Electrostatic Capture of $PM_{2.5}$ Emitted from Coal-fired Power Plant by Pulsed Corona Discharge Combined with DC Agglomeration

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Abstract: How to improve ESP collection efficiency for $PM_{2.5}$ is getting a matter of environmental concern. in this paper, a process capable of capturing $PM_{2.5}$ efficiently was proposed, which utilizes a pulsed corona discharge combined with dc agglomeration. a laboratory-scale wire-plate electrode configuration was established. the particle electrostatic charging and number concentration distribution of $PM_{2.5}$ have been measured by an electric low pressure impactor (elpi) at real time with the size range from 0.007 μm to 10 μm. the particle charging and collection efficiency characteristics of $PM_{2.5}$ were quantitatively investigated under different applied pulse peak voltage. the results show that for a certain given operating condition, $PM_{2.5}$ collection efficiency increases with the increasing pulse peak voltage. dc voltage agglomeration is used to achieve a number reduction exceeding 90% on the submicron fraction of particles. this research may provide a new technology for efficient removal of $PM_{2.5}$ from flue gas in coal-fired power plant.

Keywords: $PM_{2.5}$, pulsed corona discharge, DC agglomeration, particle charging, collection efficiency

1 INTRODUCTION

Electrostatic precipitators (ESP) have been widely used as one of the most common particulate control devices for collecting aerosol particulate emissions from coal combustion [1-3]. The ESP removes more than 99% of the particulates from the flue gas in terms of mass concentration. However, the particle collection efficiency of the conventional ESP in terms of number concentration is relatively low, especially for $PM_{2.5}$, which results in a large number of aerosol particles emission in the atmosphere[4-6]. Therefore, there has been an interest in improving the ESP collection efficiency for the submicron particles. One of the most efficient methods for improving ESP collection efficiency for submicron particles is the particle agglomeration[5,7,8]. Recent studies have reported that high agglomeration efficiency of bipolar-charged submicron particles was achieved. Researchers adopted both negative and positive corona chargers to realize bipolar-charged particles for DC and AC agglomeration[9-13]. Since most of the submicron particles escape from the ESP due to insufficient particle charging, short positive pulse corona energization has been used to enhance the particle charging and achieve particle bipolar-charged[14-16]. It is well known that particle charging is the key to electrostatic agglomeration. Therefore, in order to maximize the collection efficiency of the submicron particles, it is very important to understand the particle charging characteristics.

In this paper, a wire-plate ESP with positive pulsed corona energization combined with DC agglomeration was designed. In this system, the first ESP electric field serves to collect the large-sized particles, the second and third ESP electric field promotes an enhancement of submicron particle charging, and the last ESP electric field accelerates the particle agglomeration and collects the enlarged particles. The particle charging and collection efficiency characteristics enhanced by pulsed corona discharge combined with DC agglomeration were experimentally investigated under different pulse peak voltages.

2 EXPERIMENTAL

2.1 Experimental Setup

A schematic diagram of the experimental system is shown in Fig. 1. It mainly consists of a fly ash generator, an ESP with two kinds of power supplies, and an ELPI measurement system. The test fly ash particles were dried and generated by a vibration feeder with constant dosage characteristics. After that, the fly ash particles were mixed with particle-free air to obtain desired flow rate and then introduced into the ESP. The ESP is of wire-plate structure,

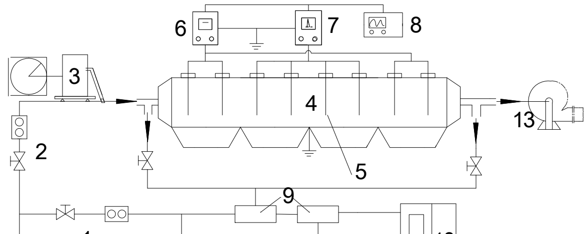

Fig. 1 Schematic diagram of the experimental system
(1) compressor; (2) flowmeter; (3) fly ash feeder; (4) ESP; (5) discharge electrode; (6) DC supply; (7) pulse supply; (8) oscilloscope; (9) dilution system; (10) ELPI; (11) computer: (12) vacuum pump; (13) exhauster

which consists of four electric fields with two polished stainless-steel plates as the collection plates and eight wire discharge electrodes in middle. The first and last electric fields of the ESP are supplied by negative DC, while the second and third electric fields are supplied by positive pulse. The diameter of the discharge electrode used is 1.0 mm with an effective length of 200 mm. The distance between wire and plate is 60 mm, and the wires are placed at intervals of 100 mm. The two plates are grounded. The schematic diagram of the ESP is shown in Fig. 2. A digital oscilloscope (TDS3034B, Tektronix, USA) with a high-voltage probe (P6015A, Tektronix, USA) was connected to the discharge electrodes to measure the applied positive pulse peak voltage and negative DC voltage.

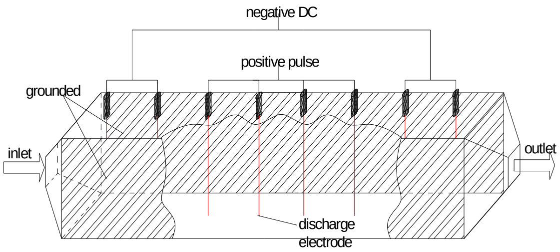

Fig. 2 Schematic diagram of the ESP

2.2 Particle Number and Electrostatic Charge Measurement

An isokinetic sampler and two-stage dilution system were coupled in line with an electrical low pressure impactor (ELPI, Dekati, Finland) to measure the particle size distributions and number concentrations upstream and downstream of the ESP at real time. The particles are sampled through a unipolar corona charger, where particle surfaces are saturated with positive charges. Subsequently, the charged particles enter a low pressure cascade impactor where particles are separated according to their inertia and consequently their aerodynamic diameter. With a filter stage, particles are collected and detected in 12 stages covering a size range from 0.007 μm to 10 μm. Upon particle deposition on the impactor collection plates of the individual stages, charges carried by the particles are measured with sensitive (fA level) multichannel electrometers. The measured current values are inverted to yield particle number concentrations using transfer functions provided by the manufacturer. In order to measure the original electrostatic charges on the particles, the corona charger of ELPI instrument should be turned off. A Sogevac model SV25 vacuum pump (Leybold, France) was operated at a pressure drop of 100 mbar across the ELPI, resulting in an air flow rate of 10 L/min through the impactor. The instrument was turned on for 1 h before the measurements according to the manufacturer's specifications. The ELPI setup is shown schematically in Fig. 3.

2.3 Data Analysis

For particle charging calculation, we assume that: (1) Particles are spherical; (2) Particles of the same diameter have the same charging amount. Then the charges on each impactor stage were derived from the electric current data by calculating the area under the curve in the current versus time plot for each particular stage. The average number of charges per particle, *n*, for a given size fraction was calculated by dividing the charges by that particular particle number using the following equation:

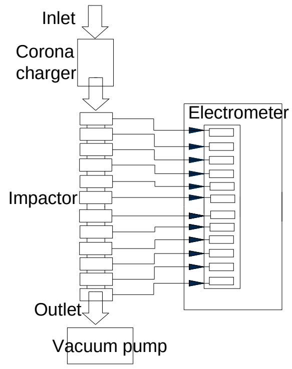

Fig. 3 Schematic diagram of ELPI setup

$$n = \frac{I}{QNe} \tag{1}$$

where I is the measured current on each stage (fA), Q is the ELPI flow rate (10 L/min), N is the particle number concentration (particle s/cm^3), e is the elementary charge (1.602×10^{-19} C).

The collection efficiency, η, was evaluated with the number concentrations of the aerosol particle corresponding to each stage measured at the ESP inlet and outlet:

$$h = \frac{(N_{\text{inlet}} - N_{\text{outlet}})}{N_{\text{inlet}}} \tag{2}$$

where N_{inlet} and N_{outlet} are the particle number concentrations at the ESP inlet and outlet, respectively.

3 RESULTS AND DISCUSSION

3.1 Applied Power Supply Outputs

The ESP is supplied by both negative DC voltage of 15 kV and positive pulse voltage ranges from 0-60 kV. The negative DC voltage offers particle pre-collection in the first electric field, where most of the large particles are removed. And the negative DC voltage in the last electric field enhances particle agglomeration and collection. The positive pulse power supply in the second and third electric fields was designed to upgrade the particle charging amount. The minimum rising time of the pulse generated is about 300 nano seconds and the pulse frequency ranges from 7 Hz to 300 Hz. Fig.4 shows the waveforms of the negative DC and positive pulse voltages applied in the experiments. As shown in Fig.4, the positive pulse peak voltages were 25 kV, 38 kV, 48 kV and 53 kV, respectively.

3.2 Particle Ratio Resistance and Number Concentration Distributions

The fly ash particle ratio resistance was measured by a DR type ratio resistance analyzer. We characterized the particle ratio resistance under different test temperatures for three times. The experimental data is shown in Tab.1. It is found that the experimental fly ash is of high ratio resistance. The results in Table 1 also show good data reappearance.

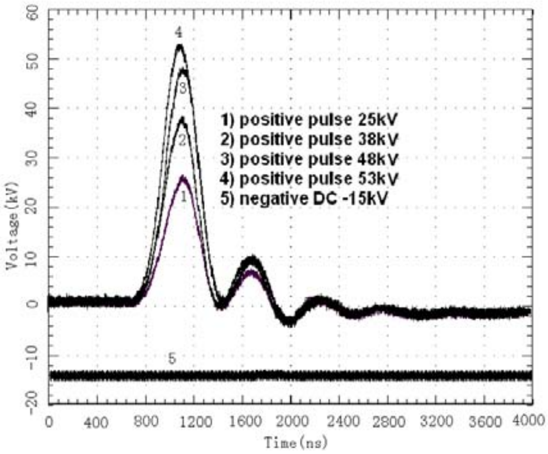

Fig. 4 Oscillogram of negative DC and positive pulse

Table 1 Survey of fly ash ratio resistance

Temperature (℃)	1st data (Ω·cm)	2nd data (Ω·cm)	3rd data (Ω·cm)	Average (Ω·cm)
20	1.03E+11	1.06E+11	9.74E+10	1.02E+11
100	1.08E+11	1.10E+11	1.12E+11	1.10E+11
110	1.17E+11	1.21E+11	1.20E+11	1.19E+11
120	1.36E+11	1.38E+11	1.41E+11	1.38E+11
130	1.83E+11	1.87E+11	1.91E+11	1.87E+11
140	2.14E+11	2.19E+11	2.20E+11	2.18E+11
150	2.23E+11	2.25E+11	2.29E+11	2.26E+11
160	3.68E+11	3.77E+11	3.83E+11	3.76E+11
170	1.26E+12	1.31E+12	1.36E+12	1.31E+12
180	1.31E+13	1.35E+13	1.33E+13	1.33E+13

We characterized the fly ash particle number concentration for a certain feed loading by ELPI for 2 min after the feed loading was stable. Fig.5 shows the fly ash particle number concentration and cumulative distributions at the experimental feed loading. As shown in Fig.5, PM2.5 occupies a large particle number proportion in the total number. The mass concentration of fly ash feed loading was 9869.72 mg/m^3.

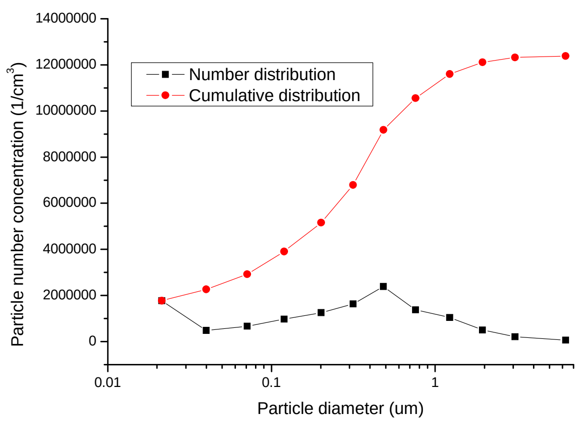

Fig. 5 Particle number concentration and cumulative distributions

3.3 Particle Charging Enhanced by Pulsed Corona Discharge

Experiments have been carried out to investigate the particle charging characteristic enhanced by pulsed corona discharge. DC power supply in the last electric field of the ESP was turned off. The effect of pulse peak voltage on the particle charging was also discussed. Experiments were performed by changing the pulse peak voltage with the fly ash feed loading and pulse frequency constant at 9869.72 mg/m^3 and 300 Hz, respectively. By the equation (1), the average number of charges per particle was calculated. The results are shown in Fig. 6.

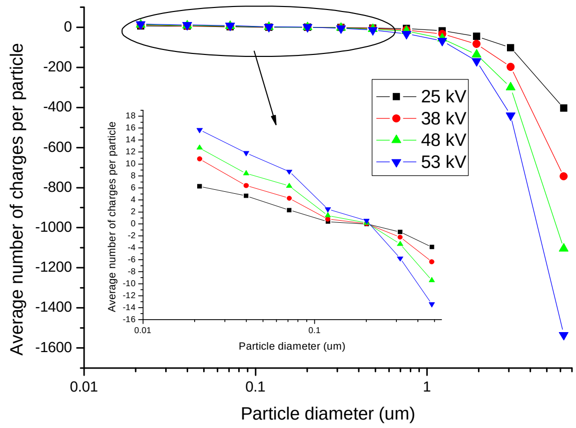

Fig. 6 Average number of charges per particle as a function of pulse peak voltage

For the pulsed corona discharge, the process of particle charging consists of two periods, the electron charging in pulse corona discharge duration and the ion charging after the pulse corona discharge duration[17,18]. During the pulsed corona discharge, electrons collide with particle by the electric field force, hence, most of the particles are negatively charged due to field charging mechanism. And the amount of electrons captured by particle is dependent on its diameter. The larger the particle is, the more electrons it captures [19]. After that, the space remains net positive ions because a large number of electrons have been captured. The diffusion charging mechanism takes place due to the ruleless thermal motion through gas diffusion. The smaller the particle is, the stronger the thermal motion is. Hence, two competing simultaneous processes take place: particle negatively charged by the field charging and neutralization of the charged particles by the diffusion charging. As a result, the final particle charging state depends on the combined effects of the field charging and diffusion charging mechanisms.

As shown in Fig. 6, we find that under different pulse peak voltage, the fly ash particles are bipolar-charged, containing both positive and negative charged particles. Particles smaller than 0.1 μm are found to be positively charged, while particles larger than 0.3 μm are negatively charged. And for particles smaller than 0.1 μm, the average number of charges per particle decreases with the increasing particle diameter; while for particles larger than 0.3 μm, the average number of charges per particle increases rapidly with the increasing particle diameter. For the particles those diameters are between 0.1 μm and 0.3 μm, they are found the most difficult to be charged. Hence, different particle size fractions can contribute differently to the particle charging.

The results indicate that for particles larger than 0.3 μm, the field charging is the dominant mechanism. While for particles smaller than 0.1 μm, the diffusion charging is the dominant mechanism. And for particles whose diameter are between 0.1 μm and 0.3 μm, the field charging mechanism and diffusion charging mechanism are equivalent, which finally results in charge neutralization.

As shown in Fig. 6, we also find that the average number of charges per particle increases with the increasing pulse peak voltage. It has been known that with higher applied pulse peak voltage, the intensity of pulsed corona discharge increases, which means there are more electrons and positive ions produced in the ESP. Hence, the particle charging is enhanced by increasing pulse peak voltage.

3.4 Particle Collection by Pulsed Corona Discharge Combined with DC Agglomeration

Based on the experiments performed, DC power supply in the last electric field was turned on to provide DC agglomeration for the charged particles. The fly ash feed loading was 9869.72 mg/m^3 and the pulse frequency was kept constant at 300 Hz. Typical records of particle number concentration and collection efficiency at different pulse peak voltages are represented in Fig.7 and Fig.8. As shown in Fig. 7 and Fig.8, we find that without pulsed corona discharge, DC power supply offers low collection efficiency for PM2.5, and its collection efficiency is degraded rapidly with the decreasing particle diameter, which is mainly due to insufficient particle charging. By increasing the number of DC electric field, its collection efficiency is improved, but it is not that satisfying. However, the collection efficiency for $PM_{2.5}$ has been significantly improved by pulsed corona discharge combined with DC agglomeration due to the enhancement of particle charging and agglomeration. DC voltage strengthens the collisions between particles highly charged by pulsed corona discharge through Coulomb force and electric field force, which accelerates particle agglomeration and collection. In this situation, the collection efficiency curve is of "V" shape. For particles larger than 0.2 μm, the collection efficiency increases as the particle diameter increases; while for particles smaller than 0.2 μm, the collection efficiency decreases as the particle diameter increases. And there is a lowest collection efficiency of particle whose diameter is near 0.2 μm due to charge neutralization. The results also show a positive correlation between the particle collection efficiency and the average number of charges per particle. It agrees well with the particle charging characteristics discussed above. Furthermore, we can find that the collection efficiency is improved by increasing the pulse peak voltage. Pulse peak voltage of 53 kV combined with negative DC agglomeration achieves a number reduction exceeding 90% for $PM_{2.5}$.

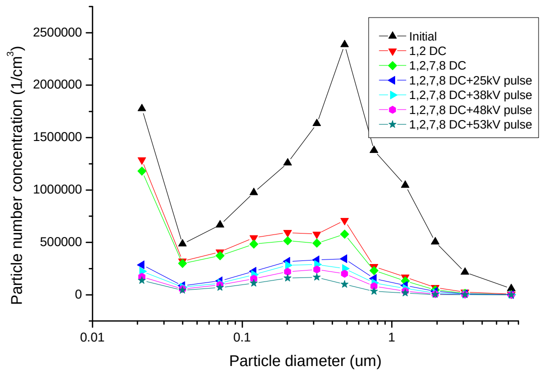

Fig. 7 Particle number concentration at different experimental conditions

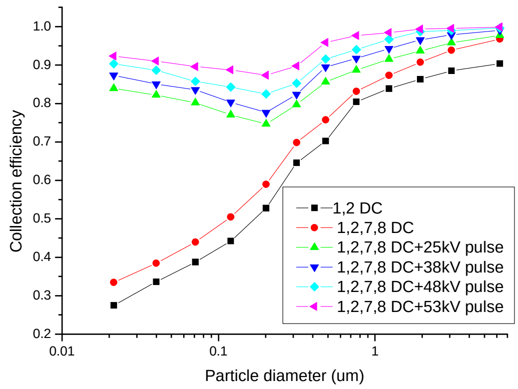

Fig. 8 Collection efficiency at different experimental conditions

4 CONCLUSIONS

In this paper, a laboratory-scale wire-plate ESP with pulsed corona energization combined DC agglomeration was proposed. Experimental studies were performed to investigate the charging characteristics and collection efficiency of aerosol particles emitted from coal combustion. A method of using ELPI for measuring particle charges was successfully developed. Polarity and charge level at different particle size fractions were used to characterize the electrostatic charge profile of the fly ash particles. It provides a better understanding of electrostatic charging of fly ash particles enhanced by pulsed corona discharge. For pulsed corona discharge combined with DC agglomeration under the given experimental condition, the particle collection efficiency curve is of "V" shape. The average number of charges per particle and the particle collection efficiency increase with the increasing pulse peak voltage. And there is always a positive correlation between the particle collection efficiency and the average number of charges per particle. Based on our present investigations, 53 kV pulsed corona discharge combined with negative DC agglomeration achieves a high collection efficiency exceeding 90% for $PM_{2.5}$.

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