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Introduction

Electrostatically charged sprays are used in a wide range of applications. They include the coating of surfaces as with paint spraying, the production of fine powders and the control of pollutants. The phenomenon of electrostatic spraying has been much researched particularly for the cases of dielectric fluids in paint spraying and conductive fluids in fine metallic powder production [1,2]. Although the literature on electrostatic spraying is voluminous, the parametric dependence of the size distribution of the spray under various conditions still lacks precise definition. The focus of this study is the generation of charged water droplets for the production of ions and radicals in flue gases by pulsed corona discharges to control SO_2 and NO_x [3].

As a first step in evaluating charged sprays for such use, a laboratory-scale injection system was evaluated by measuring atomization performance of needle injectors over a wide range of parameters [4]. Sauter mean diameter (SMD) determined with a Phase/Doppler Particle Analyzer (PDPA) was used as the measure of atomization performance. The independent parameters investigated include applied voltage, needle size, flow rate and $NaNO_3$ concentration (used to vary the solution conductivity). Because the spray was only about 2 mm wide at the sampling point, SMD measured at a single location was taken to be representative of the spray. This assumption was tested by taking radial traverses through the spray. Current flow from the needle to a collector plate 6 cm below was measured with and without solution flow to quantify the relative current-carrying capacities of the spray and the surrounding air.

Equipment and Procedures

The needle was mounted inside a screened test stand equipped with a three-axis positioning mechanism (Fig. 1). Seven needle sizes ranging from about 0.1 to 0.3 mm I.D. (gauge numbers from 32 to 21) were tested. Applied voltage ranged from 5 to 10 kV, solution flow rate from 0.02 to 0.82 cc/min, and $NaNO_3$ concentration from 0.125 to 8 percent. The $NaNO_3$ was dissolved in deionized water to form solutions of known electrical conductivity. A syringe pump delivered the solution to the needle. Current from the regulated power supply was monitored with a multimeter. Current delivered to a 25x25 cm aluminum collector plate 6 cm below the needle was measured with an electrometer. The two current readings generally agreed within 3 percent. Ambient humidity was measured periodically with a sling psychrometer. For some tests, humidity was monitored continuously with a dewpoint hygrometer.

PDPA measurements of SMD were performed at a single location 1 cm below the needle tip in the densest part of the spray (determined by scattered light intensity). The sprays were narrow at this location, with a total included angle of about 10 degrees and a diameter of roughly 2 mm. In spite of this tight distribution, SMD varied somewhat with location. However, because each spray was sampled at or near its densest location, the SMDs reported herein are believed to offer a meaningful relative measure of performance. The PDPA data rate was about 200 attempts/sec but ranged as high as 1400 attempts/sec. Ten thousand samples were typically recorded for each run. Acceptance rates generally fell between 80 and 95 percent. Modal diameters recorded with each data set were roughly 10 microns less than the SMD and exhibited the same overall trends. SMD is used herein because of occasional ambiguity in modal diameter.

Results and Discussion

A test matrix was devised that extended each parameter over its full range for selected values of the other independent variables. This section reports the effects of applied voltage, needle size, solution flow rate and solution conductivity on SMD. Current measurements taken with and without solution flow and the implications for atomization quality are also discussed.

Applied Voltage Variation. The effect of applied voltage on injector performance is shown in Figure 2. SMD was measured for 24- and 31-gage needles at a solution flow rate of 0.15 cc/min and a $NaNO_3$ concentration of 4 percent. With the 31-gage needle, voltage was varied over the intended range of 5 to 10 kV. With the larger 24-gage needle, an atomized spray could be achieved only for voltages exceeding 6 kV.

With both needles, SMD showed a general decrease with increasing voltage. Little change was observed for voltages exceeding 8 kV. SMDs for the 31-gage needle were appreciably lower than those for the 24-gage needle except at 9.5 and 10 kV. The spray became more highly dispersed with increasing voltage. With the 24-gage needle, two distinct streams were sometimes observed at the 9, 9.5 and 10 kV settings. The radial location of the center of the spray (defined as the region that scattered the most light) varied significantly with applied voltage, moving $\pm$ 1 mm at the sampling location 10 mm below the needle tip.

Effect of Needle Size. Figure 3 presents the effect of needle size on SMD for an applied voltage of 8 kV, a flow rate of 0.15 cc/min and a concentration of 4 percent $NaNO_3$. SMD was observed to increase monotonically with needle size, ranging from about 100 microns with the smallest (32-gage) needle to 180 microns with the 21-gage needle. This result can be attributed to the larger-diameter cylindrical streams from the larger needles breaking up into correspondingly larger droplets. Current was found to decrease with increasing needle size, perhaps reflecting a lower current-carrying capacity of the larger drops. The reduced current may also have been due to reduced corona discharge, since a duller needle tip is less effective at promoting airborne current.

Flow Rate Variation. The variation of SMD with solution flow rate for an applied voltage of 8 kV and $NaNO_3$ concentration of 4 percent is illustrated in Figure 4. Flow rates ranging from 0.02 to 0.82 cc/min were tested with both 24- and 31-gage needles. SMD increased with flow rate for both needles, with the exception of the results recorded at the highest flow rate with the 31-gage needle, for which SMD was sharply lower. Current was roughly constant with flow rate, suggesting that the larger drop sizes at higher flows may have been due to lower charge density.

A radial traverse was conducted at the maximum flow rate with the 31-gage needle to see if the change in SMD could be attributed to radial variation in drop size. The results revealed a modest effect of location on SMD, but not of sufficient magnitude to explain the sharp drop in SMD under these conditions. (A traverse conducted under reduced flow rate (0.15 cc/min) revealed a stronger dependence on location.) Current flow and ambient humidity (measured continuously with the dewpoint hygrometer) were not significantly different when the anomalous data were recorded.

Effect of Solution Concentration. Eight solutions ranging from 0.125 to 8 wt. percent $NaNO_3$ were tested to determine the effect of concentration on SMD. An applied voltage of 7 kV and a flow rate of 0.21 cc/min were used with 27- and 30-gage needles. The results (Figure 5) show an average value of about 200 microns and no discernible trend in SMD with concentration. The SMDs recorded with the 27-gage needle were slightly higher than with the 30-gage needle, consistent with the results of Figure 3.

Three of the runs recorded with the 27-gage needle at 8 percent $NaNO_3$ resulted in much higher SMDs (roughly 320 microns) than any other runs. These runs were recorded immediately after turning on the power supply and increasing the voltage setpoint smoothly from zero to the desired 7 kV. When this procedure was repeated, however, SMDs of about 200 microns were recorded. Current readings were also affected, with values of 0.9 and 1.0 microamps corresponding to SMD values of 320 and 200 microns, respectively. This behavior suggests a bistable equilibrium in which current and droplet size are not uniquely related to voltage. Unfortunately, a thorough investigation of this finding could not be carried out with the instrumentation on hand.

Current Measurements With and Without Spray. To better understand the relative contributions of electron transport via droplet surface and corona discharge, current was measured with and without spray with 27-, 31- and 32-gage needles. The spray tests were conducted with a flow rate of 0.42 cc/min and a concentration of 4 percent. The spray results (Fig. 6a) show a practically linear increase in current with voltage for all three needles. Current was found to be inversely proportional to needle size. Possible explanations include: 1) the smaller needle tips create a stronger corona discharge, and 2) the smaller needles produce a finer droplet stream with a higher surface-to-volume ratio and therefore a capacity to carry more electrons at the same surface charge density. In the no-spray tests (Fig. 6b), the 27- and 32-gage needles exhibited a threshold of about 7 kV below which current did not flow. The 31-gage needle exhibited no such behavior. Once current flow was established with all three needles, a linear increase with voltage was observed. Current again varied inversely with needle size.

A comparison of the spray and no-spray tests reveals that, for the 27-gage needle, current flow with spray was higher than without spray. The 31- and 32-gage needles, however, exhibit the opposite trend, except for the values below the 7-kV threshold for the 31-gage needle. No ready explanation can be offered for this behavior, which was also observed in earlier, similar tests.

Conclusions and Recommendations

The following conclusions can be drawn on the basis of this preliminary evaluation:

1) SMD initially decreased with applied voltage but reached a minimum value at about 8 kV.
2) SMD increased monotonically with needle diameter for gages ranging from 21 to 32.
3) SMD increased with flow over the range 0.02 to 0.82 cc/min, with the exception of values recorded with a 31-gage needle at 0.82 cc/min, for which SMD was sharply lower.
4) Varying solution concentration had no effect on SMD. A bistable equilibrium state was observed in which current and SMD varied between widely disparate values, all other conditions constant.
5) Current was found to increase with applied voltage under both spray and no-spray conditions. Current was higher without spray for 2 of the 3 needle gages tested.

Future efforts should be directed toward a better understanding of electron transport via droplets and corona discharge in view of the apparent interaction between the two mechanisms.

Acknowledgments

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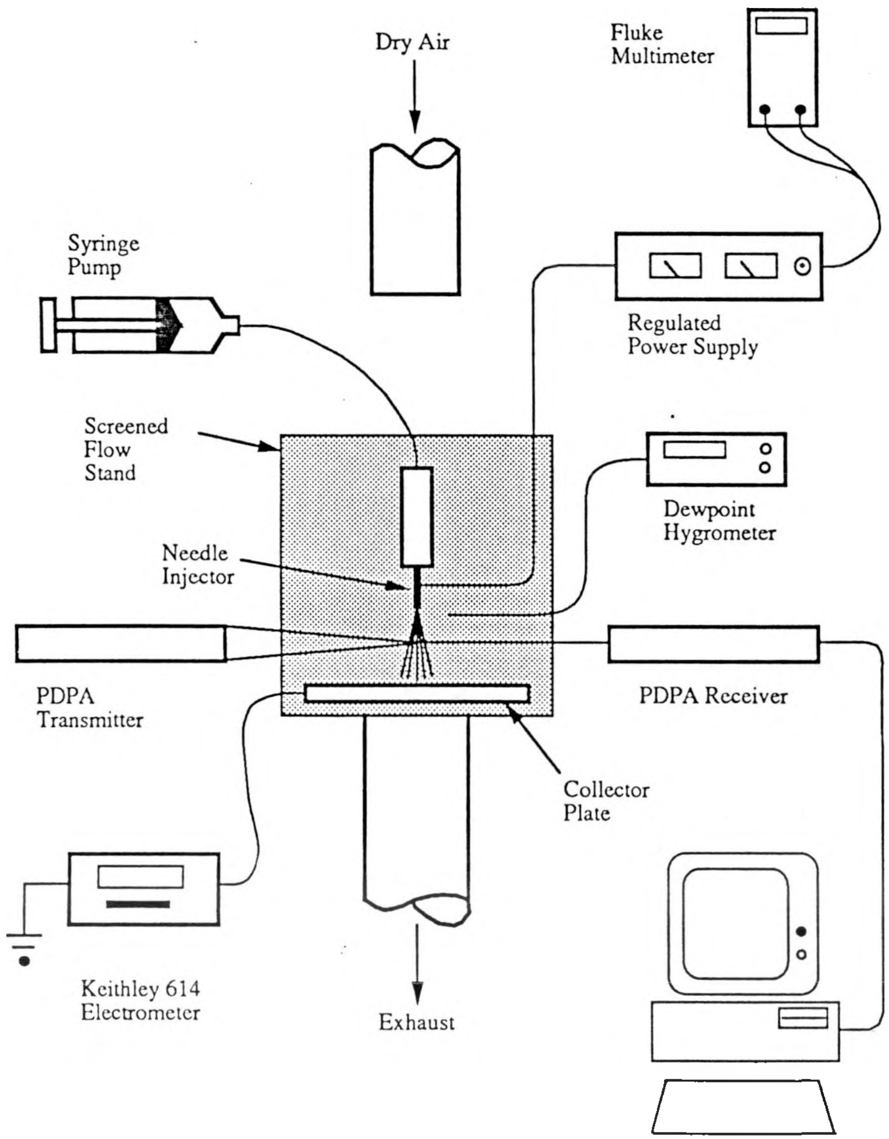


Figure 1. Experimental Apparatus

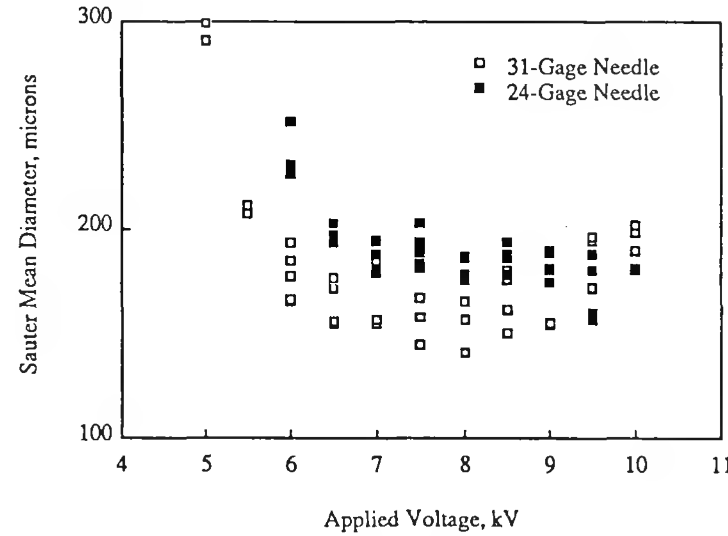


Figure 2. Sauter Mean Diameter Versus Voltage for 24- and 31-Gage Needles, Flow 0.15 cc/min, NaNO3 Concentration 4 Percent

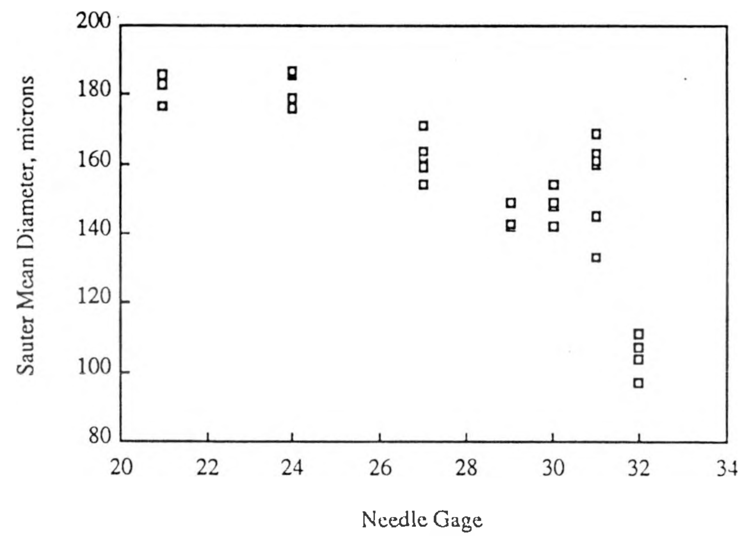


Figure 3. Sauter Mean Diameter Versus Needle Gage for Voltage of 8 kV, Flow 0.15 cc/min, NaNO3 Concentration 4 Percent

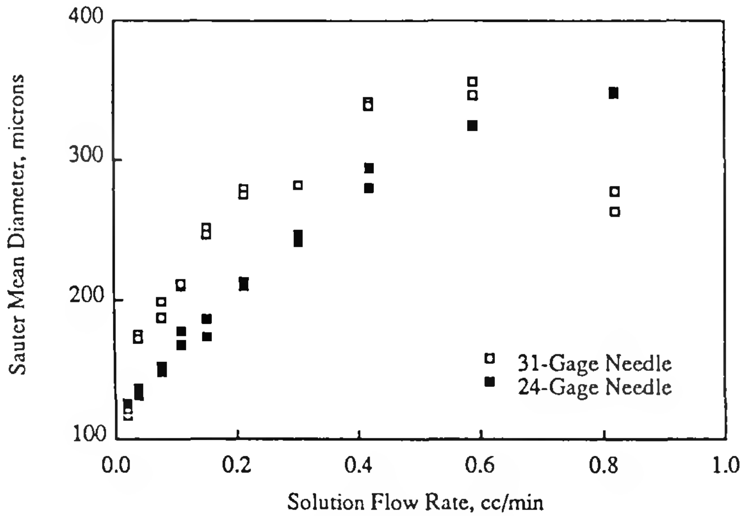
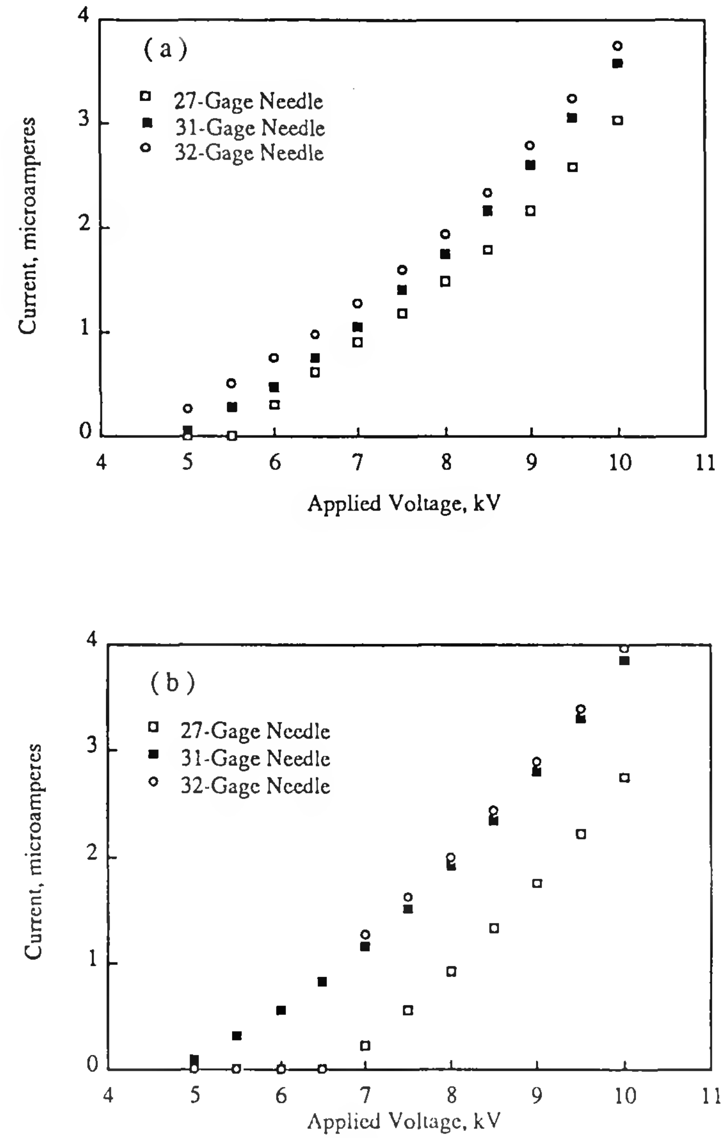


Figure 4. Sauter Mean Diameter Versus Solution Flow Rate for Applied Voltage 8 kV, NaNO3 Concentration 4 Percent and 24- and 31-Gage Needles



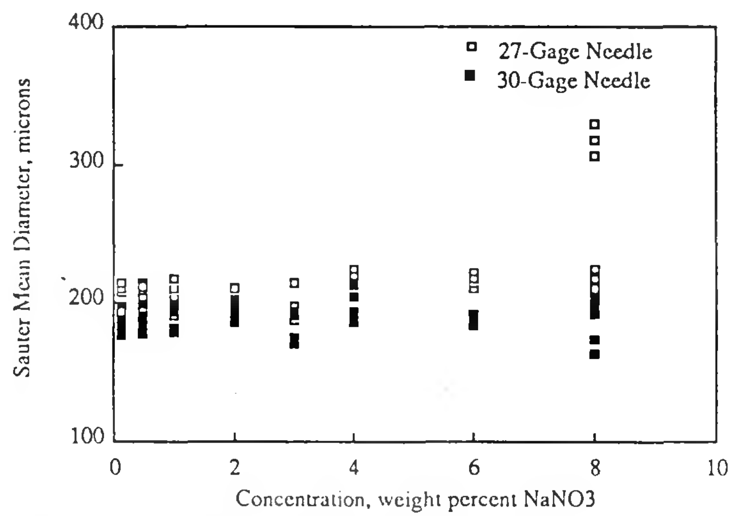


Figure 5. Sauter Mean Diameter Versus Solution Concentration for Applied Voltage 7 kV, Flow 0.21 cc/min, Needles 27- and 30-Gage

Figure 6. Current Versus Applied Voltage for Three Needle Sizes Under (a) Spray and (b) No-Spray Conditions. Spray Flow was 0.42 cc/min, NaNO3 Concentration 4 Percent.