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Full Length Article

Electric agglomeration modes of coal-fired fly-ash particles with water droplet humidification

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HIGHLIGHTS

- Effects of water droplet humidification on electric agglomeration were examined.
- A novel sampling method was developed for agglomerated particle observation.
- A theory of particle electric agglomeration modes was proposed.

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ABSTRACT

Electric agglomeration is a useful method to improve fly-ash particle collection efficiency in traditional electrostatic precipitators (ESPs) by increasing particle diameter and achieving particle pre-charging. In this study, a laboratory agglomerator, which consisted of a pre-charging region and a static mixer, was designed and tested for fine particle agglomeration. The pre-charging provided both positive and negative discharges in parallel channels. Fine water droplets were used to enhance particle agglomeration and collection efficiency in a downstream small ESP. The operating effects were evaluated under various applied voltages and droplet concentrations. Experimental results showed that the presence of water droplets effectively improved coal-fired particle agglomeration, pre-charging, and collection in the ESP. The total number collection efficiency improved from 53.91% to 86.02% compared with the condition without the agglomerator. In addition, a novel sampling method was used to observe agglomerated particles using scanning electron microscopy, and theoretical adhesive force analysis supported the proposal of a series of power-plant particle electric agglomeration modes.

1. Introduction

Submicron particulate matter emitted from stationary sources can cause serious pollution because these small particles can stay suspended in air and can penetrate into the human respiratory and circulatory systems [1,2]. Submicron particles, which comprise various chemical compositions including nitrates, sulfates, organic compounds, and heavy metals [3,4], can cause adverse health problems such as aggravation of asthma, nonfatal heart attacks, and even lung cancer [1]. Therefore, research on fine particle emission properties and control technologies has drawn growing attention.

Particle agglomeration, a method to increase mean particle size, is drawing interest in increasing the collection efficiency of electrostatic precipitators (ESPs) in coal-fired power plants in which the particle charge and migration velocity are low for submicron particles [5–7]. Particles that are in contact with one another generally adhere and form agglomerates, for which adhesive forces become increasingly important compared with particle inertia or gravity [8]. Adhesive forces include London-van der Waals force, attractive electrostatic force, and surface tension of the liquid layer [9–11]. Common agglomeration methods are based on the idea of increasing adhesive forces such as chemical-induced agglomeration [12], condensation-induced agglomeration [13], and electric agglomeration [14–20], as well as the idea of increasing particle vibration and collision such as acoustic agglomeration [21,22].

Among the aforementioned methods, electric agglomeration enables positive and negative particle charging to generate electrostatic attractive forces and particle collision, which is strengthened by an external electric field or mixers, the effects of which have

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been studied and proven. Bai et al. [23] investigated particle agglomeration in an alternating electric field with results showing that submicron particles were effectively agglomerated and collected in a high-velocity flow field. Kanazawa et al. [20] studied a two-stage ESP with a bipolar charging section and achieved a result that the number distribution rate of smoke particles in diameter of 0.3–1.0 μm was reduced from 75% to 18% after bipolar discharge. Maisels et al. [24] used a Monte Carlo method to simulate bipolar particle charging and agglomeration process and demonstrated that the particle size distribution was clearly changed when high particle number concentrations prevailed. Thonglek et al. [14] introduced a high-voltage pulse power supply to produce non-thermal plasma agglomeration, thereby achieving a number reduction efficiency of over 90% for all submicron particle sizes. Zhu et al. [25] designed a closed-loop laboratory ESP with a bipolar pre-charger that yielded a grade number collection efficiency of 95%–98%, while the number collection efficiency without a pre-charger was over 87%, which could not be improved by increasing the collection surface area or duration time. The above mentioned research demonstrates that electric agglomeration is effective for enhancing submicron particle number collection efficiency. However, effects of adhesive forces on agglomeration mechanism are not well understood.

In this study, to strengthen adhesive force and surface tension between particles, water droplets were introduced into the electric agglomeration process, which is the real case in industrial flue gases with high humidity such as in wet ESP. A laboratory bipolar agglomerator employing water droplet spray was designed for fine particle agglomeration enhancement, and an ESP was placed downstream to collect pre-charged and agglomerated particles. The effects of varying applied voltages and water spray amounts on particle agglomeration and collection were evaluated by investigating the particle charging characteristics, particle number distributions, and grade collection efficiencies. Furthermore, a novel sampling method was adopted for agglomerate observation using scanning electron microscopy (SEM). Finally, particle agglomeration modes under various conditions were inferred with the support of theoretical adhesive force analysis.

2. Experimental setup and methodology

2.1. Experimental setup

Fig. 1 shows the laboratory bipolar agglomeration system consisting of a pre-charging zone, a static mixer, and an ESP. Particles are positively or negatively charged in the pre-charging zone, agglomerated in the static mixer, and finally collected by the ESP. The experimental system is characterised by an acrylic duct of 20 cm in width, 10 cm in height, and 100 cm in length. Water droplets were added into the experimental system to investigate the agglomeration promotion effects by a liquid bridge between particles. Droplet concentration was adjusted among 1.5 mg/m^3, 3.5 mg/m^3, and 5.0 mg/m^3.

The pre-charging zone consists of two separate parallel corona channels, each with a discharge electrode connected to a positive or negative power supply through a 10 MΩ resistor. The length, width, and height of the agglomerator are 20 cm, 20 cm, and 10 cm, respectively. The discharge electrodes are ribbon electrodes made of stainless steel, and the wire-plate distance is 2.5 cm. The power supplies used in the agglomerator and the ESP are high-frequency power supplies (Telsman, China).

In the mixer, a set of inclined placed cubics was employed as turbulators instead of traditional staggered arranged column-shaped pin fins, which were used in a previous study [26]. The turbulators are 3 mm-thick 5 cm × 5 cm acrylic cubics, and guide plates are added downstream to ensure uniform flow.

The ESP is 20 cm in width, 10 cm in height, and 60 cm in length, where a set of four equidistant discharge electrodes is used to create ions and an electric field. The distance between adjacent discharge electrodes is 10 cm, and the wire-plate distance is 5 cm.

2.2. Experimental procedure

In the experiment, particles were injected into the gas flow by a particle feeder, passed through a settling chamber for precipitation of large particles, and entered the agglomerator through a distribution plate. The size distribution of the tested particles was measured by a laser particle size analyzer (Mastersizer 2000, Malvern, UK). As shown in Fig. 2, the particles were polydisperse with the volume median particle diameter (D_{50}, equal number of particles above and below this size) of 20.22 μm. Water droplets were generated by an ultrasonic droplet generator and injected into the experimental system through a by-pass pipe. The size distribution of water droplets was measured by an online laser particle size analyzer (DP-02, Omec, China). The volume median diameter of water droplets was 9.11 μm. When the particle concentration became stable, the electric agglomerator was switched on by setting specific negative and positive voltages and water droplet concentrations in the flow field. The flow velocity in the chamber was 0.6 m/s and the particle residence time in the charging zone was 0.1s, which ensured sufficient charging time and minimized particle precipitation in the pre-charger [27]. Thereafter, the power supply of the ESP was switched on to investigate collection efficiencies with and without the pre-charger and different water droplet concentrations. All experiments were performed under ambient conditions and at room temperature.

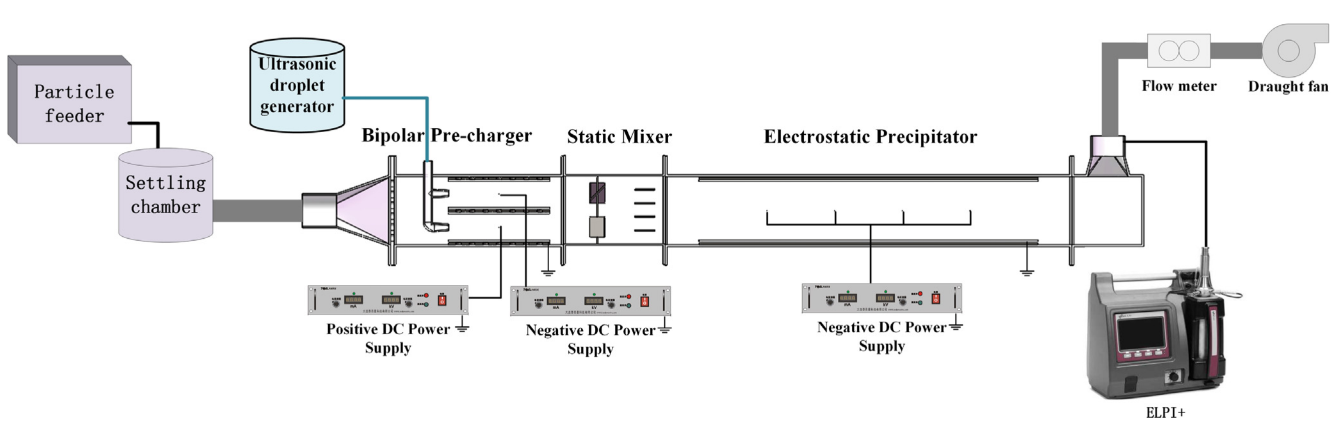

Fig. 1. Schematic of bipolar agglomeration experimental system setup.