Fuel 143 (2015) 430–437

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Fine particulate formation and ash deposition during pulverized coal combustion of high-sodium lignite in a down-fired furnace

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HIGHLIGHTS

- High content of AAEM species Zhundong lignite was combusted.
- The formation of eutectic mixtures contributes to the severe slagging near burner.
- Zhundong lignite presents higher deposition propensity than other contrast fuels.
- Zhundong lignite produces more fine particles than other contrast fuels.
- Sticky surfaces enhance deposition tendency of Zhundong lignite.

ARTICLE INFO

Article history:
Received 26 July 2014
Received in revised form 20 October 2014
Accepted 21 November 2014
Available online 8 December 2014

Keywords:
Zhundong lignite
AAEM species
Slagging
Ash deposition
Fine particulate

ABSTRACT

The high-reserve Zhundong lignite, rich in Alkali and Alkaline Earth Metal (AAEM) elements, causes severe fouling and slagging problems in stationary combustion systems. In this paper, the ash deposition propensity as well as its relation to AAEM-rich fine particulates was investigated in a 25 kW down-fired furnace possessing similar conditions to practical combustors. The high content AAEM (mainly calcium) species in Zhundong lignite results in the molten slag at the vicinity of the burner inlet, differing from other case burning high-ash-fusion (HAF) bituminous coal. The ash deposits were collected at a position with gas temperature of 800 °C, whereas the fine particulates were sampled at the same position by a two-stage nitrogen-dilution isokinetic probe. The deposition tendency of ash particles from Zhundong lignite is apparently higher than those from contrast fuels and even herbaceous biomass. It is then related to the sticky surfaces of both bare deposition tube and bulk fly ash particles, forming from large amounts of AAEM species, which enhances the deposition propensity.

1. Introduction

The Zhundong lignite coalfield with a huge reserve of 390Gt is a newly explored fuel resource in China [1]. It absolutely provides a promising alternative fuel source of the stationary coal utilization. So far more than tens of coal-fired boilers, burning Zhundong lignite, have already been built and operated near the coalfield. Although the high volatile matter causes the coal to be easily ignited, the severe fouling and slagging problems both inside the furnace and in the convective pass limit its utilization as clean fuel. Even some boilers had to be shut down for the urgent cleaning or repairing. The main reason can be attributed to the high content of Alkali and Alkaline Earth Metal (AAEM) elements in the Zhundong lignite. For example, the sodium and calcium contents are as high as 6.2% and 32.8% in coal ash, respectively. These AAEM species mainly exist as the water-soluble or ion-exchangeable occurrences in the coal matrix. So they are easy to be released accompanying with the fast coal devolatilization under the high temperature ambience [2]. The evaporated AAEM vapors will nucleate/condense to form the fine sticky particles which enhance the ash deposition in the boilers [3–6]. Even as some advanced clean coal technologies of the combined cycles are concerned, the release of the AAEM species, either during pyrolysis or during gasification/ combustion, will probably cause severe problems for the operation of gas turbines due to the corrosion/erosion of the turbine blades [2]. Therefore, the roles of AAEM species have received the persistent attentions, despite the great efforts made so far.

Similar to the Zhundong lignite, there are some other kinds of coal around the world also containing high AAEM species, e.g., the PRB sub-bituminous coal/Beulah lignite from US and the Victorian brown coal from Australia [7–9]. The fouling and slagging problems also inhibit the utilizations of these fuels. As a result, many efforts have been done on the lab-scale studies of the

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http://dx.doi.org/10.1016/j.fuel.2014.11.067
0016-2361/

releasing behavior of AAEM elements, especially Na and Ca, during coal combustion [8,10–14]. Then, other significant fundamental efforts were performed on clarifying the detailed roles of AAEM species in the pyrolysis and gasification behavior of Victorian brown coal as well as their interactions [2,15–20]. For a much larger scale related to industrial applications, some investigators studied the effects of high-content AAEM species in PRB coal or Beulah lignite on the boiler operations [7,9]. More actively, some additives such as kaolin, silica, alumina, etc. were incorporated with Victorian brown coal to form high-melting temperature composites, and then to relieve fouling and slagging problems of stationary power plants [21–24]. Generally, in one hand, these efforts above provided lots of experiences for further investigations of Zhundong lignite, which possesses much higher AAEM than previous Victorian and PRB coals. In the other hand, even for those Victorian or PRB coal themselves, very few attempts have been done for the correlation between the AAEM releasing behavior and the following ash deposition/slagging properties. Nevertheless, the role of the fine particulate mode (PM_1), as a key bridge between AAEM releasing and ash deposition [25], is scarcely concerned. In addition, the high-content AAEM species also augment fine particulate emissions, which is now becoming the principal environmental pollutants in China [26,27].

In this work, by using a 25 kW self-sustained down-fired furnace that can achieve similar conditions to practical combustors, the fine particulate formation and ash deposition during the combustion of high-sodium Zhundong lignite were investigated. Other two kinds of coals, high ash-fusion (HAF) bituminous and Hulunbuir lignite, were used as a contrast. The morphology and chemical compositions of ash slag samples from the wall near burner inlet were analyzed by SEM/EDS. The ash deposition propensity of Zhundong lignite was determined and compared with those contrast fuels. The amount and chemical compositions of fine particulate emissions were also measured. Finally, a correlation between the ash deposition propensity and the high content of AAEM species for Zhundong lignite is discussed.

2. Experimental facility and coal properties

2.1. Coal properties

The proximate, ultimate and ash composition analysis of HAF bituminous coal, Zhundong lignite and Hulunbuir lignite are presented in Table 1. In particular, the ash compositions of Zhundong lignite include 6.19% sodium, 32.78% calcium and 21.47% sulfur by weight basis, respectively.

The chemical fractionation analysis is applied to measure the mineral element occurrences. The samples were sequentially leached by water, ammonium acetate and hydrochloric acid. The residual ash was digested and submitted, together with other solution samples, for ICP-OES/MS analysis to quantitatively determine the amount of mineral elements. The detailed descriptions refer to [28]. The chemical fractionation result of Zhundong lignite is shown in Table 2. The water soluble elements mainly consist of dissolved salts like Na^+, Mg^{2+} and Ca^{2+}, while ammonium acetate soluble elements primarily contain organically-bounded matters. Hydrochloric acid soluble elements mostly are carbonates and sulfates of inherent minerals. The residual ash mostly contains metal elements oxide, sulfides and silicates [29]. From Table 2, it is noted that 93% of sodium and 69% of calcium in Zhundong lignite occur as water soluble and ammonium acetate soluble modes. These occurrences of elements are very easy to vaporize during combustion.

2.2. The 25 kW down-fired furnace and its operation conditions

The experiments were conducted in a 25 kW one-dimensional, self-sustained, down-fired coal combustor, with 150 mm ID and 3.4 m height. The detailed descriptions of this facility as well as operation procedures can be found in our other published works [3,5,25,30,31]. Fig. 1 briefly shows the schematic picture of the furnace. Fine particulate matter and ash deposits were sampled in port 4, the carbon burnout zone. The residence time in port 4 is about 1.5 s.

The temperature profile in the case burning Zhundong lignite is presented in Fig. 2. The coal feeding rate was kept at 2.88 kg/h (dry basis). The gas compositions in flue gas were recorded by a gas analyzer (MAG-5). The volume concentrations of O_2, CO_2, CO and NOx are 4%, 16.9%, 265 ppm and 600 ppm, respectively. The stoichiometric ratio of Zhundong lignite combustion is 1.24.

2.3. Sampling systems and analysis methods

The fine particulate matters were sampled by a self-designed two-stage nitrogen-dilution isokinetic sampling probe. The dilution ratio was set around 70–100 to eliminate unwanted nucleation/condensation inside the probe. Then the samples were collected and measured by Dekati Electrical Low Pressure Impactor (ELPI). The PM_{10} cyclone cutter, designed according to EPA standard 201A, was used before ELPI to get bulk particle samples. The detailed descriptions of fine particle sampling system can be found in our recent literatures [3,5].

The ash deposition probe is a custom-designed, air-cooled, temperature-controlled probe, which has also been described elsewhere [3,25,30,31]. The ash deposit collection section of the deposition probe is 50 mm long and with an outer diameter of

Table 1
Properties of HAF bituminous coal, Zhundong lignite and Hulunbuir lignite.

Proximate analysis (wt.%, dry basis)	HAF	Zhundong	Hulunbuir
Fixed carbon	55.5	63.5	49.1
Volatile matter	24.1	30.6	38.8
Ash	20.4	5.9	12.1
HHV(MJ/kg)	25.3	28.8	25.6
Ultimate analysis (wt.%, dry and ash free basis)			
C	82.51	71.60	74.05
H	4.39	3.16	4.17
O	11.28	23.85	20.47
N	0.89	0.78	1.00
S_{total}	0.93	0.52	0.31
Cl	0.02	0.09	No data
Ash compositions (wt.%)			
SiO_2	56.8	28.5	54.1
Al_2O_3	26.2	3.2	11.2
Fe_2O_3	7.0	4.0	13.8
CaO	2.7	32.8	10.9
MgO	0.7	2.9	2.1
TiO_2	1.2	0.3	0.7
SO_3	2.1	21.5	2.9
P_2O_5	0.5	Not detected	0.1
K_2O	1.0	0.6	0.5
Na_2O	0.2	6.2	0.9

Table 2
Chemical fractionation result of Zhundong lignite.

Unit: (%)	Water soluble	NH_4Ac soluble	Acid soluble	Residual
Na	57.7	35.6	4.7	2.0
Ca	2.4	66.6	29.1	1.9
Mg	6.0	74.8	13.4	5.8
Fe	0.0	0.0	63.1	36.9
K	6.7	17.5	21.4	54.4
P	0.0	0.0	70.4	29.6
S	21.4	5.9	6.2	66.5
Ti	0.0	0.0	18.5	81.5
Si	0.2	0.4	5.9	93.5
Al	0.0	0.0	15.0	85.0