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Effects of gas temperature fluctuation on the instantaneous pyrolysis of biomass particles

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ABSTRACT

Pyrolysis is a process dominating the mass loss of biomass particles during their combustion. The instantaneous pyrolysis processes of biomass particles in a hot gas with temperature fluctuation are investigated. Two types of biomass fuel, i.e., pine and almond shell, are chosen for the present study. The instantaneous mass variations of the biomass particles with diameters of 100–300 μm are calculated under different conditions. The gas temperature fluctuation has influences on the instantaneous pyrolysis processes of both pine and almond shell particles. It leads to faster mass loss of the particles and shortened time for the pyrolysis. The effects are enhanced by increasing the fluctuation amplitude of the gas temperature.

1. Introduction

The total worldwide energy consumption was about 123 billion tons of oil equivalent or about 178 billion tons of standard coal in 2008, as reported by the IEA (International Energy Agency) [1]. Of the consumed energy, 81.2% is fossil energy. Fossil fuels cannot be renewable and their reserves are limited. Meanwhile, the burning of coal and other fossil fuels emits large amounts of SO_2, NO_x, CO_2, dust, and fine particles, resulting in serious environment and global climate issues. On the other hand, biomass energy is a renewable energy. Its utilization is expected to ease the energy safety and environment issues. Thus increasing attention has been paid to this type of energy in recent years.

Biomass energy can be utilized in different ways. Among them, thermochemical conversion technology such as direct combustion has been developed. Biomass fuels are featured by high moisture content, low ash melting point, and relatively high alkaline metal contents. Co-firing of biomass with pulverized coal provides an effective manner to utilize biomass energy through direct combustion. The combustion performance of a co-firing combustor or furnace is largely influenced by the dynamic and reactive behaviors of biomass particles. A deep understanding of the behaviors of biomass particles will be beneficial to the development of co-firing technology for biomass and pulverized coal.

The behaviors of biomass particles in a co-firing combustor are extremely complex and affected by many factors. Both biomass and pulverized coal particles move and burn in a turbulent gas flow field with velocity and temperature fluctuations. The gas turbulent fluctuations impose influences not only on the instantaneous velocity and motion of pulverized coal particles, but also on their instantaneous temperature [2]. As a result, the devolatilization and char reaction processes of pulverized coal particles are affected by the gas temperature fluctuation [3]. Biomass particles release most of their mass through devolatilization during the combustion processes. The devolatilization rates are strongly dependent on the instantaneous temperature of biomass particles. But whether the gas turbulent fluctuation will have influence on the instantaneous temperature and devolatilization of biomass particles is not clear. It should be further studied. Thus the effects of gas temperature fluctuation on the instantaneous devolatilization of biomass particles are explored. Two types of biomass fuel, i.e., pine and almond shell, are chosen for the present study. The biomass particle under investigation is a single one suspended in a hot gas with uniform but fluctuating temperature.

2. Instantaneous governing equations for biomass devolatilization

Biomass particles will undergo moisture evaporation, devolatilization, and char combustion when burning in a combustor. The devolatilization processes of a biomass particle are considered here. It is assumed that the shape of the biomass particle is sphere and the temperature inside the particle is uniform. By accounting for the convective hear transfer between the gas and particle phase, the radiative heat transfer between the combustor wall and the particle, and the pyrolysis heat loss, the instantaneous

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Nomenclature

A_t	fluctuation amplitude of gas temperature
B_k	nondimensional variation rate of particle mass
B_t	fluctuation intensity of gas temperature
B_v	pre-exponential factor (s^{-1})
C_{pk}	particle specific heat (J/kg K)
d_k	particle diameter (m)
E_v	activation energy of pyrolysis reaction (J/mol)
f	fluctuation frequency of gas temperature (Hz)
m_k	instantaneous particle mass (kg)
$\dot{m}_k$	particle mass variation rate (kg/s)
m_v	accumulated volatile mass (kg)
$\dot{m}_v$	pyrolysis reaction rate (kg/s)
Nu_k	particle Nusselt number
Pr	gas Prandtl number
R	universal gas constant (J/mol K)
Re_k	particle Reynolds number
t	time (s)
T	instantaneous gas temperature (K)
T_k	instantaneous particle temperature (K)
T_w	wall temperature (K)

Greek symbols

Δh_v	heat of pyrolysis reaction (J/kg)
ε_k	particle emissivity
ζ	random number
λ	gas thermal conductivity (W/m K)
ρ_{pk}	particle material density (kg/m^3)
σ_b	Stefen–Boltzmann constant (5.67×10^{-8} W/m^2 K^4)
τ_T	turbulent time scale (s)
τ_{Tk}	particle relaxation time for temperature (s)

Subscript

0	initial

Superscripts

∞	final
$'$	fluctuating quantity
—	time-averaged quantity

particle energy equation is written as [4]:

$$m_k C_{pk} \frac{dT_k}{dt} = \pi d_k \lambda \mathrm{Nu}_k \frac{B_k}{\exp(B_k) - 1}(T - T_k) + \pi d_k^2 \varepsilon_k \sigma_b (T_w^4 - T_k^4) - \dot{m}_v \Delta h_v \tag{1}$$

where ε_k represents the particle emissivity, T_w denotes the combustor wall temperature, $\dot{m}_v$ is the instantaneous pyrolysis rate of the biomass particle, and Δh_v denotes the heat of pyrolysis reaction.

Eq. (1) can be further expressed as

$$\frac{dT_k}{dt} = \frac{1}{\tau_{Tk}}(T - T_k) + \frac{6\varepsilon_k \sigma_b}{\rho_{pk} d_k C_{pk}}(T_w^4 - T_k^4) - \frac{\dot{m}_v \Delta h_v}{m_k C_{pk}} \tag{2}$$

where τ_{Tk} is the particle relaxation time for temperature. It is defined as

$$\tau_{Tk} = \frac{\rho_{pk} C_{pk} d_k^2}{6 \mathrm{Nu}_k \lambda} \frac{\exp(B_k) - 1}{B_k} \tag{3}$$

Here B_k is the nondimensional variation rate of particle mass given by

$$B_k = \frac{-\dot{m}_k C_{pk}}{\pi d_k \mathrm{Nu}_k \lambda} \tag{4}$$

where Nu_k is the Nusselt number for gas-particle convective heat transfer. It is calculated by the following empirical correlation [5]

$$\mathrm{Nu}_k = 2 + 0.6 Re_k^{0.5} Pr^{1/3} \tag{5}$$

where Re_k is the particle Reynolds number.

Different models have been proposed for biomass pyrolysis. They include single reaction model [6], three-parallel-reaction model [7], three-step reaction model [8], distributed activation energy model (DAEM)[9], FG-DVC model [10], and Flashchain model [11]. As a first step to describe the instantaneous pyrolysis of the biomass particle under the influence of gas temperature fluctuation, the single reaction model is employed presently.

The single reaction model adopts the following pyrolysis reaction mechanism:

$$\text{Biomass} \rightarrow \text{Voltile} + \text{Char} \tag{6}$$

The instantaneous volatile release rate is given as

$$\frac{dm_v}{dt} = \dot{m}_v = (m_v^\infty - m_v) B_v \exp\left(-\frac{E_v}{RT_k}\right) \tag{7}$$

where m_v is the instantaneous accumulated volatile mass from the particle and m_v^∞ denotes the final volatile yield.

All moisture is assumed to have evolved from the particle before devolatilization. The instantaneous particle mass is calculated by

$$\frac{dm_k}{dt} = \dot{m}_k = -\dot{m}_v \tag{8}$$

The instantaneous diameter of the biomass particle is taken as unchanged during the devolatilization process. The instantaneous particle material density is obtained as

$$\rho_{pk} = \frac{m_k}{m_{k0}} \rho_{pk0} \tag{9}$$

where m_{k0} and ρ_{pk0} denote the initial particle mass and material density, respectively.

To study the influence of gas temperature fluctuation on the devolatilization of the biomass particle, the instantaneous gas temperature is assumed to be uniform in space but varies with time in the following simple harmonic way as

$$T = \bar{T}[1 + A_t \sin(2\pi f t)] \tag{10}$$

where $\bar{T}$ is the time-averaged gas temperature, A_t is the fluctuation amplitude of the gas temperature, and f represents the fluctuation frequency of the gas temperature. f is determined by the turbulent time scale, i.e., $f = 1/\tau_T$.

Since turbulence is featured by random fluctuations, the instantaneous gas temperature is also assumed to vary with time in a random way. Its probability density function (PDF) is specified by the following uniform distribution

$$p(T) = \frac{1}{T^+ - T^-}\left[H(T - T^-) - H(T - T^+)\right] \tag{11}$$

where T^+ and T^- are two parameters and $H(\xi)$ is Heaviside function. $H(\xi)$ takes the value of either 1 for $\xi \geq 0$ or 0 for $\xi < 0$. T^+ and T^- are calculated by $T^+ = \bar{T}(1 + \sqrt{3}B_t)$, $T^- = \bar{T}(1 - \sqrt{3}B_t)$. Here B_t denotes the fluctuation intensity of the gas temperature defined as $B_t = \sqrt{\overline{T'^2}}/\bar{T}$, $\sqrt{\overline{T'^2}}$ is the root mean square of fluctuating gas temperature. Within each interval of the turbulent time scale, the instantaneous gas temperature is randomly selected as

$$T = (T^+ - T^-)\zeta + T^- \tag{12}$$

where ζ is a random number between 0 and 1. Its PDF obeys a uniform distribution.