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ASSESSMENT OF HEAT LOSSES, COMBUSTION EFFICIENCY AND MAJOR GASEOUS EMISSIONS FOR THE CO-FIRING OF BIOMASS FUELS IN A FLUIDIZED BED

Kasama Janvijitsakul and Vladimir I. Kuprianov

Mechanical Engineering Program, Sirindhorn International Institute of Technology, Thammasat University,
P.O. Box 22, Thammasat Rangsit Post Office, Pathumthani, 12121, Thailand.

ABSTRACT

Models for estimating the heat losses with unburned carbon and owing to incomplete combustion in a fluidized bed system (co-) firing two biomass fuels are presented. With the use of the models, the heat losses and combustion efficiency was estimated for the conical fluidized bed combustor (conical FBC) co-firing “as-received” rice husk and sugar cane bagasse at about 82.6 kg/h and four values of excess air (about 40, 60, 80 and 100%) for different energy fractions of rice husk in the fuel blend (0.60, 0.85 and 1.0). As shown in the work, the combustion efficiency 94.12–96.35% is achievable when co-firing raw rice husk and bagasse in wide ranges of the operating conditions. For the above operating conditions, semi-empirical models were developed for predicting the peak of CO and NO_x concentrations (CO_{max} and $NO_{x,max}$, respectively), basically occurring in the bed region of the conical FBC. Axial (relative) CO/CO_{max} and $NO_x/NO_{x,max}$ profiles in the conical FBC were adequately represented by fitting equations (with the relatively high R^2, 0.837–0.984) derived using reference experimental data. With the fitting equations, assessments of the CO and NO_x reduction rates in the freeboard region of the combustor become feasible.

Keywords: Combustor, Fuel blend, Operating conditions, Semi-empirical models.

1. INTRODUCTION

In Thailand, sugar cane bagasse and rice husk are important and sustainable sources of renewable energy. Annually, about 50 million tones of sugar cane and 20 million tons of rice are produced in this country. Accordingly, tremendous amounts of bagasse and rice husk, residues from the processing of sugar cane and rice milling, are available as energy sources. Although predominant portions of bagasse and rice husk are utilized by the Thai milling industries, significant amounts of these biomass fuels are being unused and eventually lost. The aggregate power generation potential from the unused bagasse and rice husk in this country is estimated to be 394–623 MW_e [1].

The fluidized bed combustion is reported to be the most effective and environmentally friendly technology for conversion of energy from biomass fuels, including agricultural residues [2–4]. A large number of research works have been carried out on the development and study of co-firing systems, including those utilizing biomass fuels [5–6]. However, there is a lack of supporting models for estimating the combustion heat losses and efficiency as well as those for predicting major and other emissions from these systems.

This work was devoted to the development and approbation of models for estimating the combustion heat losses and efficiency for the case of co-firing “as-received” rice husk and sugar cane bagasse in a fluidized bed system. The predicting of CO and NO_x concentrations in formation/reduction regions of the combustor co-fired with the above fuels was also the focus of this study.

2. MATERIALS AND METHOD

2.1 Combustion Heat Losses and Efficiency

In combustion of fossil and biomass fuels, the heat loss owing to unburned carbon is essentially the loss basically associated with the presence of unburned carbon in the bottom ash (drained through the furnace/combustor bottom) as well as in fly ash (carried out from the system). For the fluidized bed combustor with no ash removal through the bottom part, this heat loss, as percentage of the fuel lower heating value, is estimated to be [7]:

$$q_{uc} = \frac{32{,}866}{\mathrm{LHV}}\left(\frac{\mathrm{C_{fa}}}{100-\mathrm{C_{fa}}}\right)\mathrm{A} \qquad (1)$$

For the co-firing of rice husk and bagasse with fairly the same yields of volatile matter (on dry basis), the q_{uc} can be estimated as the total sum of the corresponding energy losses by the fuels related to the heating value of the blended fuel:

$$q_{uc} = \frac{32{,}866}{\mathrm{LHV_{bf}}}\left[\frac{(\mathrm{C_{fa}})_{rh}\mathrm{A_{rh}MF_{rh}}}{100-(\mathrm{C_{fa}})_{rh}} + \frac{(\mathrm{C_{fa}})_{b}\mathrm{A_{b}}(1-\mathrm{MF_{rh}})}{100-(\mathrm{C_{fa}})_{b}}\right] \quad (2)$$

Since A_b is much lower than A_{rh} [2], and taking into account the major contribution of rice husk (MF_{rh} >0.5), the heat loss with unburned carbon for the co-firing rice husk and bagasse can be predicted by:

$$q_{uc} = 32{,}866\ \mathrm{EF_{rh}}\frac{(\mathrm{C_{fa}})_{rh}\mathrm{A_{rh}}}{\mathrm{LHV_{rh}}[100-(\mathrm{C_{fa}})_{rh}]} \quad (3)$$

where:

$$\mathrm{EF_{rh}} = \frac{\mathrm{MF_{rh}} \times \mathrm{LHV_{rh}}}{\mathrm{LHV_{bf}}} \quad (4)$$

For the case of firing pure rice husk (EF_{rh} =1), Eq. (3) takes the form similar to Eq. (1).

As follows from the above model, the volume of the required experimental data on the unburned carbon is significantly reduced since the data are limited by one fuel only.

The heat loss owing to incomplete combustion is basically calculated based on the CO, H_2 and CH_4 concentrations (vol.%) in the dry flue gas leaving the combustion system. However, the H_2 and CH_4 concentrations can be neglected for combustion systems firing fuels with excess air [7]. Hence, this heat loss, as percent of the lower heating value, for the case of co-firing of the two fuels can be estimated by Refs.[7–9] using only the CO concentration in the waste flue gas:

$$q_{ic} = 126.4\ \mathrm{CO} \times V_{dg}\frac{(100-q_{uc})}{\mathrm{LHV_{bf}}} \quad (5)$$

Assuming that the volume of dry gas is correlated with the excess air ratio and theoretical volume of air by $V_{dg} \approx \alpha V^{o}$ [8], Eq. (5) can be rewritten as:

$$q_{ic} = 126.4\mathrm{CO} \times \alpha\frac{(100-q_{uc})V^{o}_{bf}}{\mathrm{LHV_{bf}}} \quad (6)$$

where the excess air ratio α is estimated based on the experimental O_2 and CO concentrations (both being expressed in vol.%) in the dry flue gas [7,9]:

$$\alpha = \frac{21}{21-(\mathrm{O_2}-0.5\mathrm{CO})} \quad (7)$$

The V^{o}/LHV ratio is known to be at fairly the same value for a variety of solid fuels, including biomass fuels [9], and, hence, this is valid for the fuel blends.

As applied in Refs. [7,8], V^{o} can be estimated with the use of the fuel analysis on "as-received" basis. Quantifying V^{o}/LHV for the predominant biomass fuel, i.e. rice husk, the heat loss owing to incomplete combustion can be then found based on the CO emission from the reactor and α:

$$q_{ic} = 0.032\ \alpha \times \mathrm{CO}\ (100 - q_{uc}) \quad (8)$$

For the particular α, the corresponding value of EA (as volume percent) can be determined by:

$$\mathrm{EA} = 100\ (\alpha - 1) \quad (9)$$

Finally, the combustion efficiency is determined by the heat-loss method [7,8] to be:

$$\eta_c = 100 - (q_{uc} + q_{ic}) \quad (10)$$

2.2 Essential Input

In point of fact, this analytical work follows the experimental study on the conical fluidized-bed combustor (referred to as the conical FBC) co-firing "as-received" rice husk and bagasse for different values of EF_{rh} (including EF_{rh} = 0, i.e. when firing pure rice husk) [5]. The detail description of the experimental set-up is provided in Refs. [2,5].

For estimating the heat losses by the above models, the fuel properties are required along with the operating conditions. Table 1 shows the ultimate and proximate analyses of rice husk and sugar cane bagasse used in this study. The lower heating value of the fuels was estimated by Ref. [8] to be 12.34 MJ/kg for rice husk and 6.68 MJ/kg for bagasse.

As reported in Ref. [5], the co-firing tests were conducted for three fuel options, at 45%, 75% and 100% rice husk mass fractions, corresponding to EF_{rh} of 0.60, 0.85 and 1.0, respectively. The feed rate of the blended fuel was maintained at about 82.6 kg/h in all the test runs. For the particular fuel option, the biomass fuel was burned at four different values of EA: 40, 60, 80 and 100%.

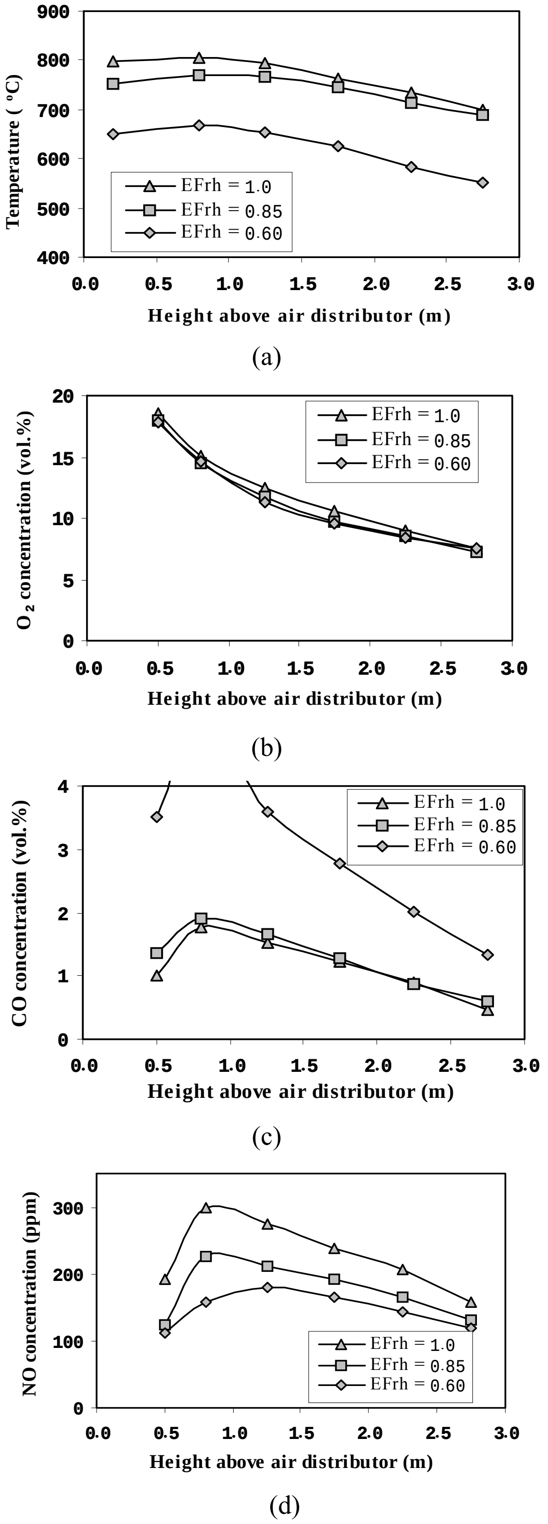
In each test run, fly ash was sampled from the cyclone for quantifying the unburned carbon in order to estimate the associated heat loss. The CO emissions were also recorded with the aim of characterization of the combustor environmental performance and estimation of the heat loss owing to incomplete combustion.

Table 1: Proximate and ultimate analyses of rice huskand bagasse (wt.%) co-fired in the conical FBC [5]

Analysis (basis)	Rice husk	Bagasse
Proximate analysis:		
Moisture ("as-received")	11.0	48.8
Ash ("dry")	14.16	2.15
Ultimate analysis ("daf") :		
Carbon	44.99	42.64
Hydrogen	6.39	6.62
Oxygen	48.15	50.48
Nitrogen	0.42	0.19
Sulfur	0.05	0.07

2.3 Temperatures and Gas Concentrations in the Conical FBC

Figure 1 shows representative axial temperature and gas concentration profiles illustrating the combustion behavior of rice husk as well as of the rice husk/bagasse blend in the conical FBC.



(a)

(b)

(c)

(d)

Fig 1. Representative axial temperature (a), O$_2$ (b), CO (c) and NO (d) concentration profiles in the conical FBC (co)-firing rice husk and bagasse (operating conditions: FR = 82.6 kg/h, EA ≈ 40% EF$_{rh}$ = variable) [5].

The temperature and gas concentration patterns (given in Fig. 1 for the particular operating conditions) are quite typical for various biomass fuels and operating conditions [2,5,10].

In the bed region of this combustor (up to 1-m level above the air distributor), the temperature profiles are reported to be quite uniform. Meanwhile, in the freeboard region (of 1–3-m height), the profiles are basically characterized by a negative gradient because of heat loss across the combustor walls at the lowered heat release rate in this region.

The experimental results on the conical FBC show that the axial temperature profiles in the combustor are (almost) independent of the excess air but apparently affected by the fuel properties, as may be seen Fig. 1a. This conclusion is quite important for this analytical work, which allows considering the temperature and excess air (or the excess air ratio) as independent variables related to the combustor operating conditions.

Another important feature of the fluidized bed combustion is associated with quite weak correlation of the axial O$_2$ profiles and the fuel properties. This fact is illustrated in Fig. 1b. As seen in Figs. 1a and 1b, the maximum combustion temperature and highest oxygen consumption rate occur in the bed region, indicating the highest combustion rate in the conical part.

One more generality found in the experiments is that associated with the emission patterns in the conical FBC. In all the test runs on this combustor, the axial CO and NO$_x$ concentration profiles are reported to have the maximum (CO$_{max}$ and NO$_{x,max}$, respectively) located at a certain distance above the air distributor (X$_{CO,max}$ and X$_{NOx,,max}$, respectively), dividing conventionally the combustor volume into the formation (lower) and reduction (upper) regions for these pollutants, as may be seen in Fig. 1c and Fig. 1d.

3. RESULTS AND DISCUSSION

3.1 Combustion Efficiency

Using the proposed models, i.e. Eqs. (3) and (8), the combustion heat losses were estimated for the above operating conditions. In accordance with the methodology, only four experimental values of the unburned carbon content (for distinct values of EA), determined for firing pure rice husk (i.e. at EF$_{rh}$ = 1), were used in the computation of q_{uc} for all the cases of interest. These values ranged from 8.1 to 10.6% when EA was varied from 39.7 to 100.2%, respectively. However, when predicting the heat loss owing to incomplete combustion, corresponding values of the CO emission (taken from Ref.[5] for distinct test runs) were involved in the computation.

Table 2 shows the heat losses and combustion efficiency of the conical FBC operated at about 82.6 kg/h for distinct fuel options and EA values. As seen in Table 2, for the particular fuel option, q_{uc} increased noticeably (in accordance with the change in unburned carbon) when EA was varied from about 40 to 100%. This fact could be explained by the reduced residence time of fuel particles during their transportation in this relatively "short" combustor [2,5]. In accordance with the model, for the particular EA, q_{uc} reduced for greater mass fractions of bagasse in the fuel blend.

Table 2: Heat losses and combustion efficiency of the conical FBC for different fuel options and excess air

EF_{rh}	EA (vol.%)	q_{uc} (%)	q_{ic} (%)	η_c (%)
1.0	39.7	3.05	0.87	96.08
	60.4	3.38	0.58	96.04
	81.1	3.75	0.35	95.90
	100.2	4.10	0.31	95.59
0.85	38.7	2.58	1.51	95.91
	61.4	2.86	1.14	96.00
	79.6	3.18	0.70	96.12
	98.6	3.47	0.47	96.06
0.60	37.2	1.83	3.25	94.12
	60.2	2.03	2.41	95.56
	81.1	2.26	1.81	95.93
	100.8	2.47	1.18	96.35

Unlike the heat loss with unburned carbon, q_{ic} was apparently decreased with higher EA because of the lowered CO emission. On the contrary, for quasi-identical values of EA, q_{ic} was increased for greater mass/energy contributions by the bagasse.

As seen in Table 2, opposite behaviors of q_{uc} and q_{ic} with the EA variation (for the fixed EF_{rh}) resulted in the apparent optimum values of EA. Thus, for EF_{rh} = 0.85, the maximum combustion efficiency (96.12%) corresponded to optimum excess air of about 80%. Meanwhile, as follows from the computational results, the maximum combustion efficiency can be improved from 96.08% to 96.35% through increasing the energy contribution by sugar cane bagasse.

Observing data in Table 2, it was concluded that the co-firing of sugar cane bagasse and rice husk in the conical FBC at the rice husk energy fractions greater than 0.6 resulted in sustainable combustion, with the 95–96% combustion efficiency.

3.2 Models for CO and NO$_x$ Formation

The experimental results on co-firing rice husk and sugar cane bagasse [5] were treated with the aim of deriving empirical models for estimating the rate of formation (in the bed region) and reduction (in the freeboard region) of CO and NO$_x$ in the conical FBC. Prior to data treatment, the emission concentrations (in ppm) were converted into CO and NO$_x$ (as NO$_2$) mass concentrations, (in g/m^3, under standard conditions).

Basically, in biomass combustion, CO formation occurs through three major heterogeneous chemical reactions of char-carbon with (1) water vapor (affected by fuel-moisture), (2) O$_2$ and (3) CO$_2$, the first reaction being predominant. These primary reactions, proceeding on the char surface (affected by fuel-ash), are followed by CO oxidation with oxygen (whose concentration is apparently dependent on the excess air ratio). Meanwhile, the CO/CO$_2$ ratio in the combustion products represents the inverse correlation with the combustion temperature [2,5,10].

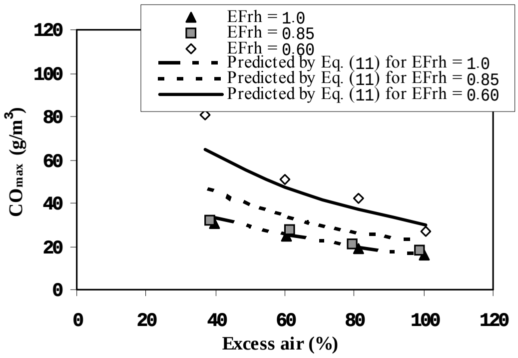
These facts led to the conclusion that the excess air ratio, bed temperature, as well as fuel moisture and ash, could be considered as the independent variables affecting CO formation in the fluidized bed combustion of biomass fuels (including fuel blends). Taking the above into account, the CO peak value, CO_{max} (g/m^3), basically observed at the exit of the bed region, for the case of the co-firing of rice husk and bagasse was represented by the fitting equation (at R^2 = 0.837):

$$CO_{max} = 1.2\times10^{7}\, A_{bf}^{\;0.25} W_{bf}^{\;0.5} \alpha^{-2}\, T_{bed}^{-2} \qquad (11)$$

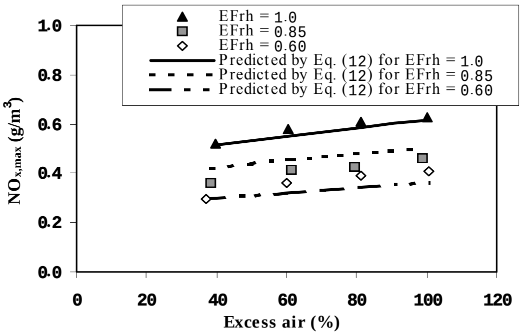
In the biomass combustion, due to relatively low combustion temperatures, the NO$_x$ is reported to form via the fuel-NO formation mechanism, when the NO formation rate depends apparently on the fuel-N, excess air and combustion (bed) temperature [2,10]. Including the above effects into the model, the NO$_x$ peak value, $NO_{x,max}$ (g/m^3), was represented by the fitting equation (R^2 = 0.848):

$$NO_{x,max} = 4.47 N_{bf} (0.4 - 0.1\, N_{bf}) \alpha^{0.5} \left[\frac{T_{bed} - 800}{1000}\right]^{0.15} \qquad (12)$$

Figure 2 compares the predicted CO_{max} and $NO_{x,max}$ with those found experimentally [5] in the conical FBC operated at 82.6 kg/h for different fuel options and operation conditions.



(a)



(b)

Fig 2. Comparison of the predicted CO_{max} (a) and $NO_{x,max}$ (b) with corresponding experimental values [5] obtained for the (co-) firing rice husk and bagasse in the conical FBC operated at 82.6 kg/h and different values of excess air.

3.3 Models for CO and NO_x Reduction

In this work, an empirical approah was applied in the developing of the models for predicting the reduction rate of CO and NOx in the freeboard region of the conical FBC [11].

In such an approach, the dependences of the relative carbon monoxide concentrations, CO/CO_{max}, on the relative distance, $X/X_{CO,\,max}$, were plotted for different fuel options and operating conditions [5]. These relative CO curves were found to depend on EA, but demonstrated apparent independence and similarity for different values of EF_{rh}. It was, therefore, managed to derive two fitting equations for two groups of the EA values: (1) of 40–60% and (2) of 80–100%.

For the range of 40–60% EA, the fitting equation was found to take the form (R^2=0.984):

$$\frac{CO}{CO_{max}} = X_0^{1.0}\exp\left[1 - X_0^{(1.09-0.02X_0)}\right] \qquad (13)$$

and for 80–100% EA it was represented by (R^2=0.972):

$$\frac{CO}{CO_{max}} = X_0^{1.78}\exp\left[1 - X_0^{(2.24-0.21X_0)}\right] \qquad (14)$$

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

Note that the fitting equations, Eqs. (13) and (14), can be used for $0.6 \le X/X_{CO,max} \le 3.5$. The predicted relative CO profiles are shown in Fig. 3 in comparison with experimental results (dots) [5] for the same fuel options and operating conditions.

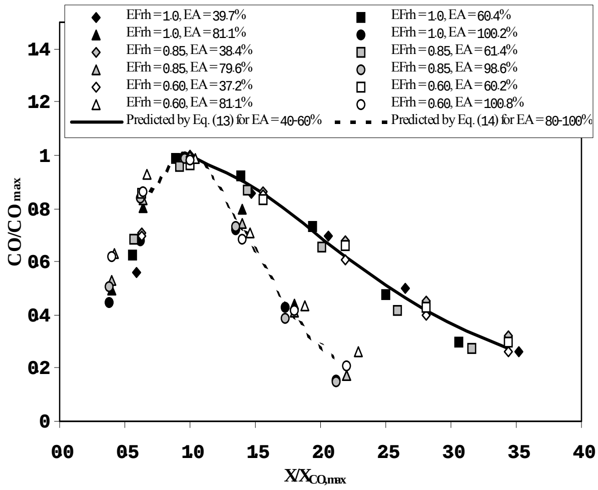


Fig 3. Dependencies of the (relative) CO concentration on the (relative) distance along the conical FBC for the (co)-firing rice husk and bagasse for different fuel options and operating conditions.

Unlike for the CO/CO_{max}, it was managed to approximate $NO_x/\ NO_{x,max}$ experimental dependencies by a single equation.

For $0.6 \le X/X_{NOx,max} \le 3.5$, the $NO_x/NO_{x,max}$ could be represented by the fitting equation (R^2=0.976):

$$\frac{NO_x}{NO_{x,max}} = Z_0^{1.4}\exp\left[1 - Z_0^{(2.13-0.175Z_0)A^{-0.18}}\right] \qquad (15)$$

where $Z_0 = X/X_{NOx,max}$ and A (wt.%) is referred to the blended fuel.

Note that the fitting equation includes the effect of the fuel-ash. This fact could be explained by the influence of the heterogeneous reaction of NO reduction by CO occurring on the char/ash particles surface.

Figure 4 shows the predicted $NO_x/NO_{x,max}$ profiles in comparison with experimental data (dots) from Ref. [5].

With the use of Eqs. (11)–(15), estimation of both CO and NO_x can be carried out for any point along the combustor height. However, reliable values of $X_{CO,max}$ and $X_{NOx,max}$ are required in the applications of the proposed models.

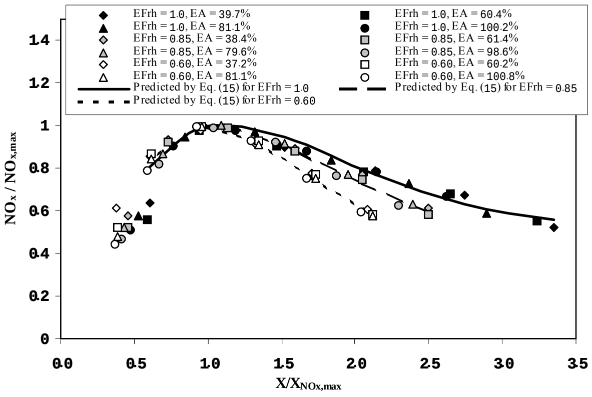


Fig 4. Dependencies of the (relative) CO concentration on the (relative) distance along the conical FBC for the (co)-firing rice husk and bagasse for different fuel options and operating conditions.

4. CONCLUSIONS

The proposed models were successfully applied for estimating the heat losses with unburned carbon and owing to incomplete combustion in a conical fluidized bed combustor co-firing “as-received” rice husk and sugar cane bagasse at about 82.6 kg/h and four values of excess air (about 40, 60, 80 and 100%) for different energy fractions of rice husk in the fuel blend (0.60, 0.85 and 1.0). As shown in this work, the combustion efficiency of 94.12–96.35% is achievable for the above fuel option and operating conditions

The empirical models (fitting equations), derived in this work based on the treatment of experimental data, can be used for the predicting of CO and NOx concentrations at any location along the combustor height, including peak values, CO_{max} and $NO_{x,max}$.

5. ACKNOWLEDGEMENT

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7. NOMENCLATURE

Symbol	Meaning	Unit
q_{uc}	Heat loss with unburned carbon	%LHV
q_{ic}	Heat loss owing to incomplete combustion	%LHV
η_c	Combustion efficiency	%LHV
C_{fa}	Carbon content in fly ash	wt.%
LHV	Lower heating value	MJ/kg
A	Ash content ("as-received" basis)	wt.%
MF	Mass fraction	-
EF	Energy fraction	-
α	Excess air ratio	-
EA	Excess air	(vol.%)
T_{bed}	Bed temperature	(K)
W	Moisture content ("a.-r." basis)	wt.%
N	Nitrogen content ("a.-r." basis)	wt.%
V^o	Theoretical volume of air	m^3/kg
V_{dg}	Volume of the dry flue gas	m^3/kg

Subscripts

Symbol	Meaning
rh	Rice husk
b	Bagasse
Bf	Blended fuel