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MODELING OF BIOMASS COMBUSTION IN THE PACKED BED USING CFD-DEM

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ABSTRACT

The combustion characteristics of biomass in the packed bed is investigated based on the CFD-discrete element method (DEM). During the combustion process, the biomass particle experienced drying, pyrolysis, combustion and cooling. The mass loss leads to the change of particle density and diameter, as the remnant composition is mainly ash. In this work, the shrinkage of packed biomass volume is modelled as the particle diameter is decreased based on DEM. The different effects of compositions in the particle on particle diameter are considered. The simulation results show good agreement with the experimental measurement.

Keywords: biomass combustion, DEM, packed bed, simulation

NONMENCLATURE

Abbreviations	
DEM	Discrete element method
VM	Volatile matter
Symbols	
m_p	Particle mass (kg)
$\boldsymbol{F}$	Force of each particle
$\boldsymbol{v}$	Velocity of particle (m/s)
c	Specific heat (J/kg/K)
T	Temperature (K)
d_p	Particle diameter(m)
V	Particle volume
ρ	Density (kg/m^3)

1. INTRODUCTION

As the renewable and environmentally friendly alternative fuel, biomass is seen as the representative of the fossil fuel. Grate-firing technology for biomass as fuel can has the wide applicability. However, the diversity of biomass compositions has the great influence on the combustion performance and emission.

Razmjoo et al measured the gas species and temperature in the industrial grate boiler, and the result showed the spatial distribution to know the grate-firing process. The key to improve the boiler efficiency is to understand the conversion process of biomass in the grate bed [1]. However, the detailed conversion characteristic of biomass block in the grate bed is hard to be observed for commercial grate boiler due to the harsh operation conditions. Therefore, researchers always investigated the biomass combustion in the packed bed instead. Based on these data from various experiments, different numerical models were developed to predict the conversion and emission of biomass as fuel [2]. Based on the self-developed code, Yang et al investigate how different operation conditions including air flow, heat value of fuel, properties of biomass particle, etc. influence the ignition of biomass [3]. Based on the same assumption, Collazo et al. conducted the three-dimensional simulation of biomass combustion under fixed-bed condition [4]. Zhou et al also developed the different model and applied it to predict the combustion of biomass in an industrial grate boiler [5].

Different from these models, the discrete element method (DEM) was used by Masmoudi et al to model the biomass combustion[6]. Constructing the cylinder particle to represent the biomass particle, Wiese et al. model the fuel conversion of wood pellet [7]. The volume shrinkage of packed biomass fuel can be directly simulated based on the DEM. In this work, the DEM is coupled with CFD to model the combustion of biomass in the packed bed, taking the simultaneous change of particle diameter and density.

2. METHODOLOGY

2.1 Discrete element method

2.1.1 Model of particle

In this method, the motion of particle is modeled in the Lagrangian coordinate. Based on the newton's second law, the momentum equation is as:

$$d\left(m_p \boldsymbol{v}_p\right)\big/dt = \boldsymbol{F}_g + \boldsymbol{F}_c + m_p \boldsymbol{g} \tag{1}$$

During the combustion process, the particle is firstly dried under the radiation condition, then the pyrolysis is released, and char is oxidized. The remaining composition is ash. Therefore, the mass conservation of particle is expressed as:

$$\frac{dm_p}{dt} = \frac{dm_{drying}}{dt} + \frac{dm_{pyrolysis}}{dt} + \frac{dm_{char}}{dt} \tag{2}$$

The temperature of particle is calculated as:

$$\frac{d\left(m_p c_p T_p\right)}{dt} = hA_p\left(T_p - T_g\right) + \sum_{j=1}^{n} q_{c,ij} \\ \sum_i r_i \Delta h_i + \sum_{j=1}^{NP} \varepsilon\sigma F_{ij}\left(T_j^4 - T_i^4\right) \tag{3}$$

The terms at the right hand express as heat convection, heat conduction between packed particles, heat from chemical reaction and the radiation from local atmosphere. In this model, the parcel is assumed to be homogeneous. The heat conduction between each particles has great important on the heat transfer in the dense packed bed. Also, the thermal radiation between packed particle is defined in the form of conductivity [8].

$$\lambda_r = 4\sigma d_p T_p^3 \tag{4}$$

2.1.2 Chemical reactions

The drying only happens as the particle temperature is higher than 373K. After drying, the volatile matter is released. The production is assumed as the gas mixture including: CH_4, H_2, CO, CO_2, $C_xH_yO_z$, H_2O. The expression of $C_xH_yO_z$ is determined by the ultimate analysis of fuel shown in Table 1. Then the char is oxidized into CO and CO_2, and the volume ratio of two gas species are related to the local temperature and oxygen concentration. The char oxidization rate is determined by the overall effect of gas diffusion and char kinetic rates. The chemical reactions are listed as follows:

$$\text{Biomass} \rightarrow \text{VM+Char+H2O(g)+Ash} \tag{5}$$

$$\text{VM} \rightarrow \text{CH}_4\text{+H}_2\text{+CO+CO}_2\text{+C}_x\text{H}_y\text{O}_z \tag{6}$$

$$(2\text{+}2\alpha)\text{char(C)+}(1\text{+}2\alpha)\text{O}_2 \rightarrow 2\text{CO+}2\alpha\text{CO}_2 \tag{7}$$

$$\text{CO+0.5O}_2 \rightarrow \text{CO}_2 \tag{8}$$

$$\text{H}_2\text{+0.5O}_2 \rightarrow \text{H}_2\text{O} \tag{9}$$

$$\text{CH}_4\text{+O}_2 \rightarrow \text{H}_2\text{O+CO} \tag{10}$$

$$\text{C}_x\text{H}_y\text{O}_z\text{+O}_2 \rightarrow \text{CO+H}_2\text{O} \tag{11}$$

The detailed information of kinetics for these reactions can be referred to our previous work [5].

2.1.3 Shrinkage of particle

During combustion process, the volume of packed biomass fuel shrinks with the mass loss. The shrinkage plays important role in the overall combustion process, as the effective height of the bed is decreased. The effective density of a particle in this work is determined by the compositions as:

$$\rho_p = \sum \rho_i f_i \tag{12}$$

Where the f_i is the mass fraction. The effective density changes with the mass fraction and becomes ash density at last. However, the bulk density of char particle is introduced to replace the ash density in this model. The effective volume of a particle also concerns the combustion process. The influence of moisture drying on volume of particle was unapparent. Referring to the model from Gerber et al. [9], the author assume that the volume is about one-third of the original particle dimension after volatile matter released. The volume is expressed as:

$$V_p = \frac{m_w}{m_{w,0}} V_{p,w_0} + \frac{1}{3}\left(1 - \frac{m_w}{m_{w,0}}\right) V_{p,w_0} \tag{13}$$

For the char particle including fixed carbon and ash, the density is assumed to be constant, but the diameter is decreased because of the mass transferred to the gas phase.

2.2 Model of gas phase

The mass, momentum and energy governing equations are used to model the gas phase [5]. As the particle is modeled by the DEM. The average temperature and diameter of particles in a cell are calculated to model the gas-particle interaction in these equations.

2.3 Introduction of experiment

The experiment about biomass combustion in the fixed-bed reactor was reported in Yang et al. work [10]. The inner diameter of the reactor is 0.2m with the height of 1.5m. The fuel is complex of potato and cardboard.

The initial packed mass of biomass is about 2.02kg. The primary air flow keeps 1.3 kg/m^2s. Table 1 shows the properties of biomass. The fuel is assumed to be a spherical particle with diameter being 2cm.

Table 1 Properties of biomass particle

Proximate analysis (wt%)		Ultimate analysis (wt%)		Physical Properties
Moisture	31.2	C	30.2	Bulk density
Ash	3.6	H	3.5	350 (kg/m3)
VM	56.4	O	31.5	Diameter
FC	12.7			2 (cm)

3. RESULTS AND DISCUSSION.

3.1 Model validation

Compared to the measurements, the model is firstly validated. Fig.1 shows the experimental and calculated results. The calculated result shows the good agreement. The heat is radiated from top flame and is absorbed by the top packed biomass particles. When their temperatures are elevated about 373K, the moisture begins to transfer to the gas phase. After that, the combusting gas species are released from the pyrolysis. Under the oxygen atmosphere, the combustion occurs and generates lots of heat. The O_2 is consumed obviously while CO_2 is produced rapidly. After the volatile matter released, the char is oxidized to CO and CO_2.

Compared to the simulation results based on pseudo continuum method [3-5], the DEM model provides the fluctuation in the result. This is probably because the heat transfer between particles is affected by the particle dimension. As shown in Fig.2, the particles at the top bed own different temperature. This cause the different rates of volatile release and combustion. At the same time, the smaller particles is not comprised of volatile matter, and its volume is less than one-third of the cold particles.

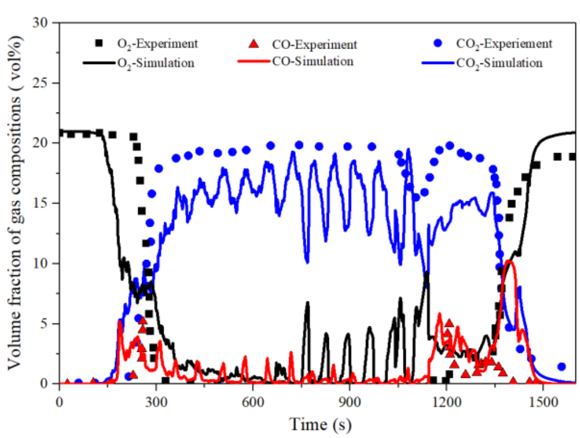

Fig.1 Comparison the calculated results with the experimental data.

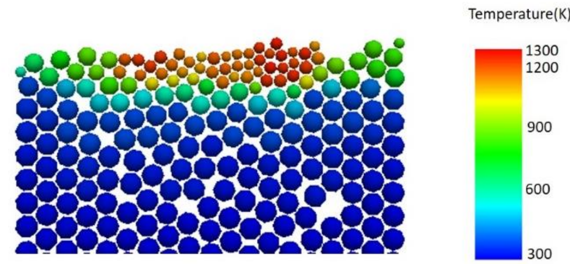

Fig. 2 Temperature distribution of packed particles.

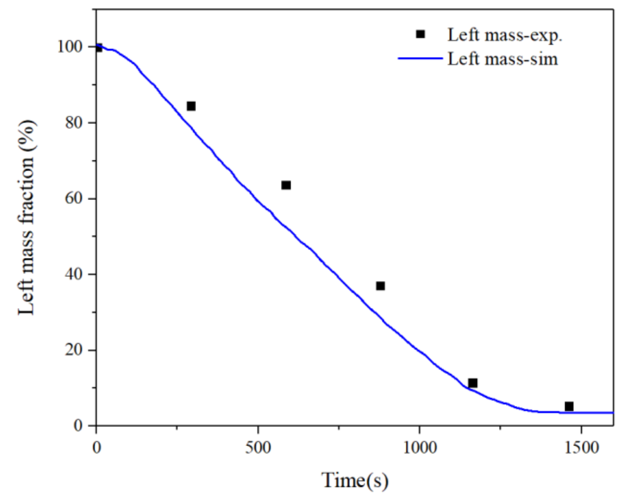

Fig. 3 Comparison the simulated to experimental left mass fraction in the packed bed

Fig.3 shows the mass left in the packed bed during the combustion process. The consumption rate is higher at the beginning of the combustion than the rate measured in the experiment, but the simulated rate becomes slowly and close to the measured.

3.2 Distribution of gas species

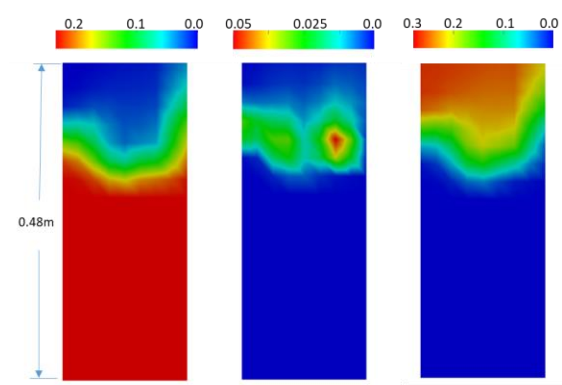

Fig 4(a) Distribution of mass fraction for gas species at 350s

Fig.4 shows the distribution of gas species including O_2, CO and CO_2 at two times. At 350s, the top fuel has been combusted, and the O_2 is exhausted. The CO is mainly produced from pyrolysis and incomplete oxidation of combustible gas as shown in section 2.1.2. Under the enough O_2 supply, the CO is converted into CO_2 quickly. The reactor is almost full of CO_2 with at 850s. As the wall temperature is assumed to be 300K, the fuel near the wall is harder to combust than that in the middle. This influences the distribution of gas species.

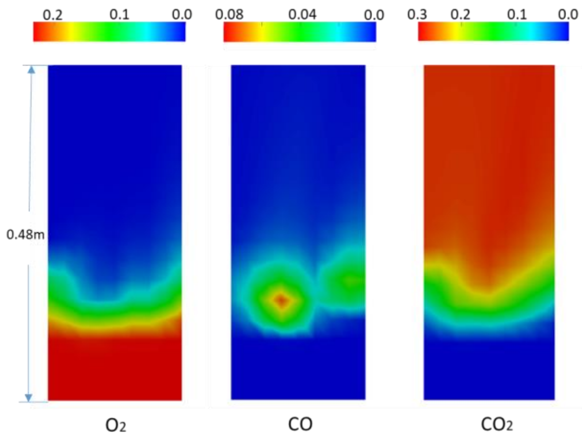

Fig 4(b) Distribution of mass fraction for gas species at 850s

3.3 Porosity of fuel bed

The bed height can be expressed in the formation of porosity of fuel bed. Taking the porosity of particle into consideration, the bulk density of a particle only comprised of fixed carbon and ash is about 107kg/m3. While the real density of char particle in this work is assumed to be 1800kg/m3. This have great influence on the porosity of fuel bed. As shown in Fig.5, if the real density of char particle is used in the model, the bed height would be much lower.

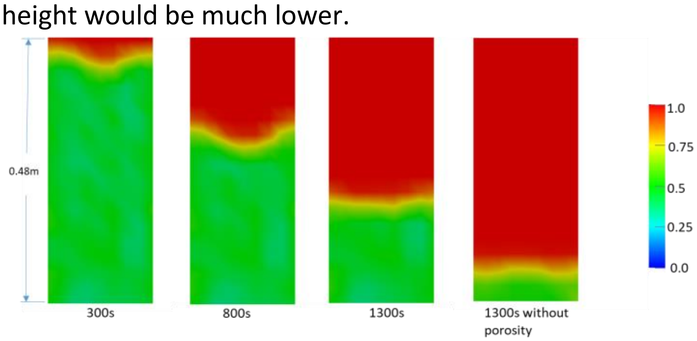

Fig. 5 Porosity contours in the fuel bed at three times

4. CONCLUSIONS

The CFD-DEM method is used to simulate the combustion process of biomass in the packed bed. The diameter and density of the particle change with the mass transfer from fuel to gas. The bulk density and volume model are used for the shrinkage of fuel bed. The model is validated by the experimental data in current work, and more simulations about the effects of operation conditions will be done and discussed in the following work.

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