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Ignition and combustion characteristics of single particles of Zhundong lignite: Effect of water and acid washing

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Abstract

The ignition and combustion characteristics of Zhundong lignite (ZDL), with and without washing to remove different forms of inherent sodium, were investigated. Water washed (ZDL-WW) and acid washed (ZDL-AW) samples were prepared by soaking the raw lignite (ZDL-Raw) in ultrapure water and 0.5 M hydrochloric acid (HCl), respectively, at 60 °C for 24 h. A single particle of a ZDL sample, ca 2.5 mm in diameter, was suspended on a silicon carbide fibre (142 µm) tip and burned in air at 1123 K in a furnace. The time-resolved ignition and combustion behaviours of the single particles were observed with the aid of combined use of a shortwave infrared camera, a CCD camera, which enabled the determination of the ignition mechanism, ignition time, burnout time and burning rate. A flame emission spectrometer was used to identify the presence of sodium in the flame. The ignition of all ZDL samples followed the joint hetero-homogeneous mechanism in the present work. Upon the homogeneous ignition, ZDL-Raw exhibited a soot free yellowish translucent flame while ZDL-WW and ZDL-AW showed sooty flames. The ignition time followed the order of ZDL-Raw>ZDL-WW>ZDL-AW while the burning rate followed the opposite order. These observations were attributed to the catalytic effect of sodium in the lignite whose amount was varied due to the water and acid washing. Sodium ions were detected in the flame of ZDL with and without washing and the intensity of sodium signal also followed the order of ZDL-Raw>ZDL-WW>ZDL-AW. It is believed that sodium ions released in the flame promoted catalytic cracking of large tar fragments and oxidation of soot precursors.

Keywords: Ignition; Sodium; Volatile flame; Washing; Zhundong lignite

1. Introduction

Zhundong coal field, one of the largest coal fields in China, is believed to play a critical role in China's future energy supply [1–4]. Zhundong lignite contains high alkali and alkali earth

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metal (AAEM) species, especially sodium [5,6]. Therefore severe slagging and fouling are incurred when Zhundong lignite is fired in utility boilers [1,2,4,6–8]. Sodium exists in Zhundong lignite in the forms of physically absorbed (water-soluble) sodium salts, organically-bonded (acid-soluble) sodium functional groups and complex sodium containing minerals (acid-insoluble) [9]. Among these, water- and acid-soluble sodium species were found to be most troublesome causing the ash deposition issues [4]. Water and acid washing can remove varying amounts of different forms of sodium in a lignite, which has been applied in a number of literature studies [3,10–14]. However, sodium species in low rank coal can also act as a catalyst promoting the combustion and gasification reactions [12–15]. Therefore, understanding the effect of washing method on the ignition and combustion characteristics is of scientific interest and practical usefulness. However, there have been very limited and sometime contradictory reports in this regard for Zhundong lignite. Weng et al. [11] and Wang et al. [16] studied the effect of sodium and alkali metals on the combustion characteristics of raw and washed Zhundong lignite using a thermogravimetric analyser (TGA). They found that the removal of water soluble and organic forms of alkali metals in Zhundong lignite increased the ignition temperature and reduced the burning rate of the lignite. Likewise, Chen et al. [3] adopted a similar methodology to that of Weng et al. [11] and Wang et al. [16] but reported that only the organic sodium played a catalytic effect in promoting the combustion of Zhundong lignite, while the water soluble sodium increased the ignition temperature and burnout time. Moreover, as emphasised by Hardesty and Pohl [17], the TGA data are not directly related to combustion characteristics and the experimental conditions are significantly different from a real combustion process in a fluidised bed combustor. Thus, a need exists for deeper, fundamental understanding of the combustion performance of Zhundong lignite.

Against the aforementioned backdrops, the current work studied the ignition and combustion characteristics of single particles of Zhundong lignite in air in an electrically heated furnace using the single particle technique [19–21]. The effect of water and acid washing, as a means to manipulate the types and amount of sodium in the lignite, on the ignition and combustion characteristics were examined in detail.

2. Experimental

2.1. Materials

A “Run of Mine” Zhundong lignite (ZDL) was used in this study. The as-received lignite was first crushed into small chucks, which were then carefully filed into spherical particles of ca. 2.5 mm in diameter, prevailing fluidised bed coal combustion. A small hole of 0.25 mm was carefully drilled into the centre of the particle to allow easy attachment of the particle to the SiC fibre. The raw sample was denoted as ZDL-Raw. Water washed (ZDL-WW) and acid washed (ZDL-AW) samples were prepared by soaking the raw lignite particles in ultrapure water and 0.5 M hydrochloric acid (HCl), respectively, at 60 °C for 24 h with a solid to liquid ratio of 1 g:50 mL [10]. The washing process allowed the removal of water-soluble and acid-soluble sodium in ZDL-Raw, respectively. These Zhundong lignite particles were dried in an oven at 378 K overnight and stored in a desiccator ready for experimentation.

The proximate, ultimate analyses of the three samples, and the chemical compositions of the ashes, are listed in Table 1. The chemical compositions of ashes prepared from the raw, water and acid washed Zhundong lignite at ashing temperature of 550 °C were analysed using ICP-AES as shown in Table 2. From Tables 1 and 2, it can be noted that water soluble sodium (ca. 87.7% of the total sodium) was the major sodium form in the Zhundong lignite used in this study. The acid soluble and insoluble sodium accounted for the remaining 12.3% of the total sodium, being 12% and 0.3%, respectively. The surface functional groups of the three samples were also analysed using an FTIR spectrometer (Thermofisher, Nicolet 6700) and the results are presented in Fig. 1. Note that similar FTIR spectra are evident for these three samples, indicating that the washing treatments did not change the organic structure of the lignite significantly.

Structural parameters of the lignite samples including the BET surface area and pore volume were determined from the nitrogen physisorption isotherms obtained using a Tristar 3020 volumetric analyser (Micromeritics Co. Ltd.). The changes in the structural parameters before and after washing treatments are summarised in Table 3.

2.2. Experimental equipment and facilities

The ignition and combustion experiments were carried out using a single particle ignition and combustion technique similar to that described elsewhere [19–21]. The experimental rig, schematically shown in Fig. 2, consisted of a horizontal tube furnace (800 mm in length and 40 mm in diameter) with a temperature control that provided a hot air environment for combustion, a particle suspension system, and a linear stepper motor for delivering the lignite particle into the furnace. The heating rates of the single particle samples were estimated to be practically constant, at ca. 100 °C s^{-1}, under the conditions investigated in the present work using the embedded thermocouple technique reported from our previous works [18,20]. The