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Performance of a sonic jet-type charger in high dust load

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ABSTRACT

Sonic jet chargers have originally been used in aerosol measurement devices for particle charging and neutralization. Here, our goal was to study if this charger type could be used in particle control devices in which particle concentrations and gas volumes are much higher. The study includes charging efficiency tests in a laboratory and with a commercial 20 kW wood pellet burner. Actual particle removal efficiency was tested with a laboratory scale parallel plate electrostatic collector. The results show that sonic jet-type chargers also have potential in filtering applications.

1. Introduction

Historically, electrostatic particle filtering technologies have been used in applications that produce high amounts of large (over 1 μm) particles. A typical example is a large-scale energy production facility based on coal combustion [15]. Fine particles have very little mass and thus were not considered to be a problem as emission regulations was and still are mainly based on total mass. The increasing knowledge of severe health effects related to fine particles has changed the situation [1,9]. New clean air regulations cover applications that were not considered harmful some years ago.

Traditional electrostatic precipitators (ESP) are naturally optimized to remove large particles. In a single-stage ESP, particle charging and removal processes are combined; therefore, charging takes place in high electric field conditions. This enhances the field charging process, and large particles acquire high particle charges. On the other hand, field charging is not a very effective mechanism for fine particles, which are mainly charged by a diffusion charging process, even in high field conditions. Efficient charging of fine particles requires large amounts of free ions and long residence times. This leads to larger volume requirements and more expensive ESPs.

High field conditions are not necessary for efficient charging when no large particles are present in the flue gas. The precipitator can then be designed to rely on diffusion charging. This approach is valid with several applications, such as diesel engines, many aerosol processes (like coating) and biomass combustion in modern burners.

In traditional ESPs the discharge electrode is located in the flue gas flow path and the flue gas conditions have a direct effect in the discharge process. The chemical composition, temperature and particle load of the flue gas change the corona characteristic and can even prevent stable corona formation [12,16]. In the ion generation process free electrons formed in the vicinity of the negative corona electrode are attached to the electronegative gas components. An extreme case is nitrogen gas with negative corona: as the electrons can't attach to nitrogen, there is no stable corona operation regime and the corona starting voltage is also the gas sparkover voltage. In practical flue gas cleaning there is always several electronegative gases presents for electron attachment and the gas composition effects the ion mobility and corona operation.

Flue gas temperature and pressure effect the voltage window of stable corona operation between corona initiation and sparkover. Increase in temperature and decrease in pressure both lead to narrower range of suitable corona voltages. In applications with high temperature and pressure these two counterbalance each other and stable corona can be obtained. Corona charger operating at atmospheric pressure levels need to be modified at temperatures above 500 °C. With modification in electrode shape and electrification EPS's has been installed to work at temperatures up to 850 °C [13].

Aggressive chemical components in the flue gas can cause

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corrosion in the discharge electrodes decreasing their life time. High corrosion resist material can be used in these cases but with increased installation and running costs.

Part of the particle matter in the flue gas accumulate to the discharge electrode surfaces and needs to be cleaned regularly to ensure proper operation. Cleaning is typically done with the same rapping method as with collection plates.

A sonic jet charger is a device that can be used to produce a large amount of free ions to be used for the diffusion charging process. The main difference to normal corona electrodes is that the corona discharge electrode is not in contact with the flue gas but is located in a separated chamber. Corona discharge and ion formation takes place in a shield gas flow. Temperature, pressure and chemical composition of the shield flow can be adjusted to optimal corona operation. The use of sonic jet charger can open new applications for ESP based filtration where devices using traditional corona electrodes fail or fall in to problems.

1.1. Sonic jet charger

A sonic jet charger can be used to produce a large number of ions for charging aerosols. It was first introduced by Whitby in 1961 and was successfully used as an aerosol neutralizer and in ion behavior studies [17]. Sonic jet-type chargers have also been used in aerosol measuring devices, as they have low particle losses and high charging efficiency [5,10,14]. Particle charging is mainly based on diffusion charging, as the only electric field is the one generated by the ions and charged particles.

Sonic jet chargers have a chamber with a small orifice that opens to an aerosol-carrying duct. Co-centric with the orifice is a corona electrode that produces the ions. The chamber has a supply of pressurized air that is purged through the orifice. The ions are carried to the flue gas through the orifice by the near-sonic-speed purge gas flow.

Sonic jet-type chargers have several advantages in electrostatic precipitation applications. As the corona discharge is produced inside a separate chamber, it is not influenced by the properties of the aerosol flow. Parameters such as gas temperature, humidity and pressure that have an effect on corona operation can be optimized. There is also a dramatic decrease in problems associated with keeping the corona electrode clean, as it operates in clean gas flow. Changes in the aerosol concentration of the gas flow do not affect the corona's operation. An ESP applying a sonic jet-type charger is a two-stage device; hence, the collection section can also be optimized freely without influencing the charging process.

Two versions of a sonic jet-type charger were used in this study (Fig. 1). The first one, with an integrated ground electrode (integrated grounded electrode charger/iGE charger) was introduced by Ref. [8]. It consists of an outer shell (a steel tube with a diameter of 26 mm) with a 2-mm diameter sonic orifice and connectors for compressed air and high voltage supplies. A sharp needle was used as a corona electrode. The corona electrode is also protected by a cap with a 3-mm diameter orifice. A 10-mm diameter rod was used as a conductor rail inside the charger. Insulating spacers keep the conductor rail and the corona needle co-centric. The sonic nozzle is made of insulating material. The corona discharge is formed between the needle and the ring electrode, which is electrically grounded via the outer shell.

An alternative design for the charger (external GE charger/eGE charger) consists of an electrically insulated outer shell (a ceramic tube with a diameter of 26 mm) with connectors for compressed air and high voltage supplies. A sharp needle was used as a corona electrode. A 10-mm diameter rod was used as a conductor rail inside the charger. Insulating spacers keep the conductor rail and the corona needle co-centric. The nozzle is made of insulating material. The corona discharge is formed between the needle and the

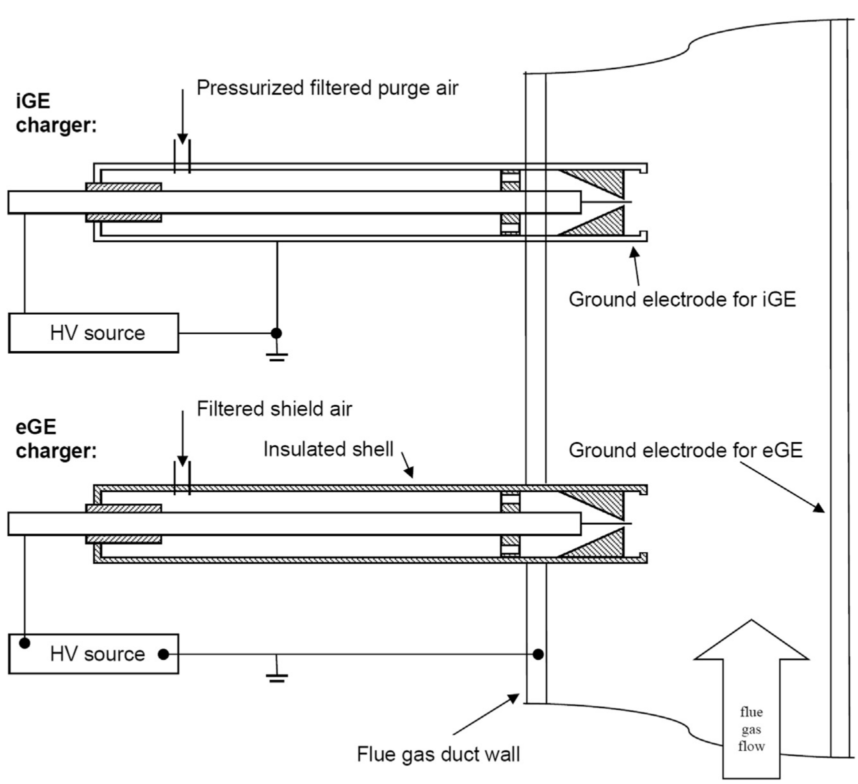

Fig. 1. A schematic diagram of the sonic jet-type chargers studied. In the iGE charger, the electric field is produced between the corona electrode and the charger body. In the eGE design, the corona field is produced between the corona electrode and the flue gas duct wall.

grounded wall structure of the flue gas duct.

In the external GE design, the produced ions are mainly purged by the electric field between the corona electrode and the flue gas duct walls. The required electric potential for the corona electrode strongly depends on the geometry of the flue gas duct and is typically above 10 kV. The purge air pressure and consumption are low, as they are mainly used to shield the electrode from the flue gas. Most of the produced ions are purged to the flue gas. Technically, this design is no longer of the sonic jet-type, as the ions leave the charger following the electric field and are not forced by the high-speed air flow. It also generates an electric field in the flue gas flow, so both diffusion and field charging processes are expected to take place. It still has the main advantage of the sonic jet type: the corona electrode is in a clean, controlled environment.

2. Experiments

The chargers were tested in a laboratory setup with a pyrolysis aerosol generator and with a 20 kW pellet burner/boiler combination. The precipitation efficiency of a laboratory-scale electrostatic precipitator using the external GE charger was also tested. The tests include:

- U/I characteristics and ion currents of the tested chargers
- Charging efficiency measurements with test aerosol
- Charging efficiency measurement with aerosol from real heating device (pellet boiler)
- Precipitation efficiency measurement with test aerosol in laboratory scale ESP

The details of the different experiments are described below.

Voltage to current (U/I) characteristics and ion currents (the currents produced by ions purged from the charger) were measured by placing chargers inside a metallic duct (supplemental material Fig. 5). The diameter of the duct was 160 mm and the length 350 mm. The exit end of the duct had a metallic grid to capture ions traveling with the airflow. The flue gas duct was grounded via a current meter to measure the ion current. The corona current and voltage were measured with the HV source.

For the charging efficiency measurements (Fig. 2), the charger was placed co-centrically inside the metallic flue gas duct using a T-junction. The diameter of the flue gas duct was 160 mm. Test aerosol was generated with a pyrolysis generator (Concept ViCount Compact Generator using Concept Smoke Oil 135) because it produces a well-defined and stable distribution of liquid particles. The generator was selected as it produces particles in the minimum electric mobility size range (between 0,1 and 1 μm) [4] that are difficult to remove by ESP's. These particles are excellent for estimating precipitation potential because diffusion charging is effected only by particle size and specifically not by particle material. Flow inside the charging section was turbulent as the purge/shield gas from the charger caused turbulence even when the flow as itself would have been laminar before the charger unit.

The aerosol concentration produced was controlled by a pre-dilution system to provide different particle mass loads. Aerosol concentration, size distribution and average charge distribution were measured using an electrical low-pressure impactor (Dekati ELPI) [2,6]. The sampled aerosol was diluted before entering the ELPI using an ejector diluter (Dekati Diluter). The entire test system was operated at room temperature. The aerosol flow rate was 0.02 m^3/s. The test aerosol particle number distributions at different concentrations are presented in Fig. 3.

The average particle charge was measured with the ELPI in a two-phase measurement. First, the particle number distribution was measured using the ELPI in normal measurement mode. In the second phase, where the ELPI's own corona charger and ion trap were turned off, the measured current from the impactor states indicates the initial net charge of the particles. The average particle charge for different particle sizes was estimated [3,7].

The external GE charger was tested with a laboratory-scale parallel plate electrostatic collector to test the actual precipitation efficiency. The collector dimensions were 1000 × 400 × 100 mm (length × width × plate distance) (supplemental information Fig. 6). The flow rate through the collector was 0.02 m^3/s, the residence time in the collection zone was 2 s, and the collection voltage was 40 kV. Aerosol for the test was produced with the same generation/pre-dilution system as with the charging efficiency measurements. An aerosol mass concentration of 530 mg/m^3 was selected for the collector test. As the test particles are in liquid form the re-entrainment from the collection plates is minimal. Removal efficiency was measured at the collector exit. The charger and collector voltages were switched on and off and the difference in particle concentrations was measured.

In the pellet burner measurements, two external GE chargers were installed inside the boiler between two heat exchanger sections (Fig. 1 In Supplemental Information). The dimensions of the box-shaped charging section were 350 × 170 × 220 mm (width × length × height). Two chargers were used to cover the

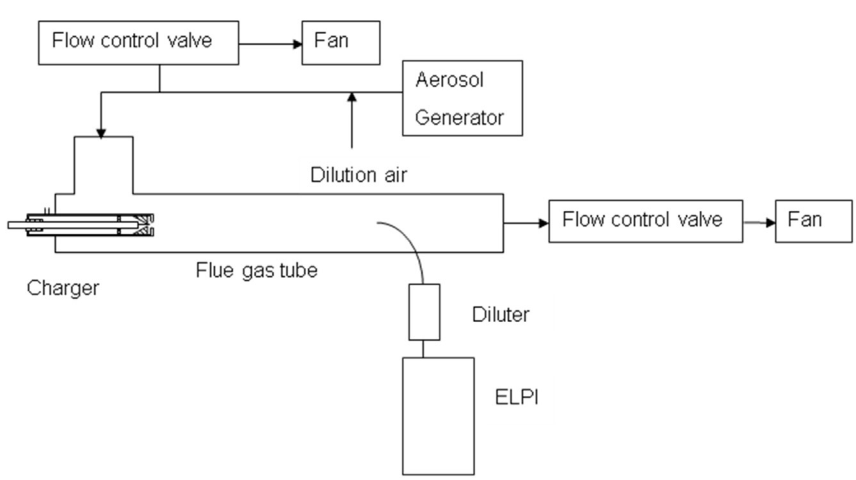

Fig. 2. Laboratory setup for the charging efficiency measurements.

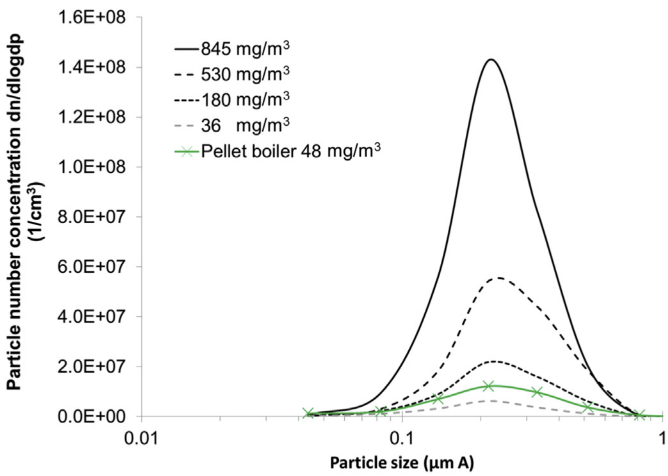

Fig. 3. Aerosol particle number distributions in laboratory measurements with different mass concentrations and the number distribution of a commercial pellet boiler. Particle size in aerodynamic diameter.

entire box volume more uniformly. The flue gas temperature in the charging section was between 120 and 150 °C. The aerosol particle number distribution at the boiler exit is presented in Fig. 3. Aerosol concentration, size distribution and average charge distribution were measured using the ELPI. The sampling point was located at the boiler exit after the second heat exchanger section. The sampled aerosol was diluted and cooled to room temperature using the ejector diluter before entering the ELPI. The commercial 20 kW pellet boiler system was manufactured by Ariterm Oy (Ariterm Biomatic + 20).

3. Results and discussion

3.1. Corona operation and ion production

With the internal ground electrode design, the corona onset voltage was between 4 and 5 kV; in practices, however, better corona stability was achieved from 6 kV potential. At 6 kV, the corona current was 7–9 µA for the positive voltage and 21–51 (−µA) for the negative voltage (Fig. 2 In Supplemental Information). Sparkover started above 8 kV (above 7.5 kV positive voltage with 2.5 bar purge air pressure). Increased corona voltage resulted in increased corona current, as expected. However, with the ion current, the increase was much smaller (Fig. 3 Supplemental Information). This similar phenomenon was observed by Ref. [14]. With increasing corona voltages, more ions deposit of the ground electrode rather than exiting the charger with the purge gas flow. Similar behavior was observed with the negative corona voltage. The negative corona currents were higher than the positive currents with same voltages. However, the ion current values did not have a similar increase, resulting in lower ion purge efficiency (Fig. 4 Supplemental Information).

Increasing the purge air pressure also increased the ion current for both polarities. In the charger geometry used, the maximum ion current was achieved with 2.5–3 bar purge air pressure. After that, an increase in pressure did not increase the ion current and, in some cases, even started to decrease it. Also, the corona discharge sometimes started to behave peculiarly. Our guess is that the air volume between the orifice and the protection cap started to oscillate, but we could not test the hypothesis.

The U/I characteristics of the charger with the external ground electrode depend on the flue gas duct geometry. As the ion current equals the corona current, higher ion currents can be achieved by increasing the corona voltage. The purge air flow does not have an effect on the ion current and is only used to keep the corona electrode clean.

3.2. Particle charging efficiency

The average particle charge distributions from the laboratory measurements are presented in Fig. 4. The results from the integrated GE charger are presented with two different particle mass loads. One charger was used. The charger voltage was −6 kV, and the corona current was between −50 and −65 µA. The purge gas pressure was 2.5 bar. Ion current can be estimated to be approximately −4.5 µA. It can be seen that as the mass load increased from 36 mg/m^3 to 180 mg/m^3, the particle average charge state decreased significantly. This suggests that the ion production of a single charger unit is too low for higher particle loads.

The results using the external GE charger with 3 different particle mass loads are shown in Fig. 4. One charger was used. The charger voltage was between −18 and −26 kV, and the charger current was between −20 and −80 µA. At the highest particle load some decrease in average charge can be noted.

Fig. 4 also shows measured charging efficiency of an industrial full scale ESP for comparison (ESP data in supplemental information). It can be estimated, that with both iGE and eGE charger more than one unit is required to achieve equivalent

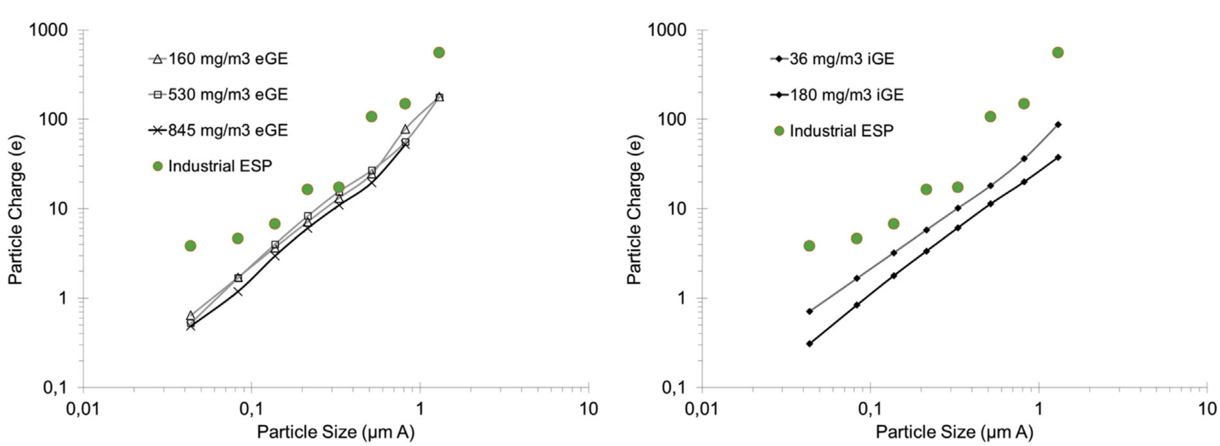

Fig. 4. Average particle charge distributions with different mass concentrations. Charger with integrated (iGE) and external (eGE) ground electrodes. Charge values below 1 elemental charge indicate that only some of the particles acquired a charge. For comparison charge distribution of an industrial ESP is also given.

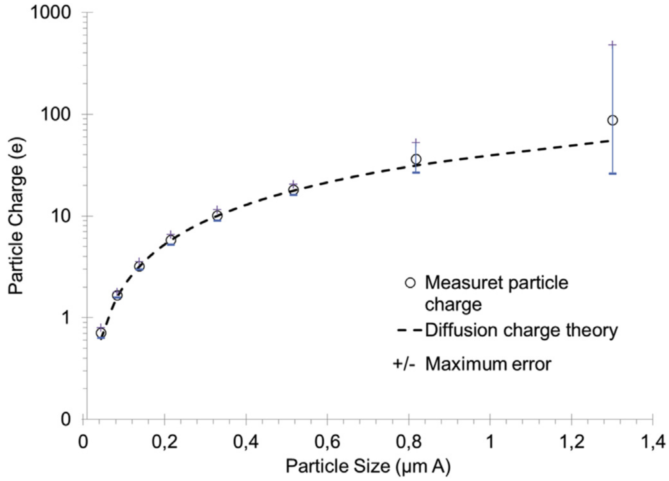

Fig. 5. Particle charge acquired with integrated GE charger. Fitted theoretical curve of diffusion charge. Particle concentration of 36 mg/m^3.

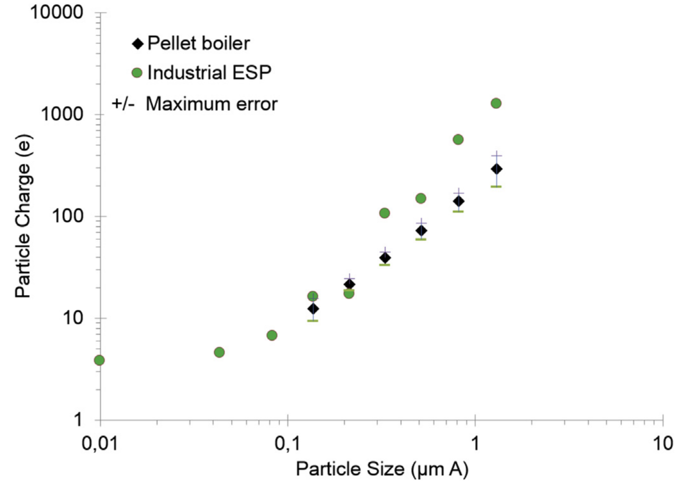

Fig. 7. Particle charge distribution achieved in the commercial pellet boiler tests. Two external GE chargers were used. Charge state measurement results from an industrial-scale ESP are also given for comparison.

particle charge state to that used in commercial ESP applications.

Negative charger voltage was selected in this comparison as negative polarity is used in industrial ESP's. Higher ion currents can be achieved with an external GE charger, resulting in better particle charging. With the integrated GE charger, the positive voltages would have resulted in more or less the same level of particle charge but with lower corona power consumption.

In Fig. 5, the integrated GE charger's efficiency (negative corona) at 36 mg/m^3 particle concentration is compared with the classical diffusion charging efficiency theory [4] (theory and formulas presented in supplemental material). It shows that the charging efficiency follows the theory quite well. The deviation of the largest particle size fraction (1.3 µm aerodynamic) from the theoretical curve suggests that there is also some field charging present. The field is formed by the space charge effect of the ions and charged particles.

The external GE charger's efficiency at 530 mg/m^3 particle concentration is shown in Fig. 6, with theoretical diffusion, field and combined charging curves [4,15]. The charge state of the larger particles indicates the presence of a field charging process, as expected.

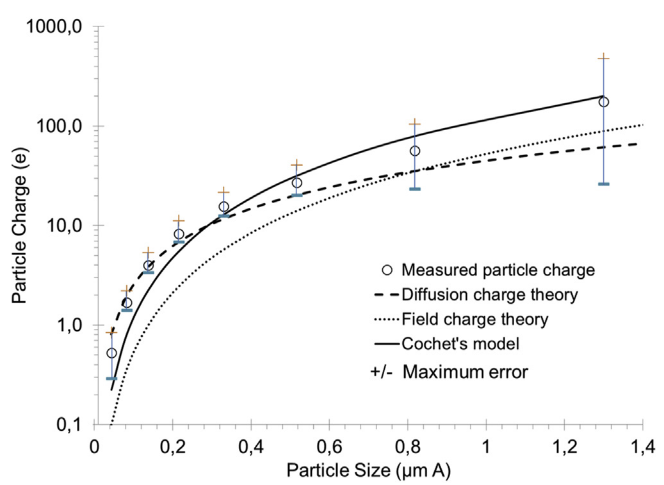

Fig. 6. Particle charge acquired with external GE charger. Fitted theoretical curves for diffusion charging, field charging and combined charging according to Cochet's model. Particle concentration of 530 mg/m^3.

The charging efficiencies of two external GE chargers tested in a commercial pellet burner are shown in Fig. 7. The charger voltages were between −37 and −40 kV, and the currents were between −120 and −200 µA each. For comparison with the achieved particle charges, the figure also presents charge measurements from a commercial ESP (ESP data in supplemental information). The comparison shows that the particle charge achieved using a sonic jet-type charger should be high enough for precipitation purposes.

3.3. ESP removal efficiency

The charged aerosol was also tested with a laboratory-scale parallel plate electrostatic collector. A single charger with an external ground electrode was used. The purge air pressure was 2.5 bar, the corona voltage was −26 kV and the average corona current was −80 µA. The collector field strength was 4 kV/cm. The collection efficiency is shown in Fig. 8. The collection efficiency was found to be 97% (from the mass concentration). Typical ESP removal

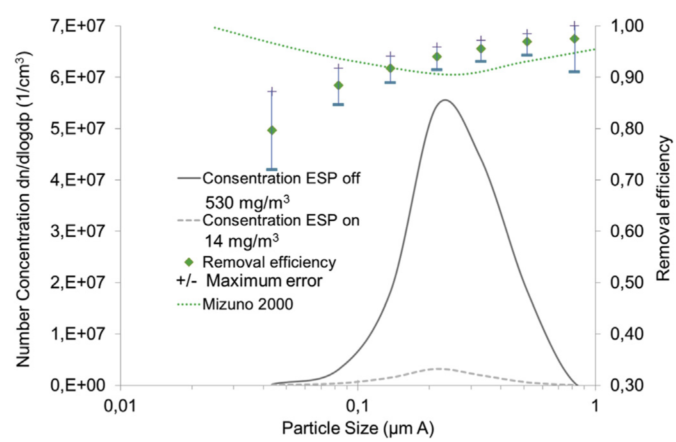

Fig. 8. Particle removal efficiency of the laboratory-scale parallel plate electrostatic collector. A single charger with an external ground electrode was used. ESP off = particle charging and ESP collection field off; ESP on = particle charging and ESP collection field on. Removal efficiency 97% from mass concentration. Removal efficiency 94% from particle number concentration. Result agree well with typical ESP removal efficiency.
(Adaptation from Ref. [11]).

efficiency (adapted from Ref. [11] is given for comparison). The drop in the removal efficiency of particles below 0.1 μm is a result of insufficient charging and more than one charger would be needed for good precipitation efficiency.

4. Conclusions

In this study, we tested two sonic jet-type chargers with high-concentration aerosols containing particles in the size range of 0.05–1 μm. Both charger types can produce enough free ions in the flue gas to enable high enough particle charges to use, for example, with electrostatic precipitation. With higher particle loads and/or larger flue gas volumes several chargers are needed to ensure good charge state specially for particles below 0.1 μm.

Of the two chargers tested, the one with external ground electrode had higher free ion output. With the integrated ground electrode design, the amount of free ions is limited due to the internal losses. With the highest achieved free ion production rate, the internal losses were almost 80%. In the charger with an external ground electrode, the ion current was almost the same as the corona current. In practical applications, both designs can be used. With low particle loads, they operate almost equally. The internal GE chargers have the advantage of working with lover HV levels than the external GE device. On the other hand, the internal GE charger requires pressurized purge air, whereas the external GE charger can use an air fan. With higher particle loads, more internal GE charger units are required to achieve the same particle charge state as external GE chargers. As an example, 12 eGE chargers would be required to increase the particle charge state at 530 mg/m^3 near to the levels that are found in large scale commercial ESP (see supplementary material). With iGE chargers at 36 mg/m^3 particle mass concentration 12 units would still generate lower charge state that the industrial reference. The size of the difference not only depends on the particle concentration but also the geometry of the aerosol channel. It may be possible to position the internal GE chargers better than the external GE chargers, as they work independently of the flue gas channel geometry. It should also be noted that with small scale biomass boilers 30–50% particle mass removal efficiency is often enough to meet the legislative requirements.

Compared to wire discharge electrodes, sonic jet-type chargers have the advantage of being shielded from the flue gas. The purge air protects the corona electrode from contamination and corrosion. As the corona electrode is in purge air, flue gas parameters like temperature have less effect on the corona characteristics. Sonic jet-type chargers can be used in processes that could be difficult with traditional ESPs.

The sonic jet-type shielded electrodes are more expensive to make than most traditional electrodes. In applications where the use of flue gas exposed to the corona electrodes does not cause problems, the shielded corona electrodes would only make the system more expensive. The shielded electrodes can find use in applications in which the cleaning of the electrodes would cause problems or in which the flue gas properties do not allow the use of unshielded electrodes. An example from the first case is small-scale biomass combustion, for which very simple, reliable, low-cost solutions are needed. Precipitation in a high temperature/corrosive environment can be selected as an example from the second case. In general the applicability of iGE and eGE sonic jet-type chargers can be listed as:

Internal ground electrode sonic jet-type charger:

- Applications with moderate particle concentration and removal efficiency requirements.
- Applications with difficult flue gas duct geometries or very difficult gases (including explosive mixtures)

External ground electrode sonic jet-type charger:

- In general applications where shielded electrodes benefit the removal process.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.elstat.2016.06.002.

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