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Physical and chemical characteristics of flue-gas particles in a large pulverized fuel-fired power plant boiler during co-combustion of coal and wood pellets

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ABSTRACT

Fossil fuel combustion should be decreased in future years in order to lower the CO_2 emissions of energy production. The reduction can be achieved by increasing the amount of CO_2-neutral fuels in energy production. Here 6–13% of coal was substituted with industrial or roasted pellets in a pulverized fuel-fired power plant without making any changes to fuel grinding or low-NO_x burners. The effect of pellet addition for the flue gas particles was studied with direct sampling from the boiler super heater area. Based on primary dilution ratio tests, transmission electron microscope images, and the natural electric charge of the particles, it was observed that particles in the flue gas are spherical and have been formed in the boiler at high temperatures. The pellet addition lowered the total particle number concentrations with all of the studied pellet–coal mixtures in comparison to the coal combustion. The 10.5% industrial pellet addition caused a second mode in the particle number size distribution. In addition, based on the chemical analysis of the collected size-fractioned particle samples, results indicated that the pellet addition did not increase the corrosion risk of the boiler. However, the changes in the particle number size distribution and total particle number concentration can affect the operation of electrostatic precipitators and flue gas cleaning.

1. Introduction

Climate change has caused a global need to reduce CO_2 emissions. These emission reductions are driven mainly by local political decisions [1,2], but larger scale political actions also exist. In principle, smaller CO_2 emissions can be achieved by reducing the usage of fossil fuels in traffic, residential needs, and in power generation. This can take place by reducing the energy consumption or by substituting fossil fuels with renewable fuels (e.g., biofuels, solar and wind power). One likely cost effective possibility in these actions is to utilize existing coal-fired power plant infrastructures and substitute the coal used in those with biomass. However, decreased CO_2 emissions and the addition of biomass can change the emission of other harmful pollutants and also increase the corrosion risks for the power plant boilers. Biomass-based fuels have a different chemical composition than fossil fuels such as coal [3]. Biomass fuels typically contain more alkali metals and chlorides [3,4], which can, in the combustion process, be vaporized into the flue gas [5]. For instance, alkali chlorides are found to be harmful for the power plant boiler materials [6]. After the combustion process, corrosion-causing elements can exist in the vapour or particle phase [7], depending on the temperature and concentrations [8]. For instance, a change in the boiler temperature profile affects the deposition locations of the alkali chloride [8]. In principle, the amount of alkali chlorides in the particle phase can be determined when the particle size distribution and chemical composition of the particles are studied simultaneously.

In addition to the temperature profile existing in the boiler and the chemical composition of the fuel, the fuel grain size also has

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an effect on the combustion process and the slagging and fouling of the super heater surfaces. The fuel grain size affects the particle size distribution after combustion in the flue gas. Ninomiya et al. [9] have studied the effect of coal grain size in terms of particle mass (PM) emission. They discovered that <63 µm coal particles produce bimodal PM distribution, with mode means of 500 nm and 4 µm. They also found that there is a small mode around 130 nm, which consisted of alkali metals, heavy metals and their sulphate, chloride and phosphate salts. The flue gas is steered to flue gas ducts and released in to atmosphere with or without some flue gas cleaning. Particle properties such as size, chemical composition, and the electric charge carried by particles affect the flue gas cleaning efficiency [10,11].

In general, the flue-gas changes in large power plant boilers can affect, for example, the corrosion of the super heater area and other parts of the flue-gas system, the flue-gas cleaning systems and, finally, the emissions of power plants. These effects depend on the characteristics of aerosol generated in the combustion process. The emissions of particles from combustion plants and other sources are governed by the Convention on Long-Range Transboundary Air Pollution of the United Nations Economic Committee for Europe. The 2012 amendments to the Convention include national emission reduction commitments by 2020 and beyond. The limit values for SO_2, NO_x, ammonia, volatile organic compounds and particulate matter (i.e., with a diameter equal to or less than 10 µm), including black carbon, are separately defined for coal and biomass with no mention of co-combustion [12]. In addition to the EU Member States, Canada, the United States, Russia and several countries of Southern and Eastern Europe, the Caucasus and Central Asia are also expected to sign the amendments. In its related legislation, the European Union also separates the emissions from coal and biomass without any mention of prospects of co-combustion [13–15].

However, the partial substitution of coal by biomass and subsequent co-combustion is one of the pathways identified in the European Industrial Bioenergy Initiative (EIBI) of the European Commission and the EU Member States. The EIBI pays attention to local variation in the available biomass feedstock options and suggests “a pragmatic approach to select the most promising options, based on transparent criteria reflecting a set of key economic, environmental and social performances expected” [16]. The European Commission deems co-combustion of biomass and coal to be “the most cost-effective option for electricity production”. Addition of biomass up to 10% share of total power output has been successfully demonstrated and the technology is commercially available. This technology makes use of existing plant infrastructure and requires only limited investments in biomass pre-treatment and feed-in systems [17]. However, “feeding, fouling and ash disposal pose technical challenges that reduce reliability and lifetime of coal plants. Higher co-firing mix will require more sophisticated boiler design, process control and fuel handling and control systems” [18]. The European Commission is hesitant towards to establish a specific policy for the co-combustion of biomass and coal. It notes that the incentives of the utilities running relevant combustion plants are national support schemes and/or the emission ceiling of the emissions trading scheme (ETS). Therefore setting a policy for co-combustion installations without similar measures for coal-combustion plants might lead to decreased use of biomass and hence, by implication, higher emissions [19].

In the United States, short tests of co-combustion have been conducted since the 1990s. The Energy Information Administration expects co-combustion to be up to 20 times more prevalent by 2024 than it was in 2010 [20]. Federal-level research into the heating qualities of different biomass contents and emissions continues [21]. The 2014 Clean Power Plan offered by President Obama and the Environmental Protection Agency mentions that, in co-combustion, the “use of some kinds of biomass has the potential to offer a wide range of environmental benefits, including carbon benefits”, and that “[I]ncreasing renewable energy (RE) use will also continue to lower other air pollutants (e.g., fine particles, ground-level ozone, etc.)” [22]. While federal level regulation is debated, individual states can use renewable energy standards (RES) to incentivize power plant operators for co-combustion [20]. However, by 2012, only 3% RPS-motivated renewable energy capacity additions came from biomass [23]. With regard to co-combustion, plant operators hesitate over the costs of acquiring and transporting the biomass, as well as the long-term effects on process equipment [20].

In this article, flue-gas aerosol from a large scale pulverized coal-fired power plant boiler is investigated. The power plant combusted various mixtures of coal and two types of wood pellet. Special attention is paid to the particle number size distributions, total particle number concentration and chemical composition of particles in the diluted flue-gas sample taken from the boiler super heater area. In addition, the effects of wood pellets on the concentrations of gaseous species and particulate matter (PM) in the flue gas are shown. The aim is to understand the effect of co-combustion of wood pellets and coal on flue-gas aerosol formation and characteristics.

2. Experimental

2.1. Power plant

The power plant where the experiments of this study occurred is situated in Helsinki, Finland. In the power plant, there are two separate boilers, both equipped with flue gas cleaning systems that include electrostatic precipitators, semi-dry desulphurization, and fabric filters, in the given order after the boiler. Boilers (363 MW_{th}) are equipped with a reheater and utilizes the natural circulation of flue gas. Boilers are equipped with 12 low-NO_x technology burners (Tampella/Babcock-Hitachi HTNR low NO_x) that are at the front wall. The combustion air and at the same time the carrier air for the pulverized fuel is preheated up to 350 °C before the boiler and grinders. Main operation principle of low-NO_x burners is air staging with secondary and tertiary air, which lowers the combustion temperature to the level of around 1100 °C. Air staging decreases NO_x formation. The power plant boiler has originally been designed to combust pulverized coal that is fed to the boiler after being ground in ball ring grinders.

2.2. Fuel properties

In this study, some of the measurements were made with 100% Russian coal and some with mixtures of coal and pellets. In the latter case, coal was substituted with 6–13% (of the boiler thermal power) wood pellets; roasted pellets or industrial pellets (see experimental matrix in Table 1). Roasted pellet is torrefactioned wood pellet, also known as black pellet, steamed pellet, torrefactioned pellet and bio coal, manufactured from wood pellets by heat treatment at approximately 300 °C.

Industrial pellet (wood pellet of industrial quality) fulfils the standard EN 14961-1 requirements having lower quality than domestic quality wood pellets. Industrial pellet can include, for example, bark, which does not exist in higher quality wood pellets. Normally, wood for industrial pellets is gained by grinding stem wood or logs to powder and, after drying, by pressing the powder to pellets. Due to the preparation principle of industrial pellets, it is more brittle than domestic pellets and it contains more ash components.