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Research article

Investigation of fragmentation and coalescence behavior of ash particles in simulated coal combustion

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ABSTRACT

In order to predict ash deposition in a pulverized coal combustion process, the fragmentation, detachment, and coalescence behavior of ash particles in coal were quantitatively evaluated to distinguish between excluded and included minerals. The experiments for simulated EM heating and simulated coal combustion were carried out in a drop tube furnace. Change in the numbers of EM and IM particles were measured at different residence times by scanning a sampling probe along the flow direction in the reactor tube. The rate constants of EM fragmentation were estimated from the simulated EM heating experiment. The solution to a system of differential equations that includes the effects of fragmentation, detachment, and coalescence as functions for the numbers of EM and IM was obtained as a kinetic model. These functions were fitted to the experimental results for simulated coal combustion experiment to obtain the rate constants for detachment and coalescence. This method was also applied to previous experimental results using three actual coal samples. The rate constants of detachment and coalescence were mainly affected by char structure during coal combustion.

1. Introduction

From the perspective of the effectively using low-rank coal, conventional pulverized coal combustion boilers have been increasingly used to burn many types of coal. When coals that are not within the acceptable range are fed into a boiler, problems such as fouling and slagging occur owing to ash deposition and melting on the surface of heat transfer tubes. Numerical simulations can be used to predict and prevent general boiler problems. Three-dimensional fluid dynamics, including the combustion reaction and heat transfer (conductive, convective, and radiative) in a boiler, can be precisely calculated with the help of recent developments in computational techniques and applications. Burning of coal particles with char fragmentation mechanisms have been installed into some CFD analyses [1,2]. However, it is difficult to simulate ash deposition behavior on a heat transfer tube, because the particle size distributions of ash entrained by combustion gas depend on not only the initial particle size distribution of ash in raw coal but also on fragmentation, detachment and coalescence during the combustion process of coal particles [3]. This is the main reason why predictions of fouling and slagging in the boiler by numerical simulation have not been put into practical use. Fig. 1 summarizes the variations in ash particles from pulverized coal combustion processes; those have been explained in many previous papers [4,5,6]. Ash particles from pulverized coal combustion can be categorized as either included minerals (IM) or excluded minerals (EM). EM particles are ash particles separated from combustible carbon. Some parts break off owing to thermal shock in the coal combustion atmosphere. On the other hand, IM are ash particles surrounded by a carbon matrix. Some parts are detached from the carbon matrix and change into EM, while the remaining parts coalesce with each other in shrinking char. These processes of fragmentation, detachment, and coalescence affect the change in ash particle size distributions during coal combustion and their subsequent deposition behavior on the surface of heat transfer tubes.

It has been reported that the detachment of fine IM particles from coal/char during combustion is a key mechanism for PM_{10} formation, while fine IM in a burning coal particle clearly undergoes coalescence to form large agglomerated ash particles [7]. On the other hand, almost all particles <0.22 μm in diameter were formed by processes such as the volatilization–condensation of SiO_2 coal [8].

Pioneering research on the modeling of ash formation during pulverized coal combustion with EM and IM concepts were conducted by

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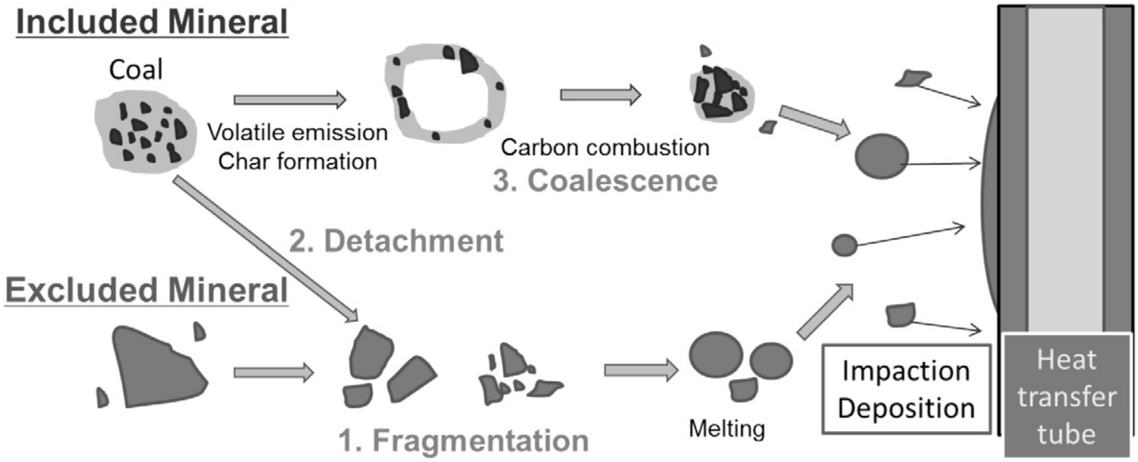

Fig. 1. Variations in ash particles in pulverized coal combustion processes.

T.F. Wall et al. [4]. Their ash formation model used computer controlled scanning electron microscope (CCSEM) data as the initial input. The coalescence–fragmentation model considering the interactions between EM and IM particles was developed to simulate the combustion of not only single but also blended coals [9]. However, the kinetic rates of ash particle formation were not considered in these models.

To elucidate the fragmentation and coalescence behavior of mineral particles in a pulverized coal combustion, char particles during the combustion reaction were sampled and analyzed for the numbers of EM and IM particles per unit volume ash using a drop tube furnace [10]. Then, the objective of the present study is to derive a model of ash fragmentation, detachment and coalescence in a pulverized coal combustion process, as kinetic rate functions. Kaolinite and potassium feldspar particles were used to simulate the fragmentation of EM. Simulated coal consisting of kaolinite particles and a polycarbonate matrix were used to simulate the detachment and coalescence of IM. Both of simulations were examined in a drop tube furnace. The reacted and fragmented particles were sampled and analyzed for EM and IM ash particles and their particle size distributions.

2. Experimental and analytical procedures

2.1. Simulated coal samples

Kaolinite and potassium feldspar particles were used to estimate the fragmentation behavior of EM particles in the combustion zone. These are common natural minerals, with different elemental compositions. They were sieved to under 48 mesh/in prior to experiments. Their average particle diameters d50, measured by a laser diffraction analyzer, were 8 μm for kaolinite and 3 μm for potassium feldspar, respectively. Table 1 shows elemental compositions of two minerals.

The same kaolinite sample was also used to prepare the simulated coal sample. The kaolinite was mixed with polycarbonate resin dissolved in dichloromethane. After the evaporation of the solvent, the mixture was pulverized by a resin crusher to obtain simulated coal, consisting of kaolinite particles as IM and a polycarbonate matrix. The average particle diameter d50 was confirmed to be 77 μm by a laser diffraction analyzer. Some kaolinite particles detached from the poly–carbonate matrix during the crushing process, and behaved as EM particles in the simulated coal sample. Table 1 shows the proximate analysis of the simulated coal sample and the ash melting temperatures.

Table 1
Elemental compositions of two minerals.

		Kaolinite	Potassium feldspar
SiO_2	wt%-dry	59.6	64.6
Al_2O_3	wt%-dry	30.2	18.7
Fe_2O_3	wt%-dry	0.13	0.13
Na_2O	wt%-dry	0.36	3.09
K_2O	wt%-dry	0.14	12.7
CaO	wt%-dry	0.04	0.28
TiO_2	wt%-dry	0.16	0.01

It has been reported that the ash particles of coals with different mineral compositions exhibit different fragmentation and coalescence behaviors during combustion [5]. Ninomiya et al. tested the use of an Mg-based additive to increase the coarse ash fraction and substantially reduce the amount of $PM_{2.5}$ [11]. The chemical form and oxidation state of iron in coal also affected the fusion and coalescence of the mineral constituents within the burning char particles to form ash particles in the 1–10 μm range [12]. Then, kaolinite and potassium feldspar were utilized to simulate EM fragmentation behavior. Both of them are natural alumino-silicate compounds, although their Al_2O_3/SiO_2 ratios were much different between them. Only kaolinite was applied as IM in simulated coal sample. Determining the quantitative effects of the elemental compositions of IM on the fragmentation and coalescence behaviors in coal char would be an important task in the future.

2.2. Drop tube furnace experiment

The fragmentation of EM particles was experimentally simulated by the rapid heating of two mineral samples, while the coalescence and detachment of IM were simulated by the combustion of simulated coal samples. Both experiments for two minerals and simulated coal were conducted using a drop tube furnace equipped with an external electric heater. Detailed specifications of the furnace have been explained in our previous work [10]. The reactor tube was made of mullite, with a length of 2 m and an inner diameter of 72 mm. A water-cooled sampling probe with an inner diameter of 10 mm was inserted from the bottom of the reactor tube. Mineral particles or simulated coal particles was fed continuously into the reactor from the injector with entrained gas. Particles dropping down through the reactor were extracted by the sampling probe, using the iso–kinetic sampling method. The probe head was scanned at distances between 100 mm and 1300 mm from the injector to collect particles at different residence times. Particles entering the probe were immediately quenched by dilution nitrogen gas to prevent them from reacting with each other. The particles were separated from the sampled gas by a quartz thimble filter, and their carbon contents were analyzed to estimate the degree of carbon conversion in the simulated coal combustion experiments. The amount of carbon and minerals in char particles were determined by thermo–gravimetric analysis to estimate the carbon conversion of char sample. Table 2 shows the experimental conditions for rapid heating of two minerals