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A Simplified Mathematical Model for Biomass Combustion in a Fluidized Bed Combustor

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***Abstract*: The combustion of biomass fuels like rice husk, sawdust, groundnut shells etc. in a grate type furnace is slow and inefficient yielding low combustion efficiency. Fluidized bed combustion of these biomass fuels was shown feasible for efficient combustion along with high combustion intensity. A mathematical model has been developed for the exit-gas composition and combustion efficiency for a laboratory scale fluidized bed biomass fuel combustor. The model allows for bubble-size variation with height and predicts the consumption of oxygen and its variation along the height, outlet-gas composition, oxygen concentration in different phases i.e., bubble, cloud-wake and emulsion phases, average O2 concentration along the bed height and combustion efficiency. Model predictions are compared with the literature data and reasonable agreement has been obtained.**

***Keywords*: biomass fuels, fluidized bed, mathematical model.**

1. Introduction

Fluidized bed combustion is emerging as a useful technique for utilizing low grade and biomass fuels in utility boilers and power plants. The history of fluidized bed technology had been reviewed by many researchers [1]-[3]. Fluidized bed combustors are usually modeled as multiphase systems consisting of two or three distinct phases. According to the two-phase theory of fluidization proposed by Davidson and Harission [4], a gas fluidized bed is considered to be composed of two phases, a dense or emulsion phase consisting of solid particles and interstitial gas, and a dilute or bubble phase consisting of rising voids, essentially free from particles. It also assumes that all the gas in excess of the minimum fluidization flow rate passes through the bed as bubbles. Some of the models have been based on this two-phase theory [5]-[7]. On the other hand, the three-phase theory, as proposed by Kunni and Levenspiel [8], assumes an additional phase consisting of a cloud-wake region. Bulk flow gas through the emulsion and cloud-wake phases is assumed to be negligibly small. Reddy and Mohapatra [9] have been developed a mathematical model for the oxygen balance for a 10 MW fluidized bed coal combustion power plant operated at Jamdoba (TISCO, India). In this model an effective chemical reaction rate of char combustion has been derived considering the single film theory of char combustion for shrinking particles.

In a fluidized bed combustor, the overall rate of combustion to be controlled by diffusion of both O_2 to the solid and of the products CO and CO_2 away from the reacting particle. With much smaller particles, whose burning rate is usually determined not by mass transfer, but by the inherent kinetics of the reaction between O_2 and carbon. The chemical reaction between O_2 and carbon is investigated by Bewes, Hayhurst, Richardson and Taylor [10]. Fabrizio Scala and Piero Salatino [11] presented a model of an atmospheric bubbling fluidized bed combustor operated with high-volatile solid fuel feedings. It aims at the assessment of axial burning profiles along the reactor and of the associated temperature profiles, relevant to combustor performance and operability.

In the present work a simple three phase model has been presented for biomass fuel combustion with underfeeding system and the model results have been validated by the data collected from a laboratory scale unit which uses rice husk, sawdust and groundnut shells as fuels.

2. Basic Assumptions of the Model

Glicksman et al. [12] proved experimentally that bubble characteristics are nearly uniform across the bed cross-section in a bed with large particles. The following assumptions are made for the present model:

1. Bubbles are carbon free, uniform in size across a given cross section and well distributed throughout the bed. The gas flowing through the bubble phase is considered to be in plug flow.
2. The reaction is isothermal, first order and does not involve a change in the number of moles.
3. Inter phase gas exchange occurs in two stages from bubble to cloud-wake and from cloud-wake to emulsion.
4. The bed consists of three phases, the bubble phase, emulsion phase and cloud-wake phase.
5. The gas-flow rate through the emulsion phase is assumed to remain the same as that under minimum fluidization conditions.

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3. Formulation of the Model

The following are the material balance equations for the reaction gas.

Bubble phase:

$$dC_b/dZ + [(K_{bc})_b\varepsilon_b/U_b]C_b = [(K_{bc})_b\varepsilon_b/U_b]C_{cw} \quad (1)$$

Cloud wake phase:

$$dC_{cw}/dZ= [\{(K_{bc})_b + (K_{ce})_b + Kf_{cw}\}\varepsilon_b/U_{cw}]C_{cw} = [(K_{bc})_b\varepsilon_b/U_{cw}] + [(K_{ce})_b\varepsilon_b/U_{cw}]C_e \quad (2)$$

Emulsion phase:

$$dC_e/dZ + [(K_{ce})_b\varepsilon_b + K\{1-\varepsilon_b(1+f_{cw})\}]C_e/U_{mf} = [(K_{ce})_b\varepsilon_b/U_{mf}]C_{cw} \quad (3)$$

Here, K is the reaction-rate constant based on unit volume of the emulsion and cloud-wake (dense) phases.

At Z=0 (bottom), the concentration is that of the incoming feed gas, i.e.

$$C_b = C_{cw} = C_e = C_0 \text{ at } Z = 0 \quad (4)$$

A. Estimation of Model Parameters

The mathematical equations for estimation of various hydrodynamic parameters in the model are presented in Table 1.

Various correlations can be found in literature for the estimation of bubble diameter in a fluidized bed. One of the widely used correlations was proposed by Mori and Wen [13], taking into account the effect of bed diameter and distributor type on bubble diameter, which is given below:

$$D_B = D_{Bm} – (D_{Bm} – D_{Bo}) \exp (-0.15/ D) \quad (5)$$

Where,

$$D_{Bm} = 1.6377[A (U –U_{mf})]^{0.4} \quad (6)$$

and

$$D_{Bo} = 0.8716 [A (U –U_{mf})/N_o]^{0.4} \quad (7)$$

Rowe and Patridge [14] studied the behaviour of bubbles in a fluid bed by using X-rays and found that the size of the wake (ratio of wake to bubble volume, f_w) averages one quarter of the total sphere volume and tends to increase as the particle size decreases. The value of f_w was taken to be 0.25. To estimate the size of the cloud f_c, the Davidson and Harrison [4] correlation is widely used, i.e.

$$f_c = 3 U_{mf} / (\varepsilon_b u_{br} – U_{mf}) \quad (8)$$

B. Mechanism of Combustion of Carbon

The rate of loss of mass of the particle is termed the burning rate (r′) and may be expressed in kgs^{-1}, gs^{-1} etc. The specific burning rate, S_c is the rate of mass loss per unit surface area and may be expressed in $kgs^{-1}\ m^{-2}$ etc. Thus, for a spherical particle

$$S_c = \frac{r'}{\pi d_c^{\,2}} \quad (9)$$

where r′ is the burning rate.

C. Mass Transfer Rate of Oxygen

The mass transfer rate of oxygen towards the surface may be characterized by the Sherwood Number, S_h given by,

$$S_h = \frac{k_g d_c}{D_g} \quad (10)$$

Where k_g is the mass transfer coefficient, d_c is the diameter of the char particle and D_g is the diffusivity of oxygen. The Sherwood number Sh is related to the carbon particle Reynolds number Re ($\rho_g U d_c/\mu$) and the Schmidt number S_c ($\mu_f/\rho_g D_g$) by correlations of the form,

$$Sh = 2(1+cRe^{1/2}Sc^{1/3}) \quad (11)$$

Table 1
Hydrodynamic parameters used in mathematical model

Parameter	Theoretical or empirical correlation	Reference
Minimum fluidization velocity	$\mathrm{Re}_{mf} = \frac{\rho_g U_{mf} D}{\mu_g} = \frac{Ar}{18+5.22\sqrt{Ar}}$	[18]
Gas viscosity	$\mu = 1.4(10^{-5})(T_b)^{1/2}$	[19]
Gas density	$\rho_g =353.2(10^{-3})/T_b$	[19]
Ratio of the cloud wake volume to the bubble volume	$f_{cw}=0.25+[3U_{mf}/(\varepsilon_{mf}u_{br}-U_{mf})]$	[4]
Gas velocity through the bubble face	$U_b =(U-U_{mf})/(1+f_{cw}\varepsilon_{mf})$	[20]
Gas velocity through the cloud wake phase	$U_{cw} = [(U-U_{mf})/(1+f_{cw}\varepsilon_{mf})] f_{cw}\varepsilon_{mf}$	[20]
Volume fraction of the bubble phase	$\varepsilon_b =U_b/U_{BA}$	[20]
Rise velocity of the cloud of the bubbles (u_b)	$U_{BA} =U-U_{mf}+u_{br}$	[4]
Rise velocity of an isolated bubble (u_{br})	$u_{br} = 0.711 \sqrt{gD_b}$	[4]
Gas interchange coefficients $(K_{bc})_b$and $(K_{ce})_b$	$(K_{bc})_b = 4.5(U_{mf}/D_b)+5.85(D_e^{0.5}g^{0.25}/D_b^{1.25})$ $(K_{ce})_b= 6.78(\varepsilon_{mf}D_bu_b/D_b^3)^{0.5}$	[8]

Where c lies between 0.3 and 0.35.

Alternatively, Chakraborty and Howard [15] suggested that the voidage ε be taken into account by including it in the expression to give,

$$Sh = 2\varepsilon + 0.69\, Re^{1/2} Sc^{1/3} \quad (12)$$

Thus, to increase the Sherwood number and hence, the mass transfer rate of oxygen, the particle Reynolds number must be increased; that means increasing the fluidizing velocity in a fluidized bed.

The specific burning rate S_c of the carbon corresponding to the mass flow rate of oxygen may be written as,

$$S_c = \lambda\, k_g (C_p - C_s) \quad (13)$$

where λ depends upon which particular oxidation reaction occurs at the surface. C_p is the oxygen concentration in the particulate phase of the bed (i.e., remote from the burning particle) and C_s is the oxygen concentration at the burning surface.

$$C + O_2 \Leftrightarrow CO_2 \quad (14)$$

for which $\lambda = 3/8$

D. Chemical Kinetic Rate

For a first-order reaction, the specific burning rate S_c may be expressed as,

$$S_c = k_c C_s \quad (15)$$

Where k_c is the reaction rate coefficient and C_s is the oxygen concentration at the carbon surface. The reaction rate coefficient k_c is normally expressed in an Arrhenius from,

$$k_c = A_C \exp(-E_A/RT_s) \quad (16)$$

Where A_C is a frequency factor, E_A is the activation energy of the carbon, R is an ideal gas characteristic constant and T_s is the absolute temperature of the carbon surface.

E. Combination of Mass Transfer and Chemical Kinetic Factors

The oxygen concentration at the char surface, C_s is not known directly. So, if it is eliminated between equations (13) and (15), the resulting expression for specific burning rate S_c becomes,

$$S_c = KC_p \quad (17)$$

Where,

$$1/K = 1/\lambda k_g + 1/k_c \quad (18)$$

If the mass transfer coefficient, k_g in equation (18) is replaced in terms of the Sherwood number.

$$Sh = (k_g d_c/D_g) \quad (19)$$

the equation (18) may be written as,

$$1/K = d_c / \lambda\, Sh\, D_g + 1/k_c \quad (20)$$

F. Solution Procedure

The model was solved numerically by making use of the Runge-Kutta fourth order technique. The average gas composition at the top of the bed is determined by using the following relations.

$$C_{avg} = (U_b C_b + U_{cw} C_{cw} + U_{mf} C_e)/ U_o \quad (21)$$

$$CO_2 = C_o - C_{avg}, \quad (22)$$

$$H_2O = [XH(1\text{-}XW)\, FR / 4\, U\, A] + [(XW)\, FR / 18U.A] \quad (23)$$

$$N_2 = (0.79/22400)(273/T_b) + [\{XN(1\text{-}XW)\}/28U.A] \quad (24)$$

Using the above equations the gas composition can be easily calculated. The consumption of oxygen (X) is given by,

$$X = 1\text{-}(C_{avg}/C_o) \quad (25)$$

$$\eta_c = \frac{FR \times XC - FC}{FR \times XC} \times 100 \quad (26)$$

Where FR is the feed rate of fuel, XC is the carbon weight percentage and FC is the flow rate of carry over stream from the combustor.

$$FC = \frac{K.C_{avg}.\pi d_c^{\,2}.MF.M_c}{\rho_c.V_p} \quad (27)$$

4. Results and Discussion

A three-phase mathematical model is developed to predict the performance of fluidized bed combustion of the selected biomass fuels. The model incorporates bubble size variation, oxygen concentration with bed height and corresponding combustion efficiencies for all the fuels. It is validated with the data obtained from a laboratory scale fluidized bed combustor.

Variations of oxygen concentrations in different phases and also variation of the average oxygen concentration along the bed height for rice husk fuel at fluidization velocity of 0.86 m/s are shown in Fig.1. The O_2 concentration in the bubble and cloud-wake phases, decrease marginally but it is steep in the emulsion phases at lower bed heights. As expected, the O_2 concentration is highest in the bubble phase followed by the cloud-wake and emulsion phases, because the main combustion reactions occur in the emulsion phase, as result of which O_2 consumption in this phase is greatest and the O_2 concentration is the lowest. In the cloud-wake phase, the oxygen consumption is due to combustion as well as transfer to the emulsion phase. However, the combustion reaction in the cloud-wake phase is slow when compared to that in the emulsion due to the presence of less particulate matter. The size of the bubble influences the oxygen concentration in different phases along the height of the bed. In laboratory type FBC having perforated distributors, the bubble growth was restricted by the combustor walls. The high oxygen concentrations in the bubble and cloud-wake phase are due to small bubble diameter. The variation of the average oxygen concentration with bed height is similar to that of the oxygen variation in the emulsion phase, indicating marginal influence of the bubble and cloud-wake phase oxygen concentration on the average oxygen concentration in the bed. Similar tendencies are observed with sawdust and groundnut shells.

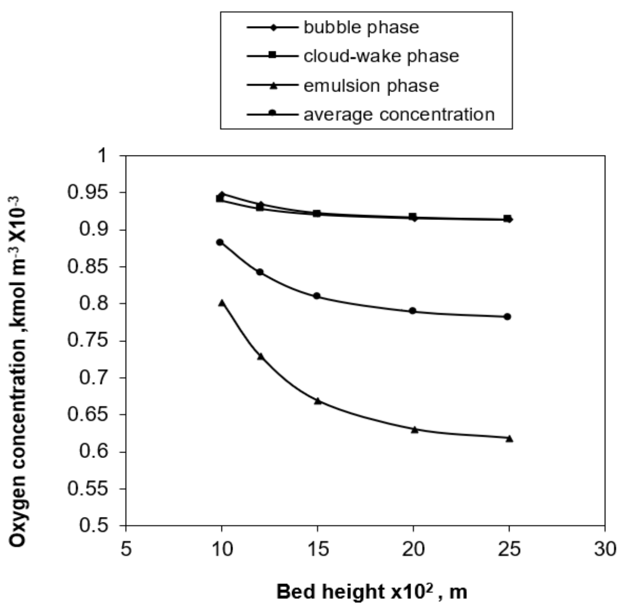

Fig. 1. Variation of oxygen concentration with bed height

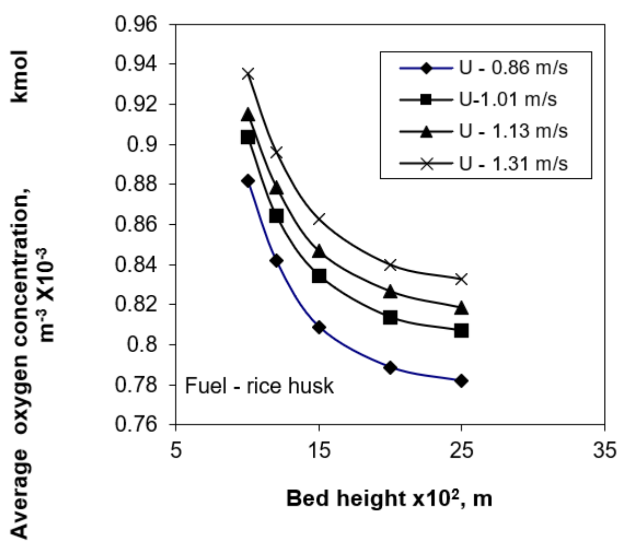

Fig. 2. Variation of average oxygen concentrations with bed height at different superficial velocities of air

Fig. 2 shows the average O_2 concentration as a function of bed height for different amounts of excess air for the same rice husk fuel. As expected, the model predicts the decrease of O_2 concentration as the bed height increases for all the excess air values. The O_2 concentration is higher at all bed levels for higher percentage of excess air. The rate of O_2 conversion with bed height in the lower levels is very fast. As the bed height increases, the rate of O_2 conversion decreases steadily.

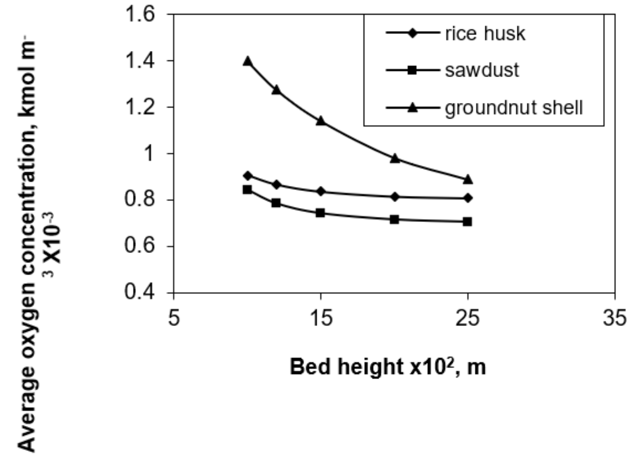

Fig. 3. Comparison of average oxygen concentration with bed height for three distinct fuels at air superficial velocity of 1.16 m/s

The average oxygen concentrations of rice husk, sawdust and groundnut shells along the bed height at a superficial gas velocity of 1.16 ms^{-1} are shown in Fig. 3. The average oxygen concentrations are continuously decreasing with increase in bed height for all the fuels. Among the fuels rice husk, sawdust and groundnut shells, oxygen concentration is high for the groundnut shells, and low for the sawdust at any bed height.

But the rate of oxygen conversion with groundnut shells is fast at the lower bed heights when compared with the other fuels. The variation in the oxygen concentrations for different fuels can be correlated with particle size. The high oxygen conversion for sawdust is due to small average particle diameter ($0.4x10^{-3}$ m against $2x10^{-3}$ m of rice husk and $8x10^{-3}$ m of groundnut shells) compared to other fuels. As the size of the particle is less more surface area is available for the same feed rate and more oxygen is likely to be consumed by the particle during the combustion process. The high rate of oxygen concentration at lower bed height for groundnut shells is due to larger particle size. Permchart and Kouprianov [16] used a conical fluidized bed combustor which consisted of two parts: (1) a conical section of 1 m height with a cone angle of 40^0 and (2) a cylindrical section of 0.9 m inner diameter and 2 m height. The biomass fuels (sawdust, rice husk and sugar cane bagasse) were used in the experimental tests and oxygen concentrations along the bed height were measured. The maximum rates of oxygen consumption were observed in the bed region for all the fuels and similar tendencies were observed in the model also.

Fig. 4 shows the variation of the exit gas concentrations, bubble diameter with excess air with rice husk fuel. From the Fig.4, as the percentage of excess air increases, CO_2 percentage in the flue gas decreases because the amount of combustibles available in the bed remains the same. At the same time the percentage of oxygen in the exit gas increases, leading to excessive loss of sensible heat in the flue gas. The percentages of CO_2 in the flue gas are compared with experimental values and are close to the model predictions. Fig.4 also shows the gradual increase of the bubble diameter with excess air. This is due to the fact that the superficial velocity and gas velocity increase as the percentage of excess air increases, leading to the gradual increase of the bubble diameter. The increase in bubble diameter causes a decrease in the gas interchange coefficients. Consequently, the O_2 conversion decreases at higher bed levels. Permchart and Kouprianov [16] measured the oxygen percentage at the top of the bed for different fuels, which was in the range of 6 to 7% against the predicted oxygen percentage in the range of 5 to 6% as shown in the Fig.4. Kouprianov and Permchart [17] studied the effects of operating conditions (load and excess air), as well as the fuel quality along the bed height and major gaseous emissions (CO_2, CO and NO_x) in a conical FBC firing mixed sawdust from different types of woods available in Thailand. The CO_2 emission profiles along the combustor height are found to be almost independent of the combustor load and fuel quality. The CO_2 concentrations gradually increased along the combustor height and at the top of the bed its value is found to be around 10%. In the model, predicted percentage of CO_2 is around 12-13% and closely follows experimental findings.

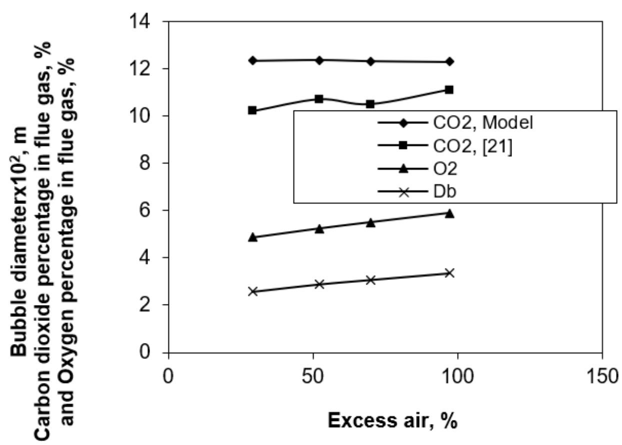

Fig. 4. Variation of bubble diameter, percentage CO_2 and O_2 with percentage of excess air

The combustion efficiencies are predicted from the model and are compared with the experimental values as shown in Fig. 5. The predicted combustion efficiencies of rice husk and groundnut shells are very close to the experimental values at all superficial velocities. With rice husk as fuel, the predicted values are in the range of 89 to 92% against the experimental value of 86 to 91%. But the predicted values are slightly higher than the experimental values. The deviation in the values may be due to the assumptions made in the model formulation. There is a remarkable difference in the combustion efficiency of experimental values and model calculations with sawdust as a fuel. The efficiencies are less in the model (85-89%) as against the experimental determinations (97 to 97.8%). As discussed, from the Fig.2 the oxygen concentration for saw dust is less compared to the other fuels and it is expected to give higher combustion efficiency due to more oxygen consumption. But the burning rate of fuel particle is a function of reaction rate constant and oxygen concentration. At the superficial velocity of 1.16 ms^{-1}, the reaction constant of sawdust is 23.6 against 13.4 for the rice husk and 5.41 for groundnut shells. To increase the burnout time of char particle high amount of oxygen must be supplied along the bed height. To increase the availability of oxygen, the bed is to be fluidized at lower superficial velocity of air. As the size of the sawdust particle is less, the entrainment of the particle from the bed increase with increase in superficial velocity of air. Therefore, low combustion efficiencies result in the case of sawdust. The higher experimental combustion efficiencies of sawdust may be due to the additional combustion of smaller particles in the freeboard zone. In contrast, in the case of groundnut shells higher combustion efficiencies are achieved due to larger particle size with less elutriation of fines.

The error band between the model and experimental results of combustion efficiencies are 2.19%-4.65% for rice husk, 8.25%-12.37% for sawdust and less than 1% in case of groundnut shells.

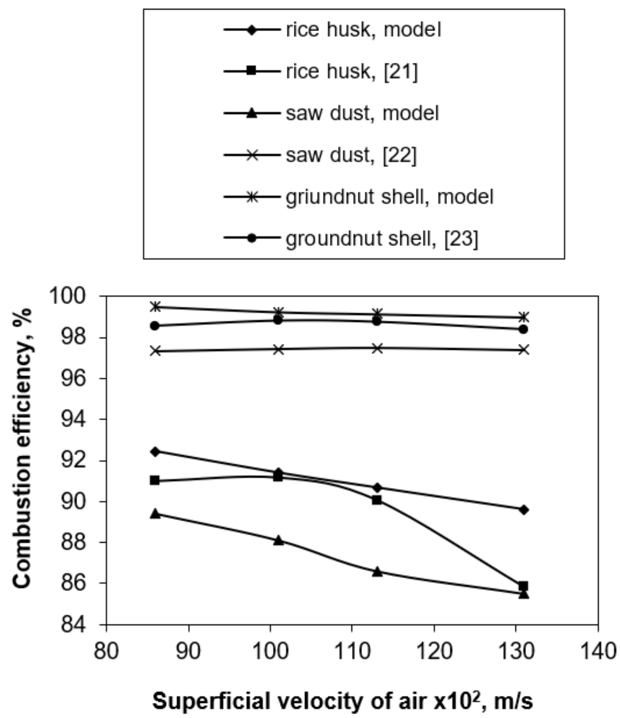

Fig. 5. Comparison of combustion efficiencies of model with experimental data for three distinct biomass fuels

5. Conclusion

- A three-phase mathematical model is developed to predict the performance of fluidized bed combustion of the selected biomass fuels with reasonable accuracy.
- Oxygen concentrations in the bubble, cloud-wake and emulsion phases decrease with bed height.
- The variation of the average oxygen concentration with bed height is similar to that of the oxygen variation in the emulsion phase, indicating marginal influence of the bubble and cloud-wake phase oxygen concentration on the average oxygen concentration in the bed.
- The predicted combustion efficiencies of rice husk and

groundnut shells are very close to the experimental values at all superficial velocities. With rice husk as fuel, the predicted values are in the range of 89 to 92% against the experimental value of 86 to 91%. There is a difference of 10 to 12 % in the combustion efficiency of experimental values and the model with sawdust as a fuel.

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Nomenclature

A	bed cross sectional area, m^2
A_C	frequency factor in Arrhenius equation
C_{avg}	average gas concentration of reactant at height Z, kmol m^{-3}
C_b	gas concentration of reactant at height Z of the bubble phase, kmol m^{-3}
C_{cw}	gas concentration of reactant at height Z of the cloud-wake phase, kmol m^{-3}
C_e	gas concentration of reactant at height Z of the emulsion phase, kmol m^{-3}
C_o	initial gas concentration of reactant, kmol m^{-3}
C_p	oxygen concentration in dense phase, kmol m^{-3}
C_s	oxygen concentration at surface, kmol m^{-3}
D	bed diameter, m
D_B	bubble diameter, m
D_{Bm}	maximum bubble diameter, m
D_{Bo}	initial bubble diameter, m
d_c	char particle size, m
D_g	diffusivity of oxygen, m^2s^{-1}
dZ	differential height, m
E_A	Reaction activation energy, MJ kg^{-1} mol^{-1}
f_c	size of cloud, m
FC	the flow rate of carry over stream from the combustor, kgs^{-1}
f_{cw}	fraction of cloud-wake phase in the bed
FR	the feed rate of fuel, kgs^{-1}
K	reaction rate constant based on unit volume of the dense phase, s^{-1}
K_{bc}	volumetric rate of gas exchange between the bubble and cloud-wake phases, s^{-1}
k_c	reaction rate coefficient, ms^{-1}
K_c	volumetric rate of gas exchange between the cloud-wake and emulsion phases, s^{-1}
k_g	mass transfer coefficient, ms^{-1}
M_c	molecular weight of carbon
MF	mass of fuel, kg
N_o	number of holes per unit surface area of distributor
R	gas constant, J $mol^{-1}K^{-1}$
r'	burning rate, kgs^{-1}
Re	Reynolds number
Sc	Schmidt number
S_c	specific burning rate, kg s^{-1} m^{-2}
Sh	Sherwood number
T_b	bed Temperature, K
T_s	surface Temperature, K
U	superficial velocity of air, ms^{-1}
U_b	superficial gas velocity of bubble phase, ms^{-1}
U_{cw}	superficial gas velocity of the cloud-wake phase, ms^{-1}
U_{mf}	minimum fluidization velocity, ms^{-1}
U_o	orifie gas velocity, ms^{-1}
V_p	volume of fuel particle, m^3
X	fractional conversion of reactant gas leaving the bed
XC	carbon, weight (%)
XH	ultimate hydrogen, weight (%)
XN	nitrogen of the feed, weight (%)
XW	ultimate moisture, weight (%)

Greek letters

ε	bed voidage
ε_b	volume fraction of bubbles
ε_{mf}	bed voidage at minimum fluidization
μ	gas viscosity, N s m^{-2}
ρ_c	char density, kg m^{-3}
ρ_g	fluid or gas density, kg m^{-3}
η_c	combustion efficiency

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