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Influence of Fuel-moisture Content and Excess Air on Formation and Reduction of CO and NO in a Fluidized-bed Combustor Fired with Thai Rice Husk

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Abstract: Formation and decomposition of major pollutants, NO and CO, in a conical fluidized-bed combustor (FBC) firing Thai rice husk was the focus of this experimental study. Effects of fuel quality (varied by changing fuel-moisture content) and operating conditions on the axial temperature and gas concentration profiles (for O_2, NO and CO) in this combustor are discussed. For the particular fuel quality, the conical FBC was tested at 82–83 kg/h feed rate for different percentages of excess air (of about 40, 60, 80 and 100%). The axial temperature profiles were found to be rather uniform, noticeably affected by fuel quality but almost independent of excess air. However, the axial O_2 concentration profiles were weakly dependent on the fuel composition. For each test run, the axial CO and NO_x concentration profiles were found to have maximums, CO_{max} and $NO_{x,max}$, at corresponding heights, $X_{CO,max}$ and $X_{Nox,max,}$ respectively, whose values were strongly affected by both fuel quality and excess air. Experimental dependencies $CO/CO_{max}= f(X/_{XCO,max})$ and $NO_x/NO_{x,max} = f(X/X_{NOx,max})$ were successfully approximated by fitting equations. With these models, one can predict the CO and NO_x concentrations in the flue gas at any arbitrary level in the combustor (above the air distributor) based on the fuel analysis and combustion conditions, excess air ratio and bed temperature.

Keywords: Temperature, Gas Concentrations, Modeling, Axial Profiles

Introduction

In Thailand, rice husk has been one of the viable biomass fuels for many years. Annually, more than 5 million tons of rice husk are produced in this country. Despite extensive utilization of this agricultural residue for heat and power generation at local rice mills, a significant amount of rice husk is being unused and eventually lost. Research and development of efficient and environmentally friendly technologies for energy conversion from rice husk and other biomass fuels are therefore the issues of paramount importance for the Thai energy-related sectors.

The fluidized-bed combustion technology is reported to be the most suitable and efficient technology for converting biomass fuels into energy [1−3]. A number of research works have been recently carried out on the fluidized bed combustion of rice husk. The combustion efficiency of fluidized-bed combustors fired with this biomass fuel is reported to be of 81 to 99%, depending on design features and operating conditions of the combustion system as well as fuel properties. Meanwhile, burning of rice husk is accompanied by sensible environmental impacts, generally being done by NO_x and CO emissions [4−7]. Because of the relatively high fuel-N content in rice husk and elevated combustion (bed) temperatures, NO_x emissions from conventional fluidized-bed systems are reported to be in the range of about 100 to 180 ppm when firing this biomass fuel at the excess air values of about 20 to 100%, respectively. Hence, lowering excess air seems to be an efficient tool for controlling the NO_x emissions from rice husk-fueled luidized-bed combustion systems.

However, at low excess air values (less than 40%), the CO emission from the fluidized bed combustion of rice husk is reported to be very high (basically, greater than 5000 ppm) and strongly dependent on excess air. On the contrary, at excess air above 60%, the CO emission is reduced to 600−1100 ppm and becomes almost independent of operating variables [4−8]

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 elevated bed temperatures [1]. An increase in the fuel moisture (by adding corresponding amounts of water to rice husk of a single fuel analysis on dry basis) seems to be an effective and least-cost technological measure for diminishing the combustion temperature and, thus, controlling NO_x emissions and mitigating undesirable ash-related processes. However, this controlling measure may likely lead to an increase in the CO emission from the combustion system [9]. Since the air supply and water adding to the fuel result in opposite responses from the CO and NO_x emissions, a detail study on the effects of the fuel-moisture content and excess air on formation and decomposition of CO and NO (the latter being the major constituent of NO_x) in the combustion system is required.

This paper dealt with the experimental study on firing Thai rice husk in a conical fluidized-bed combustor (FBC) for different fuel-moisture contents and excess air values. Effects of these independent variables on the axial temperature and gas concentration profiles (for O_2, NO_x and CO) were the focus of this work. Another goal was aimed at developing the models for predicting axial (relative) CO/CO_{max} and $NO_x/NO_{x,max}$ profiles, i.e. the fitting equations for the assessment of CO and NO_x concentrations at any location along the combustor height in the conical FBC

Methodology

Experimental set-up

The experimental tests were carried out on a laboratory-scale fluidized-bed combustor (FBC) with a cone shaped bed referred to as the conical FBC whose geometrical features and dimensions are provided in Refs. [5,10]. The combustor body was made of 4.5-mm-thick steel, insulated with the 50-mm ceramic-fiber material (for minimizing heat loss across the walls), which was covered externally by 1-mm-thick galvanized steel. A conical section of 1 m height with a cone angle of 40º was made as the bottom part, whereas a cylindrical section of 0.9 m inner diameter and 2 m height formed a cylindrical part of the combustor. Silica sand $SiO_2 \approx 90\%$ and $Al_2O_3 \approx 7\%$) of 0.3–0.5 mm in size and 40-cm static bed height used as the inert bed material in the conical FBC. Both sand particle size and bed height were selected with the aim of securing bubbling fluidized-bed mode in the conical section.

A LPG-firing burner was used for preheating the bed material during the combustor start-up. This burner was fixed at the 0.6 m level above the air distributor and inclined at 45° with respect to the horizontal. The burner was turned off upon approaching the sustainable combustion of the major fuel (generally, at the bed temperature of 550°C).

A 25-hp blower supplied air (under ambient conditions) into the combustor through the air distributor located at the bottom of the conical section. The air distributor was equipped with nine air-bubble caps, and each bubble cap was designed as a standpipe of 25.4- mm outer diameter and 50-mm height for providing air injection below the bed through 56 holes. These holes, 2-mm in diameter, were declined at 45° with respect to the horizontal plane and evenly distributed over the standpipe's cylindrical surface. In addition, there were four vertical slots of 2.5×15 mm in size, located on the top of each standpipe and used for the air injection.

A screw-type feeder was used for supplying rice husk into the combustor. This feeder was connected to the conical part of the combustor at the 0.65-m lever above the air distributor. An external cyclone with 0.4-m body diameter served for collecting particulates (char, ash and carry-over sand particles) from the flue gas leaving the combustor.

Fuel properties

Rice husk was burned for five fuel-moisture contents (11.0, 16.8, 24.9, 35.5 and 40.2 wt.%), the latter four being secured by the injection of additional water to the "as-received" rice husk. For the particular fuel quality (i.e. for a given fuel-moisture content), a series of the test runs was conducted with the aim of studying the effects of operating conditions.

Table 1 shows the fuel ultimate analyses and lower heating value (LHV), the latter being found by [11,12], for each test series corresponding to the particular fuel-moisture content. For "as-received" rice husk, it was found by laboratory analysis and equal to 11%. However, for other four test series, the fuel analyses as well as lower heating values of "as-fired" rice husk were determined using standard methodology (fuel conversion calculations) [11].

Experimental procedures

Two parameters were chosen in the experimental tests as independent variables: fuel-moisture content (W) and percent excess air (EA). For the particular rice husk moisture, the conical FBC was tested at almost constant fuel feed rate (FR), 82.5-82.8 kg/h, for four EA values of about 40, 60, 80 and 100%.

Seven thermocouples (of type K) were fixed along the combustor height as well as at the cyclone outlet for monitoring the temperature in the flue gas at different locations. For measuring the gas concentrations (O_2, NO_x and CO), the "Testo-350" gas analyzer was employed in this work. During these measurements, the flue gas was sampled through seven holes arranged at different locations (above the air distributor) in the combustor and also at the cyclone outlet. The relative measurement errors were expected to be 5% for CO and NO, and about 1% for O_2.

For each test run, the value of excess air ratio (α) was determined by [11,12] using the O_2 and CO concentrations in the flue gas leaving the cyclone. For developing the models for the assessment of CO and NO_x (as NO_2) at different locations in the combustor, the experimental concentrations of these pollutants were converted from ppm (on "dry" basis, as recorded by the gas analyzer) to g/m^3 (on "wet" basis, under standard conditions: 0^oC and 1 atm).

Results and Discussion

Based on the measured temperatures and gas concentrations, corresponding axial profiles were plotted for the fuels given in Table 1. Note that in the tests with 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-moisture contents were successful. Thus, the fuel-moisture content of about 35% can be regarded as the critical value for sustainable combustion of rice husk in this conical FBC.

Axial temperature and O_2 concentrations profiles

As an illustration, Fig. 1 shows the axial temperature and O_2 concentration profiles in the conical FBC firing rice husk at the particular, EA ≈ 60%, for different fuel-moisture contents. As seen in Fig. 1a, the axial temperature profiles were noticeably affected by the fuel quality. With higher fuel-moisture content, the temperature at all the locations along the combustor height was lowered, compared to that for firing "as-received" rice husk with W = 11.0%). Due to intensive mass-and-heat transfer, the axial temperature profiles in the bed region (i.e. at 0−1 m heights above the air distributor) were rather uniform.

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

Test series No.	W	A	C	H	O	N	S	LHV
1	11.0 [1]	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

[1] **W= 11.0%** is the fuel – moisture content in "as-received" fuel; in the other test runs, it was secured by additional water

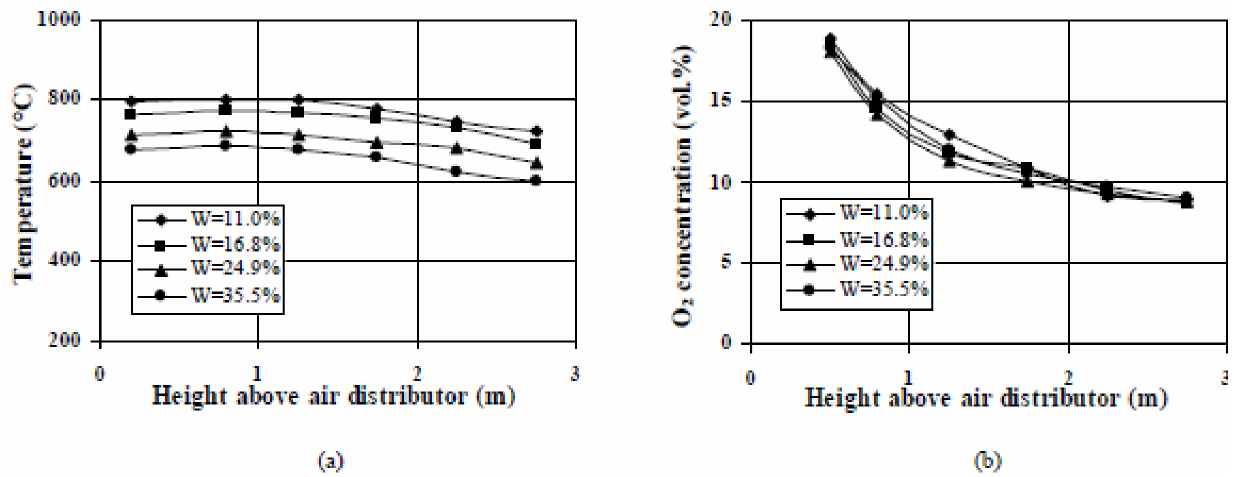


Fig. 1 Effects of the fuel –moisture content on the axial temperature (a) and O2 concentration (b) profiles in the conical FBC firing rice husk at FR ≈ 82.6 kg/h and EA ≈ 60%

However, in the freeboard region (i.e. at 1−3 m heights), the temperature gradually lowered along the combustor height, because of the heat loss across the combustor walls accompanied by the reduced heat release in this region.

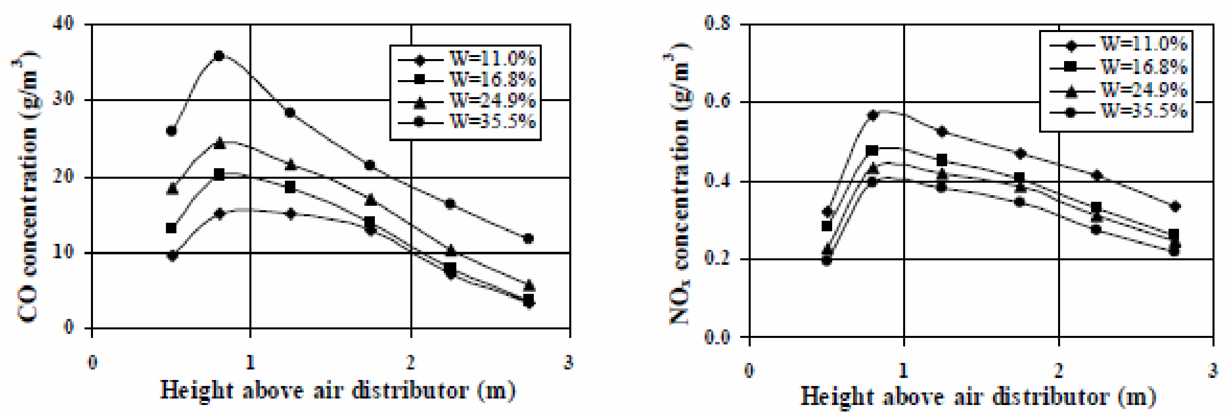
Comparison of the temperature profiles for EA ≈ 60% with those for other values of excess air showed a quite weak effect of this operating variable on the temperature pattern in the combustor. For the particular EA, the temperature reduced by 130–150°C at all the locations along the combustor height when increasing the fuel-moisture content from 11% to 35%.

As seen in Fig. 1b, for the particular EA, the O_2 concentrations were almost independent of the fuel-moisture moisture. This trend was also confirmed by the experimental results for other values of EA. Meanwhile, for the particular fuel quality, the axial O_2 concentration profiles were apparently affected by excess air, especially in the freeboard region. An increase in the EA value led to the higher O_2 concentrations in the flue gas at the combustor top and, accordingly, in the waste (stack) flue gas.

Formation and reduction of CO and NO_x

Fig. 2 shows the effects of the fuel-moisture content on the axial CO and NO_x concentration profiles in the conical FBC for the same operating conditions as in Fig.1. For all the test runs, these profiles were found to have the maximum (CO_{max} or $NO_{x,max}$) at the corresponding height ($X_{CO,max}$ or $X_{NO,max}$), whose location (above the air distributor) divided conventionally the combustor volume into the formation ($X < X_{CO,max}$ or $X < X_{NOx,max}$) and reduction regions ($X > X_{CO,max}$ or $X > X_{NOx,max}$) for each pollutant.

As follows from data in Fig. 2a, in the test run for the highest fuel-moisture content, the CO_{max} was significantly greater than that for the "as-received" rice husk. Two factors were likely responsible for this elevated CO formation rate in the bed region for the higher fuel-moisture contents: (1) reduction in the bed temperatures (see Fig. 1a), leading to an increase in the CO/CO_2 ratio during char-C oxidation, and (2) higher concentrations of water vapor, which enhanced the contribution of the "wet" char-C oxidation (generally, to CO) on the surface of char particles [1].



(a) (b)

Fig.2 Effects of the fuel – moisture content of the axial CO (a) and NO_x as NO_2 (b) concentration profiles in the conical FBC firing rice husk at FR ≈ 82.6 kg/h and EA≈60%

Meanwhile, the significant reduction in the CO concentration at different locations along the combustor height occurred in the freeboard region, where CO was likely oxidized in homogeneous reactions with OH radicals and O_2, both being predominant in this region [13]. However, the CO (including CO_{max}) concentration was strongly diminished in both regions with higher value of excess air, due to the enhanced rate of homogeneous oxidation of CO by oxygen.

As seen in Fig. 2b, for the particular EA value, the axial NO_x concentration profiles were noticeably affected by the fuel quality. With higher fuel-moisture content, the NO_x concentrations diminished because of the lowered fuel-N content and reduced in-bed temperatures [1]. For the temperatures recorded in this study, the NO_x was formed in the fluidized-bed region basically owing to the fuel-NO formation mechanism, through oxidation of the nitrogenous species, such as HCN and NH_3, released from fuel particles with volatile matter, and oxidation of fuel-N retained in the char [1,14].

In the freeboard region, the axial NO_x concentration profiles were found to decline with fairly the same gradients for different fuel-moisture contents (as may be seen in Fig. 2b) and EA values. In this region, the NO_x reduction may likely occur via reactions of NO with fuel-C and CO on the surface of chars and also with NH_3 (at O2 deficiency) [1,14].

Modeling COmax and NOx,max

As mentioned above, CO formation is basically dependent on the combustion conditions, such as the excess air (ratio) and bed temperature, as well as the fuel-moisture content. Apart from them, the fuel-ash content is expected to have minor effects on the CO formation [5]. All these factors could be therefore considered as the key variables affecting CO_{max}.

Based on statistical treatment of experimental results, the fitting equation for predicting CO_{max} (g/m^3, in the "wet" flue gas under standard conditions) was derived by taking into account the above variables in the following form :

$$CO_{max} = 5.7\times10^{6}\alpha^{-2}A^{1/3}W^{1/2}T_{bed}^{-2} \qquad (R^2 = 0.934) \qquad (1)$$

where T_{bed} is the bed temperature (K), and the fuel-moisture and fuel-ash contents are represented as the percentages (wt.%). Fig. 3a compares predicted [by Eq. (1)] CO_{max} values with experimental ones for firing some 82.6kg/h rice husk in this conical FBC at different values of excess air. As seen in Fig. 3a, for the relatively low fuel-moisture contents (11–24%), the predicted and experimental CO_{max} values were in quite good agreement. However, for higher fuel-moisture contents, the computational accuracy in the assessment of CO_{max} by Eq. (1) became lower. For the ranges of the excess air and fuel-moisture content applied in this work, the CO_{max} can be predicted within the relative error of ±15%.

Analysis of the NO_x experimental concentrations showed that the NO_x formation was apparently affected by three variables: the fuel-N content, excess air ratio and the bed temperature. Based on these variables, the fitting equation for the predicting of $NO_{x,max}$ as $NO_{2,max}$ (g/m^3, in the "wet" flue gas under standard conditions) was represented as follows:

$$NO_{x,max} = 4.5N(0.4-0.1N)\alpha^{0.5}\left(\frac{T_{bed}-800}{1000}\right)^{0.15} \qquad (R^2 = 0.855) \qquad (2)$$

where the fuel-N content is represented as the percentage (wt.%). By structure, Eq. (2) is similar to the correlation for predicting the "fuel-and-prompt" NO_x emissions from the "low-temperature" combustion of a fossil fuel in a boiler furnace [11]. The comparison between predicted [by Eq. (2)] and experimental $NO_{x,max}$, for the same operating conditions as for CO_{max}, is shown in Fig. 3b. The relative error in the assessment of $NO_{x,max}$ was estimated to be within ±15% for wide ranges of variation in the excess air ratio and fuel-moisture content.

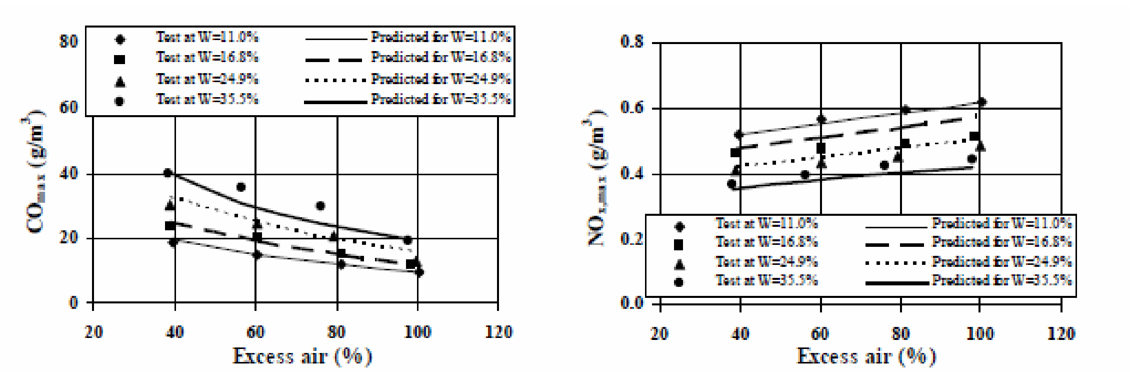


Fig.3 Predicted and experimental CO_{max} (a) and $NO_{x,max}$ as $NO_{2,max}$ (b) in the conical FBC firing rice husk at FR ≈ 82.6 kg/h for different values of EA

Relative (dimensionless) axial CO and NOx concentration profiles

Unlike CO_{max} and $NO_{x,max}$, $X_{CO,max}$ and $X_{NOx,max}$ showed their independence of EA and fuel-moisture content, as followed from the results in Fig. 2 and analysis of the experimental results for different EA values.The relative carbon monoxide concentration, CO/CO_{max}, versus the relative distance, $X/X_{CO,max}$, for all the test runs (e.g. for different fuel qualities and operating conditions) are represented in Fig. 4a by (experimental) dots. As seen in Fig. 4a, the experimental dependencies of CO/CO_{max} on $X/X_{CO,max}$ were similar, being however affected by excess air. Depending on this operating variable, the experimental dots were grouped around two trends: (1) for 40–60% EA and (2) 80–100% EA. For these two ranges of EA, the following fitting equations, or empirical models, were proposed for the (dimensionless) axial CO/CO_{max} profiles, valid for the different range of $X/X_{CO,max}$

- for 40–60% EA, $0.5 \le X/X_{CO,max} \le 3.5$:

$$\frac{CO}{CO_{max}} = X_0^{1.72}\exp\left[1 - X_0^{(1.61 - 0.12X_0)}\right] \qquad (R^2 = 0.940) \tag{3}$$

- for 80–100% EA, $0.4 \le X/X_{CO,max} \le 2.6$:

$$\frac{CO}{CO_{max}} = X_0^{1.68}\exp\left[1 - X_0^{(1.70 - 0.02X_0)}\right] \qquad (R^2 = 0.845) \tag{4}$$

where $X_0 = X/X_{CO,max}$.

Comparison of the predicted [by Eqs. (3) and (4)] and experimental axial CO/CO_{max} profiles is shown in Fig. 4a. The deviation of the experimental dots from the fitting curves in this graph could be characterized by 15% relative error. Unlike the CO/CO_{max}, the relative $NO_x/NO_{x,max}$ profiles were found to be independent of both the fuel-moisture content and EA, as may be seen observing the experimental dots in Fig 4b. It was, therefore, managed to approximate the $NO_x/NO_{x,max}$ experimental dependencies by a single fitting equation. For $0.7 \le X/X_{NOx,max} \le 3.2$, the axial $NO_x/NO_{x,max}$ profile could be represented by the following equation, or empirical model:

$$\frac{NO_x}{NO_{x,max}} = Z_0^{1.05}\exp\left[1 - Z_0^{(1.07 - 0.05Z_0)}\right] \qquad (R^2 = 0.974) \tag{5}$$

where $Z_0 = X/X_{NOx,max}$.

Fig. 4b compares the predicted [by Eq. (5)] and experimental axial $NO_x/NO_{x,max}$ profiles. The relative error of deviation of the experimental dots from the fitting curve was estimated to be 10%. With the use of the Eqs.(3)–(5), one can predict the axial CO and NO_x profiles in the combustor as well as the

NO_x and CO concentrations at the combustor top (which are supposed to be closer to the emission characteristics of this combustor) for the desired operating conditions and combustor geometry. With these correlations, one can reduce significantly the volume of experimental data to be recorded. Furthermore, Eqs.(3)–(5) can be applied in the study of formation and reduction (rates) of major pollutants in a fluidized bed combustion system operated on the particular fuel under particular operating conditions. While CO_{max} and $NO_{x,max}$ are found by Eqs. (1) and (2), respectively, the reliable dependencies of $X_{CO,max}$ and $X_{NOx,max}$ on operating variables, basically obtained from the experiments, should support the above models for dimensionless CO and NO_x profiles.

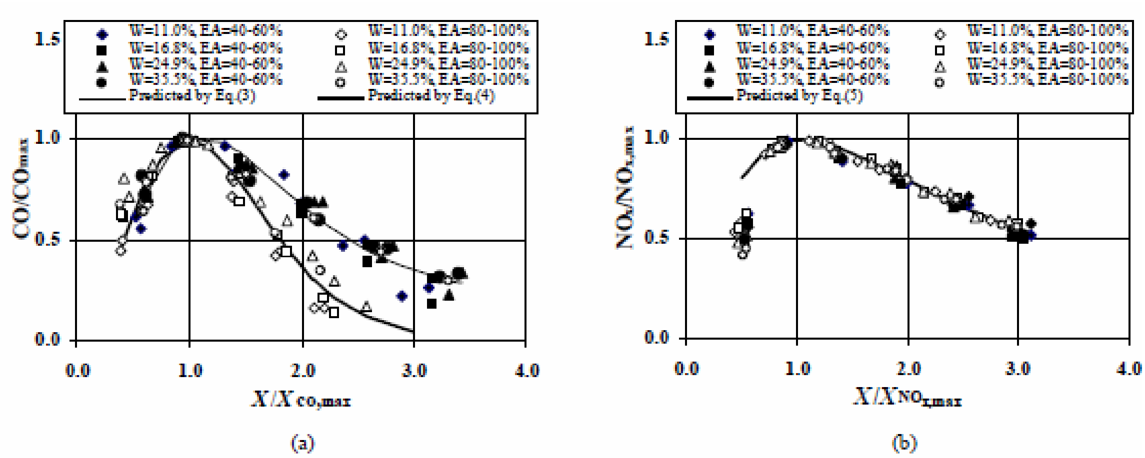


Fig.4 Effects of the fuel – moisture content and EA on the relative CO (a) and No_x(b) concentrations represented as the functions of the relative axial distance in the conical FBC firing rice husk at FR ≈ 82.6 kg/h

Conclusions

The conical FBC was successfully tested when firing 82.5−82.8 kg/h Thai rice husk of different qualities, with 11–35.5% fuelmoisture contents (secured by adding water to the fuel of a single analysis on dry basis), for various percentage of excess air (of about 40, 60, 80 and 100%). However, attempts to burn rice husk with higher fuel-moisture content (about 40%) failed in the combustion tests. During the experimental tests, data on CO and NO_x (as NO_2) concentrations along over the combustor height were generated for the above fuel qualities and operating conditions.

The following major conclusions have been derived from this work:
• the axial temperature profiles in the conical FBC are rather uniform, noticeable affected by the fuel-moisture content, but weakly affected by the excess air;
• both fuel-moisture content and excess air perform sensible effects on CO and NO formation and reduction in the combustor;
• all axial CO and NO_x concentration profiles have maximums, CO_{max} or $NO_{x,max}$ (as $NO_{2,max}$), at corresponding heights, $X_{CO,max}$ or $X_{NOx,max}$, respectively, and these peak concentrations in the fluidized bed are affected by both the fuel quality and excess air ratio with different extents;
• the empirical correlations (or empirical models) for CO_{max} or $NO_{x,max}$ (as $NO_{2,max}$) are proposed in this work, both including the effects of fuel properties and operating conditions;
• for this conical FBC, the dependencies $CO/CO_{max} = f(X/X_{CO,max})$ and $NO_x/NO_{x,max} = f(X/X_{NOx,max})$ can be readily approximated by the fitting equations (empirical models) with R^2 = 0.84–0.97. While the CO_{max} and $NO_{x,max}$ are determined by the above empirical models, the reliable dependencies of $X_{CO,max}$ and $X_{NOx,max}$ on fuel properties and operating variables should support the models for the dimensionless axial CO and NO_x concentration profiles.

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