers, such as bed material accumulation and ash deposition, are caused by the elevated bed temperature [4]. The increase in the fuel moisture (by adding some amount of water to "as-received" rice husk) seems to be an effective and least-cost technological measure for reducing the bed temperature and, thus, controlling the NO_x emissions as well as mitigating the above ash-related processes.

This paper deals with an experimental study on the combustion of Thai rice husk in a fluidized bed system at different fuel moistures and operating conditions. Effects of the fuel properties and excess air on the combustion efficiency and environmental performance (NO_x and CO emissions) of the reactor were the focus of this study.

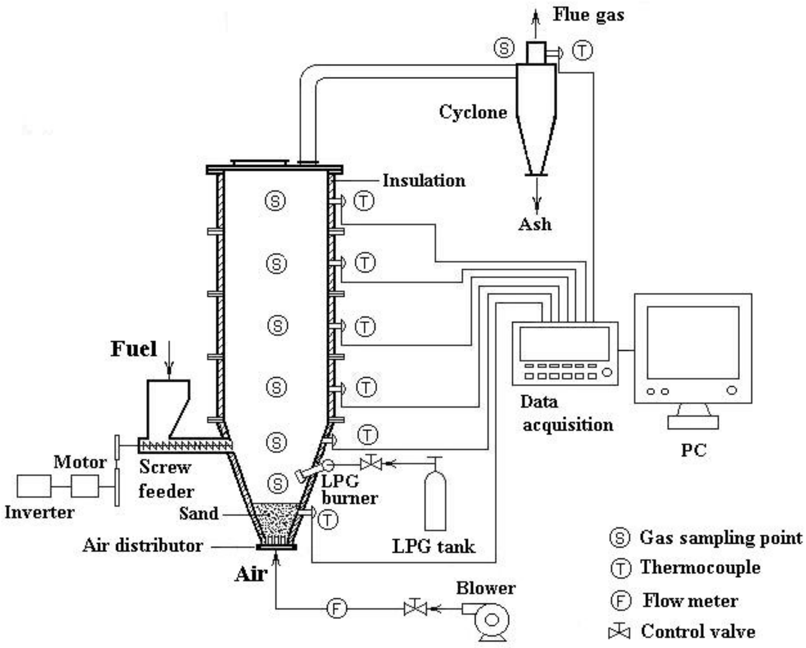


Fig 1. Schematic diagram of the experimental set-up with the conical fluidized-bed combustor.

Table 1: Ultimate analysis (wt.%) and lower heating values (MJ/kg) of rice husk used in the experimental tests at variable fuel moisture (W = fuel moisture, A = fuel ash; LHV = lower heating value).

Test series No.	W	A	C	H	O	N	S	LHV
1	11.0	12.99	34.19	4.86	36.60	0.32	0.04	12.34
2	16.8	12.15	31.97	4.54	34.21	0.30	0.03	11.37
3	24.9	10.96	28.85	4.10	30.88	0.27	0.03	10.02
4	35.5	9.42	24.78	3.52	26.52	0.23	0.03	8.25
5	40.2	8.73	22.98	3.27	24.59	0.22	0.02	7.47

2. METHODS AND MATERIALS

2.1 Experimental Set-up

The schematic diagram of the experimental set-up is shown in Fig 1. The combustor was designed for firing up to 100 kg/h of biomass fuel. The conical fluidized-bed combustor (FBC) consisted of two parts: (1) a conical section of 1 m height with a cone angle of 40°, and (2) a cylindrical section of 0.9 m inner diameter and 2 m height. The combustor was made of 4.5-mm-thick steel, and insulated with 50-mm ceramic-fiber material covered externally by 1-mm-thick galvanized steel.

Silica sand ($SiO_2 \approx 90\%$) of about 0.3–0.5 mm in size and 40-cm static bed height was used as the inert bed material in the combustor. A 25-hp blower supplied air (under ambient conditions) into the combustor through an air distributor. During the combustor start-up, an LPG-firing burner was used for preheating the bed material. Upon attaining appropriate bed temperature (normally, of about 550°C), the burner was turned off.

The combustor was equipped with a screw-type feeder supplying rice husk over the bed at a 0.65 m level above the air distributor. An external cyclone collected ash particles from the flue gas.

2.2 Fuel Properties

Rice husk was used as the fuel in this experimental study. The tests were carried out at five values of fuel moisture, of 11.0, 16.8, 24.9, 35.5 and 40.2 wt.%. For the particular fuel moisture, a series of the test runs was conducted with the aim of studying the effects of operating conditions.

Table 1 shows the fuel ultimate analysis and lower heating value (LHV), the latter being found by Ref.[10], for each test series corresponding to the above fuel moistures. As seen in Table 1, the moisture content in “as-received” rice husk was equal to 11%. However, in other four test series, the fuel moisture was secured by additional water injected into the fuel prior to the tests.

2.3 Experimental Procedures

In accordance with the work objectives, two parameters were chosen in the experimental tests as the independent variables: the fuel moisture (W) and percentage excess air (EA). For the particular fuel moisture (or in each test series), the conical FBC was tested at quasi-identical fuel feed rate (FR), of 82.5–82.8 kg/h, for four EA values, of about 40, 60, 80 and 100%.

During the tests, temperatures and O_2 concentrations as well as concentrations of major gaseous pollutants (CO and $NO_x = NO + NO_2$) were measured in the flue gas along the combustor height and at the cyclone outlet.

Seven thermocouples (of type K) were fixed along the combustor height and also at the cyclone outlet for monitoring the temperature. For measuring the gas concentrations, the “Testo-350” gas analyzer was employed.

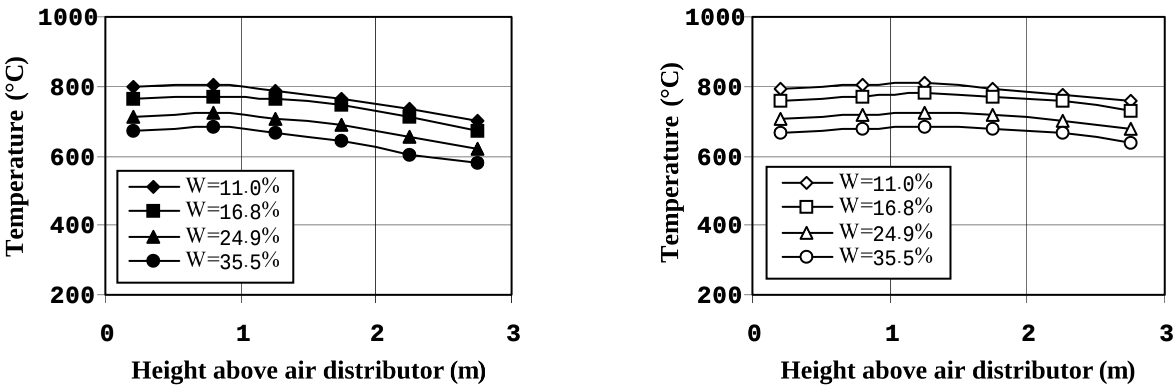
In this work, EA was determined by Ref. [10] using the O_2 and CO concentrations in the flue gas at the cyclone outlet. In some test runs of each series (at EA of 40, 60 and 100%), fly ash was sampled for determining the amount of unburned carbon with the aim of quantifying associated heat loss. For these runs, the heat loss with unburned carbon and the heat loss owing to incomplete combustion (determined with the use of CO concentrations in the flue gas at the cyclone exit) were quantified by Ref. [10].

3. RESULTS AND DISCUSSION

3.1 Major Combustion Characteristics

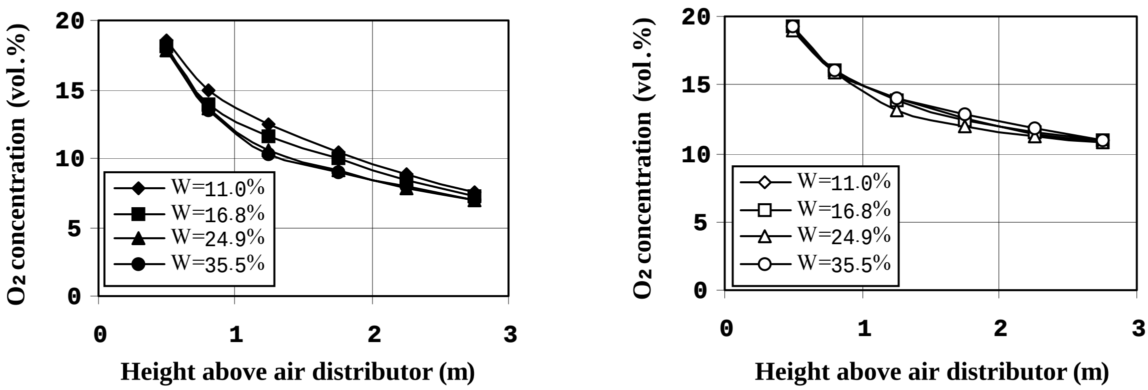
In the test runs at W = 40.2% (Test series No. 5 in Table 1), all attempts to burn this high-moisture rice husk failed because of instability and disruption of the combustion, whereas the tests at lower fuel moistures were successful. As may be concluded, the 35% fuel moisture seems to be the critical value for firing rice husk in this fluidized-bed combustor.

Figure 2 shows the axial temperature profiles in the conical FBC firing 82.5–82.8 kg/h of rice husk at different fuel moistures, for two values of excess air, of EA ≈ 40% (in Fig. 2a) and EA ≈ 100% (in Fig. 2b). As seen in Fig. 2, the profiles were rather uniform and strongly affected by the fuel-W. With higher fuel moisture, the temperatures at all the locations over the combustor height were lowered (compared to those for rice husk of “as-received” basis, i.e. with W = 11.0%). Comparison of the temperature profiles for EA ≈ 40% with those for EA ≈ 100% showed a quite weak effect of



(a) (b)

Fig 2. Effects of the fuel moisture on the axial temperature profiles in the conical FBC firing rice husk at EA ≈ 40% (a) and EA ≈ 100% (b).



(a) (b)

Fig 3. Effects of the fuel moisture on the axial O_2 concentration profiles in the conical FBC firing rice husk at EA ≈ 40% (a) and EA ≈ 100% (b).

excess air on the temperatures in the combustor, especially in the bed region. For the applied values of EA, the temperature reduction of 130–150°C was observed at all the locations along the combustor height when the fuel moisture was increased from 11 to 35%.

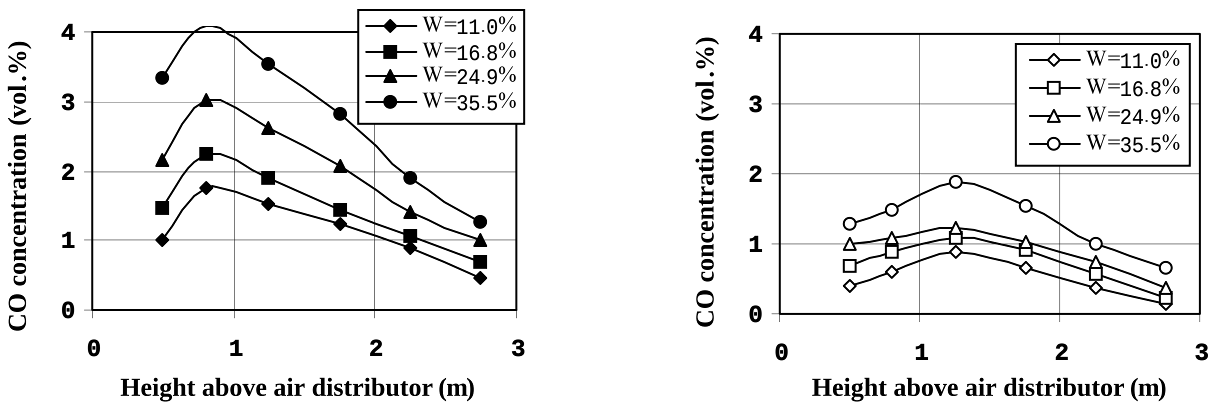
The axial O_2 concentration profiles are shown in Fig. 3 for the same, as in Fig. 2, operating conditions. As seen in Fig. 3, for the particular excess air, the O_2 concentrations were weakly dependent on the fuel moisture. This fact was also confirmed by the experimental results for other EA values. Meanwhile, at the same fuel moisture, the axial O_2 concentration profiles were apparently affected by excess air, especially in the freeboard region. As follows from comparison the data in Fig. 3a and Fig. 3b, an increase in EA led to higher O_2 concentrations at the combustor top.

3.2 Pollutants Formation And Reduction

Figure 4 shows the effects of fuel moisture and excess air on the CO concentrations in the conical FBC. For all the fuel moistures and EA values, the axial CO concentration profiles were found to have a maximum, CO_{max}, whose locations (above the air distributor) divided conventionally the combustor volume into formation (lower) and reduction (upper) regions for these pollutants, as seen in Fig. 4 for both EA values.

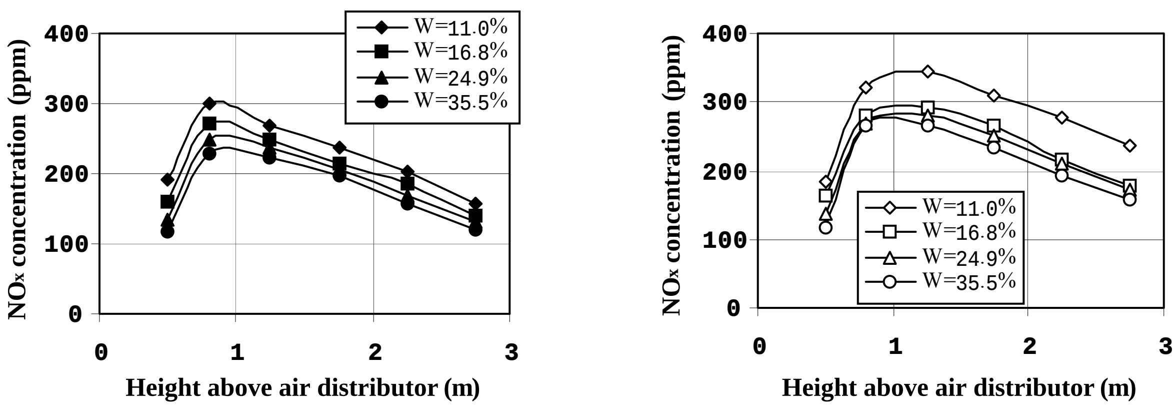
As follows from the data in Fig. 4, in the test run with the highest fuel moisture, the CO_{max} was significantly greater than that for the rice husk of mass “as-received”. Two factors were likely responsible for this elevated CO formation in the bed region with higher fuel moisture: (1) lower bed temperatures (see Fig. 2) leading to the increase in the CO/CO_2 ratio during carbon oxidation, and (2) higher concentrations of water vapor enhancing the contribution of carbon “wet” oxidation (generally, to CO) occurring on the surface of char particles [4]. However, as compared in Fig. 4a and Fig. 4b, CO_{max} was strongly diminished at higher values of EA because of the enhanced rate of homogeneous oxidation of CO by oxygen in this region.

Meanwhile, as may be seen in Fig. 4b, significant reduction in the CO concentrations along the combustor height took place in the freeboard region where CO was likely oxidized in homogeneous reactions with OH radicals and O_2, both being predominant in the freeboard region [11].



(a) (b)

Fig 4. Effects of the fuel moisture on the axial CO concentration profiles in the conical FBC firing rice husk at EA ≈ 40% (a) and EA ≈ 100% (b).



(a) (b)

Fig 5. Effects of the fuel moisture on the axial NO_x concentration profiles in the conical FBC firing rice husk at EA ≈ 40% (a) and EA ≈ 100% (b).

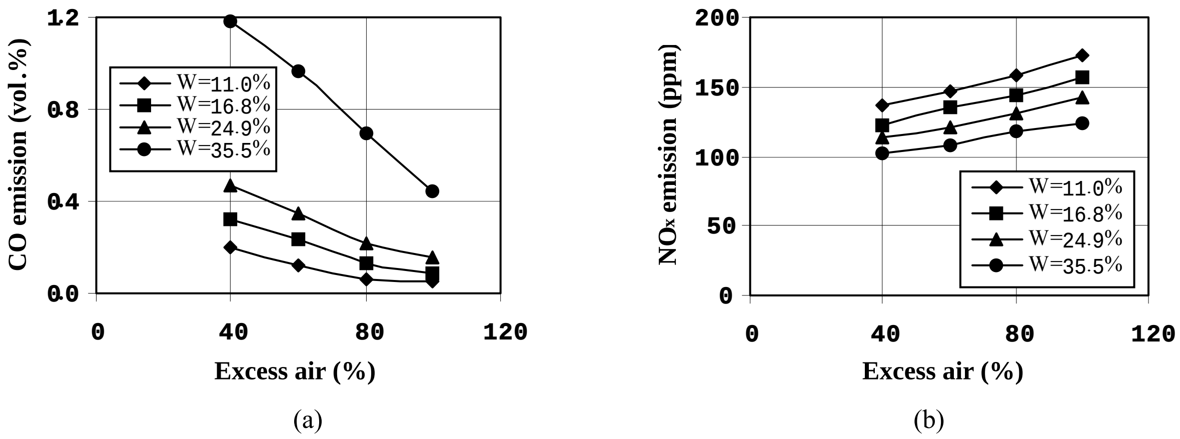


Fig 6. Effects of the fuel moisture and excess air on the CO (a) and NO_x (b) emissions from the conical FBC firing rice husk at the 82.5–82.8 kg/hr feed rate.

Comparison of the axial NO_x concentration profiles in the conical FBC is shown in Fig.5. For the particular EA, the axial NO_x concentration profiles were noticeably affected by the fuel moisture. The NO_x concentrations at all the combustor locations were found to diminish for higher fuel moistures. However, with increasing EA, the NO_x concentrations were increased (as may be compared in Fig. 5a and Fig. 5b). Like for CO, all the axial NO_x concentration profiles possessed a maximum, $NO_{x,max}$, whose location made it possible to distinguish conventionally the formation and reduction regions. Because of lower fuel-N and temperature level in the conical FBC, NO_x was expected to form in the biomass fuel combustion owing to the fuel-NO mechanism of NO_x formation in the fluidized bed occurring through: (1) oxidations of the nitrogenous species released from the fuel particles with volatile, such as HCN and HN_3, and (2) oxidation of fuel nitrogen retained in the char.

In the freeboard region, the axial NO_x concentration profiles were found to decline with fairly the same gradients for all the fuel moistures and excess air values. In this region, the NO_x reduction may likely occur via reactions of NO with NH_3 (at O_2 deficiency) and also with fuel-C and CO on the surface of chars [4,12].

Figure 6 shows the effects of the fuel moisture and EA on the CO and NO_x emissions from the conical FBC. As seen in Fig. 6a, the CO emission could be effectively controlled by the air supply (EA); however, the opposite effect of this control on the NO_x emissions took place (see Fig. 6b). As follows from the experimental results, increasing in the fuel moisture (by adding water to rice husk) promotes mitigating the NO_x emissions followed, however, by the increase in the CO emission and, accordingly, deterioration in the combustion efficiency of the reactor.

3.3 Combustion Efficiency

Table 2 shows the heat losses with unburned carbon and owing to incomplete combustion as well as the combustion efficiency of the conical FBC (all as the percentage of the fuel LHV), for the selected fuel moistures and operating conditions.

The heat loss associated with unburned carbon was found to demonstrate a weak dependence on the fuel moisture, especially at low values of EA, whereas it was apparently affected by EA. Slight increase in this heat loss with higher EA could be explained by the diminishing of the residence time of fuel particles in the conical FBC [5].

As discussed in Fig. 6a, the CO emission was increased when firing rice husk with higher moisture contents. Taking into account this effect and also the reduced LHV for higher fuel moistures, the heat loss owing to incomplete combustion was significantly

Table 2: Heat losses and combustion efficiency (LHV%) for the conical FBC firing rice husk at 82.6 kg/hr and different values of excess air for the selected fuel moistures.

Fuel moisture (wt.%)	Excess air (%)	Heat loss owing to unburned carbon (%)	Heat loss owing to incomplete combustion (%)	Combustion efficiency (%)
11.0	40	3.05	0.87	96.08
	60	3.38	0.58	96.04
	100	4.10	0.31	95.60
24.9	40	3.08	2.10	94.82
	60	3.42	1.79	94.79
	100	4.67	1.02	94.32
35.5	40	3.66	5.34	91.00
	60	4.11	5.09	90.80
	100	4.82	2.85	92.33

increased in comparison to that for the "as-received" rice husk. The effect of EA on this heat loss was found to be quite strong as well.

As follows from the data in Table 2, the combustion efficiency is apparently reduced with higher fuel moistures. However, the excess air values of 40–60% seem to be the optimal one for achieving the best performance of the combustor (in terms of both the combustion efficiency and NO_x emissions) when firing rice husk with 11–25% fuel moisture. However, EA should be increased (up to 100%) when firing high-moisture fuel (W > 30%).

4. CONCLUSIONS

A conical FBC was successfully tested when firing rice husk at the 82.5−82.8 kg/h fuel feed rate for different fuel moistures and excess air percentages. However, attempts to burn rice husk at high values of fuel moisture (over 40%) failed in the combustion tests.

The following conclusions could be made based on the conducted research work:

- By adding water to the "as-received" rice husk, the bed temperature could be effectively reduced (by up to 150^{o}C) leading to the mitigation of both NO_x emissions and ash-related problems (agglomeration and depositions) when firing rice husk in a fluidized bed system.
- Excess air performed minor effects on the temperature at all the locations in the conical FBC; hence, temperature and excess air can be considered as independent variables affecting the combustion chemistry.
- The fuel moisture and excess air showed strong effects on the CO emission characteristics (axial profiles and emissions from the combustor) as well as on the heat loss by incomplete combustion.
- When firing rice husk with the 11–25% fuel moisture, the excess air should be maintained at 40–60% level, whereas for high moistures (W > 30%) rice husk, the excess air should be increased up to 100% for achieving the highest combustion efficiency at the minimized NO_x emissions.

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