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Fine particle collection of an electrostatic precipitator in CO_2-rich gas conditions for oxy-fuel combustion

Bangwoo Han, Hak joon Kim, Yong jin Kim *

Environment and Energy Systems Research Division, Korea Institute of Machinery and Materials, 104 Sinseongno, Yuseong-gu, Daejeon, 305-343, Republic of Korea

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ABSTRACT

The collection of particles in CO_2-enriched environments has long been important for the capture of CO_2 in order to clean gases via oxy-fuel combustion. We here report on the collection characteristics of fine and ultrafine particles using an electrostatic precipitator (ESP) in a CO_2-enriched atmosphere. In order to understand the characteristics of particle collection in CO_2-rich gas mixtures, the ionic properties of a CO_2-enriched atmosphere was also investigated. The electrical mobility of the ions in a CO_2-enriched atmosphere was found to be about 0.56 times that found in a conventional air atmosphere, due to the higher mass of CO_2 gas compared to that of air. The low electrical mobility of ions resulted in a low corona current under CO_2-enriched conditions. The collection efficiency of particles in a CO_2-rich atmosphere for a given power consumption was thus somewhat lower than that found in air, due to the low quantity of particle charging in CO_2-enriched air. At the same time, higher temperatures led to the higher electrical mobility of ions, which resulted in a greater collection efficiency for a given power. The presence of a negative corona also led to a greater collection efficiency of particles in an ESP than that achieved for a positive corona.

1. Introduction

Over the past century, the consumption of large amounts of fossil fuel has resulted in global warming due to the emission of greenhouse gases such as CO_2. Although alternative energy sources, such as fuel cells and solar energy, have been developed to reduce these emissions, they have not yet shown the potential to satisfy current demands for energy. As one of the principal future sources of energy, coal has again become important because of its stability of supply and relatively low cost (Buhre et al., 2005). However, any greenhouse gases emitted during the combustion of coal must be reduced in order that coal can continue to be used in a CO_2-constrained future. As a means of capturing CO_2 gas during combustion, the technology of oxy-fuel combustion has recently enjoyed considerable interest (Buhre et al., 2005; Sheng et al., 2007; Tan et al., 2006). Because oxy-fuel combustion makes use of oxygen as an oxidant instead of air and of CO_2 gas as a recycled medium of combustion, and because the products of combustion therefore mainly consist of CO_2 and water, it is easy to return and capture CO_2 gas that has a high purity.

Electrostatic precipitators (ESPs) have enjoyed widespread use for collecting the fine and ultrafine particles generated during the combustion of coal. ESPs make use of the formation of a corona discharge to charge and collect aerosol particles. Particle charging is primarily influenced by ionic mass and mobility, and thus a small mass and high mobility lead to a high charging quantity of particles (Fuchs, 1963). Changes in the composition of the gas during oxy-fuel combustion can therefore have a significant effect on the performance of ESPs, because the ionic properties and particle charging states in ESPs are generally changed by the composition of the surrounding gas. The effect of using a mixture of gases on the resulting ionic properties must be studied in order to assess the collection of particles by ESPs in CO_2-rich gas mixtures with any confidence.

Sheng et al. (2007) investigated the characteristics of the submicron particles emitted from a bench-scale oxy-fuel combustion system and found that the size distribution of the particles emitted showed a somewhat lower yield of the submicron particles than that produced by combustion in air. Mikoviny et al. (2007) studied the ozone and carbon monoxide generated from negative coronas in a CO_2 atmosphere. Recently, Suriyawong et al. (2008) investigated the collection characteristics of submicron particles in a cylinder-wire ESP using an oxy-fuel combustion system with a variety of O_2–CO_2 and N_2–CO_2 compositions, and found that the particle penetration in O_2–CO_2 was one to two orders of magnitude higher than that in O_2–N_2. However, the ionic properties in different compositions of gases were not studied in any detail, which no doubt explains the lack of coherence in their experimental data and calculations. The characteristics of particle collection for different compositions of gases were compared using a fixed corona current, but these should have been compared using a fixed power consumption, in order to analyze the collection characteristics from an economic point of view.

In the study described herein, ionic current and mobility were investigated for different air–CO_2 mixtures. The collection characteristics

* Corresponding author. Tel.: +82 42 868 7475; fax: +82 42 868 7284.
E-mail address: yjkim@kimm.re.kr (Y. Kim).

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of the fine and ultrafine particles in the ESP were also investigated as a function of power consumption at various temperatures and air–CO_2 mixtures, as well as at different gas velocities and corona polarities. The performance of ESPs in the fine and ultrafine particles was assessed due to the change of gas composition and temperature judging from the change of ionic properties.

2. Experiments

Fig. 1 shows the experimental setup used in the study. It consists of a particle generator, an air/CO_2 gas supply system, an electric tube furnace, an ESP, a high voltage power supply, and a particle measurement system. Three kinds of gas composition, namely pure (100%) air, 50% air/50% CO_2, and 20% air/80% CO_2 were supplied to the tube furnace by means of air and CO_2 gas cylinders and their respective mass flow controllers. Potassium chloride (KCl) fine and ultrafine submicron particles with a size range of 10–500 nm were generated by a constant output atomizer (Model 3076, TSI, St. Paul, MN) with air as the carrier gas at a flow rate of 2 l/min. The mixture was passed through an aerosol neutralizer (Model 3012, TSI, St, Paul, MN) and a diffusion dryer (Model 3062, TSI, St, Paul, MN) to remove any humidity and initial electric charges that may have been generated during particle atomization. The mean diameter, number concentration, and geometric standard deviation of the particles were about 75 nm, 6.0×10^6 particles/cm^3, and 1.7, respectively. They were then mixed and diluted with the air/CO_2 mixture and thus the total number concentrations of the test particles became about 0.82–1.1×10^5 particles/cm^3 which have a negligible effect on particle coagulation (Hinds, 1999) and they were introduced into the electric tube furnace, which was heated to 300 °C. The particles were then passed through the ESP, which contained two parallel metal collection electrodes of 160 mm (H) × 260 mm (L) with a distance between them of 55 mm (W), and through three corona discharge electrodes, each consisting of 14 pins placed at a distance of 90 mm along the central axis between the two collection electrodes. The ESP was covered with glass wool to insulate it thermally. The difference in temperature between the inlet and the outlet of the ESP was less than 30 °C, and the residence time of the particles in the ESP was in the range 0.52–0.86 s. A power supply (30 kV/10 mA) was connected to the discharge electrodes of the ESP for their high voltage supply in the range 0–20 kV. The ionic current was measured using a microammeter that was connected to the grounded collection plate. The particle measurement system used was a scanning mobility particle sizer (SMPS, Model 3936, TSI, St. Paul, MN), which consisted of a long differential mobility analyzer (long-DMA, model 3071, TSI, St. Paul, MN) and a condensation particle counter (CPC, model 3776, TSI, St. Paul, MN). The aerosol and sheath gas flow rates in the SMPS were 0.3 and 3.0 l/min, respectively. The particle collection efficiency (CE) of the ESP was measured by comparing the downstream particle number concentration (N_o) with the upstream number concentration (N_i), both measured using the SMPS, at high voltage, as per the following equation:

$$CE = \left(1 - \frac{N_i}{N_o}\right) \times 100. \quad (1)$$

The mobility distributions of ions for different compositions of air–CO_2 were measured using a nano-DMA (Model 3085, TSI, St. Paul, MN) with positive and negative applied voltages of 0–10 V and an aerosol electrometer (Model 3068, TSI, St. Paul, MN). The sheath gas flow rate of the nano-DMA was 20 l/min and the ionic steam flow rate was 2 l/min.

3. Results and discussion

3.1. Ionic mobility distributions

In order to measure the electrical mobility of the ions for different compositions of air–CO_2, the ions were generated by passing the studied air/CO_2 gas mixtures through an Am-241 radioactive neutralizer. The ions that were generated in the ESP could not be detected at its outlet, because most of them were lost in the ESP due to the high electric field formed inside it. The electrical mobilities of the ions generated in the ESP in different gas mixtures may be inferred from those of ions generated from radioactive sources, because they exhibit almost identical ionic properties regardless of the ionic source (i.e. corona discharge, radioactive source, dielectric barrier discharge (DBD), or soft X-ray), provided that the surrounding gas is the same (Shimada et al., 2002; Kwon et al., 2006; Han et al., 2009). The experimental conditions were as shown in Table 1.

The mobility distributions of positive and negative ions for different mixtures of air and CO_2 were as shown in Fig. 2. The peak mobilities of the positive and negative ions in air were about 1.20 and 1.93 cm^2/(Vs) respectively, which are values similar to those reported

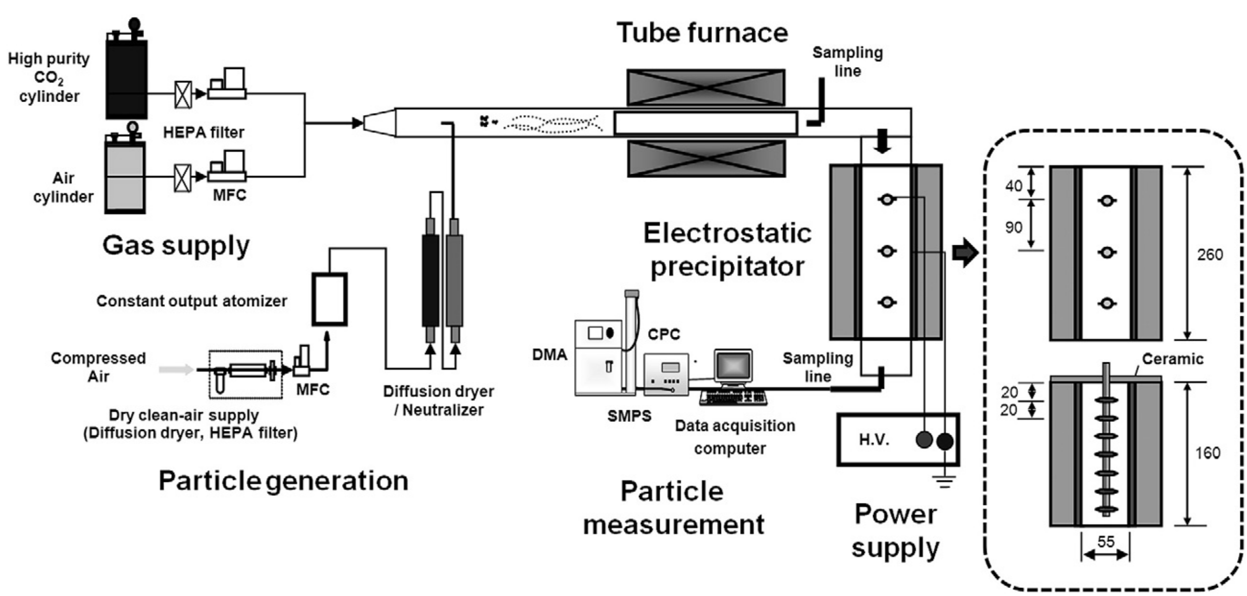

Fig. 1. Schematic of the experimental setup developed in the study.