

Semi-Empirical Modeling of CO and NO Axial Profiles in a Fluidized-Bed Combustor Fired with Pelletized Biomass Fuels

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Abstract

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This work presents the results from a study on firing some Thai biomass fuels (rubber wood sawdust, eucalyptus bark, teak sawdust, rice husk, and cassava rhizome) in a pelletized form in a conical fluidized-bed combustor using silica sand as the bed material. During the combustion tests, all fuels were burned at an identical heat input (~200 kW_{th}), while ranging excess air from ~20% to ~80%. Under fixed operating conditions, temperature, O₂, CO, and NO were measured along the reactor centerline for each biomass. As revealed by the experimental results, the major pollutants, CO and NO, showed fair similarity of their axial profiles inside the reactor. Models for predicting dimensionless axial profiles, CO/CO_{max} and NO/NO_{max} (both as a function of the dimensionless axial distance from the air distributor, X_{CO}/X_{COmax} and X_{NO}/X_{NOmax} , respectively) were derived via statistical treatment of experimental results. Supporting semi-empirical equations for quantifying CO_{max} and NO_{max}, including the effects of fuel properties and operating conditions, were proposed for the selected biomass fuels. With the proposed models, CO and NO can be estimated for any arbitrary level above the air distributor in the conical FBC for individual firing of biomasses with similar properties at typical values of excess air.

Keywords: pelletized biomass fuels; fluidized-bed combustion; operating conditions; similarity of CO and NO; modeling axial profiles.

1. Introduction

Thailand is one of the world's largest exporters of agricultural products and foods. The Thai agricultural industry is one of the established economic sectors in this country producing a large variety of agricultural crops including rice, sugar cane, cassava, sunflower, etc. A tremendous amount of biomass by-products and residues is consequently generated by the agricultural sectors. Some of these biomasses, e.g., rice husk, sugarcane bagasse, cassava rhizome, sunflower shell, and some others, show their potential as fuel in direct combustion systems used for heat and power generation [1-3].

As known, biomass fuels have a limited storage life, depending on fuel properties (both physical and chemical) and storage conditions. Compared to coal, the calorific value and bulk density of most biomasses are rather low, leading to the higher storage cost and causing logistic problems [4]. By densification of agricultural by-products and residues through their pelletizing, characteristics of biomasses as fuel can be substantially improved, ensuring several advantages of the pelletized fuels over "as-received" biomasses [5].

Fluidized-bed combustion technology is the most preferred technology for energy conversion from various types of biomass [6]. However, combustion of some biomasses in a fluidized-bed reactor is accompanied by the substantial emission of gaseous pollutants (mainly, NO and CO), the emission rate of those is dependent on the combustion method, fuel properties, as well as on design features and operating conditions of a furnace/combustor [6,7]. The CO emission is essential for characterizing combustion efficiency of a biomass-fueled combustion system [1,3].

When burning biomass in a well-designed and properly operated fluidized-bed system, the CO and NO emissions from the combustion are basically affected by the fuel properties and operating conditions [1,3,6-8]. The CO emission is mainly dependent on combustion conditions (excess air and bed temperature, the latter being dependent substantially on the fuel heating value), whereas the NO emission is mainly influenced by the fuel-N (major factor), excess air (medium factor), and bed temperature (minor factor), according to the fuel-NO formation mechanism [6]. So, the CO emission can be effectively controlled by proper air supply and bed temperature, whereas in conventional fluidized-bed combustion, a reduction in the NO emission can be mainly achieved by lowering excess air and/or burning biomass with low fuel-N.

This study was aimed at studying the behavior of CO and NO in a fluidized-bed combustor for firing five types of pelletized Thai biomasses under variable operating conditions (excess air). The focus of the study was given to the analysis of a potential similarity of the axial CO and NO profiles between the selected pelletized fuels and operating conditions, with a final goal to propose semi-empirical models, which would fairly describe the behavior of these pollutants in both formation and oxidation/reduction regions.





Fig. 1 Schematic diagram of the experimental set up for combustion tests with pelletized biomass fuels.

2. Materials and Methods

2.1 Experimental

Fig. 1 shows the schematic diagram of an experimental set up with the fluidized-bed combustor using a cone-shaped bed (referred to as 'conical FBC') used in this study. The combustor consisted of two refractory-lined steel sections connected coaxially: a conical (lower) module of 40° cone angle, 0.9 m height, and 0.25 m inner diameter at the bottom plane, and a cylindrical section of 2.5 m height and 0.9 m inner diameter. In both sections, the refractory–cement insulation of 50 mm thickness covered (internally) the combustor steel walls to minimize heat loss to the

surroundings. The combustor was equipped with stationary Chromel-Alumel thermocouples (of type K) to measure temperature of combustion products (gas) at different points during the combustor start up and transition regimes. The gas was sampled at different points via gas sampling ports (see Fig. 1) for its further analysis using a new model "Testo-350" gas analyzer.

Besides the combustor, the experimental set up included a 25-hp blower for air supply to the reactor, a screw-type fuel feeder, a cyclone for collecting ash from the flue gas, and also some facilities for measurement, acquisition and treatment of experimental data. An air distributor with nineteen bubble caps was employed to induce a fluidized bed.

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

Property	CR	EB	RBS	RH	TSD					
Proximate analysis (wt.%)										
Moisture	6.59	6.3	8.5	8.81	8.12					
Volatile matter	67.42	43.1	59.9	54.4	66.86					
Fixed carbon	19.58	39.9	29.8	18.59	21.02					
Ash	6.41	10.7	1.8	18.2	4					
Ultimate analysis (on as-received basis, wt.%)										
С	43.21	41.7	44.7	37.47	42.93					
Н	5.68	4.6	5.36	4.64	7.94					
0	36.72	36.1	39.33	30.29	36.71					
Ν	1.32	0.54	0.25	0.59	0.3					
S	0.07	0.06	0.06	n/a	n/a					
Structural analysis (on dry and ash-free basis, wt.%)										
Hemi-cellulose	10.81	3.95	17.69	0.62	0.65					
Cellulose	31.22	32.82	52.08	49.76	44.21					
Lignin	15.21	27.03	12.28	17.36	19.1					
Density (kg/m ³)	1555	2050	1627	1685	1176					
LHV(kJ/kg)	17,050	14,700	17,500	14,360	18,180					



Sample	Composition (as oxides, wt.%)											
	CaO	K ₂ O	MgO	P_2O_5	SO ₃	Cl	SiO ₂	ZnO	MnO	Fe ₂ O ₃	Al_2O_3	TiO ₂
CR	26.2	31.11	11.66	19.56	3.65	0.77	4.77	0.07	0.13	1.6	0.04	0.19
EB	72.08	8.51	2.53	1.64	0.82	1.39	4.81	0.05	3.45	2.56	1.52	0.21
RBS	48.84	25.01	13.63	5.1	3.84	0.22	n/a	0.21	0.79	0.74	1.04	0.09
RH	6.63	6.68	0.86	n/a	0.33	0.42	83.18	0.04	0.5	1.16	0.06	0.05
TSD	16.52	11.38	4.78	8.77	1.3	0.07	41.34	0.05	0.18	8.27	6.66	0.55

Table 2. Composition of fuel ash (wt.%) in the selected pelletized biomass fuels.

In this combustor, quartz sand with the solid density of 2650 kg/m³ and the particle size of 0.3-0.5 mm was used as the bed material.

2.2 The fuels

Table 1 shows the properties of pelletized biomass fuels – rubber wood sawdust (RBS), eucalyptus bark (EB), teak sawdust (TSD), rice husk (RH), and cassava rhizome (CR) – used in this experimental study.

From Table, the major chemical structure of all the fuels included mainly hemi-cellulose, cellulose, lignin, as well as some minor extractives. Compared to the unprocessed biomasses, the solid density of the pelletized fuels were comparatively high, 1176–2050 kg/m³. From the proximate analysis, all the fuels used in this study had significant content of volatile matter, a moderate proportion of fixed carbon, but relative low contents of fuel moisture and ash (except rice husk), which resulted in a substantial value of the lower heating value (LHV) comparable with that of low-rank coal. Due to the substantial fuel-N, CR can be considered as a problematic fuel with regard to NO emission. Because of quite low fuel-S, SO₂ formation and emission were not addressed in this work.

Table 2 shows the standard analysis of fuel ash in the selected pelletized biomass fuels determined with an X-ray fluorescence technique. As seen in Table 2, the RH and TSD ashes had a predominant proportion of Si, followed by elevated contents of Ca and K, whereas Ca and K were among the predominant components in the ashes of RBS, EB and CR. Note that the high proportion of K in the CR and RBS ashes can cause severe bed agglomeration that would occur during fluidized-bed combustion of these biomasses if silica/quartz sand were used as bed material. However, the ashes of CR and RBS contained the substantial proportions of Ca and Mg (as well as of P in the CR ash), i.e., the components responsible for the formation of eutectics with high melting points. These eutectics increase the defluidization temperature to a level over the bed temperature, thus preventing bed agglomeration in a fluidized-bed furnace/combustor [9]. Therefore, no bed agglomeration was expected in this study on the conical FBC using silica sand as the bed material.

2.3 Experimental planning

During the test run for given operating conditions, temperature, O₂, CO, and NO were measured along the combustor centerline. Prior to testing, steady state conditions of the combustor were verified based on the stability of two temperatures: (1) at the top of the conical section (i.e., in the expended fluidized bed of quartz sand) and (2) at the reactor top (both measured using the above-mentioned fixed thermocouples). At a steady state, the time-domain fluctuations of these temperatures did not exceed ± 2 °C. In each test run, the excess air coefficient (α) was determined according to Ref. [10] using actual O₂ and CO (ignoring C_xH_y) at stack. The percentage of excess air was then calculated using its correlation with α as: EA = 100(α – 1).



Fig. 2 Axial temperature profiles in the conical FBC when firing the selected pelletized biomass fuels at the combustor heat input of $\sim 200 \text{ kW}_{\text{th}}$ and excess air of (a) 40% and (b) 80%.

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Fig. 3 Axial O_2 profiles in the conical FBC when firing the selected pelletized biomass fuels at the combustor heat input of ~200 kW_{th} and excess air of (a) 40% and (b) 80%.

All the experiments were performed at the identical heat input ($\sim 200 \text{ kW}_{\text{th}}$) to the combustor, while ranging excess air from 20% to 80% when burning an individual fuel.

3. Results and Discussion

3.1 Combustion characteristics

Temperature and oxygen concentrations are important factors in combustion chemistry, affecting both the fuel burnout, as well as formation and oxidation/reduction in different regions of the reactor.

Fig. 2 shows the axial temperature profiles in the conical FBC when firing the selected pelletized biomass fuels at similar heat input to the reactor for excess air of 40% and 80%. With some exemption (mainly, for EB), the bed temperature in the conical section was quite similar for all the fuels, which can be attributed to the identical heat input (~200 kW_{th}) when burning distinct biomasses. However, in the upeer (cylindrical) section, temperature apparently decreased, mainly due to heat losses across the combustor walls.

From Fig. 2, an increase in excess air resulted in some reduction of temperature at all points inside the reactor, basically caused by the dilution effects of excessive air.

Fig. 3 depicts the axial profiles of O_2 for the same fuels and operating conditions, as in Fig. 2. At levels of 0.5–2 m above the air distributor, the profiles showed some differences, especially in the test runs at lower excess air (40%), which can be explained by the difference in reactivity of the fuels. When switching excess air to higher (80%) excess air, the profiles for different biomasses were quite similar and showed higher O_2 at all the points due to the higher air supply. It can be seen in Fig. 3 that O_2 indicated the substantial oxygen consumption in the conical section and showed gradual diminishing in the cylindrical section to the level solely dependent on excess air.

3.2 Formation and oxidation/reduction of the major gaseous pollutants in the conical FBC

As an illustration, Fig. 4 shows the axial CO and NO profiles for the selected fuels fired in the conical FBC at the heat input $\sim 200 \text{ kW}_{\text{th}}$ for the only



Fig. 4 Axial (a) CO and (b) NO profiles in the conical FBC when firing the selected pelletized fuels at the combustor heat input of ~200 kW_{th} and excess air of about 40%.

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percentage of excess air (\sim 40%). However, in all the test runs (for the entire range of excess air), these profiles exhibited two specific regions inside the reactor with different net results of the pollutants formation and oxidation/reduction.

In the first region (Z < 0.6 m), i.e., below the level of fuel injection, CO rapidly increased along the axial direction, mainly due to biomass devolatilization and further oxidation of volatile C_xH_y and char-C [11], while the rate of oxidation reactions was relatively low. In the second region (Z > 0.6 m), where the oxidation reactions were predominant, CO diminished along the combustor height to low values at the combustor top. Due to the opposite trends in the two regions, all the axial CO profiles showed the maximum, CO_{max}, at the level $X_{COmax} = 0.6$ m above the air distributor, i.e., in the vicinity of fuel injection.

Like CO, the axial NO profiles exhibited two specific regions with the maximum, NO_{max}, at X_{NOmax} = 0.6 m. In the first region (Z < 0.6 m), the rate of NO formation from nitrogenous volatile species (mainly, NH₃) was significantly higher than that of NO reduction, basically occurred via catalytic reactions of NO with CO on the surface of fuel char/ash particles [6] and also through homogeneous reactions of NO with NH₃ and light hydrocarbon radicals [11]. In the second region (Z > 0.6 m), the rate of the abovementioned secondary (reduction) reactions prevailed the rate of NO formation, resulting in the substantial reduction of NO in the cylindrical section. At 0.6 m < Z < 1.5 m the NO reduction rate was substantial, mainly due to the elevated CO in this region.

Note that the axial CO and NO profiles at another three excess air values showed similar trends and characteristics, which were numerically different for different test runs. Moreover, for each pollutant, all the profiles for the selected fuels and specified excess air value showed a fair similarity, which allowed applying statistical methods for deriving semi-empirical models to describe behaviors of CO and NO inside the reactor [7].

3.3 Semi-empirical modeling of CO_{max} and NO_{max}

Using the numerical values of CO_{max} and NO_{max} obtained experimentally, as well as the abovementioned $X_{COmax} = 0.6$ m and $X_{NOmax} = 0.6$ m, the dependencies of the relative gas concentrations on the relative axial distance, $CO/CO_{max} = f(X_{CO}/X_{COmax})$ and $NO/NO_{max} = f(X_{NO}/X_{NOmax})$, were plotted for all the test runs performed in this study and then fitted using the statistical method. To make these dependences usable, CO_{max} and NO_{max} were represented as semiempirical models accounting for the effects of key parameters on formation of CO and NO in the combustor [6,11].

The model predicting CO_{max} (ppm) with the $\pm 20\%$ error, which includes the effects of the excess air ratio (α) and the bed temperature (T_{bed} , K), was obtained statistically (at $R^2 = 0.91$) as:

$$CO_{max} = 811 \alpha^{-1.17} (T_{bed})^{-0.13}$$
(1)

By structure, Eq. (1) is similar to the previously proposed model for predicting of CO_{max} for firing various types of biomass in a conical FBC [7].

However, the model for the calculation of NO_{max}, accounting for the effects of fuel-N (wt.%, in the pelletized fuel), the excess air ratio (α), and the bed temperature (T_{bed} , K), was statistically derived (at $R^2 = 0.97$) as:

$$NO_{max} = 1785a^{1.15}N^{0.11}(T_{had})^{0.69}$$
(2)

With Eq. (2), one can predict the NO_{max} within the $\pm 10\%$ error band.

3.4 Dimensionless axial profiles of CO and NO

The experimental dependencies of CO/CO_{max} and NO/NO_{max} on the relative distance along the height in the conical FBC when firing the selected pelletized biomass fuels at the specified range of excess air are shown (by dots) in Fig. 5.

For the range of $0.8 \le X_{CO}/X_{COmax} \le 5.1$, the experimental CO/CO_{max} as the function of X/X_{COmax}



Fig. 5 Comparison of the experimental and predicted (a) CO/CO_{max} and (b) NO/NO_{max} versus the relative axial distance in the conical FBC for firing the selected pelletized fuels at excess air of 20%, 40%, 60% and 80%.

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can be fairly fitted (at $R^2 = 0.79$) by a single equation as:

$$\frac{\text{CO}}{\text{CO}_{\text{max}}} = \left(\frac{X_{\text{CO}}}{X_{\text{CO}_{\text{max}}}}\right)^{-1.8} \exp\left[1 - \left(\frac{X_{\text{CO}}}{X_{\text{CO}_{\text{max}}}}\right)^{\left(-2.3 + 0.45\frac{X_{\text{CO}}}{X_{\text{CO}_{\text{max}}}}\right)}\right] \quad (3)$$

For comparison, the CO/CO_{max} profile was predicted by using Eq. (3) for variable X/X_{COmax} and plotted in Fig. 5a (as solid line) together with the experimental dots.

For similar range of the relative axial distance, 0.8 $\leq X_{\text{NO}}/X_{\text{NOmax}} \leq 5.1$, the experimental dependence of NO/NO_{max} on *X*/*X*_{NOmax} was fitted at *R*² = 0.86 and can be represented as:

$$\frac{\text{NO}}{\text{NO}_{\text{max}}} = \left(\frac{X_{\text{NO}}}{X_{\text{NO}_{\text{max}}}}\right)^{-1.2} \exp\left[1 - \left(\frac{X_{\text{NO}}}{X_{\text{NO}_{\text{max}}}}\right)^{-1.2}\right]$$
(4)

Likewise, the axial NO/NO_{max} profile was obtained from Eq. (4) and represented in Fig. 5b (as solid line) for its comparison with the experimental data.

With the proposed models (Eqs. (3) and (4)), CO and NO can be estimated for any arbitrary level above the air distributor in the conical FBC, for individual firing of the selected fuels, as well as biomasses with similar fuel properties in this combustion technique at the specified range of excess air.

It should be noted that the axial CO/CO_{max} and NO/NO_{max} profiles in the conical FBC are independent of the combustor's dimensions, while the dimensional "scaling" of the two profiles are ensured by X_{COmax} and X_{NOmax} , which coincides with the level of fuel injection into the combustor.

4. Conclusions

Five Thai biomass fuels (rubber wood sawdust, eucalyptus bark, teak sawdust, rice husk, and cassava rhizome) in a pelletized form have been successfully combusted in a conical fluidized-bed combustor at the identical input heat ($\sim 200 \text{ kW}_{\text{th}}$) to the reactor for the range of excess air of 20% to 80%. Axial profiles of major gaseous pollutants, CO and NO, are substantially affected by the fuel type and operating conditions (excess air) in the reactor, and exhibit apparent similarity in all combustion trials. Semi-empirical models have been statistically derived for predicting the axial CO/CO_{max} and NO/NO_{max} profiles with the sufficient accuracy. With the proposed models, CO and NO can be predicted at any point along the centerline of the combustor fired with the selected fuels, or other biomasses with similar fuel properties, at typical values of excess air. Based on the models, rough assessment of CO and NO emissions from the combustor can be performed as well.

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6. References

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