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Comprehensive coal quality index for evaluation of coal agglomeration characteristics

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ABSTRACT

A comprehensive analysis of coal quality factors affecting coal agglomeration characteristics was carried out. The influence weight of seven main coal quality indices on agglomeration was calculated by the entropy method. Furthermore, a reliable and comprehensive coal quality index was obtained to evaluate the characteristics of coal agglomeration by the agglomeration experiment results. The proximate analysis, ultimate analysis, and petrographic analysis results were applied for the analysis of organic constituents. The XRF and ash fusion temperatures were applied for the analysis of inorganic constituents. Results show that there is an absolute positive correlation between the C/H, FC/V and the characteristics of coal agglomeration. Both of the vitrinite content and the average reflectivity of the vitrinite have a positive effect on the coking ability of coal. Alkali oxides not only have a low melting point but also can react with Si and Al to form low melting point eutectics. Both of these characteristics result in coal ash slagging. The entropy method was adopted to analyze the effect weight of C/H, FC/V, vitrinite content Vi, vitrinite average reflectivity R_{ave}, ash deformation temperature (DT), Base/Acid ratio (B/A) and Silicon ratio (G) on the agglomeration characteristics of coal. The weights are 11%, 10%, 26%, 12%, 9%, 14% and 18%, respectively. Among them, vitrinite content had the largest effect, and DT had the least effect. In addition, an empirical index of coal agglomeration characteristics is proposed, and the discriminant limits are provided. The results are helpful to the evaluation of coal agglomeration, and useful to the safe and efficient operation of boilers.

1. Introduction

Coal is the dominant energy source in China, and about 70% of total electricity generation is from coal. During the process of coal-fired power generation, the agglomeration of fuel often occurred in boilers, especially the fluidized bed combustor [1]. The agglomeration will seriously reduce the combustion efficiency and lead to waste of fuels. Furthermore, the large slag block formed on the heating surface of boilers will not only worsen the heat transfer of the heating surface but also cause safety accidents [2]. Therefore, it is necessary and significant to study and analyze the coal agglomeration in the combustion process for the safe and efficient operation of boilers in industry.

At present, most studies of the agglomeration problem focus on the slagging which is caused by the fusion of ash in coal. However, in fact, a great many coals used for combustion have a degree of coking ability. In coking process, there also will be molten materials formed, which can cause the agglomeration phenomenon. Therefore, the agglomeration phenomenon indeed includes both of the coking and the slagging. For the coal with coking ability, the agglomeration phenomenon caused by the organic components in the combustion process cannot be neglected. Therefore, it is necessary to make a comprehensive analysis of coking and slagging in the combustion process for predicting the potential agglomeration possibility of coking coal.

It is known that coking and slagging characteristics are determined by the organic and inorganic components of the coal, respectively [3,4]. Currently, the research on coking ability mainly concentrated in the field of coal chemical industry. For coking coals, when the temperature increases, the coals always go through a specific process: thermoplastic properties soften, swell, and eventually re-solidify [5]. According to many researchers, there are many parameters which affect coke performance. Precisely, the coal rank parameters (moisture, volatile matter, carbon, etc.), petrographic composition, and impurities (ash, sulfur, and alkali contents) together control the quality of coals and fundamentally affect the coking coal quality [6,7]. Zhang [8] conducted coking experiments on 19 individual coals and 64 coal blends and found that coal with volatile content has a 22% −26% better coking ability. Speight [9] and Ghosh [10] found that the caking tendency of coals rises dramatically between 25% and 35% (by weight) volatile

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matter content (or between 81% and 92% (by weight) of carbon in coals, with a maximum at 89% carbon) and then decreases. Hower et al. [11] studied the coking characteristics of a number of eastern Kentucky coals and found that the coking ability increased with increased vitrinite maximum reflectance. Miller [12] analyzed the effect of petrographic composition on coking and considered the vitrinite as the most critical component of coal for coking. Moreover, there are a large number of appraising methods to evaluate the coking property, using indices such as Roga Index (RI), Caking Index ($G_{R.I.}$), Plastic Layer Index (Y) and other parameters.

Meanwhile, there are a large number of inorganic elements in coal, formed kinds of inorganic oxides known as mineral compositions such as SiO_2, TiO_2, Al_2O_3, CaO, MgO, Na_2O, K_2O, P_2O_5, Mn_3O_4, SO_3, Fe_2O_3, etc [10]. The minerals undergo a series of changes at high temperatures, and the slagging phenomenon occurred when the temperature reaches a certain value. Liu [13] studied the melting behavior of seventeen representative coal samples using SEM and XRD, and found that the ash fusion temperatures (AFTs) decreased with increasing Fe_2O_3 content. For the effect of the CaO content, the AFTs reached a minimum value when the CaO content approaches 30% and then increases once again. Shao et al. [14] reported phosphates together with the eutectics of Fe_2O_3 and SiO_2 might play the most important role in bed agglomeration during sludge combustion by forming low melting point compounds with alkalis. Additionally, some publications indicated that increased P_2O_5 content enhances the development of low-melting-point phases in the ash [15–17]. Base on much such research on ash compositions, there are some predictive and empirical indices introduced to evaluate the slagging tendency—such as Base/Acid ratio (B/A), Silica/Alumina ratio (SiO_2/Al_2O_3), Silica ratio (G), Iron/Calcium ratio (Fe_2O_3/CaO), and Composite Index R.

The present study made a relatively comprehensive analysis including proximate analysis, ultimate analysis and petrographic analysis of the coal quality characteristics for the five coals. The combustion experiment with muffle furnace and coal ash preparation experiment were carried out. In addition, SEM was used to analyze the morphology of the five coal coking samples. The composition of five coal ash and the ash fusion temperature were analyzed by XRF and triangular pyramid method. Based on the test and analysis of coal quality, an objective weight analysis method (Entropy Method) in the field of statistics [18] was used to analyze the effect weight of seven indices (C/H, FC/V, vitrinite content Vi, vitrinite average reflectance R_{ave}, ash deformation temperature (DT), B/A and G) on the degree of agglomeration of coal in combustion process. Furthermore, combined with the combustion results of five coals in a muffle furnace, an empirical formula for the evaluation of a coal agglomeration in combustion process was obtained, and the corresponding evaluation limits were given.

2. Experiments and methods

2.1. Experiments

The experimental procedures involve sample preparation and coal analysis, combustion experiment and agglomeration analysis, ash preparation and the melting characteristics analysis.

2.1.1. Sample preparation and coal analysis

Five coal samples which were frequently used as a source of power in the Heilongjiang Province were selected as the experimental materials. The proximate analysis of coals was measured by the Proximate Analyzer (5E-MAG6700, Changsha Kaiyuan Instruments, PRC). The proximate analysis was to measure the moisture, volatile matter, and ash content of the coal samples successively at different temperatures and residence time. The remaining part defaulted to the fixed carbon content. The coal sample was dried to constant quality at 105 °C–110 °C and the reduced mass was the moisture content. The coal sample was insulated from the air and heated for 7 min at 900 ± 10 °C, and the volatile content was the reduced mass minus the moisture content. For the ash content, the coal sample was put into a muffle furnace by raising the temperature up to 500 °C in more than 30 min and kept that temperature for 30 min and rose up to 815 ± 10 °C; then after 1 h, the residue mass was the ash content.

The ultimate analysis of coals was measured by the Ultimate Analyzer (VARIO MACRO CUBE, Elementar, Germany). The ultimate analysis was to burn or decompose the coal sample at high temperature and convert the test elements into gas for analysis. Analytical gases were analyzed by purge-trap adsorption and desorption on three special columns and then detected by a thermal conductivity detector (TCD) to determine the content of each element.

The petrographic analysis was performed with the microscope (LEICA DM2500P, LEICA, Germany) and the photometer (MSP200, J&M, Germany), following the procedures in the Chinese standards (GB/T6948-2008 and GB/T8899-2013). About 2 g of the coal sample was mixed with shellac (at a volume ratio of 2:1) and heated to 50 °C to prepare a briquette, and then the briquette was polished. The polished briquette was analyzed by microscope for its maceral compositions, and the same briquette was used to analyze the vitrinite reflectance in oil.

2.1.2. Combustion experiment and agglomeration analysis

The combustion experiment was conducted in a muffle furnace. Five coal samples were milled and sieved to about 0.2 mm in size, and each sample weighing 2 g was put in a crucible, then the crucible was placed directly into the high-temperature (1000 °C) muffle furnace for 7 min. After the combustion, the degree of agglomeration was evaluated according to the Char Residue Characteristic (CRC) value, which was used to evaluate the potential coking ability of coal in 8 ranks by the shape and strength of the coal char in the proximate analysis, just like the Free Swelling Index (FSI) in America. It is classified into weakly (Rank 1–2), medium (Rank 3–5), strongly (Rank 6–8). Rank 1–2 refers the coal char is still in powder without agglomeration. Rank 3–5 refers the coal char is agglomerated but can be crushed by finger press. Rank 6–8 refers the agglomerated coke with silver-white luster on its surface is formed, and it cannot be crushed by a finger press.

Moreover, the micro-morphology of char was observed by scanning electron microscopy (SEM) (EVO18, produced by Carl Zeiss, Jena, German). X-ray diffraction (XRD) (Empyrean, produced by Panalytical, Netherlands) and X-ray fluorescence (XRF) (PW4400, produced by Panalytical, Netherlands) were used to analyze the mineral compositions and element contents.

2.1.3. Ash preparation and the melting characteristics analysis

The ash of coal samples was prepared in a muffle furnace based on the Chinese standard GB/T212-2008. The specific process of ash preparation is the same as the determination of ash content in the proximate analysis, which has been introduced in Section 2.1.1. The elements of the ash were measured by XRF. Moreover, several commonly used indices for the prediction of slagging were evaluated, including the Base/Acid ratio (B/A), Silicon ratio (G), Silicon/Calcium ratio (SiO_2/CaO), and Iron/Calcium ratio (Fe_2O_3/CaO). Finally, The characteristic temperatures of coal ash fusion were measured by using the triangular pyramid method.

2.2. Methods

The entropy method firstly appeared in thermodynamics and was introduced into the information theory later by Shannon [19]. Nowadays, it has been widely used in engineering, economy, finance, etc. The entropy theory is an objective way for weight determination. Tian and Du [20] used the entropy method to evaluate the performance of mechanical products, and the results were in good agreement with the actual conditions. Fang [21] et al. used entropy method in the field of financial investment, which proved the simplicity and scientificity of entropy method in market state forecasting. Xu [22] et al. In the field of