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NUMERICAL STUDY OF BIOMASS CO-COMBUSTION WITH CONSIDERATION OF DISTINCT CHARACTERISTICS OF THE FUEL CONSTITUENTS

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ABSTRACT

To address the difficulty and drawbacks of low-quality biomass such as municipal solid waste (MSW) combustion in grate boilers, co-combustion is proposed. In order to investigate how the distinction in the physical and chemical property of the fuels influences the combustion characteristics, a fuel bed model is developed with separate consideration for each fuel constituents. In this model, the kinetic parameters of chemical reactions are determined independently from single fuel combustion and applied in co-combustion simulations. It is found that the participating fuels demonstrate differences in their consumption rate and reaction peak during co-combustion. Moreover, the combustion can be improved obviously by blending in 30% of higher rank fuel.

Keywords: renewable energy, co-combustion, biomass combustion, numerical simulation, modeling, mixed fuel

NOMENCLATURE

Abbreviations	
ar	As received
db	Dry basis
HHV	Higher heating value
Symbols	
X_M	Mass fraction of constituent M
M	Solid fuel constituent M in the blend

1. INTRODUCTION

Biomass is used extensively and globally for heating, steam production, and power generation, due to its carbon neutral characteristics and good renewability. For industrial applications, this type of fuel is usually packed and combusted on the grate without complicated pre-treatment. Moreover, grate combustion is also a straightforward and common treatment method for wastes such as municipal solid wastes (MSW) and sewage sludge. However, these waste-derived low-quality fuels usually have relatively high ash and moisture content, which results in both ignition difficulty, combustion disruption and incomplete burnout. Therefore, mixing and co-combustion with higher quality fuel are applied to make better use of the fuel and leverage the fuel cost for energy production at the same time. Among the various technologies, direct co-combustion through premixing and co-feeding is easier to apply and economical.

The numerical model can effectively predict the behavior of new technologies. Different considerations for solid in the fuel bed classify the models into continuous models and discrete element models. The continuum model offers more computation efficiency for large scale application. Based on the continuum solids assumption, Gu et al. conducted parametric studies MSW combustion in packed bed [1]. In addition, experiments on co-combustion prove its viability in improving the combustion for low rank fuels, and some

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synergistic effects are also witnessed. Gil et al. found that during biomass and coal co-combustion, each fuel has its own individual conversion stages taking place in different temperature ranges and combine to be the macroscopic processes [2]. Moreover, Meng et al. also found a reduction in NO_X emission when corn is co-combusted with pine wood [3]. On the other hand, Xu et al. proved the feasibility of municipal solid waste co-incineration with the sludge up to 67% moisture for treatment purposes [4]. Yang et al. investigated the effect of moisture content and devolatilization rate on woodchip and MSW combustion through simulating blended fuel combustions[5].

The current continuum fuel bed model for packed combustion accounts for co-combustion as premixed to be one type of fuel, which neglected the individuality of the participating fuel. This simplification will impose limitations when the fuels are of different chemical or physical properties or when there is synergistic interaction between the two fuels. Therefore, the aim of this study is to develop a model that treats the two fuels as individual participating components during direct co-combustion. Each fuel is described by its own physical properties and the thermal conversion processes are captured by its individual sets of kinetic parameters. Furthermore, the effect of different mixing ratio and fuel interaction will be investigated in future studies.

2. METHODOLOGY

2.1 The model for fuel mixture constituents

The one-dimensional conservation equations describing the materials are shown in *Table 1*. To model the constituent independently, one set of conservational equations represented by equation (5-7) is solved for each fuel. The characteristics of the heterogeneous reactions for each constituent fuel M are determined independently, including the chemical balance and kinetic parameters for volatile pyrolysis and char oxidation. To do this, each fuel used is validated individually against experimental results from single fuel combustion. During the simulation of the co-combustion, all these parameters including the physical properties and compositions are incorporated separately for the description of each constituent M, as shown in equation (9-11). In addition, the bed shrinkage is defined for the mixed fuel packing and summation of the overall conversion behavior is used to interact with the gas phase as given in equation (1-4).

The fuel bed model integrates with the fuel scale CFD model for the furnace to simulate the entire grate boiler. Additional information about the parameters used and the development of the model can be found in reference [6].

Table 1 Fuel bed model equations

equations and descriptions	no.
Gas phase balance equations	
$\frac{\partial(\rho_g \varepsilon)}{\partial t} + \frac{\partial(\rho_g \varepsilon v_g)}{\partial y} = \sum S_{sg,M}$	1
$\frac{\partial(\rho_g \varepsilon v_g)}{\partial t} + \frac{\partial(\rho_g \varepsilon v_g v_g)}{\partial y} = -\frac{\partial p}{\partial y} + F$	2
$\frac{\partial(\rho_g \varepsilon h_g)}{\partial t} + \frac{\partial(\rho_g \varepsilon v_g h_g)}{\partial y} = \frac{\partial}{\partial y}\left((k_g + k_{g,t})\frac{\partial T_g}{\partial y}\right) + (S_p)_{mix} h_{sg}(T_s - T_g) + Q_g$	3
$\frac{\partial(\rho_g \varepsilon Y_i)}{\partial t} + \frac{\partial(\rho_g \varepsilon v_g Y_i)}{\partial y} = \frac{\partial}{\partial y}\left((D_{i,g} + D_{g,t})\frac{\partial(\rho_g \varepsilon Y_i)}{\partial y}\right) + S_{i,g}$	4
Solid conservation equations for fuel constituent M	
$\frac{\partial(\rho_{s,M} X_M (1-\varepsilon))}{\partial t} + \frac{\partial(\rho_{s,M} X_M (1-\varepsilon) v_s)}{\partial y} = -S_{sg,M}$	5
$\frac{\partial(\rho_{s,M} X_M (1-\varepsilon) h_s)}{\partial t} + \frac{\partial(\rho_{s,M} X_M (1-\varepsilon) v_s h_s)}{\partial y} = \frac{\partial}{\partial y}\left(\lambda_s \frac{\partial T_s}{\partial y}\right) + Q_{rad}(y) + (S_p)_M h_{sg}(T_g - T_s) + Q_{s,M}$	6
$\frac{\partial(\rho_{s,M} X_M (1-\varepsilon) Y_{i-M,s})}{\partial t} + \frac{\partial(\rho_{s,M} X_M (1-\varepsilon) v_s Y_{i-M,s})}{\partial y} = S_{j-M,s}$	7
Blend fuel shrinkage velocity	
$v_s = a_1 \frac{\sum R'_{evp,M}}{\rho_2 \omega_{2A}(1-\varepsilon_A)}(1-V_{B,A}) + a_2 \frac{\sum R'_{pyr,M}}{\rho_3 \omega_{3B}(1-\varepsilon_B)}(1-V_{C,B}) + a_3 \frac{\sum R'_{char,M}}{\rho_4 \omega_{4C}(1-\varepsilon_C)}(1-V_{D,C})$	8
Heterogeneous reactions	
$H_2O(l) \rightarrow H_2O(g)$ $S_{m,M} = (S_p)_M m_{m,M} \begin{cases} h_m(Y_{m,s} - Y_{m,g}) & , T_s < 373K \\ (h_{sg}(T_g - T_s) + \varepsilon\sigma(T_g^4 - T_s^4)), & T_s > 373K \end{cases}$	9
$(VM_{pseudo})_M \xrightarrow{pyr,M} \sum \beta_{i,M} \cdot (\text{species-i})$ $S_{pyr,M} = A_{pyr,M} \exp(-E/RT_s) m_{VM,M}$	10
$\varphi C + O_2 \rightarrow 2(\varphi - 1)CO_2 + (2-\varphi)CO$ $S_{char,M} = -(A_p)_M P_{O_2}(1/k_{d,M} + 1/k_{r,M}) m_{char,M}$ $k_{r,M} = A \exp(-E/RT_s)$	11

2.2 Fuel validation and mixing

For the co-combustion study, the fuels are blended on an energy basis, with a constant energy input of 32MJ/s. Two sample fuels are used to represent lower quality fuel with high ash content, lower heating value and vice versa. The properties of the fuel used for co-combustion is given in *Table 2*. The ash content for the lower quality fuel is more than 30%.

The fuel bed model results are inputted into the freeboard model as boundary conditions. The simulation results are validated against the measured temperature from thermal couples T1-T9 mounted along the flue gas flow path, the results are shown in *Fig. 1*, a good agreement between the simulation results and experimental results has been achieved, which indicate that the model is accurate.

Table 2 Fuel properties

Proximate Analysis (wt%, ar)			Ultimate Analysis (wt%, db)		
ash content	Low	High		Low	High
HHV (MJ/kg)	14.13	6.2	C	42.32	16.67
moisture	21.89	20.44	H	4.99	2.29
volatile	55.00	31.8	O	40.33	17.02
char	17.97	9.08	N	1.22	1.05
ash	5.14	38.68	S	0.28	1.22

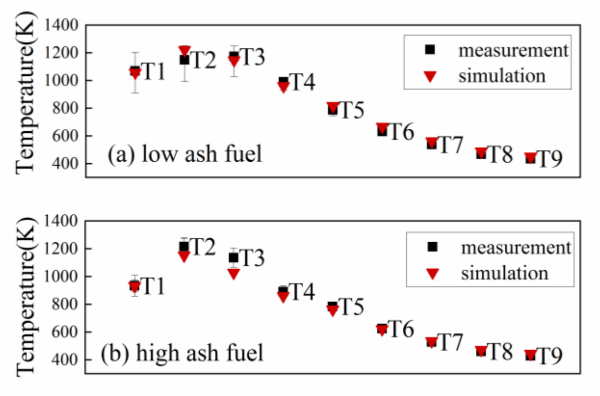

Fig. 1 Temperature validation along the flow path

3. RESULTS AND DISCUSSION

3.1 Single fuel combustion characteristics

The thermal conversion characteristics of single fuel combustion are analyzed first. *Fig. 2* shows the fuel carbon content evolution during combustion along the grate. The carbon content in the high ash fuel depletes very quickly and left with limited reactive content to maintain stable gas emission into the freeboard, and the complete reaction of the high ash fuel is earlier than low-ash fuel. This gas release characteristics also result in a low combustion temperature in the bottom mixing zone as shown in T1 in *Fig. 1*, which may cause insufficient radiation for fuel ignition.

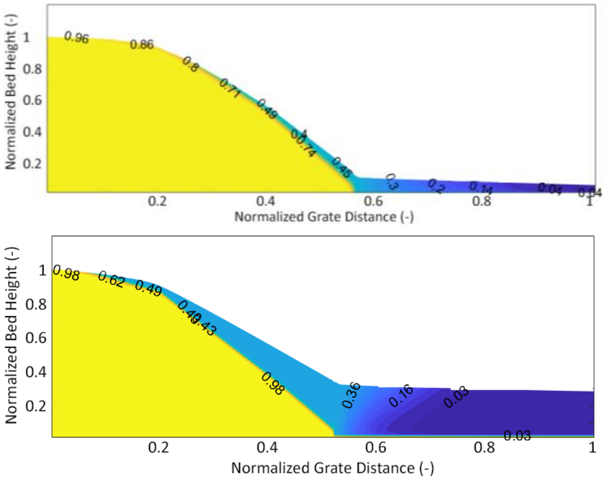

Fig. 2 Fuel consumption and carbon content distribution in the fuel bed, (a) low ash fuel; (b) high ash fuel

Moreover, the temperature profile in *Fig. 3* demonstrates that the overall combustion temperature is low for high ash fuel, and the combustion zone is narrow. This will not only cause combustion instability but also inefficient heat transfer in the boiler. Therefore, the objective of co-combustion with lower quality fuel aims at improving stable combustion and enhance heat exchange at the same time to maximize energy utilization.

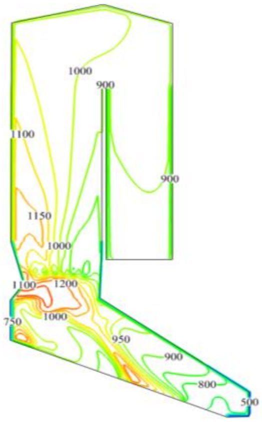

Fig. 3 The freeboard temperature profile of high ash fuel

3.2 Co-combustion

After fixing the individual reaction kinetics, the two fuels are blended and combusted together with a 1:1 energy ratio. Because of the difference in their heating value, the initial mass fraction of the high ash fuel is 70%. The decrease of the mass fraction of the two fuels is not concurrent, which is a result of the distinctive reaction rates as shown in *Fig. 4*. Moreover, the total fuel consumption rate is more prolonged for low ash fuel. The high ash fuel starts with a peak in devolatilization rate and has an overall higher consumption rate because of the high initial mass fraction. Furtherly, after the oxidation of the high ash fuel is nearly completed towards the end of zone4, the low ash fuel char oxidation rate exhibits a small peak which is beneficial for the overall fuel burnout.

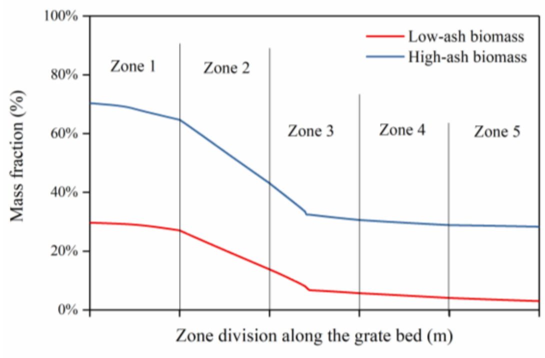

Fig. 4(a) Fuel mass fraction change during co-combustion

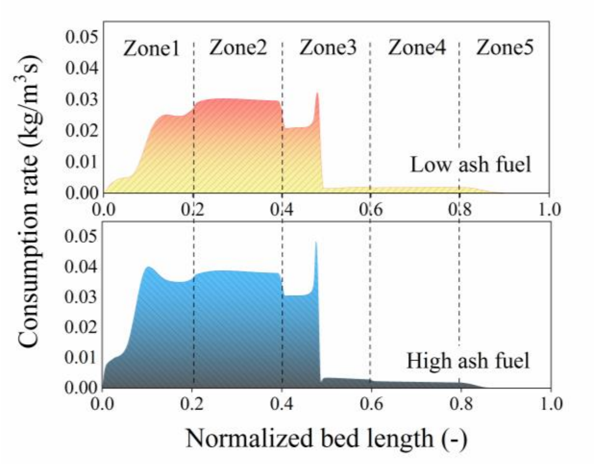

Fig. 4(b) Individual fuel consumption rate during co-combustion

Fig. 4(c) Freeboard temperature for mixed fuel

4. CONCLUSIONS

In this study, the co-combustion of low-quality fuel with high ash content to improve its combustion behavior was investigated. To account for the difference in the participating fuel during co-combustion the continuous fuel bed model was modified and extended. While modeling the co-combustion on the grate, each fuel's particulars and specific kinetics was implemented their own conservation equations as part of the bed model. As a result, the advanced fuel bed model successfully reproduced the difference in the conversion process of individual fuel during co-combustion. The simulation result also shows evident improvement in combustion stability and temperature. Moreover, the extended model also enables the future application to simulate inter-fuel reaction and potentially synergistic effect during blende co-combustions.

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