

Influence of Fuel Moisture and Excess Air on Formation and Reduction of CO and NO_x in a Fluidized-Bed Combustor Fired with Thai Rice Husk

R. Kaewklum^{1,*}, V.I. Kuprianov¹, K. Janvijitsakul¹
and W. Permchart²

¹ School of Manufacturing Systems and Mechanical Engineering,
Sirindhorn International Institute of Technology, Thammasat University,
Pathum Thani, 12121, Thailand. Tel.: (662) 986-9009 ext. 3323

² Department of Agricultural Engineering,
King Mongkut's Institute of Technology Ladkrabang,
Bangkok, 10520, Thailand.

*Corresponding author: rachadaporn@siit.tu.ac.th

Abstract: Formation and decomposition of major gaseous pollutants, CO and NO_x, in a conical fluidized-bed combustor (referred to as 'conical FBC') firing Thai rice husk was the main focus of this experimental study. Effects of fuel quality (varied by changing the fuel-moisture content) and operating conditions on axial temperature and O₂, CO and NO_x concentration profiles in the combustor are discussed. For each fuel quality, the conical FBC was tested at 82–83 kg/h fuel feed rate for different values of excess air (of about 40, 60, 80 and 100%). The axial temperature profiles were found to be rather

uniform and noticeably affected by the fuel quality, showing, however, their independence of excess air. The axial O_2 concentration profiles were weakly dependent on the fuel composition exhibiting basically the influence of excess air. 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 $X_{NO_x,max}$, respectively, whose values were strongly affected by both fuel quality and excess air. Experimental dependencies $CO/CO_{max} = f(X/X_{CO,max})$ and $NO_x/NO_{x,max} = f(X/X_{NO_x,max})$ were approximated by proposed fitting equations. With these models, one can predict the CO and NO_x concentrations in the flue gas at any arbitrary level in a conical FBC using fuel analysis, excess air ratio, and bed temperature.

Keywords: Temperature; Gas concentrations; Axial profiles; Combustion efficiency.

Introduction

In Thailand, rice husk has been one of the major biomass fuels for many years. Annually, some 5 million tons of rice husk are produced in this country, which correspond to about 75×10^9 MJ of energy potential, as estimated based on the 15 MJ/kg fuel calorific value. Research and development of efficient and environmentally friendly technologies for energy conversion from rice husk and other biomass fuels are, therefore, 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 98% depending on design features and operating conditions of the combustion system and fuel properties. Meanwhile, the combustion of rice husk is accompanied by sensible environmental impacts, basically done by NO_x and CO emissions [4–7]. Because of the relatively high fuel-N content in rice husk and elevated combustion (bed) temperature, 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 excess air values of about 20 to 100%, respectively. Hence, the combustion at low excess air is proven to be an efficient tool for controlling the NO_x emissions from fluidized-bed combustion systems burning rice husk.

However, at low excess air values (less than 40%), CO emission from the fluidized-bed combustion of rice husk is reported to be very high (greater than 5000 ppm) and strongly dependent on excess air. On the contrary, at excess air above 60%, 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 agglomeration of bed material and ash deposition (slagging and fouling), are caused by elevated bed temperature [1]. Increasing the fuel moisture (by adding corresponding amounts of water to “as-received” rice husk) seems to be an effective least-cost technological measure to diminish the

combustion temperature, which could eventually result in the reduction of NO_x emissions and mitigation of undesirable ash-related processes. However, this controlling technique may likely lead to an increase of CO emission from the combustion system [9]. Since the water addition and air supply (or excess of combustion air) cause opposite responses of the CO and NO_x emissions, a detail study on effects of the fuel moisture and excess air on formation and decomposition of CO and NO (the major constituent of NO_x) in the combustion system is required.

This paper deals with the experimental study of firing Thai rice husk in a conical fluidized-bed combustor (referred to as ‘conical FBC’) for variable fuel-moisture and excess air. Compared with columnar (cylindrical and prismatic) fluidized-bed combustors and furnaces, the conical FBC ensures sustainable ignition and combustion of various biomass fuels at substantially less amount of the bed material and, correspondingly, shorter start-up time, the latter being important for saving auxiliary fuel [5]. Apart from this, the conical FBC with its small amount of the bed material seems to be suitable for firing high-volatile biomass fuels and wastes with elevated ash content.

Effects of the fuel moisture and excess air on axial temperature and gas concentration profiles (for O_2 , CO and NO_x) were the focus of this study. Another goal of this work was to develop models for predicting relative axial $\text{CO}/\text{CO}_{\text{max}}$ and $\text{NO}_x/\text{NO}_{x,\text{max}}$ profiles and assessment of CO and NO_x concentrations at any location along the height in the conical FBC, including those at the combustor exit.

Methodology

1. Experimental set-up

Experimental tests were carried out on a laboratory-scale 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 covered externally by 1-mm-thick galvanized steel in order to minimize the heat loss across the walls. A conical section of 1 m height with a cone angle of 40° was, in effect, 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 ($\text{SiO}_2 \approx 90\%$, $\text{Al}_2\text{O}_3 \approx 7\%$) of 0.3–0.5 mm particle size and 40-cm static bed height was used as the inert bed material in the conical FBC. The above cone angle as well as the range of sand particle size secured the bubbling fluidized-bed mode in the conical section of the combustor [5,10].

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 with a -45° inclination angle. The burner was turned off upon approaching sustainable combustion of the biomass fuel (normally, 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. 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, each 2-mm in diameter, were inclined 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 cross-sectional dimensions, located on the top of each standpipe and used for the air injection.

A screw-type feeder was employed to supply the fuel into the combustor. The screw feeder was connected to the conical part of the combustor at the 0.65-m level above the air distributor, thus, securing the over-bed fuel feeding.

An external cyclone with 0.4-m body diameter served to collect particulates (char and ash particles) from the flue gas leaving the combustor.

2. Fuel properties

Rice husk was burned in the conical FBC for five fuel-moisture contents, of 11.0, 16.8, 24.9, 35.5 and 40.2 wt.%, the latter four being secured by water addition to the "as-received" fuel (with the 11% fuel moisture content). Table 1 shows the fuel ultimate analysis and lower heating value (LHV) for all five test series corresponding to the above fuel-moisture contents.

Note that the fuel ultimate analysis and lower heating value of "as-received" rice husk were obtained by laboratory analysis. However, for other four fuel options, these properties were determined on "as-fired" basis using standard methodology of fuel conversion calculations [11].

3. Experimental procedures

Two parameters were chosen in the experimental tests as independent variables: the fuel-moisture content (W) and percent excess air (EA). For the particular fuel moisture (or fuel quality), 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 to record the temperature in the flue gas at different locations. To measure the gas (O₂, CO and NO_x) concentrations, a “Testo-350” gas analyzer (Testo, Germany) was employed in this work. During the measurements, flue gas was sampled through seven holes arranged at different levels (above the air distributor) in the reactor as well as the cyclone exit. The measurement accuracies were within $\pm 5\%$ for CO and NO, and $\pm 1\%$ for O₂. For each test run, the excess air ratio, α , was determined by [11,12] using the O₂ and CO concentrations in flue gas leaving the cyclone. Based on this value, percent excess air was then estimated as $EA = 100(\alpha - 1)$.

To develop models for assessment of CO and NO_x (as NO) 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/m³ (on “wet” basis, under standard conditions: 0°C and 1 atm).

Results and Discussion

Using the temperatures and gas concentrations recorded at

different locations along the combustor height, corresponding axial profiles were plotted for the fuels shown in Table 1. Note that in the tests at $W = 40.2\%$ (Test series No.5, as seen 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.

Table 1. Ultimate analysis (wt.%) and lower heating values (MJ/kg) of rice husk used in experimental tests (W = fuel-moisture, A = fuel-ash, LHV = lower heating 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” rice husk; in other test series, the fuel-moisture content was secured by the addition of water to the “as-received” fuel.

1. Axial temperature and O_2 concentrations profiles

As an illustration, Fig. 1 shows the axial temperature (Fig. 1a) and O_2 concentration (Fig. 1b) profiles in the conical FBC firing rice

husk at EA \approx 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 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 height above the air distributor) were rather uniform.

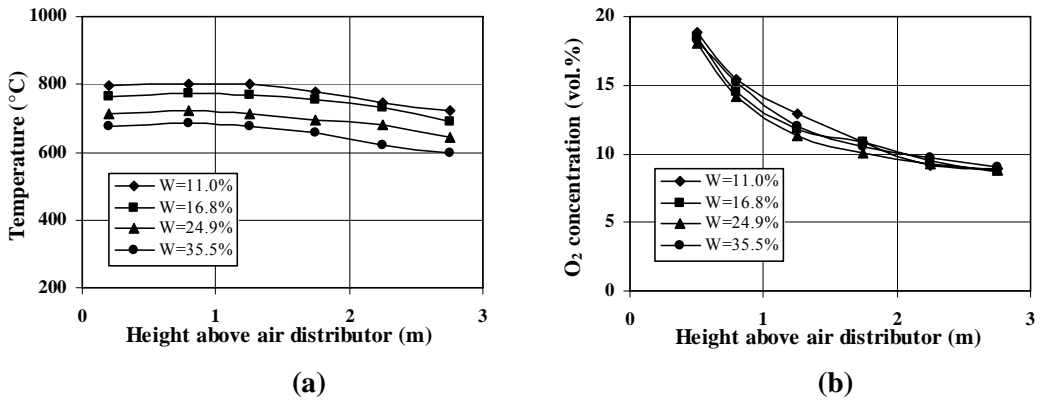


Figure 1. Effects of the fuel-moisture content on the axial temperature (a) and O₂ concentration (b) profiles in the conical FBC firing rice husk at FR = 82.5–82.8 kg/h and EA \approx 60%.

However, in the freeboard region (i.e., at 1–3 m height above the air distributor), the temperature gradually lowered along the combustor height due to the heat flux across the combustor walls (or heat loss), which occurred at a significantly lower heat release rate in this region.

Comparison of the temperature profiles for EA \approx 60% with those for other excess air values showed quite weak effects of this

operating variable on the temperature profiles in the combustor. For the range of EA, the temperature reduced by 130–150°C at all locations along the combustor height when increasing the fuel-moisture content from 11% to 35%.

As seen in Fig. 1b, the O₂ concentrations were almost independent of the fuel-moisture moisture in the tests for EA ≈ 60%. This trend was also confirmed by the experimental results for other values of EA (40, 80 and 100%). Meanwhile, for the selected fuel quality, the axial O₂ concentration profiles were apparently affected by EA, especially in the freeboard region. An increase in the EA value led to the higher O₂ concentrations in flue gas at the combustor top and, correspondingly, at the stack (cyclone exit).

2. Formation and reduction of CO and NO_x

Fig. 2 shows the effects of the fuel-moisture content on the axial CO (Fig. 2a) and NO_x (Fig. 2b) concentration profiles in the conical FBC for the same operating conditions, as in Fig.1. For all these test runs, the axial profiles were found to have maximums (CO_{max} and NO_{x,max}) at corresponding heights ($X_{CO,max}$ and $X_{NOx,max}$), whose location above the air distributor divided conventionally the combustor volume into formation ($X < X_{CO,max}$ and $X < X_{NOx,max}$) and reduction regions ($X > X_{CO,max}$ and $X > X_{NOx,max}$) for each pollutant.

As follows from data in Fig. 2a, in the tests for burning rice husk with the highest fuel-moisture content, CO_{max} was significantly greater than that for “as-received” rice husk. Two factors were likely responsible for higher CO formation rate with increasing the fuel-

moisture content: (1) reduction in the bed temperatures (see Fig. 1a), leading to the increase in CO/CO₂ ratio during char-C oxidation, and (2) higher concentrations of water vapor enhancing the contribution of “wet” char-C oxidation (generally, to CO) on the surface of char particles [1].

Meanwhile, a significant reduction in the CO concentration at different locations along the combustor height was found to occur in the freeboard region, where CO was likely oxidized in homogeneous reactions with OH radicals and O₂, both being predominant in this region [13].

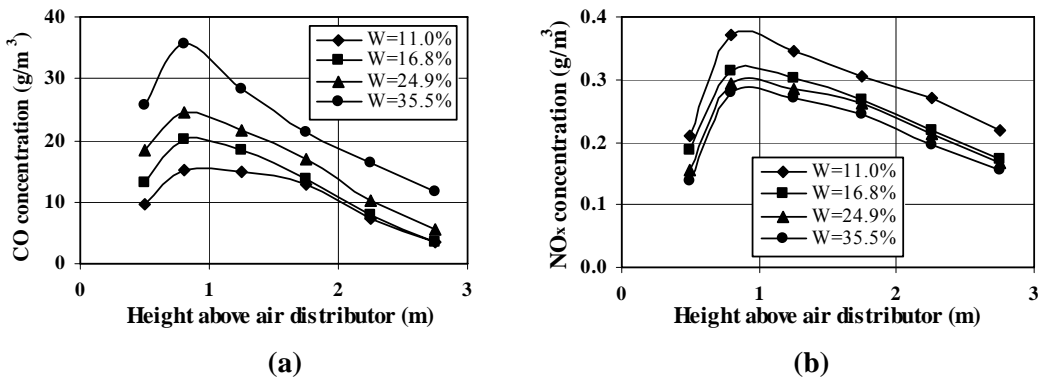


Figure 2. Effects of the fuel-moisture content on the axial CO (a) and NO_x as NO (b) concentration profiles in the conical FBC firing rice husk at FR = 82.5–82.8 kg/h and EA ≈ 60%.

However, with higher value of excess air, the CO (including CO_{max}) concentration reduced significantly in both regions, basically, 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 concentration diminished because of the lowered fuel-N and “in-bed” temperature [1]. For the combustion temperatures recorded in this study, NO_x was likely formed in the fluidized-bed region, basically, owing to the fuel-NO formation mechanism, i.e., through oxidation of nitrogenous species, such as HCN and NH_3 , released from fuel particles with volatile matter and, also, 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 seen in Fig. 2b) and EA values. In this region, 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 O_2 deficiency) [1,14].

3. Modeling CO_{\max} and $\text{NO}_{x,\max}$

As mentioned above, CO formation is mainly dependent on the combustion conditions, such as excess air ratio (α), bed temperature (T_{bed} , K) and fuel-moisture content (W , wt.%). Apart from these parameters, the fuel-ash content (A , wt.%) is expected to have a minor influence on CO formation [5]. All these factors could therefore be considered as the key variables affecting CO_{\max} .

Based on a statistical treatment of the experimental results, the fitting equation for predicting CO_{\max} (g/m^3 , in “wet” flue gas, under standard conditions) was derived by using the above variables as:

$$\text{CO}_{\max} = 5.7 \times 10^6 \alpha^{-2} A^{1/3} W^{1/2} T_{\text{bed}}^{-2} \quad (R^2 = 0.934) \quad (1)$$

Fig. 3a compares the predicted CO_{max} values [by Eq. (1)] with the experimental ones for firing 82.5–82.8 kg/h rice husk in this conical FBC at different values of excess air. As seen in Fig. 3a, for the relatively low fuel-moisture content (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 excess air and fuel-moisture content, the CO_{max} can be predicted using Eq. (1) with a relative error of ±15%.

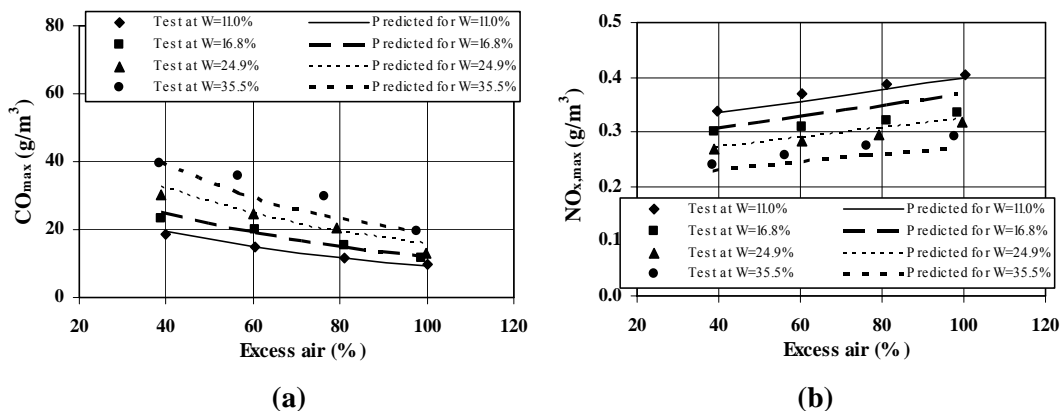


Figure 3. Predicted and experimental CO_{max} (a) and NO_{x,max} as NO_{max} (b) in the conical FBC firing rice husk at FR = 82.5–82.8 kg/h for different values of EA.

Analysis of the NO_x experimental concentrations showed that NO_x formation was apparently affected by three variables: fuel-N content (N, wt.%), excess air ratio (α) and bed temperature (T_{bed} , K). Using these parameters as independent variables, the fitting equation for predicting NO_{x,max} as NO_{max} (g/m³, in “wet” flue gas, under

standard conditions) was derived as:

$$\text{NO}_{x,\max} = 2.9N(0.4 - 0.1N)\alpha^{0.5} \left(\frac{T_{\text{bcd}} - 800}{1000} \right)^{0.15} \quad (R^2 = 0.876) \quad (2)$$

By structure, Eq. (2) is similar to the correlation for predicting “fuel-and-prompt” NO_x emissions from the “low-temperature” combustion of a fossil fuel in the furnace of a boiler proposed in Ref. [11].

The comparison between predicted [by Eq. (2)] and experimental $\text{NO}_{x,\max}$, for the same operating conditions as for CO_{\max} , is shown in Fig. 3b. The relative error in the assessment of $\text{NO}_{x,\max}$ was estimated to be within $\pm 15\%$ for wide ranges of the excess air ratio and fuel-moisture content.

4. Relative (dimensionless) axial CO and NO_x concentration profiles

Unlike CO_{\max} and $\text{NO}_{x,\max}$, $X_{\text{CO},\max}$ and $X_{\text{NO}_x,\max}$ 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, $\text{CO}/\text{CO}_{\max}$, versus relative distance, $X/X_{\text{CO},\max}$, for all test runs (e.g., for different fuel qualities and operating conditions) are depicted in Fig. 4a using the experimental dots. As seen in Fig. 4a, the experimental dependencies of $\text{CO}/\text{CO}_{\max}$ on $X/X_{\text{CO},\max}$ were similar but were 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 ranges of X/X_{CO,max}:

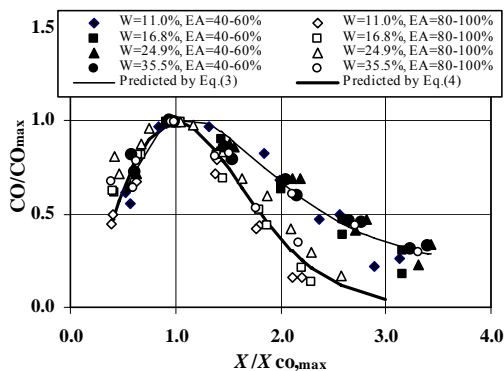
- for EA = 40–60% (at 0.5 ≤ X/X_{CO,max} ≤ 3.5):

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

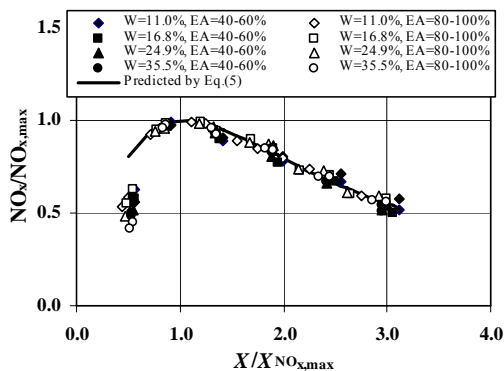
- for EA = 80–100% (at 0.4 ≤ X/X_{CO,max} ≤ 2.6):

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

where X₀ = X/X_{CO,max}.



(a)



(b)

Figure 4. Relative CO (a) and NO_x (b) concentrations represented as a function of the relative axial distance in the conical FBC firing rice husk at FR = 82.5–82.8 kg/h for variable fuel-moisture content and EA.

Comparison of the predicted [by Eqs. (3) and (4)] and experimental axial CO/CO_{max} profiles is shown in Fig. 4a. Deviation of the

experimental dots from the fitting curves in this graph was within the $\pm 15\%$ relative error.

Unlike the $\text{CO}/\text{CO}_{\max}$ profiles, the relative $\text{NO}_x/\text{NO}_{x,\max}$ profiles were found to be independent of both the fuel-moisture content and excess air, as seen in Fig 4b. It was, therefore, man aged to approximate the $\text{NO}_x/\text{NO}_{x,\max}$ experimental dependencies by a single fitting equation. For $0.7 \leq X/X_{\text{NO}_{x,\max}} \leq 3.2$, the axial $\text{NO}_x/\text{NO}_{x,\max}$ profile could be represented by the following equation, or empirical model:

$$\frac{\text{NO}_x}{\text{NO}_{x,\max}} = Z_0^{1.05} \exp\left[1 - Z_0^{(1.07 - 0.05Z_0)}\right] \quad (R^2 = 0.974) \quad (5)$$

where $Z_0 = X/X_{\text{NO}_{x,\max}}$.

Fig. 4b compares the predicted [by Eq. (5)] and experimental axial $\text{NO}_x/\text{NO}_{x,\max}$ profiles. The relative error of deviation of the experimental dots from the fitting curve was found to be within $\pm 10\%$.

Using Eqs.(3)–(5), one can predict the axial CO and NO_x profiles in the combustor and, also, 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 on formation and reduction (rates) of these major pollutants in a fluidized-bed combustion system operated on the particular fuel under particular operating conditions. The magnitudes of CO_{\max} and $\text{NO}_{x,\max}$ can be found by Eqs. (1) and (2), respectively, while the reliable dependencies of $X_{\text{CO},\max}$ and $X_{\text{NO}_{x,\max}}$

on operating variables (basically, obtained from the experiments) should support the above models for dimensionless CO and NO_x profiles.

Conclusions

The conical FBC has been successfully tested for firing 82.5–82.8 kg/h Thai rice husk with variable fuel-moisture content, from 11 to 35.5% (secured by adding water to the fuel of a single analysis on a dry basis), at different percentages of excess air (of about 40, 60, 80 and 100%). Rice husk with higher fuel-moisture contents (40% and up) is not usable as the fuel in this fluidized-bed combustion system.

During the experimental tests, data on CO and NO_x (as NO) concentrations along the combustor height were generated for the above fuel qualities and operating conditions.

The following major conclusions have been derived from this work:

- axial temperature profiles in the conical FBC are rather uniform, noticeably affected by the fuel-moisture content, but weakly influenced by excess air;
- both fuel-moisture content and excess air have sensible effects on the formation/reduction of CO and NO_x in the bottom/freeboard regions of the combustor;
- axial CO and NO_x concentration profiles in the combustor exhibit maximums, CO_{max} and NO_{x,max} (as NO_{max}), at corresponding heights, $X_{CO,max}$ and $X_{NOx,max}$, respectively, and these peak concentrations in the fluidized bed are differently affected by both fuel quality

and excess air ratio;

- empirical correlations (or empirical models) for CO_{\max} or $\text{NO}_{x,\max}$ (as NO_{\max}) are proposed in this work, both including the effects of fuel properties and operating conditions;
- for this conical FBC, the relative dependencies $\text{CO}/\text{CO}_{\max} = f(X/X_{\text{CO},\max})$ and $\text{NO}_x/\text{NO}_{x,\max} = f(X/X_{\text{NO}_x,\max})$ can be approximated by fitting equations (empirical models) at $R^2 = 0.84\text{--}0.97$. The CO_{\max} and $\text{NO}_{x,\max}$ are determined by the above empirical models, while reliable dependencies of $X_{\text{CO},\max}$ and $X_{\text{NO}_x,\max}$ on the fuel properties and operating variables should support the models for the developing of the dimensionless axial CO and NO_x concentration profiles.

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