SUBTASK 2.11 – AN INVESTIGATION INTO THE EERC STAGED ELECTROSTATIC PRECIPITATOR CONCEPT

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ABSTRACT

A new concept of electrostatic precipitator (ESP), named a Staged ESP (an Energy & Environmental Research Center proprietary), was conceived in June 2004. The concept is based on a simple design that can be retrofitted on existing coal-fired power plants to provide high particulate matter (PM) collection efficiency without compromising reliability. A prototype of Staged ESP was designed, fabricated, and tested in two different combustion coal flue gases with different fly ash resistivities. Several design parameters of the Staged ESP were evaluated under various operating conditions to optimize PM collection performance. A set of particulate sampling data, including aerodynamic particle sizer, scanning mobility particle sizer, and U.S. Environmental Protection Agency Method 5 data, was collected to determine PM emissions of the Staged ESP configurations. These data were compared against data collected with a conventional ESP configuration. Compared to PM capture performance in conventional ESPs, an additional 30% to 70% reductions on total PM emissions were achieved for Staged ESPs in flue gas with medium- to high-resistivity fly ashes. Experimental data proved that the Staged ESP concept is capable of achieving higher PM collection efficiency, especially for particles in the submicrometer size range typically thought difficult to capture in an ESP.

TABLE OF CONTENTS

LIST OF FIGURES

SUBTASK 2.11 – AN INVESTIGATION INTO THE EERC STAGED ELECTROSTATIC PRECIPITATOR CONCEPT

EXECUTIVE SUMMARY

The Staged electrostatic precipitator (ESP) concept is based on a simple design that can be retrofitted on existing coal-fired power plants to provide high particulate matter (PM) collection efficiency without compromising reliability. The concept was conceived at the Energy & Environmental Research Center in June 2004. A prototype unit was then designed, fabricated, and tested in a pilot-scale combustion system with two different low-rank coals. Several design parameters of the Staged ESP were evaluated under various operating conditions to optimize PM collection performance. Extensive particulate sampling, including aerodynamic particle sizer, scanning mobility particle sizer, and U.S. Environmental Protection Agency Method 5, were conducted to determine PM capture efficiencies of the Staged ESP prototype under various conditions. Preliminary pilot-scale testing data have proved that, by simply optimizing flue gas flow pattern within the prototype unit, the Staged ESP concept is capable of achieving higher PM collection efficiency, especially for particles in the submicrometer size range typically thought difficult to capture in an ESP.

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BACKGROUND

The most common particulate control approach employed on coal-fired boilers in the United States is the electrostatic precipitator (ESP). Of the approximately 1100 coal-fired utility boilers in the United States, about 90% are equipped with dry ESPs. Many of the older ESPs were originally designed to collect only 0.1 lb/million Btu of total mass particulate matter (PM). The ESPs constructed since 1977 are typically under the somewhat stricter NSPS (New Source Performance Standards) emission limit of 0.03 lb/million Btu and 20% opacity, but since these ESPs are now aging, many will require upgrades to remain in compliance.

Furthermore, since the ambient air quality standard is now based on fine particles ($PM_{2.5}$), there is interest in controlling $PM_{2.5}$ emissions rather than total mass emissions. Since ESP collection efficiency is much lower for fine particles, existing ESP technology may not be adequate to control $PM_{2.5}$ emissions to the level required.

A recent example where much stricter emissions were required for an existing plant is the Craig Station in Colorado, which was required as part of a settlement of a Sierra Club lawsuit to replace the plant's ESPs with baghouses (1) to meet a new emission limit of 0.015 lb/million Btu and 5% opacity. Because of the requirement to completely replace the old ESPs and the required additional fan capacity for the higher pressure drop with the baghouses, the project was very costly compared to a simple upgrading of an existing ESP. If a superior technology were available that could achieve much better fine-particle collection efficiency for the same-sized ESP, an environmentally sound approach would be available to upgrade existing ESPs at a much lower cost than current approaches.

ESP theory is based on the assumption of continuous and complete turbulent mixing through the entire length of an ESP. However, in-depth analysis of this assumption along with empirical data indicates that this assumption is an oversimplification (2) and that there is significant potential to improve the fine-particle collection efficiency by modification of the ESP geometry and flow patterns. Building on recent findings from other work and positive results from investigatory testing, a Staged ESP can achieve higher total PM collection efficiency and significantly better fine-particle collection efficiency than similarly sized conventional ESPs. Furthermore, the design of such an ESP would be very simple and would require minimal developmental work leading to commercialization.

CONCEPT DESCRIPTION

The configuration of the Staged ESP is proprietary. However, it can be divulged that a Staged ESP consists of an arrangement of precipitation electrodes and precipitation collection plates that direct flow in a modified path, which facilitates higher PM collection levels, even for particles at submicron size typically thought difficult to capture in an ESP.

The Staged ESP concept is based on a simple design that can be retrofitted on existing plants to provide high collection efficiency without compromising reliability.

OBJECTIVES

The overall objective of this project was to develop a Staged ESP that could achieve better total and fine-particle collection efficiency than conventional modern ESPs for a given housing size. Achieving greater capture efficiency in a similar capital equipment footprint could result either in a coal-fired power plant achieving tighter emission goals or that it could achieve status quo emissions when replacing an aging ESP with the new technology for a significantly lower capital cost and footprint.

Developmental objectives for this project were as follows:

- Quantify the level of control that can be achieved for both larger and submicron particles, with both high- and low-resistivity coal fly ash, and compare results between the unique Staged ESP and a conventional parallel plate ESP configuration.

- Make improvements to the gas flow pattern within the prototype to achieve higher collection efficiency for total PM than that of a conventional ESP.

- Make improvements to the gas flow pattern within the prototype to enhance collection efficiency for submicron PM.

TEST REGIMEN

The test effort was divided into two separate funding years. The first year of the investigation focused on designing, building, and testing a prototype Staged ESP for use in investigative tests. Pilot-scale combustion tests were completed to determine the PM collection efficiency with the Staged ESP technology for low-resistivity ash and to compare to conventional ESP performance with the same fly ash-laden flue gas. The second year of the investigation examined the efficacy of the new technology on a high-resistivity ash.

Initial Investigation

During the initial investigation, a detailed mechanical design was developed to embody the Staged ESP concept. This detailed design was then fabricated at the Energy & Environmental Research Center (EERC). The prototype Staged ESP was designed to treat approximately 130 scfm of flue gas, the standard flue gas flow rate for the EERC's coal-fired particulate test combustor (PTC). The unit was specifically designed so that, within the same housing, it could be operated either in a conventional ESP mode or one of several staged configurations by reconfiguring the stages. This allowed for the most valid comparisons of performance of the Staged ESP concept with conventional ESP technology.

The PTC has been extensively employed in previous particulate control research at the EERC. A large base of previous data generated with the PTC for ESPs, fabric filters, and the advanced hybrid particulate collector was available for comparison with results from this project. Since the PTC was fired with pulverized coal, it generated a particle-size distribution typical of larger-scale firing so that both submicrometer and supermicrometer particle control could be evaluated.

Three different Staged ESP configurations were evaluated during the pilot-scale test to determine the PM emission levels at various corona currents. The results were compared to those of corresponding conventional ESPs with similar size and process conditions so that valid conclusions could be made as to the level of improvement achieved by the staged configuration. Extensive particulate measurements were completed with both a scanning mobility particle sizer (SMPS) and an aerodynamic particle sizer (APS), which provided near real-time measurement on PM emissions as a function of size over the range 0.02 to 15 µm. This facilitated testing of a maximum number of experimental parameters in the least amount of time. U.S. Environmental Protection Agency (EPA) Method 5 samples were collected under selected operating conditions at the outlets of the Staged ESP and conventional ESP to verify PM emission measurement using APS and SMPS.

Follow-Up Investigation

Based on recent findings from other work and results from the previous year's test effort, further testing of the Staged ESP was performed in 2008. Test results from the first year of investigation indicated clear benefits for the Staged ESP concept; however, to better assess differences, additional tests with a higher-resistivity ash were conducted in 2008.

The original Staged ESP prototype was fabricated with multiple sight ports to facilitate evaluation of the flow distribution and dust collection patterns. During the initial investigation, the flue gas flow pattern through the Staged ESP was observed to be suboptimal. A number of iterative steps were taken to correct the problem. The flow patterns were significantly improved to the point that valid testing could be completed, but further improvements were needed to complete additional testing. In an effort to improve flow patterns and flow balance, several alternative inlet configurations were fabricated for retrofit into the original prototype unit.

The prototype Staged ESP was again installed on the existing EERC PTC in a manner identical to that employed during the initial investigation. The testing with the PTC was conducted over the course of approximately 36 hours from start-up to shutdown. The coal burned was a Powder River Basin subbituminous coal (from the Absoloka mine).

As a result of low sodium content in Absoloka coal, the electric resistivity of Absoloka fly ash is an order magnitude higher than that of Beulah fly ash, which is considered challenging for PM capture with conventional ESPs. During this phase of investigation, the team evaluated capture of submicron particulate matter and used an SMPS and total particulate capture measured by EPA Method 5. This provided exact particle emissions as a function of particle size over the range of 0.02 to 0.5 µm under various corona currents. EPA Method 5 samples were collected under selected testing conditions for both Staged and conventional ESPs to verify PM emissions.

RESULTS AND DISCUSSION

Initial Investigation Results

Proof of concept testing was completed in June 2005 to evaluate PM collection efficiency of the Staged ESP concept. The results were compared with PM emissions from conventional ESP with similar size and operating conditions. North Dakota Beulah lignite was combusted in the PTC to generate fly ash with a typical size distribution for low-rank lignite-based flue gas.

Three different Staged ESP configurations (henceforth referred to as SE-1A, SE-1B, and SE-2) and two corresponding conventional ESP configurations (henceforth referred to as CE-1 and CE-2) were tested. SE-1A and SE-1B were comparable to CE-1, because they were of similar size and utilized similar operational conditions. Similarly, SE-2 and CE-2 were also comparable.

By varying the electric voltage applied, *V*, corona currents, *I*, were measured for SE-1A in stagnant air, cold air flow, and hot air flow, respectively, to establish a current–voltage correlation. The resulting V-I curves are plotted in Figure 1, showing no significant changes on V-I correlation under the three different conditions. Also plotted in Figure 1 are the V-I curves

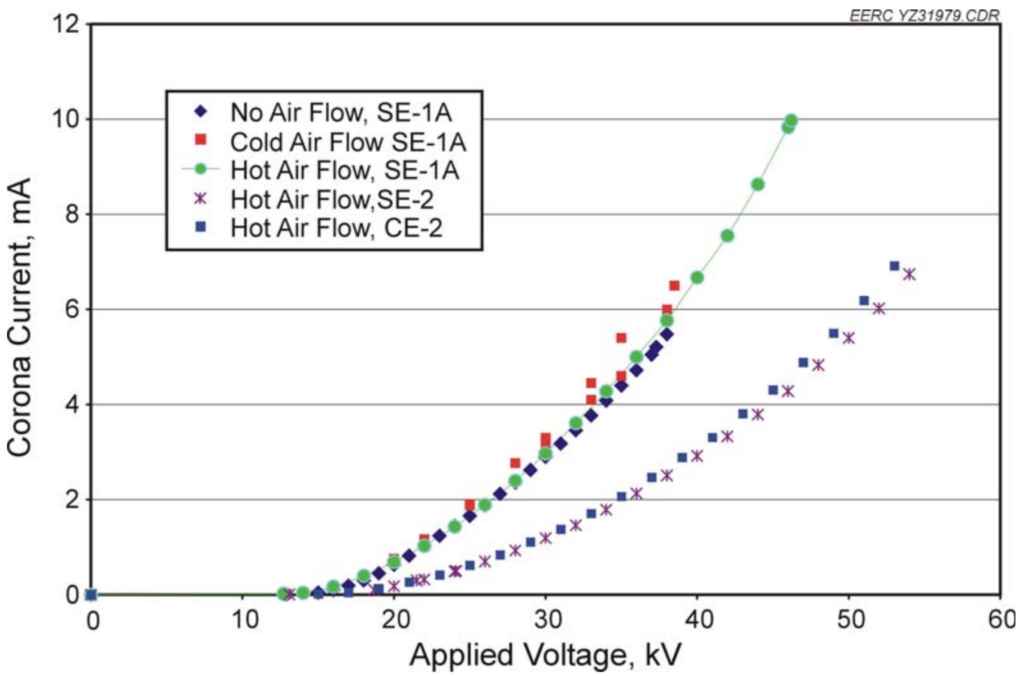

Figure 1. Electrical characteristics of Staged ESP configuration and conventional ESP configuration.

for SE-2 and CE-2 in hot air flow condition. SE-1 generated much higher corona current than both SE-2 and CE-2 at the same applied voltage. There was no significant difference in V-I correlation between SE-2 and CE-2.

The APS instrument provided real-time supermicron PM emission measurements for the Staged ESP and conventional ESP configurations at varying corona currents. These data are shown in Figures 2 and 3. At 8 mA of corona current, SE-1A, SE-1B, and CE-1 performed similarly. Supermicron PM emission measurements from the three different ESP configurations (SE-1A, SE-1B, and CE-1) were approximately 0.1 mg/m^3. It is noted that the APS instrument only measures particles in the size range of 0.5–15 µm and that the particle mass concentration is calculated based upon measured particle number concentrations in flue gas multiplied by an assumed particle density of 2.4 g/cm^3.

When corona current was decreased from 6 mA to 2 mA, SE-1B outperformed SE-1A and had PM emissions of 0.5 mg/m^3, 1.8 mg/m^3, and 7.8 mg/m^3 at corona currents of 6 mA, 4 mA, and 2 mA, respectively. The overall PM capture by SE-1B was comparable to CE-1 at various corona currents. SE-1B may have exhibited a marginally better PM collection efficiency than CE-1 at 2 mA corona current. As shown in Figure 3, SE-2 exhibited PM capture efficiency similar to that of CE-2 at 5 mA current level. However, CE-2 outperformed SE-2 in PM collection under reduced currents of 1–3 mA.

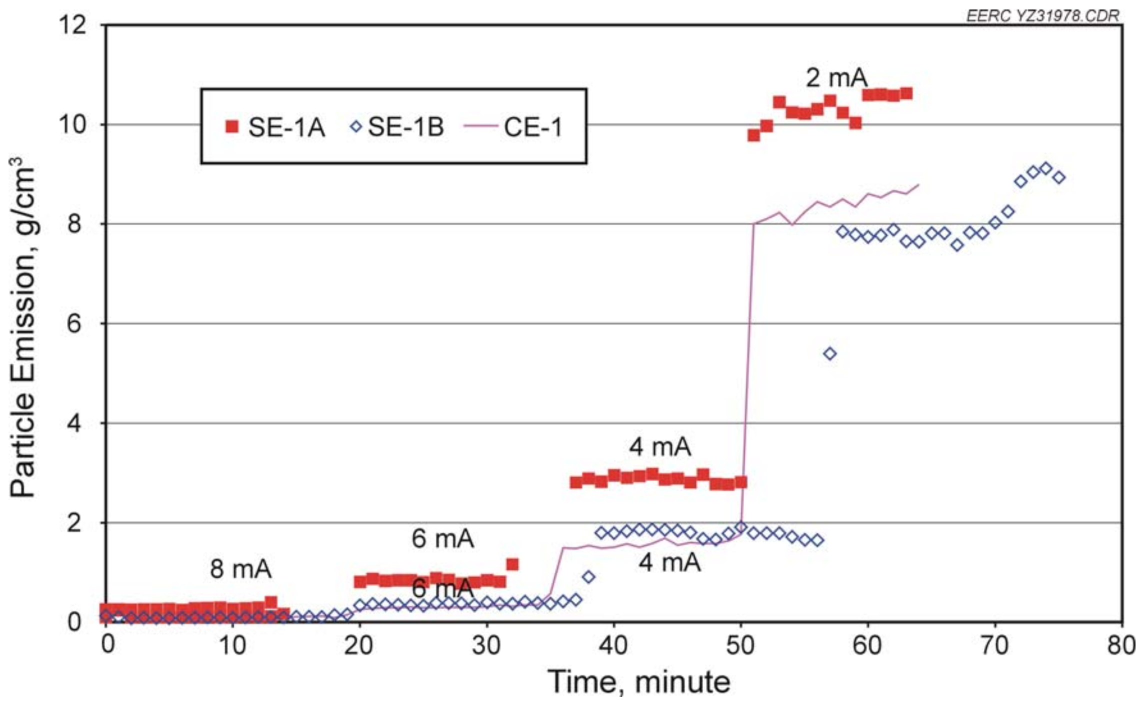

Figure 2. PM emissions for Staged ESP configurations SE-1A and SE-1B and for conventional ESP configuration CE-1.

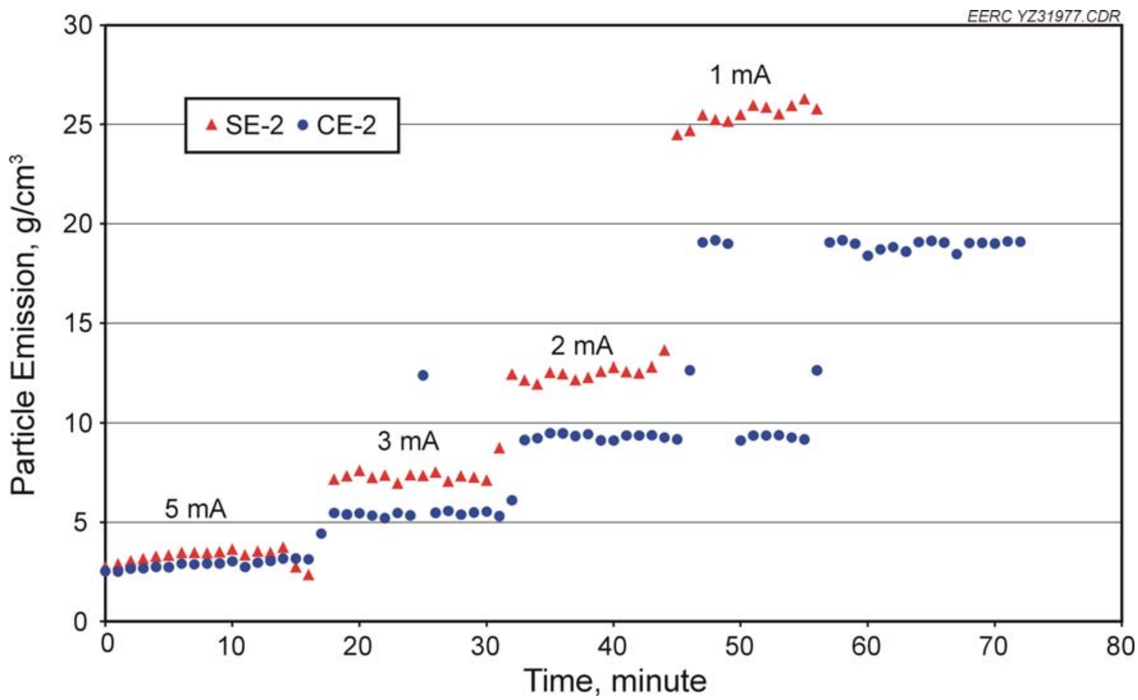

Figure 3. PM emissions for Staged ESP configuration SE-2 and for conventional ESP configuration CE-2.

Plotted in Figure 4 are supermicron particle-size distributions in the outlet flue gas for SE-1B and CE-1 at various corona currents. The APS measurements indicate that both SE-1B and CE-1 exhibited similar supermicron particle-size distributions in their respective outlet flue gases at similar corona currents. However, particle-size distributions in the submicrometer range in the outlet flue gas differed between the Staged ESP configuration and the conventional ESP configuration. SMPS measurements were conducted in the outlet flue gas at various corona currents with both the Staged ESP configuration and the conventional ESP configuration. The corresponding submicrometer size distributions are plotted in Figure 5. SE-1A and SE-1B outperformed CE-1 in capturing particles smaller than 0.1 µm. The submicron particle capture efficiencies of SE-2 and CE-2 were nearly identical.

To further verify the PM capture efficiency of the Staged ESP configuration, EPA Method 5 sampling was performed at the outlet of SE-1A and SE-1B to determine total PM concentration in the flue gas. Both Staged ESP configurations were operated at 8 mA corona current during the entire sampling period. The measurement results are plotted in Figure 6. Also included in Figure 6 are the PM emission data from CE-1, operated at the same corona current level. EPA Method 5 data indicated that the approximate additional 30% reductions on total PM emissions were achieved for SE-1A and SE-1B compared to PM emissions from CE-1 when they were all operated at 8 mA.

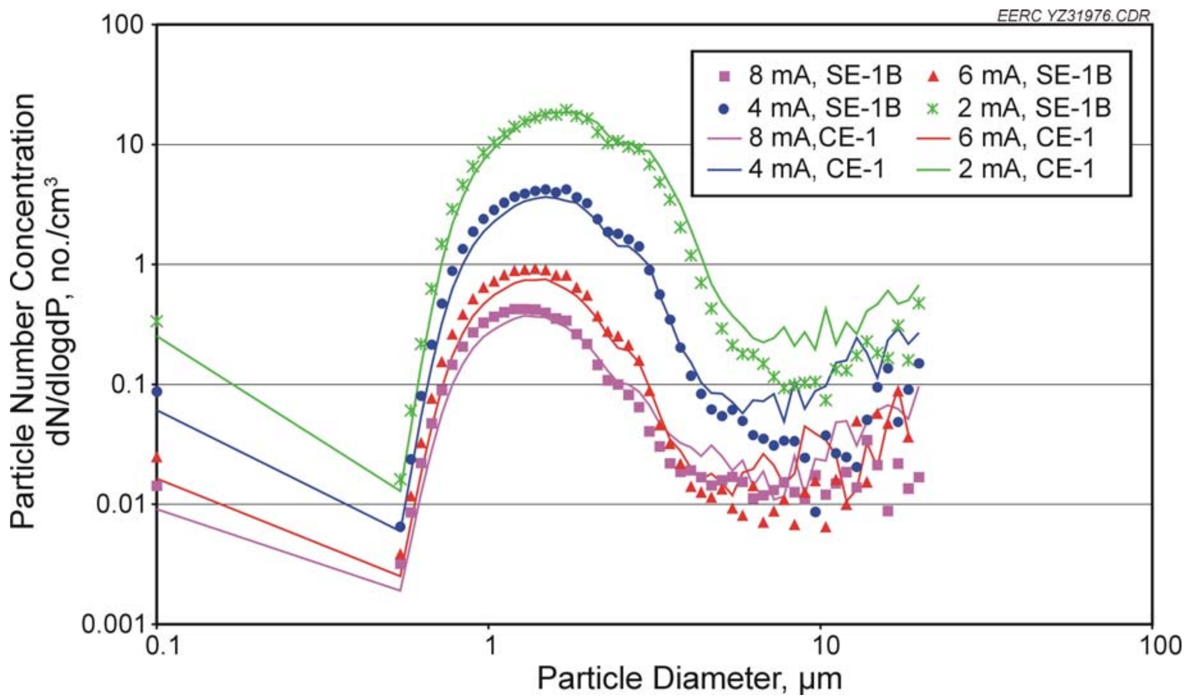

Figure 4. Supermicron particle-size distribution for all prototype unit configurations.

Follow-Up Investigation Results

Test data from the initial investigation indicated that the Staged ESP concept may potentially exhibit better PM capture efficiency than a conventional ESP configuration, especially for submicron particles that are very difficult to capture in conventional ESPs. Consequently, additional pilot-scale tests were conducted in February 2008 to further investigate PM capture with the Staged ESP configuration in an Absoloka coal-based flue gas. Absoloka coal is considered challenging because the fly ash it generates in a pulverized coal combustion system has high electrical resistivity, making it difficult to capture in a conventional ESP. Laboratory measurements indicate that the electric resistivity of the tested Absoloka coal ash is an order of magnitude higher than that of North Dakota Beulah coal ash used in previous tests.

The Staged ESP inlet was modified to improve the flue gas flow pattern to maximize PM capture efficiency, especially submicron particle capture. Both EPA Method 5 and SMPS sampling were performed at the outlet of the Staged ESP/SE-1A configuration under various corona currents. CE-1 was also tested to determine PM emissions as a comparison. Plotted in Figures 7 and 8 are the measured submicron particle-size distributions in the outlet flue gas of SE-1A and CE-1.

Under the same 1 mA corona current, SMPS measurements of SE-1A indicated clearly lower submicron particle emissions than that of CE-1. Moreover, SMPS data indicate PM collection performance of SE-1A was consistent under varied corona currents, which was not observed during the initial investigation. The consistent PM capture of SE-1A was likely because

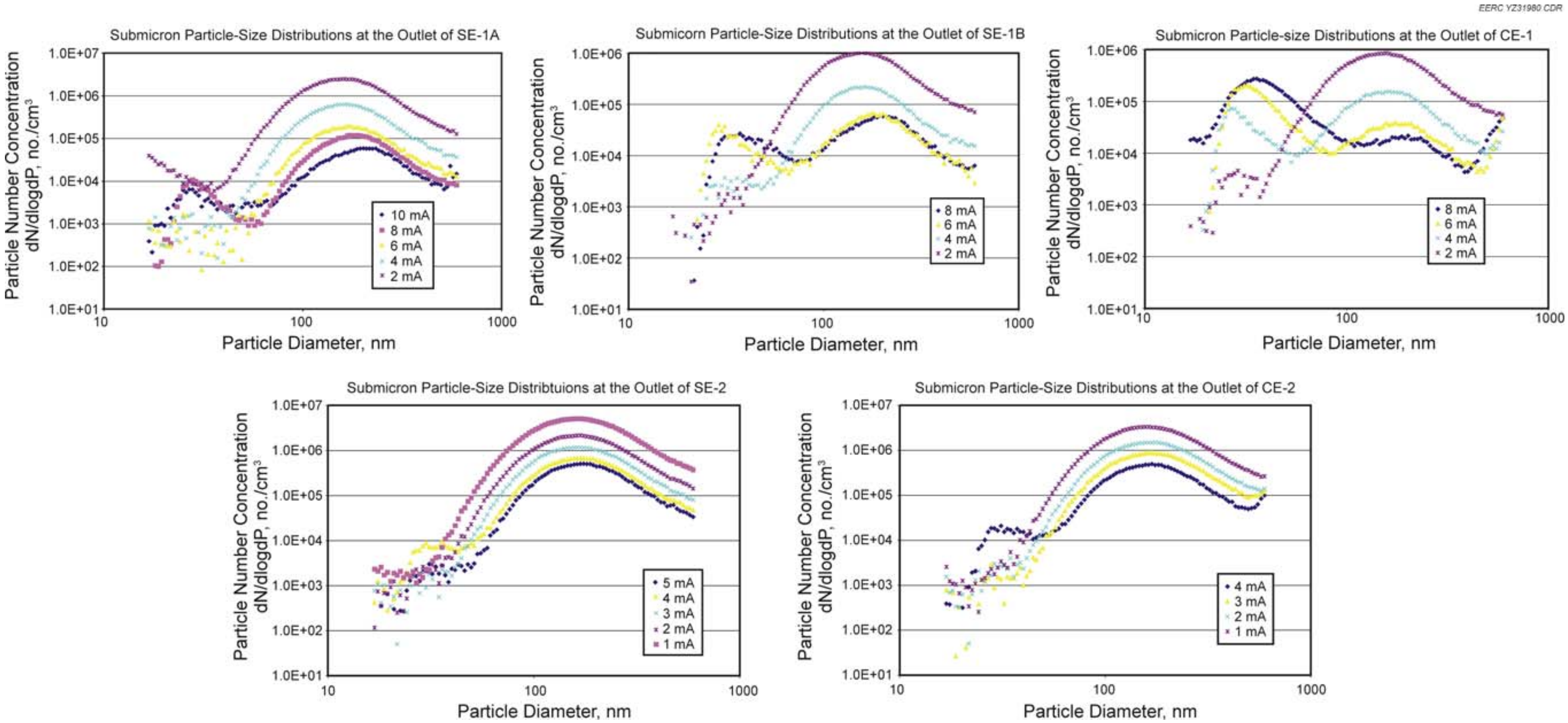

Figure 5. Submicron particle-size distribution for all prototype unit configurations.

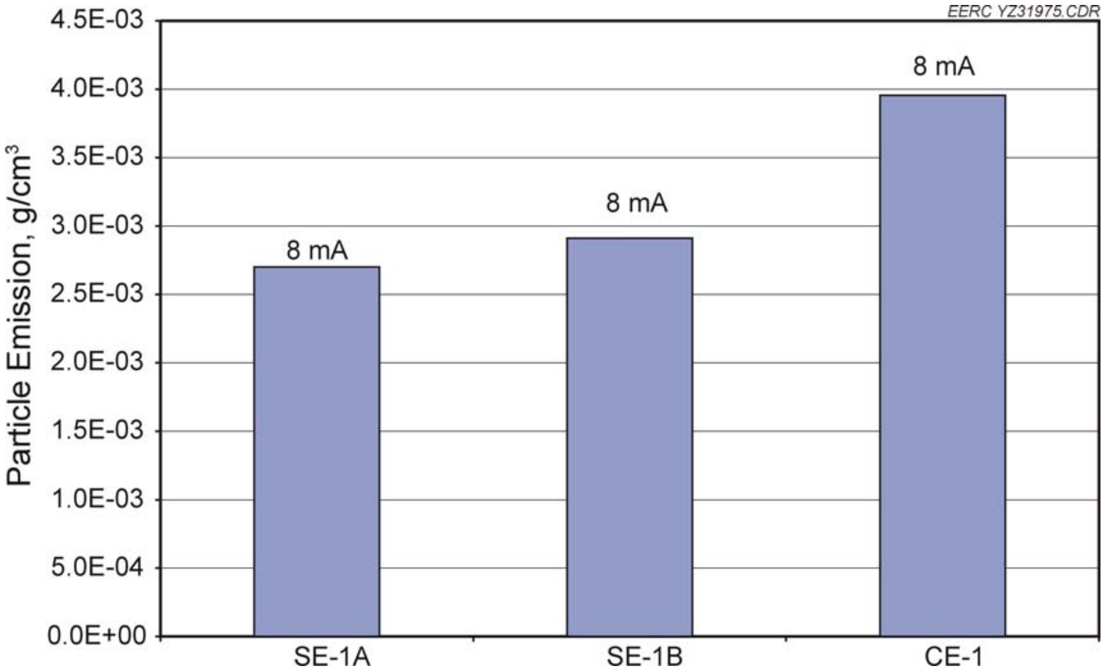

Figure 6. PM emissions of Staged and conventional ESP configurations (EPA Method 5 results).

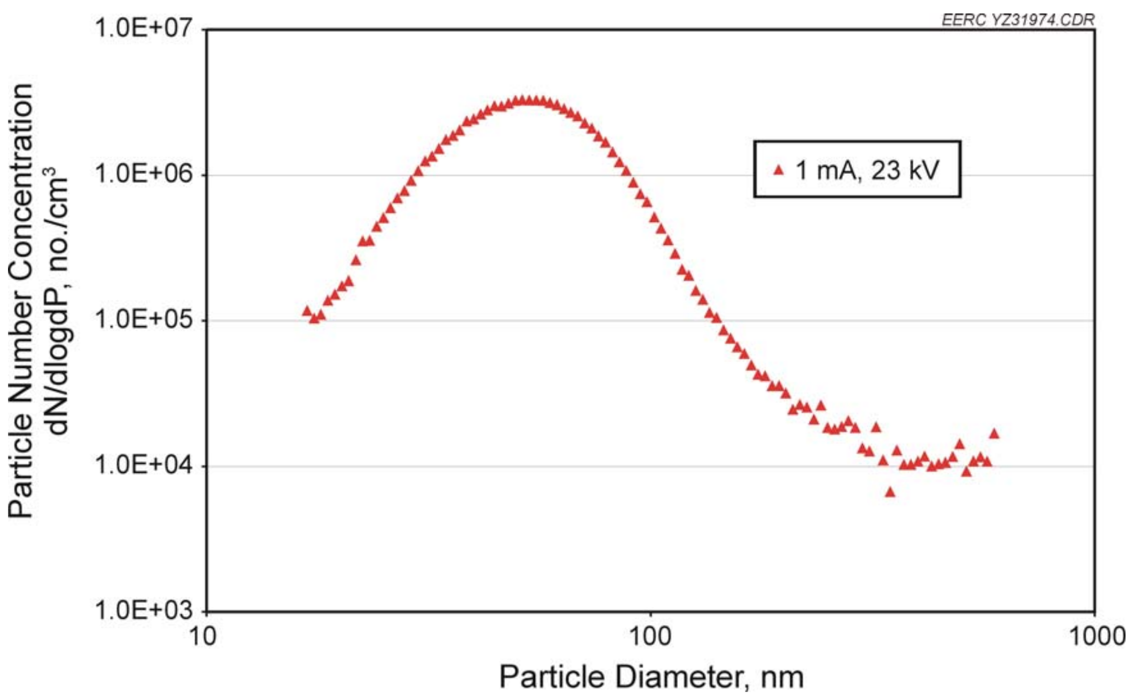

Figure 7. Submicron particle-size distributions at the outlet of CE-1.

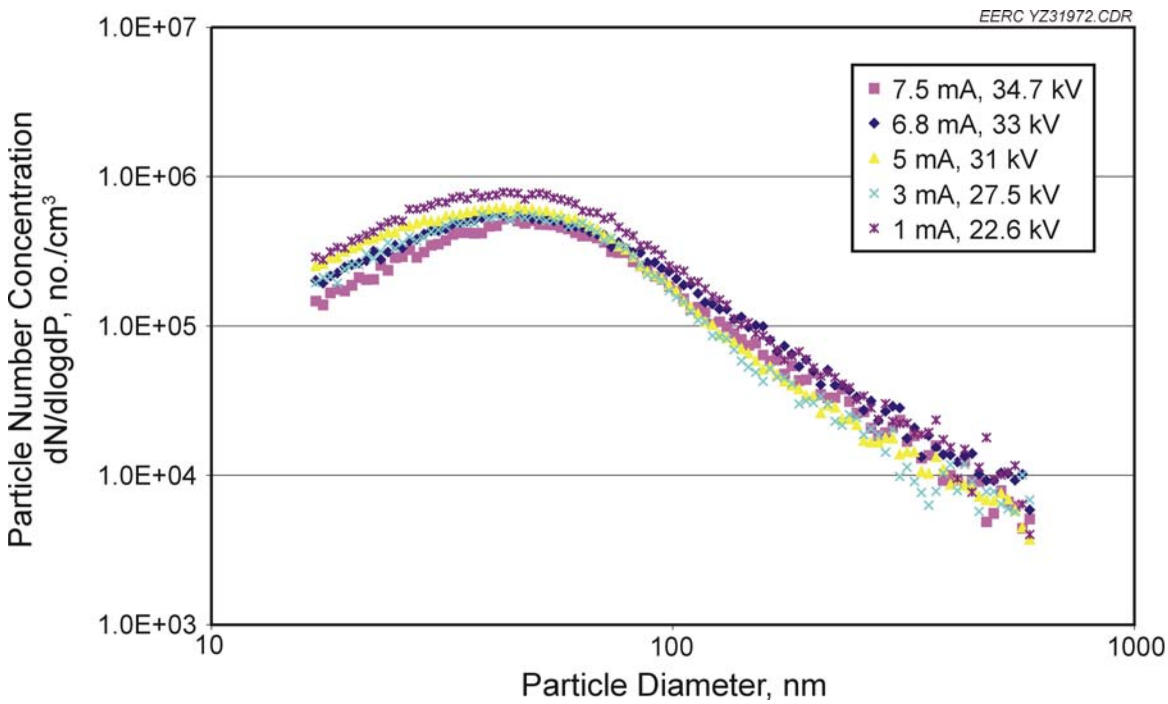

Figure 8. Submicron particle-size distributions at the outlet of SE-1A.

of the improved gas flow pattern within the Staged ESP. Total PM emissions from SE-1A and CE-1 were verified by measuring total PM concentrations in the outlet flue gas using EPA Method 5. The results are summarized in Figure 9. Additional 48%–73% reductions in total PM emissions were obtained for SE-1A compared to CE-1 at 5 mA corona current. At 1 mA corona current condition, a very low corona current level, total PM emissions from SE-1 were dramatically increased up to 0.44g/m^3, while SE-1A was reasonably maintained at 0.12g/m^3, approximately 73% lower than that of CE-1. In conclusion, SE-1A clearly outperformed CE-1 in this high-resistivity fly ash environment for PM capture.

The pilot-scale testing data proved that Staged ESP is a more effective PM control device than conventional ESP and is capable of providing consistent high PM capture efficiency in various flue gas environments in various operating conditions.

CONCLUSION

Pilot-scale proof-of-concept tests were conducted to evaluate Staged ESP performance in two different coal flue gases. A set of particulate sampling data, including APS, SMPS, and EPA Method 5 data, was collected to determine PM emissions of the Staged ESP configurations. These data were compared against data collected with a conventional ESP configuration. Preliminary pilot-scale testing data proved that, by simply optimizing the flue gas flow pattern within the prototype unit, the Staged ESP is capable of achieving higher total PM collection efficiency as well as PM in the submicrometer size range typically thought difficult to capture in an ESP. Compared to PM capture performance in a conventional ESP, 30% to 70% reductions in

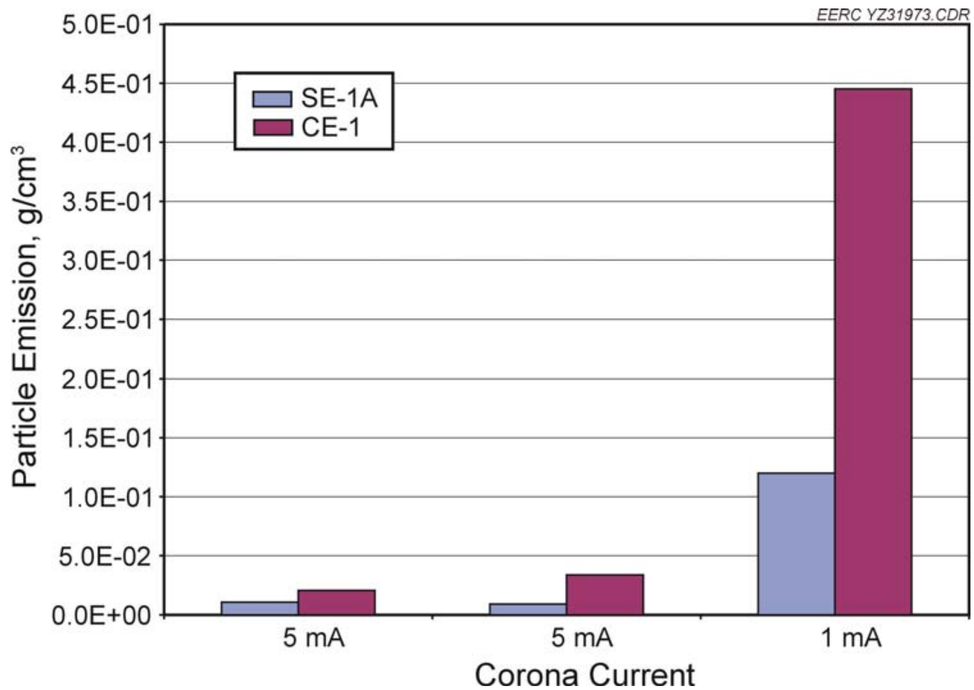

Figure 9. Particle emissions of SE-1A and CE-1 (EPA Method 5 results).

total PM emissions were achieved for Staged ESPs in flue gas with medium- to high-resistivity fly ashes.

RECOMMENDATIONS FOR FURTHER STUDY

Because test results prove the Staged ESP concept is capable of significantly improving total PM capture and, more importantly, fine PM capture, it is recommended that the concept be investigated further to determine its commercial potential.

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