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Trace element concentration and reduction of typical Chinese bituminous coals via dry physical separation techniques

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HIGHLIGHTS

- A dry physical separation flowsheet was proposed to clean the run-of-mine coal.
- Removal percentages of ash and sulfur contents and the major TEs in coals were compared.
- Concentration and reduction of the major TEs in coals via the dry separation were analyzed.

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ABSTRACT

Dry physical separation techniques were used to clean typical Chinese bituminous coals by removing their ash and sulfur contents and major trace elements. Different dry coal separators, such as the conventional dense-medium gas–solid fluidized bed separator, vibrated dense-medium gas–solid fluidized bed separator, and triboelectric separator, were used to clean various-sized coal samples. Results suggested that the coal quality could be significantly improved through coal cleaning, which removed the mineral impurities of coal and therefore decreased its ash and sulfur contents. The majority of the trace elements were efficiently removed from run-of-mine coals and were found concentrated in the tailings after separation, thereby showing the highest removal efficiency for several harmful elements, including As, Co, Cr, Hg, and Mn in particular. Despite the removal percentage of the majority of trace elements, which obviously decreased with a decrease in the particle size of the coal sample, the overall removal efficiency satisfied the requirements of coal cleaning. The proposed dry physical separation flowsheet provides an alternative efficient approach to coal cleaning that can be utilized in the arid and water shortage countries.

1. Introduction

Coal plays a significantly important role in the fuel industry as the primary material in electricity generation and coal chemical processes. However, the direct coal-firing causes considerable environmental pollution through the emission of hazardous gases and solid wastes. Trace elements (TEs) present in coal, such as mercury, arsenic, and lead, exert significantly adverse effects on the ecological environment and public health [1].

A few scientists from many countries have contributed to the in-depth researches on the investigation of TEs in coals from various viewpoints. Dai et al. [2] reviewed the geochemistry of TEs in Chinese coals, including their abundance, genetic types, and effects on human health problems caused by domestic coal combustion, as well as the recovery of valuable TEs. Vejahati et al. [3] clarified the association of TEs with coal and minerals and their behavior during coal utilization. Wang et al. [4] focused on the mineral microspherules in Chinese coals and their geological and environmental significance. Luttrell et al. [5] evaluated the coal preparation technologies to control TEs emissions. Some researchers also investigated the behaviors of TEs and minerals in coal during preparation and combustion [6–10]. The aforementioned achievements significantly suggest that coal cleaning based on the physical separation technique efficiently assists in reducing not only the mineral impurities of coal, but also the TEs associated with such minerals. Consequently, the TEs in run-of-mine (ROM) coals have a great potential to be concentrated and removed through physical coal-cleaning techniques, such as coal preparation and beneficiation.

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The use of water-based separation technologies of coal is currently dominant in the coal processing industry; such technologies include hydraulic jigging, dense medium cyclone separation, spiral separation and coal slime flotation. However, water-shortage, which has become a worldwide problem, greatly limits the utilization of wet coal separation, particularly in some water-deficient but coal-rich countries (China, India, and South Africa). Thus, air-based separation technologies of coal, including air jigging, air table, FGX separator, and dense medium gas–solid fluidized bed separator (DMFBS), have been developed since the 1920s [11–14]. In particular, DMFBS has been recognized as a potential technology for coal cleaning because it has the advantages of low cost of investment, zero water use, high separation efficiency, and wide range of separating density. Many scientists have focused on the development of the DMFBS technique in recent years and have realized considerable achievements [15–18]. Researchers at China University of Mining and Technology (CUMT) have contributed to theoretical and practical studies on the gas–solid fluidized separation technology since the 1980s [19–23]. They successfully clarified the separation theory of DMFBS and realized the efficient separation of a 6–50 mm coal via a conventional DMFBS. The separation of 1–6 mm fine coal was successfully improved by introducing vibration energy into a conventional DMFBS to form a vibrated DMFBS [24]. In addition, some investigations have also been conducted on the separation performance of <0.074 mm coal fines at CUMT and have obtained a few satisfied results [25–27].

The fluidization characteristics of DMFBS and the separation performances of various-sized coals via different dry coal separation techniques have been carefully investigated, with a large quantity of theoretical analysis and experimental verification [22]. However, few studies have been conducted on the effects of dry separation technique on TEs concentration and reduction of coal. A deep understanding is required for the removal performance and efficiency of TEs in various-sized coals via different types of dry separators. Thus, in the present investigation, a dry physical separation flowsheet was proposed and used to clean various-sized coals. The concentration and reduction of ash and sulfur contents and the 24 trace elements of various-sized coal samples were studied by comparing the coal qualities before and after separation. This study aims to provide some fundamental results for the utilization of dry physical separation techniques in the fields of hazardous elements removal for coal cleaning.

2. Experimental

2.1. Materials

A typical Chinese bituminous coal was used as the testing coal sample. The ROM coal sample of >50 mm was crushed to the size fraction of below 50 mm firstly. Then, the coal samples were divided into six size fractions of 25–50, 13–25, 6–13, 1–6, 0.074–1 and <0.074 mm with using a set of testing screens. The ash content (A_d), sulfur content (S_t), and the sulfur forms of the coal samples were summarized in Table 1. The density composition analysis of the coal samples was conducted through the test of floating and sinking densimetric separation, with zinc chloride (ZnCl) as dense medium. The coal samples were separated into various density fractions of <1.3, 1.3–1.4, 1.4–1.5, 1.5–1.6, 1.6–1.8, 1.8–2.0 and >2.0 g/cm^3.

2.2. Dry physical separation approach

A dry physical separation flowsheet was used to clean the coal samples, with its schematic diagram shown in Fig. 1. Several previous achievements indicated that 6–50 mm coarse coal could be effectively separated into clean coal and tailing through a conventional fluidized bed separator (CFBS) [21]. The efficient separation of 1–6 mm fine coal could be realized with a vibrated fluidized bed separator (VFBS) [24]. Less than 0.074 mm coal fines could be treated by a triboelectric separator (TS) for coal cleaning [25–27]. The efficient dry separation of 0.074–1 mm coal fines was still difficult to achieve. Therefore, 0.074–1 mm coal fines were collected after screening and its separation was not considered in this study. The combined dry physical separation approach efficiently cleaned various-sized coals. In the separation, the magnetite powder with a broad size range of 0.074–0.3 mm was used as separating medium for CFBS and VFBS. Finally, the clean coals and tailings were obtained for coal samples with sizes of 25–50, 13–25, 6–13, 1–6 and <0.074 mm. The ash and sulfur contents of the various products were measured after sufficient separations. These products were collected to perform the trace element analysis and to validate the effects of harmful element removal using the physical separation technique.

2.3. Analytical methods of TEs

Based on the common measurement methods for various TEs, different measuring approaches were adopted to perform the analysis of TEs in the coal samples. Most concentrations of the TEs were analyzed and determined using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). Cold Vapor Atomic Absorption Spectrometry (CV-AAS) was adopted to analyze the element of Hg. The method of Ion Selective Electrode (ISE) was used to analyze the element of Cl.

3. Results and discussion

3.1. Analysis of the coal samples

The density composition of the coal sample was analyzed via the float-and-sink experimental measurements. Table 2 shows the yields, ash contents, and sulfur contents of various density fractions of 1–50 mm coal. The density composition of the coal sample presented a notable double-peak distribution. This observation indicated that the density fractions were mainly concentrated in the range of 1.3–1.5 g/cm^3 (1.3–1.4 and 1.4–1.5 g/cm^3) and in >2.0 g/cm^3. The yields of these two density fractions were 61.71% and 20.79%, respectively, which accounted for >80% of total coal sample. The coal sample mainly consisted of low- and high-density particles with a small amount of middle-density particles, indicating sufficient dissociation.

Coal ash is derived from the mineral substance in coal, which consists of the residue after burning the mineral substance. A lower coal ash content usually indicates a good coal quality. Sulfur is a

Table 1
Ash content, sulfur content, and the sulfur forms of the coal sample.

Size fraction of coal (mm)	Ash content (%)	Sulfur forms and content (%)			
		S_s	S_p	S_o	Total
1–50	21.16	0.04	0.52	0.31	0.87
<0.074	18.09	/	/	/	0.72