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Review of arsenic behavior during coal combustion: Volatilization, transformation, emission and removal technologies

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ABSTRACT

Growing public awareness of the environmental impact of coal combustion has raised serious concerns about the various hazardous trace elements produced by coal firing. Arsenic deserves special attention due to its toxicity, volatility, bioaccumulation in the environment, and potential carcinogenic properties. As the main anthropogenic source of arsenic is coal combustion, its behavior in power plants is of concern. Unlike mercury, arsenic behavior in coal combustion has not been subjected to systematic, in-depth research. Different researchers have reached opposing conclusions about the behavior of arsenic in combustion systems and, as yet, there is relatively little research on arsenic removal technologies.

In this paper, the volatilization, transformation, and emission behavior of arsenic and its removal technologies are discussed in depth. Factors affecting the volatilization characteristics of arsenic are summarized, including temperature, pressure, mode of occurrence of arsenic, coal rank, mineral matter, and the sulfur and chlorine content of the fuel. The behavior of arsenic during oxy-fuel combustion and the effect of combustion atmosphere (O_2, CO_2, SO_2 and $H_2O(g)$) are also reviewed in detail.

In order to better understand the pathways of arsenic in a power plant environment, a particular focus in this work is the transformation mechanism of ultra-fine ash particles and the partitioning behavior of arsenic. Finally, the effects of air pollution control devices (APCDs) on arsenic emissions are examined, along with the effectiveness of flue gas arsenic removal technologies with different kinds of adsorbents, including calcium-based adsorbents, metal oxides, activated carbon, and fly ash.

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1. Introduction

Although renewable and nuclear energy sources are becoming increasingly important for our future energy demand, coal combustion is still the dominant source for power generation in the energy mix in the foreseeable future. With increasing public awareness of the environmental impact of coal combustion, serious concerns have been raised regarding the emissions of various hazardous trace elements from power plants, such as mercury, arsenic, lead, and cadmium [1]. Among the most harmful elements, arsenic is receiving increasing attention due to its toxicity, volatility, bioaccumulation in the environment (enriched in biomass such as in hyperaccumulator plants [2–4]), and potential carcinogenic properties. Arsenic can affect the gastrointestinal tract, circulatory system, liver, kidneys, and skin [5]. Nearly all types of arsenic compounds are toxic, with As^{3+} being 50 times more toxic than As^{5+}. Inorganic arsenic exposure in humans is also strongly associated with lung cancer, while ingestion of inorganic arsenic can cause skin cancer [6]. Incidents of adverse health risks resulting from arsenic contamination in the environment have been reported in many countries. It has been reported that more than 3000 cases of arseniasis in villages in Guizhou (a typical area of arsenic contamination in China, which can also be found in other parts of the world) were caused by the use of locally mined high-arsenic coal. In addition, arsenic is the main cause of denitrification catalyst poisoning in selective catalytic reduction (SCR) systems [7–9]. In 2011, the US Environmental Protection Agency (EPA) [10] announced the first formal nationwide regulatory standard to “limit toxic gas emissions of power plants”, including an emission limitation for arsenic. Subsequently, in 2016, the EPA [11] published the latest national emission standards for hazardous air pollutants from coal- and oil-fired electric utility steam generating units. The emission limits for arsenic in various sources are listed in Table 1 below.

These strict emission limits underscore the need to study the volatility and transformation behavior of arsenic during coal combustion.

2. Arsenic in coal

2.1. Concentration of arsenic in coals around the world

The concentrations of arsenic in coals around the world are shown in Table 2. Due to the differences in post-depositional processes and coalification processes [12–17], large variations in arsenic content occur.

Although for most coals the average concentration of arsenic is 0.5–80 μg/g [15], some, for example those in southwestern China, have an extremely high concentration. The flue gas generated by high-arsenic coals may cause serious poisoning and deactivation of the SCR catalysts. Moreover, dispersion of arsenic-enriched fly ash can also contaminate soil and groundwater with resultant local arsenic poisoning.

2.2. Speciation of arsenic

Arsenic in coal occurs in three dominant forms: pyrite, organic, and arsenate [31–33]. Chen et al. [34] analyzed 147 Chinese coal samples from different coal-forming ages and ranks, and found that inorganic arsenic mainly occurred with sulfur in pyrite, especially as a substitute for sulfur in pyrite-type compounds [35–38]. Using chemical analyses from an electron probe micro-analyzer (EPMA), Savage et al. [39] suggested most arsenic was present in solid solution in pyrite, rather than in micro-inclusions of separate arsenic phases. Filby et al. [40] found that arsenic was always associated with inorganic elements. However, Goodarzi [41–43] suggested that for some Canadian coals arsenic had an organic association, while a strong organic association for arsenic was also suggested for a Texas lignite [44]. Factor analysis of 350 shale samples from the Illinois coal basin revealed association of arsenic with pyrite and organic matter [45].

Guo et al. [46] chose three Chinese coals to study the thermal stabilities of arsenic. Yunnan (YN) coal contained much more arsenic and sulfur than Datong (DT) and Yima (YM) coals. X-ray diffraction (XRD) results showed that the main mineral components in DT and