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An experimental investigation into the characteristics and deposition mechanism of high-viscosity coal ash

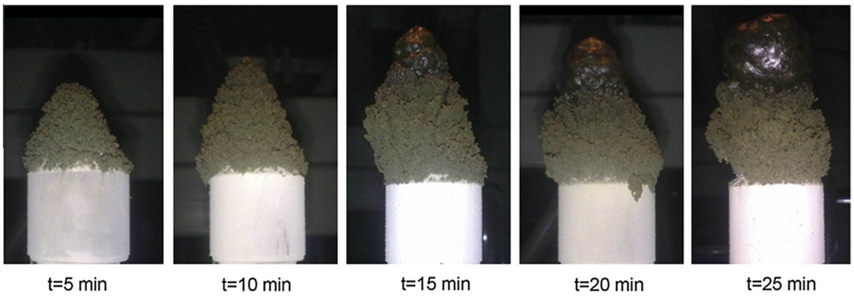
Chao Luan [a,b], Changfu You [a,*], Dongke Zhang [b]

[a] Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing 100084, China
[b] Centre for Energy (M473), The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia

HIGHLIGHTS

- Coal ashes were categorized into two groups of high and low viscosity based on their temperature.
- The deposition mechanism of high-viscosity ash was found to transform from fouling to slagging.
- The effect of ash chemistry and operating conditions on high-viscosity ash deposition was systematically investigated.

GRAPHICAL ABSTRACT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ABSTRACT

Coal-fired boilers often develop massive fouling and slagging deposits on heat transfer surfaces in areas where coal ash particles have relatively high viscosities ($\geqslant 10^6$ Pa s). In order to investigate the characteristics and mechanism of the problems, experiments were performed in a drop tube furnace and by use of a slagging probe in this study. The results showed that fouling deposits developed on the probe in the first stage, and then transformed into partially or fully fused slagging deposits. The deposition of high-viscosity coal ash was closely related to both the experimental conditions and the chemical composition of the ash. A low temperature on the probe surface and a high impact velocity of ash particles significantly inhibited ash deposition for the high-viscosity ash. The relative deposition ratio of high-viscosity ash, defined as the ratio of the mass of the deposit on the probe to the total mass of ash fed into the DTF, increased along with time initially and then diminished after reaching the maximum. Fine ash particles had higher deposition tendency compared to coarse particles, probably due to local eddies between the fingers on the front of the probe. The chemical compositions of coal ashes had an observable effect on the deposition behavior of high-viscosity ash. The findings of this work are significant for understanding the mechanism of high-viscosity ash deposition and determining the effect of key operating conditions relevant to deposition of high-viscosity ash.

1. Introduction

Ash deposition is a common problem occurring in combustion process of solid fuels such as coal and biomass. Deposition is usually classified into two generic types: slagging and fouling. Slagging is the formation of partial or fully melts on heat transfer surfaces and refractory in the radiant portions of the boiler, while fouling is the formation of ash deposits normally by desublimation and sintering on convective heat transfer surfaces [1–3]. Hatt and Rimmer [4,5] proposed a classification system for slagging deposits, classifying slags into four basic types: metallic, amorphous, vesicular and sintered. Likewise, Hurley [6,7] provided an outline of fouling regimes, classifying fouling deposits into two main cate-

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[*] Corresponding author. Tel./fax: +86 10 62785669.
E-mail address: youcf@tsinghua.edu.cn (C. You).

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gories: high temperature fouling and low-temperature fouling. Deposition can adversely affect the operation and performance of the equipment. It may inhibit heat transfer to the working fluid, reducing the processing capacity and overall efficiency of the process, and may even cause shut down of the boilers [8].

The deposition potential of a coal ash has been evaluated using numerous tests and analytical techniques. Various empirical indices have also been proposed to estimate the deposition tendency; these include the base to acid ratio (B/A), alkali metal percentage, slagging factor, fouling factor, and the silica ratio derived from the chemical composition analysis of the ash [3]. Ash fusion temperatures were studied as a parameter used to predict ash deposition behavior by many researchers [9–13].

Prediction of ash deposition behavior can also be based on the viscosity of the ash particles [9,14,15]. A low viscosity makes it easier to dissipate the energy of an ash particle upon impact. For that reason, often particles with low viscosity stays on the surface upon impact simply because their energy after impact is not high enough to make them rebound. Viscosity is a most direct influencing factor for ash deposition and is very important for the prediction of ash behavior in a furnace. Almost all current slagging models are based on the ash viscosity. Ash viscosity can be measured using several methods [16,17], amongst which the high-temperature rotating cone viscometer is the most widely used system for ash viscosity measurement due to its simplicity in construction and operation [18–21]. This system works under an assumption that molten coal ash behaves as a Newtonian liquid which has a viscosity range of 0.1–10^6 Pa s [22,23]. Consequently, it provides accurate results only if the ash materials are at temperatures higher than the temperature of critical viscosity (T_{cv}), which is defined as the temperature at which the viscosity properties of the molten slag change on cooling from those of a Newtonian fluid to those of a Bingham plastic (non-Newtonian liquid) due to crystallization [24]. At temperatures lower than T_{cv}, serious errors will be produced. Ash viscosity can also be estimated from the ash chemical composition and temperature [18]. Accordingly, many researchers have developed models for the prediction of the ash viscosity [25–29]. However, Winegartner [3] indicated that any calculated values relating viscosity of the slag to temperature are meaningless at temperatures below T_{cv} due to poor accuracy.

Ash particles experience a wide range of temperatures in the furnace. The temperature near the water-cooled furnace walls is approximately 550 °C while at the flame center it can be as high as 1500 °C and even higher. Thus, the viscosity of the ash particles also undergoes significant changes. Some researchers suggested that when the viscosity of ash particles is larger than 10^7 Pa s, the ash particles are no longer sticky enough to slag on the heat transfer surfaces [30]. Senior and Srinivasachar [31] classified the viscosity data of coal ashes into two groups for the viscosity based slagging model: one group has viscosities less than 10^4 Pa s (high temperature) and the other has viscosities greater than 10^4 Pa s (low temperature). Similarly, ashes may be categorized into two groups based on the temperature an ash experiences:

(1) High-viscosity ash: The ash at a temperature lower than its T_{cv}, usually with a viscosity equal to or greater than 10^6 Pa s;
(2) Low-viscosity ash: The ash with a temperature higher than its T_{cv}, usually with a viscosity smaller than 10^6 Pa s.

Few researchers have studied the deposition characteristics of high-viscosity ashes. A drop tube furnace (DTF) with a deposition probe was used to carry out the experiments. The deposition behavior of the high-viscosity ash was investigated under different conditions including probe surface temperature, impact velocity of ash particles, deposition time, particle size, and ash chemical compositions.

2. Experimental

2.1. Ash characterization

Six types of coal ash were selected for the experimentation. The coal ashes, identified as 1–6# ash samples, were collected at the ESP filters of five different power plants in China. Tables 1 and 2 show the ash fusion temperatures, density and mean diameter and chemical compositions. Ash 1# and 6# were collected from the ESP filters of the same power plant but were sieved into different particle size fractions. There was a variation in the chemical compositions between ash 1# and 6# because of the different formation mechanisms of ash particles with different sizes [32]. The effect of particle size on the deposition phenomenon was studied with ash 1# and 6#.

2.2. Experimental setup

The laboratory experimental system consisted of two parts: a DTF and a deposition probe (Fig. 1). The DTF is 2.5 m high with an internal diameter of 50 mm. The deposition probe has a cone at the top tip with an angle of 120°, and a diameter of 25 mm at its base, and was inserted into the furnace chamber from the bottom of the DTF. The probe, which was made of steel, was cooled to 600–900 °C by compressed air and the probe surface temperature was measured using a thermocouple. This allowed the surface temperature of the probe to be controlled by adjusting the flow rate of the compressed air.

The DTF was electrically heated to a pre-set temperature of 1200 °C. Air entrained the coal ash into the DTF. The ash was heated when dropping down through the furnace chamber. Some of the ash particles impacted and stuck on the probe surface forming a deposit. After each run lasting between 5 and 25 min, the probe was withdrawn from the furnace and the deposit was removed from the probe for further analysis. The mass of the deposit was then measured. The feeding rate of the ash was controlled to 1 g/min by the feeder. The total mass of ash fed into the DTF was calculated after a specified time period. The relative deposition ratio is proposed and defined as the ratio of the mass of the deposit on the probe to the total mass of ash fed into the DTF.

$$R_d^r = \frac{\text{the mass of the deposit on the probe}}{\text{the total mass of ash fed into the DTF}} \times 100\%$$

where R_d^r is the relative deposition ratio, the superscript stands for “relative”, and the subscript stands for “deposition”. With this parameter, the deposition tendency can be evaluated and compared qualitatively among different coal ashes under the effects of diverse conditions.

2.3. Experimental conditions

The DTF temperature was set to 1200 °C for each experiment. The following operating parameters influencing the deposition behavior of the ashes were examined.

(1) Probe surface temperature. The temperature of the deposition probe surface was controlled to 600, 700, 800 and 900 °C in the experiments in order to simulate the effects of heat-transfer surface conditions on deposition in utility boilers.
(2) Impact velocity of the ash particles. The ash particles were considered to have the same velocity as the gas flow in the DTF due to their small sizes. Thus, the impact velocity of the ash particles was controlled by the flow rate of the feeding air. In this research, impact velocity varied between 0.2 and 1.0 m/s.