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Orthogonal design process optimization for particle charge distribution of mosquito coil smoke aerosol enhanced by pulsed corona discharge

Jian-Ping Jiang *, Zhong-Yang Luo, Hao Chen, Dong Zhou, Dong-Hui Sha, Meng-Xiang Fang, Ke-Fa Cen

State Key Laboratory of Clean Energy Utilization, Zhejiang University, 38 Zheda Road, Hangzhou, PR China

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ABSTRACT

Pulsed corona discharge (PCD) is one of the most commonly used methods for particle charging. In this study, a mosquito coil smoke aerosol with a diameter smaller than 0.5 μm was used to investigate the charging of fine particles using an electrical low-pressure impactor (ELPI). The average number of charges per particle increases as the particle diameter becomes larger. Orthogonal design and single-factor analysis were carried out to optimize the particle charging conditions. The factors range as follows: wire–wire distance, d_{ww} = single one wire and three wires with a distance of 3–9 cm; wire–plate distance, d_{wp} = 3–6 cm; impulse-peak voltage, V = 30–45 kV; and impulse frequency, f = 100–300 Hz. The results show that d_{ww} is the dominant factor, and the optimal conditions are as follows: a) for diameter smaller than 0.04 μm: d_{wp} = 5 cm, d_{ww} = 9 cm, V = 35 kV, and f = 300 Hz; b) for the size range of 0.04–0.2 μm: d_{wp} = 4 cm, d_{ww} = 9 cm, V = 45 kV, and f = 300 Hz; c) for the size range of 0.2–0.48 μm: d_{wp} = 4 cm, d_{ww} = 9 cm, V = 45 kV, and f = 100 Hz. Moreover, the particle charging is much more difficult for the particle with a diameter of 0.2 μm than the others.

1. Introduction

Fine particulate matters ($PM_{2.5}$), which contain many toxic organic compounds and heavy metals, severely affect human health and environment [1–4]. Electrostatic precipitators (ESPs) are widely used for removing particulate matters at power plants; however, the removal efficiency for $PM_{2.5}$ is low due to insufficient particle charging [5–8]. Compared with the particle charging in a DC electric field, pulsed corona discharge (PCD) has been used to enhance the charging of aerosol particulate matters because of its higher charging efficiency than DC energization with much higher density and mobility of electrons [3,5,7–12]. Several experimental and theoretical studies have been conducted to understand the charging of aerosol particles enhanced by PCD [3,7–13]. As the short-duration positive PCD process mainly consists of two charging periods: electron charging during discharging duration and positive ion charging between two discharges, the mechanisms peculiar to particle charging in pulsed electric field (PEF) are very complex, and a detailed theoretical analysis has not been conducted. In this study, the particle charge distribution of mosquito coil smoke aerosol, which is the average number of charges per particle, was investigated in a PEF.

In PEF, the charging of aerosol particles is mainly driven by the migration and diffusion of free electrons and ions [3,7,12], mainly containing two regimes namely field charging [3,12,14–20] and diffusion charging [3,12,14–17,20–26]. Because of the different values of mobility for positive ion and electron, the short-duration positive PCD is mainly a bipolar charging process, while the DC corona discharge is mainly a unipolar charging process, and the particle equilibrium charging state in PEF depends on the combined effects of the diffusion charging and field charging [3,7,11,27]. In field charging [3,18–20], the electrons or gaseous ions are transported to the particle surface along the field lines. During the discharging duration, most of the particles are negatively charged by electrons due to field charging [3,7,27]. In diffusion charging [3,12,21–26], particles are charged because of the random thermal motion of the gaseous ions in the gas. Between two discharges, lots of electrons get lost, while positive ions remaining in space, particles are positively charged by positive ions due to diffusion charging, especially for ultra-fine particles [3,7,27].

In PEF, the charging of aerosol particles varies with the particle diameter, i.e., the larger particles are mainly dominated by field charging of electrons, while the smaller particles are mainly dominated by diffusion charging of positive ions [3,7,12]. The PCD and charging of aerosol particles in PEF using a wire–plate reactor are affected by many factors such as wire–wire distance, wire–plate distance, impulse-peak voltage, and impulse frequency [3,5,7,11–13,27–32]. The effects of different factors on particle charging may vary with particle diameters and have an interaction with each other. To optimize the particle charging conditions, an orthogonal design arranged by a standardized orthogonal table [4] was used to conduct four-factor experiments at four levels. Moreover, a single-factor analysis was used to investigate in detail the charging of aerosol particles in PEF.

* Corresponding author.
E-mail address: zyluo@zju.edu.cn (Z.-Y. Luo).

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2. Experimental setup and methodology

2.1. Experimental setup

The schematic diagram of the experimental apparatus is shown in Fig. 1, mainly consisting of a charge chamber, aerosol feeder, particle sampler and measuring instruments. The charge chamber is made of a wire–plate reactor with three wire electrodes and two plate electrodes. The gap between the plate electrodes and the spacing of adjacent wire electrodes are adjustable. These stainless steel electrodes were placed inside a cuboid polymethylmethacrylate box (effective discharge volume: $260 \times 140 \times 120$ mm^3). The wire electrodes with a diameter of 1.5 mm and a length of 120 mm were energized with a positive voltage by a high-voltage pulse power supply, and the plate electrodes were sound grounded. A gas mixture flowed through the reactor at a constant flow rate of 10 L/min to match the flow rate of electrical low-pressure impactor (ELPI). The voltage of the wire electrodes and the impulse frequency were measured with a high-voltage probe (Japan Finechem Co., Inc. P150-GL) and a digital oscilloscope (Tektronix DPO4034), and the current flowing through the plate electrodes was monitored using a current probe (Tektronix TCP0150) and the oscilloscope. All the experiments were carried out in atmosphere, i.e., the ambient temperature of 25 °C, the ambient relative humidity of 50% and the ambient pressure.

The narrow-pulse, high-voltage power supply was produced by the China Academy of Engineering Physics, model PPCP-SO.4-1. The impulse frequency of the narrow-pulse, high-voltage power supply could be varied from 10 to 300 Hz, and the pulse width (FWHM) and rise time of the voltage waveform of the PCD were constant at 400 and 200 ns, respectively. The maximum pulse peak voltage was about 60 kV. Fig. 2 shows the typical waveforms of the single-pulse voltage and current detected from the wire–plate discharge reactor with a wire–plate distance of 3 cm and a wire–wire distance of 9 cm for the three wire electrodes. As shown in Fig. 2, the impulse-peak voltage

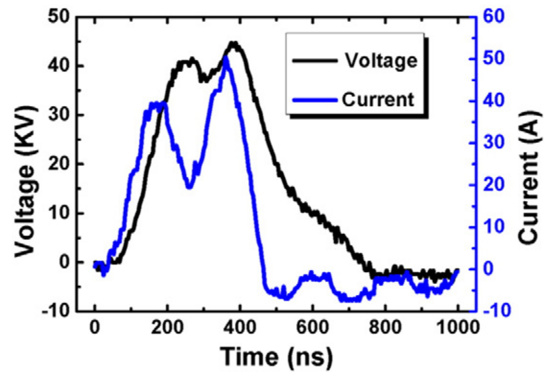

Fig. 2. Typical waveforms of discharge voltage and current as a function of time: a wire–plate distance of 3 cm and a wire–wire distance of 9 cm for the three electrodes, an impulse-peak voltage of 45 kV, and an impulse frequency of 100 Hz.

was 45 kV, and the impulse frequency was 100 Hz. The current signal increased immediately with increasing voltage. The discharging duration was constant at about 400 ns, but the duration between two discharges decreased with the increase of the impulse frequency.

2.2. Measurement of particle size and charge distributions

A series of standard isokinetic sampling nozzles were coupled with an ELPI (Dekati, Finland) [3,7,12,13,27,33,34] to measure the particle charge distribution and number concentration at the outlet of the PCD reactor in real time. The particles were separated according to their inertia and aerodynamic diameter by the ELPI with a filter stage in the size range of 0.02–10 μm with a total of 12 stages. With the isokinetic sampler, a Dekati Cyclone (SAC-65, Dekati, Finland) with a cut diameter of 10 μm was employed for removing the coarse particles from the aerosol. Prior to entering the impactor, the particles were saturated with

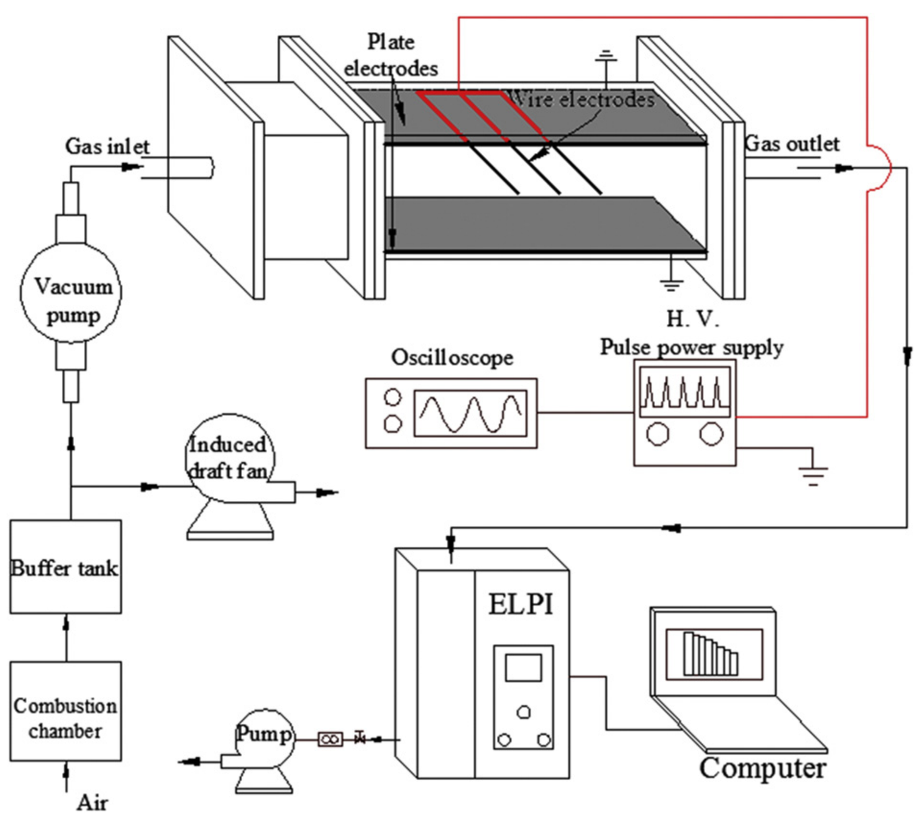

Fig. 1. Experimental setup.