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Effect of electrode configuration on particle collection in a high-temperature electrostatic precipitator

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ABSTRACT

This study investigated the influence of electrode configuration on corona discharge and particle collection from 300 K to 900 K. Electrodes of different shapes (rod, saw, and screw), diameters (3, 5, and 8 mm), and intervals (55, 110, and 165 mm) were tested in an experimental-scale electrostatic precipitator (ESP). Results showed that a high current was generated with a saw electrode and increased the particle collection efficiency, particularly for fine particles (diameter smaller than 0.1 μm), with the best particle collection efficiency being 99.8% at 300 K. However, with an increase in temperature, the rod electrode obtained an applied voltage higher than those of other electrode types and, as a result, generated relatively high particle collection efficiencies at 700 K and 900 K. Increasing the electrode diameter from 3 mm to 5 mm improved the applied voltage, whereas increasing this diameter from 5 mm to 8 mm reduced the discharge current. Among electrodes with different diameters, the electrode with a diameter of 5 mm achieved the best particle collection efficiency (87.4%) at 900 K. The applied voltages of the electrodes with different intervals were almost similar, but the discharge currents varied significantly. The best particle collection efficiencies were achieved by the electrode with an interval of 55 mm at 300 K and 500 K, but at 700 K and 900 K, the electrode with an interval of 110 mm obtained the best result. The interval between electrodes should be expanded with an increase in temperature to avoid the offsetting of electric field between neighboring electrodes.

1. Introduction

Particles in high-temperature gas cause various problems in many industrial processes. For example, coal fly ashes in high-temperature flue gas induce wear and tear in equipment and pipes, as well as poisoning and attrition of catalysts in selective catalytic reduction systems for NO_x control [1,2]. Thus, numerous industries that involve high-temperature gas utilization require high-temperature particle removal technology.

Many technologies have been developed for high-temperature particle collection, such as high-temperature cyclone separation, high-temperature ceramic filtration, high-temperature metal filtration, granular bed filtration, and high-temperature electrostatic precipitation [3–6]. Electrostatic precipitators (ESPs) have been used extensively to remove suspended particles given its advantages of low pressure drop (<500 Pa), low operation cost, absence of plugging, high collection efficiency (usually higher than 99%), and capability of treating large amounts of gas [7–9].

Particles in ESP are removed according to the following processes. High voltage is applied to the discharge electrode to induce corona discharge. Electrons and ions are generated and establish discharge current flows. Particles in gas streams are charged by the electric field and the ions, and are then transferred to collection electrodes by a Coulomb force [7]. Corona discharge and particle collection have been investigated by experimental and numerical method for high-temperature electrostatic precipitation. Biomass syngas purification was conducted by Villot et al. [8] at temperature of 783 K and 953 K and pressure of 0.2 MPa in an experimental wire-cylinder ESP. Particle collection efficiency of 96% was obtained at 953 K. Application of novel electrodes containing rare earths materials, which were characterized for thermionic emission was studied in wire-cylinder ESP by Gu et al. [10], and particle collection efficiencies of over 90% were obtained. A wire-cylinder ESP combined a photoelectric charger was used to investigate carbon nanoparticle collection by Kim et al. [11] from 967 K to 1112 K. The photoelectric charger allowed for 28.5% efficiency

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improvement in particle collection. Wang et al. [12] and Xiao et al. [13,14] investigated the proportions of electron current and ion current and the particle collection in a wire-cylinder ESP at high temperatures and evaluated the energy consumption index. In previous studies [15–17], authors investigated corona discharge characteristic for various electrode geometries and gas compositions, and the particle migration velocities for different particle sizes at various temperatures. The results showed the obvious decrease of particle collection efficiencies from 300 K to 900 K. According to previous studies, particle collection efficiency decreases with an increase in temperature, which limits the application of high-temperature ESP. Accordingly, the development of high-temperature ESP requires further research.

The distributions of the electric field and the electron/ion concentration bear a strong relationship to the electrodes; as a result, the particle collection process is influenced [18]. Various studies have been conducted to investigate the effects of electrode configuration on particle collection. The voltage–current characteristics, current distributions, and particle fractional collection efficiencies of two types of discharge electrodes were studied by Jędrusik and Świerczok [19] in a laboratory-scale ESP. Niewulis et al. [20] studied the vortices in the ESP with longitudinal and transverse wire electrodes. The results showed that the collection efficiency strongly depends on the discharge electrode positions. Podliński et al. [21,22] and Farnoosh et al. [23] studied the behaviors of different kinds of discharge electrodes in a laboratory-scale ESP. The electrodynamic secondary flow was closely related to the electrode configuration, and the differences in collection efficiencies of the electrodes were up to 8%. Navarrete et al. [24] investigated the rapping reentrainment of ESP with barb, pipe–spike, and twisted rod electrodes, it was found that an ESP with a high-energy electrode was preferable. According to previous studies, the optimization of electrodes was effective in enhancing particle collection efficiency. However, these studies were carried out at temperature from 293 K to 573 K. Research on electrode optimization for high-temperature ESP is limited, and the present understanding on the design and operation of traditional ESPs is not suitable for ESPs at high temperature [15,25].

Therefore, this study was committed to investigating the behaviors of different electrodes in a high-temperature ESP. Electrodes of different shapes, diameters, and intervals were tested in an experimental-scale ESP from 300 K to 900 K. The voltages and currents of the different electrodes were compared at various temperatures. Particle collection efficiencies were analyzed to determine the appropriate electrode at specific temperatures. The practical implications and limitations of certain electrodes were investigated at different temperatures. The results provide a reliable guide to design the appropriate electrodes for practical high-temperature ESPs.

2. Experimental approach

2.1. Experimental setup

The schematic of the experimental system is shown in Fig. 1. This system consists of five parts, namely, the sections for high-temperature flue gas generation, micro-particle feeding, experimental-scale ESP, high-voltage power source, and particle sampling and analysis. These sections are described in detail in a previous work [16]. The high-voltage power supply utilized in the experiment was a negative high-voltage power supply (DRTDM 40/2.0, WHSXHT, China) with a maximum output voltage of 40 kV and a maximum current of 50 mA. The experimental ESP had two steel grounding parallel plates functioning as collection electrodes. The collection electrodes were 840 mm in length, 240 mm in height, and separated by a distance of 120 mm. The total ESP collection area was 0.40 m^2. Three corundum plates (99.5% in purity) were placed on the top of the ESP and served as insulators to avoid current leakage. High-temperature sealant was employed to avoid gas leakage [16]. The parameters of the unit and operation condition have been summarized in Table 1. An electrical low-pressure impactor (ELPI) (ELPI-01, Dekati, Finland) and diluter (DI-1000, Dekati, Finland) replaced the impactor (PM10, Dekati, Finland) used in the previous work to measure the particles in the sampling gas more accurately and in real time. The diluter was a two-stage mixer, which mixed the sampling gas with a certain amount of clean air to reduce the particle concentration, thereby meeting the ELPI measurement limit. The ELPI was employed to measure the fractional number densities of the differently sized particles in the sampling gas. The sampling gas passed through a unipolar positive-polarity charger, wherein the particles were charged electrically by the small ions produced in a corona discharge. Subsequently, the charged particles were classified based on size in a low-pressure impactor, which was an inertial device that categorized particles according to aerodynamic diameter. When particles were deposited on the collection plates of the impactor at individual stages, the charges carried by the particles were transferred to sensitive (fA-level) multichannel electrometers. The measured current values were inverted to calculate the particle number concentrations. The sampling gas of the ELPI was extracted by a vacuum pump (SV25B, Leybold, France) and set to 10 L/min [26].

Different electrodes were used in the experiment and characterized according to shape, diameter, and interval. These parameters are listed in Table 2. Three differently shaped electrodes were utilized in the experiment, namely, rod, saw, and screw electrodes. Detailed illustrations of these electrodes are shown in Fig. 2. The rod electrode was 5 mm in diameter and 180 mm in length. The saw electrode was composed of seven pairs of saws on both sides along a line; the saws were parallel to the plate. The screw electrode had a length of 180 mm, an interior diameter of 3 mm, and an exterior diameter of 5 mm. The rod electrodes employed in the experiment had diameters of 3, 5, and 8 mm and intervals of 55, 110, and 165 mm. The interval for the electrodes with different diameters was 110 mm, and the diameter of the electrodes with varying intervals was 5 mm. Four temperatures were tested during the experiment: 300, 500, 700, and 900 K. The gas velocity of the flue gas in the ESP was maintained at 0.3 m/s at all temperatures.

2.2. Characteristics of test particles

The particle used in this experiment was obtained from a coal-fired power station in Zhejiang, China. The chemical composition of this particle is presented in Table 3. The coal ash chemical composition was analyzed according to GB/T 1574-2007, which is the standard testing method for the analysis of coal ash in China [27]. The test was carried out in the State Key Lab of Clean Energy Utilization. The deviation of the result was added in the Table 3. The size distribution of the testing particle was measured with a laser particle size analyzer (LS-230, Coulter, US), as presented in Fig. 3(A). The particle specific resistivity, which was measured with a high-temperature particle resistivity meter, ranged from 90 °C to 800 °C, as displayed in Fig. 3(B), while the error-bar was hard to identify for of the particle specific resistivity changed from $1.91 \times 106\ \Omega$ cm to $4.17 \times 1011\ \Omega$ cm during the test. The mechanism of the equipment employed to measure particle size and specific resistivity was introduced in a previous article [16]. All the tests on particle characteristics were performed twice to ensure that all results were repeatable.

The median particle diameter (d_p) was 16.7 μm, and the volume ratios of $PM_{d<2.5}$ (particles with an aerodynamic diameter smaller than 2.5 μm), $PM_{2.5<d<10}$ (particles with an aerodynamic diameter