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Combustion modelling of pulverized biomass particles at high temperatures

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Abstract

Biomass co-firing is becoming a promising solution to reduce CO₂ emissions, due to its renewability and carbon neutrality. Biomass normally has high moisture and volatile contents, complicating its combustion behaviour, which is significantly different from that of coal. A computational fluid dynamics (CFD) combustion model of a single biomass particle is developed in this work, to predict the mass loss properties and temperature profile during the biomass devolatilization and combustion processes, by solving the energy and mass transport equations. The biomass devolatilization reaction was simulated by a two-competing-rate model and the biomass char burnout rate was controlled by both kinetics and diffusion to predict the particle size changes. The resulting predicted temperature profiles show good agreement with experimental data. The results also shed light on the effects of biomass particle size, air temperature and oxygen concentrations on biomass particle combustion behaviour.

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1. Introduction

Biomass is a sustainable fuel that can deliver a significant reduction in net carbon emissions when compared with fossil fuels, and additional environmental and social benefits could also be expected [1]. However, the combustion properties of biomass are significantly different from those of coals, due to high volatile contents and low energy densities. Understanding the single particle combustion mechanism is a first step in understanding biomass combustion and possible co-firing with coals.

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| | |
|------------------|---|
| C_{SW} | Swelling factor |
| D | Diffusion coefficient of vapor in the bulk (m^2/s) |
| dp | Particle diameter (m) |
| f_h | The fraction of the heat that particle absorbs from surface reaction |
| $f_{v,0}$ | The fraction of volatiles in the particle |
| $f_{w,0}$ | The fraction of moisture in the particle |
| k_i | Intrinsic reaction rate coefficient, $i=1, 2$, ($kg/m^2\text{-Pa}\cdot s$) |
| m_F | Mass fraction of combustible species |
| m_O | Mass fraction of oxygen |
| m_p | Particle mass (kg) |
| $m_{p,0}$ | Initial particle mass of particle (kg) |
| $m_v(t)$ | Volatile yield up to time (kg) |
| n | Apparent reaction order |
| $P_{O_2,\infty}$ | Oxygen partial pressure (Pa) |
| S_p | External surface area of the particle (m^2) |
| α_1 | Volatile yield factor at low temperatures |
| α_2 | Volatile yield factor at high temperatures |

Most previous models [2-5] for single biomass particle combustion qualitatively described the two basic stages of biomass combustion: devolatilization and char oxidation. However, there is a clear lack of a suitable biomass combustion model that considers fully the change of particle size during both devolatilization and char oxidation processes, as well as the model feasibility to representing more faithfully true boiler furnace conditions, in which biomass particles are heated up to high temperatures very rapidly.

This paper investigates biomass combustion behavior at a high heating rate, using high temperatures that are similar to the conditions expected in a real furnace. A computational fluid dynamics (CFD) combustion model of a single biomass particle is developed in this work, to predict the mass loss properties and temperature profile during the biomass devolatilization and combustion processes, by solving the energy and mass transport equations. Biomass devolatilization reaction was simulated by a two-competing-rate model that considers the swelling properties of a biomass particle during its devolatilization process, and ultimately, the biomass char burnout rate as controlled by both kinetics and diffusion, is simulated with an empirical method that predicts particle size change.

2. Method

2.1 Devolatilization

The amount of high temperature volatile matter (HTVM) yielded over and above the amount of standard volatile matter is revealed by the proximate analysis. The predicted yield of volatile matter as a function of temperature is thus important for practical combustion models. The two-competing-rates model was employed in two steps to simulate devolatilization and then predict the high temperature volatile matter yield [6]. In this model, the first reaction (A_1 , E_1 , and α_1) is used to calculate the devolatilization rate at lower temperatures, while the second reaction (A_2 , E_2 , and α_2) plays a dominant role at higher temperatures. The two kinetic rates are weighted to yield an expression of weight loss during the devolatilization process:

$$\frac{m_v(t)}{m_{p,0}} = \int_0^t (\alpha_1 k_1 + \alpha_2 k_2) \exp(-\int_0^t (k_1 + k_2) dt) dt \quad \text{Eq.(1)}$$

where $m_v(t)$ is the volatile yield over time, and $m_{p,0}$ is the initial particle mass at injection. The kinetic rates are expressed in Arrhenius form.

2.2 Swelling coefficient

The drag force is a function of the particle diameter (d_p). The diameter of a particle may change significantly during devolatilization based on its swelling coefficient. The particle diameter can be calculated according to its swelling property:

$$\frac{d_p(t)}{d_{p,0}} = 1 + (C_{sw} - 1) \frac{(1-f_{\omega,0})m_{p,0} - m_p}{f_{v,0}(1-f_{\omega,0})m_{p,0}} \quad \text{Eq.(2)}$$

where, the second term in the right hand side is the ratio of the mass that has been devolatilized to the total volatile mass of the particle. The effect of swelling on the drag force during biomass devolatilization should be taken into account, due to the significant content of volatile matter in biomass.

2.3 Char oxidation

Char oxidation models are usually based on either apparent or intrinsic kinetics. In intrinsic models, the char oxidation rate is related to the internal surface area of the char particle. The evolution of the internal surface area is very complicated, which is why the apparent kinetic models are widely used. Models based on apparent kinetics have frequently been used to model char oxidation rates under conditions limited by the combined effects of chemical kinetics and diffusion, specifically Regime II conditions. With such a model, the char oxidation rate can be predicted as follows[7]:

$$\frac{dm_p}{dt} = S_p k \left(P_{O_2, \infty} - \frac{dm_p}{dt} \frac{1}{S_p D} \right)^n \quad \text{Eq.(3)}$$

3. Results and discussions

The studied biomass properties are listed in Table 1. Further tests are carried out to get the apparent kinetics of devolatilization and char oxidation at high heating rates and high temperatures, which are similar to real furnace conditions.

Table 1. Fuel properties

| | Proximate analysis, wt% | | | | Ultimate analysis, wt% | | | | LHV ^{7db} (MJ/kg) |
|----------------------|-------------------------|------------------------|------------------|-------------------|------------------------|-----------------|-----------------|-----------------|-------------------------------|
| | Moisture ^{ar} | Volatile ^{db} | FC ^{db} | Asb ^{db} | C ^{db} | H ^{db} | O ^{db} | N ^{db} | |
| Woody biomass | 7.20 | 72.78 | 22.99 | 4.23 | 51.83 | 6.28 | 37.03 | 0.44 | 17.28 |

These obtained kinetics are used here to predict detailed biomass combustion behavior. The weight loss of 0.1mm biomass particle at air temperatures of 500°C, 700 °C, and 900 °C is studied; the results are shown in Figure 1(a). It is clear that the high temperature significantly enhances the biomass mass loss at the devolatilization stage; while a longer residence time is required to completely burn-out char. It is probable that the elevated temperature complicates the char oxidation process; further data analysis is required for confirmation. In addition, the weight loss of different particle sizes (0.05mm, 0.1mm and 0.2mm) at the same air temperature of 700 °C is studied based on the biomass combustion model; the results are shown in Figure 1(b). As expected, both the devolatilization rate and char burnout rate are high

for smaller particle size biomass: the larger the size of biomass particle the longer the time it takes to complete the whole combustion process.

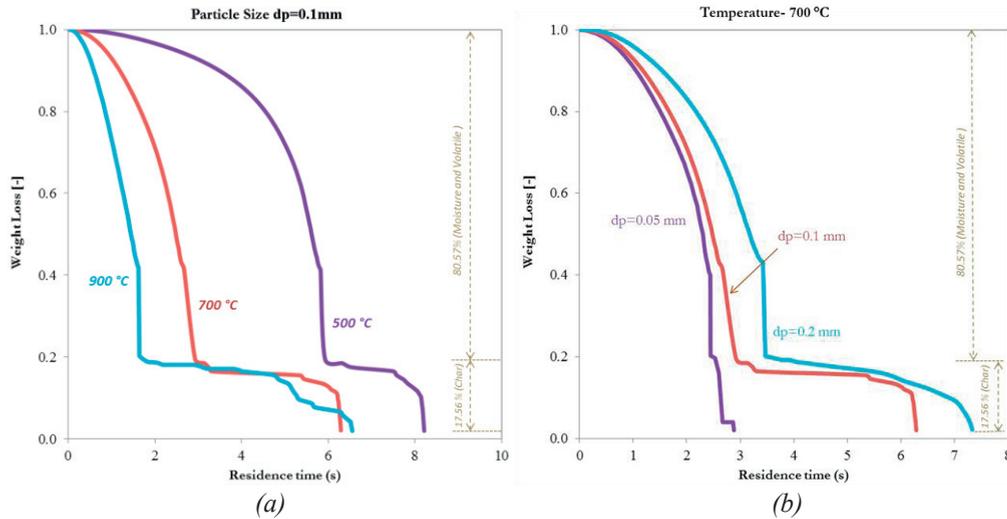


Figure 1. Weight loss curves (a) different agent air temperatures; (b) various particle sizes

4. Conclusion

A computational fluid dynamics (CFD) combustion model of a single biomass particle has been developed in this work. The biomass devolatilization reaction was simulated by a two-competing-rate model and the biomass char burnout rate was controlled by both the kinetics and diffusion to predict the particle size changes. The results showed that the high temperature significantly enhanced the biomass mass loss at the devolatilization stage; while a longer residence time was required to completely burn-out char. In addition, both the devolatilization rate and the char burnout rates were highest for smaller particle size biomass, whereas the larger biomass particles took longer to attain complete combustion.

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