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Two-stage electrostatic precipitator with co- and counter-flow particle prechargers

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ABSTRACT

Lab-scale, two-stage electrostatic precipitation system comprising of precharging stage, in which PM2.5 particles are electrically charged, and collection stage, in which the charged particles are removed from the flowing gas by electric field, was investigated in this paper. Two types of electrostatic particle prechargers were compared with respect to the collection efficiency of the system: (1) co-flow precharger, in which ionic current was generated co-currently with the gas conveying the particles, and (2) counter-flow precharger, in which ionic current was generated oppositely to the flowing gas. In each case, the electrodes of precharger were supplied with DC or AC high-voltage in order to compare the effect of discharge mode on the collection efficiency of two-stage electrostatic precipitator. The collection stage was formed by two parallel-plate electrodes connected to DC high voltage source. Plate electrodes without discharge points (spikes) are corona-free electrodes, which prevent the collection stage from electrical discharges, and reduce the probability of back discharge ignition. The back discharge decreases collection efficiency of conventional electrostatic precipitators.

It was concluded that the co-flow electrode configuration of the precharger, supplied with DC high voltage, has the highest total number collection efficiency for PM2.5 particles, higher than 95% and the mass collection efficiency larger than 99%. The counter-flow precharger provided only about 90% number collection efficiency of two-stage electrostatic precipitator. It was also shown that by AC electrode excitation, the collection efficiency of the system is lower than for DC supply. The two-stage electrostatic precipitators allowed obtaining higher fractional collection efficiency for PM2.5 particles than other conventional systems and can be recommended as highly effective devices for gas cleaning in power plants or cement industry.

1. Introduction

Fractional number collection efficiency of electrostatic precipitators for particles smaller than 2.5 μm (PM2.5) in power plants decreases with decreasing particle size, and for the most unfavourable conditions, for particles of the size of 100 nm–500 nm, can be as low as 50% [16,53,54,66,67]. Low collection efficiency in this size range results from low electric charge on those particles, and low electric force driving the particles towards collection electrode. The second mechanism decreasing the collection efficiency is electrostatic re-entrainment of particles. Particles forming a layer on the collection electrode can be re-charged in electrostatic field and repelled when electrical forces are larger than the cohesive force. Two-stage electrostatic precipitators, in which particles are pre-charged by ionic current in the first stage, and collected in the second stage, free of electrical discharges, have been developed in 1970s and 1980s in order to increase the collection efficiency of PM2.5 fly ash particles [45,47–49,64]. This type of electrostatic precipitator was usually placed as last or instead of last field in industrial precipitation system.

There are many variants of electrostatic particles prechargers in two-stage electrostatic precipitators: boxer charger, nozzle-charger equipped with corona electrodes, corona-triode charger, quadrupole precharger, or alternating electric field precharger [31,32,42,48]. Those prechargers could charge all particles to the same polarity (unipolar prechargers) or to two opposite polarities (bipolar prechargers), with the goal of particles agglomeration. In all of those devices the ionic current is generated transversely to the flowing gas, and therefore those devices are sometimes called “cross-flow prechargers”.

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Charging of fly ash particles by ionic current in electric field is a universal and easy to control method. In conventional electrostatic precipitators, this process is accomplished by producing gaseous ions by discharge electrode system. The charged particles are next deposited onto collection electrode. Rods of various cross-sections equipped with sharp spikes of different designs are usually used as discharge electrodes [15,33–36]. The electrodes are supplied with DC or pulse superimposed on DC voltage to generate the ionic current. In two-stage electrostatic precipitators such charging systems are rarely used because in the point-plate electrode configuration the magnitude of charge is limited due to precipitation of larger particles on the electrodes. Because the charge on particles must be maximized and particle loss within the precharger has to be minimized, for their effective precipitation, charging by ionic current in alternating electric field has been proposed, particularly in order to increase the electric charge on submicron particles [1,29,31,44,46,48]. Various constructions of unipolar prechargers utilizing this concept have been proposed and investigated in the literature. Reviews of corona particle chargers can be found in papers of [9,10,24,26,30].

In one of versions of bipolar prechargers, the particles were charged to opposite polarities in AC corona discharge [19,65,68]. Clouds of oppositely charged particles flowing one after another attract and the particles can collide and agglomerate. Because in the electric field of collection stage the oppositely charged clouds of particles are deflected towards opposite electrodes, the particles of opposite sign collide and can agglomerate [68]. After particle agglomeration, the collection efficiency of agglomerator/precipitator system was close to 100% for particles of the size of 1 μm, but it decreased to about 10% for nanoparticles (0.03 μm).

Although co-flow particle chargers were used for charging of aerosol particles in the field of aerosol research [2,5–7,17,20,22–28,41,62,63], there are only a few examples of using co-flow prechargers for electrostatic precipitation [21]. have developed an electrostatic precipitator with sawtooth-like discharge electrode for co-flow charging and precipitation of particles. For the same voltage magnitude, particles penetration through that device was about two times lower for negative corona than for positive polarity of the discharge electrode. Electrostatic precipitator comprising of a set of V- and X-shaped collection electrodes, arranged alternately and transversally to the gas flow has been developed [43]. In that electrode system, ionic current was generated co-currently with flowing gas. Back-corona discharge was eliminated in such system, and overall collection efficiency was increased to a level higher than 90% [51]. have constructed two-stage electrostatic precipitator for application as gas cleaning device in road tunnels. Flat plates with spiked edges on both up-flow and down-flow sides were used as discharge electrodes prior to particle precipitation by flat plate electrode system. However, their constructions were different from those proposed and investigated in this paper.

Co-flow particle chargers were also used to increase collection efficiency in hybrid filters [3] (cf. also [4]). A hybrid electrostatic precipitator with co-flow particle precharger, in which 10 layers of wire screens were placed one after another perpendicularly to the gas flow, with a fibrous filter at the end has been developed in Refs. [3,4]. The filter was designed for the removal of particles smaller than 0.1 μm, via simultaneous action of Brownian diffusion and electrostatic deposition. Larger particles were deposited onto the screens by electrostatic forces, while diffusional deposition onto the fibres was effective for smaller particles. A hybrid filter comprising sharp discharge electrodes and grounded filter made of stainless steel fibres has been developed by Refs. [37,50]. In those devices, co-flow charging and precipitation of particles was realized in a single stage. This type of filter is particularly suitable for removal of submicron particles. The collection efficiency of that filter was almost independent of particle size, and slightly increased with particle loading. Back corona discharge was not observed in this type of filter. In Ref. [50] it has been noted that fine particles were captured in the first few layers of porous filter by the action of electrostatic forces, in contrast to standard fibrous filters, in which filtration occurs throughout the depth of filter. The penetration of fine particles decreased with flow velocity decreasing, that was attributed to higher charge acquired by the particles during longer residence time in the charger. Authors showed that there was not a significant dependence between particle penetration and particle size, regardless of face gas velocity. They also noted that accumulation of nonconductive material on a porous filter did not create back corona discharge.

Counter-flow corona precharger was used only by Ref. [18]. In that device, a set of needles was facing a grounded grid screen. The needles at high potential generated negative corona wind, which charged the particles conveyed by the gas. By mounting those needle-screen systems in series, the velocity of corona wind as high as 3 m/s was achieved. Cross-flow prechargers, with discharge current generated perpendicularly to flowing gas, were tested in many papers, for example, in our paper [32]. Co- or counter-flow prechargers for charging of fly ash particles in two-stage electrostatic precipitators using parallel-plate collection stage have hitherto not been investigated.

In this paper, collection efficiency for various versions of laboratory scale two-stage electrostatic precipitator comprising of co- or counter flow precharger, supplied with the DC or AC high voltage, which can operate as unipolar or bipolar prechargers, respectively, and parallel-plate particle collector supplied with DC voltage has been determined. The collection stage has no discharge electrode, and the precipitation occurs due only to electrostatic field acting on pre-charged particles flowing between the electrodes that reduces the power consumption by this type of precipitator and minimizes the chance for back-discharge onset. Co- and counter-flow electrostatic prechargers for various electrode supply modes have been investigated experimentally in order to maximize the collection efficiency of such system for the removal of PM2.5 particles. In particular, the concept of particle charging in AC corona discharge in co- or counter-flow prechargers, and its effect on the collection efficiency of two-stage electrostatic precipitator has also been tested. Both, positive and negative results of the experiments have been presented and discussed. The results are published for the first time in this paper and those types of prechargers have not been considered previously.

2. Experimental

The measurements were carried out at an experimental set-up shown schematically in Fig. 1. The stand consisted of PMMA channel of square cross section, of 160 × 160 mm. The dashed line in Fig. 1 shows the channel edges. A HEPA filter was placed at the inlet of the channel, to eliminate particles from the environment air, and flow straightener, to eliminate air vortices. An exhaust fan was mounted at the outlet of the channel to control the air flow rate. MgO particles of mass mean diameter of about 0.5 μm and mass density of 3.58 g/cm^3 were used as test particles. The particles were generated to the aerosol phase from their colloidal suspension in methanol. The colloidal suspension was first blended and then stirred by magnetic stirrer during 1 h before its atomization by Aerosol Generator ATM 226 (TOPAS). The solid particles were formed after solvent evaporation from the atomized droplets. The produced aerosol was injected to the channel at its inlet. The concentration of particles was measured at the outlet of the channel using Aerosol Particle Size Spectrometer LAP 322 (TOPAS).