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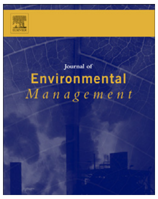

Research article

Fly ash classification efficiency of electrostatic precipitators in fluidized bed combustion of peat, wood, and forest residues

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ABSTRACT

The increasing use of biomasses in the production of electricity and heat results in an increased amount of burning residue, fly ash which disposal is becoming more and more restricted and expensive. Therefore, there is a great interest in utilizing fly ashes instead of just disposing of it. This study aimed to establish whether the utilization of fly ash from the fluidized bed combustion of peat, wood, and forest residues can be improved by electrostatic precipitator separation of sulfate, chloride, and some detrimental metals. Classification selectivity calculations of electrostatic precipitators for three different fuel mixtures from two different power plants were performed by using Nelson's and Karnis's selectivity indices. Results showed that all fly ashes behaved similarly in the electrostatic separation process SiO_2 resulted in coarse fractions with Nelson's selectivity of 0.2 or more, while sulfate, chloride, and the studied detrimental metals (arsenic, cadmium, and lead) enriched into fine fractions with varying selectivity from 0.2 to 0.65. Overall, the results of this study suggest that it is possible to improve the utilization potential of fly ashes from fluidized bed combustion in concrete, fertilizer, and earth construction applications by using electrostatic precipitators for the fractionating of fly ashes in addition to their initial function of collecting fly ash particles from flue gases. The separation of the finer fractions (ESP 2 and 3) from ESP 1 field fly ash is recommended.

1. Introduction

Biomass is a sustainable energy source used to produce electricity and heat. The use of renewable energy is encouraged by the political goals of European Union, such as “The 2030 climate and energy framework”, which has set the target to increase the share of renewable energy sources to at least 27% of EU energy consumption by 2030 (European Commission, 2014). Biomass fly ash is the residue produced from the combustion of biomass in power plants, paper mills, and other biomass burning facilities. Biomass, i.e., wood, bark, and other forest residues, is sometimes co-fired with peat. Among combustion methods, fluidized bed combustion (FBC) is efficient and commonly used due to its ability to utilize low-grade fuels with fluctuating quality, composition, and moisture content or mixtures of fuels in situ capture of SOx and low NOx emission (Patel et al., 2017). However, the fly ash originating from FBC has limited utilization potential, unlike ashes from pulverized coal combustion, and until recently these types of fly ashes have been disposed of. However, disposal is becoming more and more restricted and expensive; therefore, additional applications in which fly ashes could be utilized efficiently are in demand.

Some fly ashes can be utilized in soil improvement (Lanzerstorfer, 2011; Pedersen, 2003), earth construction (Ohenoja et al., 2016a, 2016b), and as a fertilizer (Budhathoki and Väisänen, 2016; Dahl et al., 2009; Ingerslev et al., 2011; Nurmesniemi et al., 2012) if their properties comply with quality regulations. The regulations are country-specific, although international regulations exist as well. For example, the Finnish national legislation MMM 24/11 (Finnish Ministry of Agriculture and Forestry, 2011), which came into effect in 2011, regulates the utilization of ash as a field or forest fertilizer and sets minimum acceptable content for Ca, the sum of phosphorous and potassium, and the maximum content for detrimental metals. Fly ashes used in earth construction must comply with Government Degree 591/2006 concerning the recovery of certain wastes in earth construction amended by Government Degree 403/2009 (Finnish Ministry of the Environment, 2009,

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p. 403). For concrete application, the European standard SFS-EN 450-1 (Finnish Standards Association, 2012) sets the maximum values for chloride and sulfate; however, it should be noted that the use of FBC fly ashes in concrete is not standardized in EN 450-1, which applies to ashes originating from pulverized coal combustion where the coal content must be over 60%, or over 50% when coal combustion takes place with pure wood. However, these limit values still provide a guideline for fly ash utilization in concrete. However, FBC fly ash utilization in concrete has been studied in few papers (Rajamma et al., 2015, 2009; Rissanen et al., 2017).

Quite commonly, the excessive content of heavy metals can prevent the use of fly ashes in the aforementioned applications. Manskinen studied the fuel composition of two different ashes and two different ash fractions (bottom and fly ash) originating from FBC and concluded that only bottom ash is able to be utilized as is (Manskinen, 2013). For other ash fractions, the heavy metal content was too high. In particular, the cadmium content in fly ash produced from wood combustion is known to often exceed regulations (Narodoslawsky and Obernberger, 1996; Pedersen, 2003). Cadmium is considered the most harmful of all heavy metals because it remains in the soil, becomes enriched in food chains, and is toxic to organisms (Orava et al., 2006). In addition to heavy metals, the utilization of fly ash in concrete applications is limited by chlorides and sulfates. The presence of chlorides and sulfates in cementitious materials can reduce durability through deterioration of the microstructure (Rajamma et al., 2009).

In the combustion process, electrostatic precipitators are commonly used to collect particles from flue gases using an electrical force (Intra et al., 2010; Jaworek et al., 2013; Van de Velden et al., 2008) due to their relatively inexpensive use and high collection efficiency: typically over 99% (Lind et al., 2003; Mizuno, 2000). Quite often, an electrostatic precipitator consists of two or three units connected in a series to ensure high collection efficiency. The particle size of fly ash is the largest in the first collector chamber and the finest in the last chamber. In a pulverized fuel fired boiler system, the concentrations of environmentally available volatile metals, like cadmium (Cd), copper (Cu), lead (Pb), and zinc (Zn), increased towards finer grained ESP fractions (Świetlik et al., 2012). Also, in FBC systems, the concentrations of heavy metals have been found to be at their lowest in the first collector chamber and highest in the last chamber (Orava et al., 2006). Orava et al. found that the heavy metal concentration can be reduced by applying electrostatic precipitation fractionation: for cadmium concentration, the reduction was as high as 70%. Therefore, it can be said that electrostatic precipitation is an acceptable method for fractionating fly ash, in addition to its original function of collecting fly ash particles from flue gases.

Even though there is great potential to use electrostatic precipitators as classifiers and to separate more hazardous fractions, there is no comprehensive study about the classification selectivity of electrostatic precipitator units. In addition, there is no information whether it is possible to separate sulfate and chloride using electrostatic precipitators. This is significant because the separation of those elements is important when fly ash is utilized as a cement replacement material. Therefore, this study aimed to establish whether the utilization of fly ashes from FBC of peat, wood, and forest residues can be improved by electrostatic precipitator separation of sulfate, chloride, and some detrimental metals. Classification selectivity calculations of electrostatic precipitators for two different Finnish power plants were performed by using Nelson's and Karnis's selectivity indices. This paper presents first time the use of these indices for the electrostatic precipitators; the indices have been used previously in screening, cleaning, fractionation, and flotation studies (Hautala et al., 2009; Karnis, 1997; Körkkö, 2012; Nelson, 1981). Fly ash samples were collected from both power plants with three different fuel mixtures to show the potential variations in ash quality: low, average, and high peat content.

2. Materials and methods

2.1. Fly ashes

The work was done using fly ashes from two different Finnish power plants. The fuel of the first power plant consists of a mixture of peat and forest industry residuals, mainly bark, in a 250 MW bubbling fluidized bed boiler (BFBB) while in the other boiler peat is burned together with wood in a 100 MW circulating fluidized bed boiler (CFBB), Fig. 1a. No limestone is added in either plant, except that, in the first case, a paper mill sludge containing $CaCO_3$ is fed into the boiler from time to time. The fly ash samples were collected in both power plants with three different fuel mixtures: low, average, and high peat content. The exact proportion of peat content in the fuel is not known. However, in the “low peat mixture,” the peat content is roughly 30%–40% of the total mass of fuel; in the “average peat mixture,” it is around 50%; and, in the “high peat mixture,” the peat content is around 60% of the mixture. The fly ash samples were collected from three fields of the electrostatic precipitators (ESPs) so that the first field is marked as 1, the second as 2, and the third as 3 (Fig. 1b). The mass shares of the ESPs are different depending on the power plant: at the first plant (BFBB), field 1 has a mass share of 84%, field 2 has a mass share of 14%, and field 3 has a mass share of 2%; at second plant (CFBB), they are 60%, 30%, and 10%, respectively. In total, 18 different fly ashes were studied. The sample names and origin are presented in Table 1.

The chemical composition, loss on ignition (LOI), specific surface area (BET), and particle size of all 18 fly ash samples were studied (see supplementary materials, Table S1). The chemical composition of all fly ashes was mainly made up of CaO, SiO_2, Al_2O_3, and Fe_2O_3. Fly ashes contained also from 3% to 12% of sulfate and from 0.1% to 0.8% of chloride. Trace elements reported here were arsenic (As), cadmium (Cd), and lead (Pb) since those elements are typically the most critical for these types of ashes.

2.2. Methods

2.2.1. Analysis of fly ashes

The particle size distribution of the fly ash samples reported as a volumetric median size (d_{50}) was measured with the laser diffraction technique (Beckman Coulter LS 13320) using the Fraunhofer model and dry procedure. The main chemical components of fly ash were determined from a melt-fused tablet using XRF (X-ray fluorescence analysis from Omnian Pananalytics, Axiosmax 4 kV). The melt-fused tablet was produced from 1.5 g of fly ash melted at 1150 °C with 7.5 g of X-ray Flux Type 66:34 (66% LiB_4O_7 and 34% $LiBO_2$). Trace elements were measured with inductively coupled plasma atomic emission spectroscopy (ICP-OES) from wet digested samples. The microwave-assisted wet digestion was performed using a 3:1 ratio of HNO_3 and HCl acid mixture for 0.5 g of fly ash at 175 °C according to EPA3051A (United States Environmental Protection Agency, 2007). Specific surface area measurement was based on the physical adsorption of gas molecules on a solid surface using Micrometrics ASAP 2020 and results were reported as BET isotherm.

2.2.2. Selectivity calculations

Since the aim was to determine whether the utilization of fly ashes could be improved by fractionation with electrostatic precipitator, selectivity calculations were performed for ESP 2 and 3 fields. Typically, fly ashes from 2 to 3 fields are mixed with fly ash from ESP 1 at silos, but, by changing the process slightly, fractions