Journal of the Energy Institute xxx (2016) 1–10

Contents lists available at ScienceDirect

Journal of the Energy Institute

journal homepage: http://www.journals.elsevier.com/journal-of-the-energy-institute

Investigation on ash deposition characteristics during Zhundong coal combustion

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A R T I C L E I N F O

Article history:
Received 24 August 2016
Received in revised form
8 November 2016
Accepted 14 November 2016
Available online xxx

Keywords:
Zhundong coal
Sodium
Calcium
Iron
Slagging mechanism

A B S T R A C T

The reserves of Zhundong (ZD) coal in China are huge. However, the high content of Na and Ca induces serious slagging and fouling problems. In this study, the ZD coal was burned in a DTF (drop tube furnace), and the ashes collected at different gas temperature with non-cooling probe were analyzed to obtain the ash particle properties and their combination mode. The results showed that Na, Ca and Fe are the main elements leading to slagging when the gas temperature is about 1000 °C during ZD coal combustion, but their mechanisms are quite different. Some sodium silicates and aluminosilicates and calcium sulfate keep molten state in the ashes collected at 1000 °C. These molten ash particles may impact and adhere on the bare tube surface, and then solidified quickly. With the growth of slag thickness, the depositing surface temperature is increased. The molten ash particles might form a layer of molten film, which could capture the other high fusion temperature particles. The Fe_2O_3 sphere were captured by the formed molten slag and then they blended together to form a new molten slag with lower melting temperature.
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1. Introduction

Coal is the most important source of energy around the world, and this structure of energy sources would most likely last a long time in the future. Especially in China, coal consumption exceeds 50% of the total amount of all over the world, and still more than 70% generated energy is produced by thermal power plant [1]. Zhundong (ZD) coalfield, located in Changji, Xinjiang province, is the largest integrated coalfield in China. To date, it is estimated that the coal reserves amount to 164 Gt. This region will have the priority to develop in future [2]. At present, due to the easy exploitation of opencast coal, the price of ZD coal is very low (less than 80 CNY per ton); meanwhile, the ZD coal has a lot of advantages, such as high volatile property, low ash yield, low ignition temperature, etc. Therefore, more and more nearby power plants tend to burn ZD coal to reduce the production costs [3]. However, the high content of sodium in ZD coal induces serious problems such as slagging and fouling of boiler heating surface, especially at the platen superheater area [4].

In general, the process of that ash depositing on boiler tubes from the flue gas mainly concluded three transport mechanisms: diffusion, thermophoresis and inertial impaction [5]. Tomeczek [6] pointed out that thermophoresis is the primary transport mechanism for submicron particles (<1 μm) to adhere to boiler tube; Fine particles (1–10 μm) are principally controlled by turbulent diffusion to stick to the tube surface; For large particles (>10 μm), inertial impaction is the most important transport mechanism. The submicron particles are commonly rich in AAEMs (alkali and alkaline earth metals), on the contrary, an amount of Si and Al exists in the large particles [7]. Ichiro Naruse [8] reported that Fine particles of size less than 3 μm mainly consisted of the initial layer, by contrast, the main body of deposit is molten slags which are caused by the impact and adherence of fused particles. Vassile et al. [9] pointed out that higher contents of Ca, Mg, Fe and Na in coal ash resulted in lower the AFTs (ash fusion temperatures), while an increase in the contents of Si, Al, and Ti in coal ash increased the AFTs. Therefore, the sodium, calcium and iron species in coal induce serious slagging problems [10], however, the slagging mechanisms of these inorganic elements are quite different.

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http://dx.doi.org/10.1016/j.joei.2016.11.003
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Please cite this article in press as: B. Wei, et al., Investigation on ash deposition characteristics during Zhundong coal combustion, Journal of the Energy Institute (2016), http://dx.doi.org/10.1016/j.joei.2016.11.003

During slagging process, the deposit surface temperature increases gradually for the thermal resistance increasing with the slags growth. The different physical and chemical reactions happened in different slagging stages. Several researchers have found that there is obvious layered structure in deposits on heat transfer during high alkali coal combustion. Li et al. [11] pointed out that an amount of submicron particles (PM_1) which were composed of sodium sulfates and chlorides could deposit on the bare tube and form the sticky initial layer by thermophoresis mechanism. After that, a sticky coating layer on the surfaces of large fly ash particles was formed by coagulation with the ultrafine particles ($PM_{0.2}$) and heterogeneous condensation of gas phase AAEMs species, which absolutely increased the adhesion between ash particles through the formation of either liquid bridges or solid bridges. Zhou et al. [12] have reported that gaseous NaCl could react with SO_2 to form gaseous Na_2SO_4, which may condensed on surface of deposits and fly ash particles directly, meanwhile, the gaseous NaCl also could react with silicates or aluminosilicates to form alkali-rich silicates or aluminosilicates, which could impact and adhere on deposit surface for the relatively low melting temperature. In addition, he did not found $CaSO_4$ in any layers. Wu et al. [13] reported that the inner layer was rich in Na, Fe and S. The higher content of $CaSO_4$ was found in all three layers. From the above analysis, it can be seen that the layered slagging will happen during high alkali coal combustion for certain, however, there are disagreements on the chemical constitutes in different layers, especially on the inner layer is rich in Fe or not, and the existence of $CaSO_4$ in slagging.

Aiming to solve the slagging problems during high alkali coal combustion, several full-scale furnaces burning ZD coal have been investigated to explore the slagging mechanism. Wang et al. [14] sampled the deposits along with the gas flowing direction in a 350 MW boiler burning high alkali Zhungdong coal, and found that the content of Ca and S in furnace exist and horizontal gas flue area was higher than that of the others place significantly. The similar results were obtained by Dai et al. [15]. FerNandez-Turiel et al. [16] observed that the deposits that came from the hot zone in the furnace (800−1200 °C) were very hard, and had a beige-colored surface and showed fresh fractures. The deposits consisted of a framework of anhydrite crystals with agglomerates of irregular particles of grass. These studies indicated that $CaSO_4$ played an important role in slagging process when the gas temperature is about 1000 °C, however, it was not clear on why the deposits were mainly composed of $CaSO_4$ rather than Na bearing compounds, and what was the role of Na salts in slagging process at that temperature condition.

The iron species were considered as an important contribution during deposition and slagging process [17]. The Fe^{2+} formed in reducing atmosphere in boiler had lower melting temperature, and could reduce the ash fusion temperature [18]. The ash particles in which mass fraction of Fe_2O_3 exceeds 5%, were proved easily to be fused, and would aggravate slagging. In addition, the iron species was generally used for flux agent to reduce the ash fusion point [19]. The mass fraction of Fe_2O_3 in ZD coal is generally more than 10%, so it can be deduced that Fe also plays an important role in ZD coal slagging. However, the ways that Fe participates in slagging during high alkali coal combustion are not specific enough.

Recently, Li et al. [20] found that when the probe temperature maintained at 973 K by water-cooled, significant sintering and fusion in the deposit were observed, where fine particles had melted and incorporated into coarse ash particles or aggregates, leading to increased particles sizes and the formation of hauyne. Blending a bituminous coal could control the severe ash deposition of ZD coal effectively [21]. In most of investigations, for simulating the slagging state in furnace, the probes used in lab-scale furnace were water-cooled. Besides that, many studies sampled slags directly in full-scale furnace when the boiler shut down for further analysis. The sampled slags formed through a series of different physical and chemical reactions at different temperatures with slags growth. In order to obtain the slagging mechanism in detail, the ash particle properties in flue gas and the combination mode of different type of ash particles at different temperature should be understood firstly. In addition, the role of different elements in slagging at high temperature condition must be decoupled.

In this study, to analyze the slagging mechanism of Na, Ca and Fe during high alkali coal combustion, the high alkali ZD coal was burned in a drop tube furnace (DTF), and ashes were collected at different gas temperature with non-cooled probes. The collected ashes were analyzed by X-Ray Fluorescence (XRF, S4-Pioneer, Bruker Co., Germany) and SEM-EDS (scanning electron microscope-Energy Dispersive Spectrometer) to obtain the ash particle properties and their combination mode of different ash particles. According to the experimental results, the slagging mechanisms of Na, Ca and Fe were proposed to provide references on solving slagging problems during high alkali coal combustion.

2. Fuel properties and experimental setup

2.1. Fuel properties

In the present study, one ZD coal was used. The properties of ZD coal and ash are listed in Table 1. It can be seen that the content of moisture (air dry basis) and volatile (as received basis) in coal reached 14.8% and 31.34% respectively. It can be deduced that the experimental ZD coal belonged to lignite category. The mass fraction of ash (as received basis) is only 6.92%. The contents of Na_2O, CaO, SO_3 and Fe_2O_3 are 3.73%, 18.94%, 20.44% and 12.55% respectively, which are greater than the common coal in China. By contrast, the mass fraction of Al_2O_3 is lower, only 7.06% in ash. The deformation temperature (DT) is only 1255 °C, and the flowing temperature (FT) is only 30 °C larger than the DT. Higher content of Na, Ca and Fe, very minor Al content and the lower ash fusion temperature indicate that the serious slagging and fouling problems will happen during furnace operation.

2.2. Experiment facility and sampling

The schematic diagram of DTF and ash deposited probe in this study are shown in Fig. 1. The DTF system mainly consists of the fuel feeding unit, an electrically heated furnace, the ash sampling unit. The coal powder was fed into the injection probe with water-cooling by a screw feeder, and the feed rate was 1.5 g/min. A 3000 mm long corundum reaction tube with an inner diameter of 60 mm was housed in the furnace. The experiments were carried out at 1 atm and the furnace temperatures were set at 1350 °C, 1250 °C, 1150 °C and 1000 °C respectively. The primary air that connected with the injection probe carried the coal powder and flowed into reaction tube together. The secondary air flow into reaction tube from the interval between reaction tube and injection probe. The ash sampling probe was inserted into the reaction tube at the bottom of the furnace. The sampling temperatures were set 1200 °C (if furnace temperature higher than 1200 °C, otherwise, the sampling temperature was set at the furnace temperature), 1000 °C, 800 °C and 600 °C, which

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