Reprinted from ENVIRONMENTAL SCIENCE & TECHNOLOGY, Vol. 8, Page 360, April 1974

Collection of Aerosol Particles by Electrostatic Droplet Spray Scrubbers

Michael J. Pilat,[1] Steven A. Jaasund, and Leslie E. Sparks

Water and Air Resources Division, Department of Civil Engineering, University of Washington, Seattle, Wash. 98195

■ Theoretical calculations and experimental measurements show that the collection of small aerosol particles (0.05- to 5-μ diameter range) by water droplets in spray scrubbers can be substantially increased by electrostatically charging the droplets and particles to opposite polarity. Measurements with a 140-acfm two-chamber spray scrubber (7-sec gas residence time) showed an increase in the overall particle collection efficiency from 68.8% at uncharged conditions to 93.6% at charged conditions with a dioctyl phthalate aerosol (1.05-μ particle mass mean diameter and 2.59 geometric standard deviation). The collection efficiency for 0.3-μ particles increased from 35% to 87% when charged.

The principles of electrostatics, as discovered by Coulomb (1785), were first successfully applied to the control of particulate air pollutant emissions by Cottrell (1908) whose research results gave rise to the large-scale utilization of dry electrostatic precipitators as industrial gas cleaning devices. White (1963) and Oglesby and Nichols (1970) have authored comprehensive publications on conventional dry electrostatic precipitators.

In the mid 1950's, wet electrostatic precipitators were developed that use water continuously to wash the particle collection electrodes. Water is injected into these precipitators by either overhead weirs and/or overhead sprays. Thus, these wet electrostatic precipitators still have the same general configuration as dry precipitators with the added feature of water-washed plates.

In the early 1940's, an electrostatic droplet spray scrubber consisting of electrically charged water droplets collecting aerosol particles charged to the opposite polarity was proposed by Penney (1944). He patented an "electrified liquid spray dust precipitator" involving particle charging by corona discharge and droplet charging by either ion impactor or induction. With a water loading of about 5 gal/1000 acf, a single spray nozzle charged to 9,000–10,000 V, particle charging with a corona wire in a 3-in. diameter metal cylinder (12,500 V), and a scrubber chamber 6⅜ in. diameter and about 24 in. in length, Penney reported an increase in the dust collection efficiency from 13.8% with no charging to 44.8% with the particles and droplet charged to opposite polarity.

Eyraud et al. (1966) reported high particle collection efficiencies with a wet electrostatic scrubber using negatively charged droplets and uncharged aerosol particles generated by the pyrolysis of vulcanized rubber. The scrubber consisted of centrally located water spray tubes inside a 1-meter diameter cyclonic spray scrubber 3.5 meters high. The electric potential on the water sprays was 60,000 V and the liquid to gas loading ratio was 45.5 gal/1000 acf.

An electrostatic space charge scrubber involving water droplets and aerosol particles charged to the same polarity that then precipitates onto the scrubber walls was proposed by Hanson and Wilke (1969). They calculated that 299 gal of water per minute in the form of 5-μ diameter droplets charged to 10,000 V would be required for 97% collection efficiency of 1.0-μ diameter particles in a gas flow of 100,000 cfm (2.99 gal/1000 acf).

[1] To whom correspondence should be addressed.

Theoretical Calculation of Particle Collection Efficiency

Kraemer (1954) theoretically and experimentally investigated the collection of negatively charged dioctyl phthalate aerosol particles (about 0.8 μ in diameter) onto positively charged (6000-V) metal spheres (0.64–1.1 cm in diameter). Considering these studies, Kraemer and Johnstone (1955) predicted a single droplet (50-μ diameter droplet charged negatively at 5000 V) collection efficiency of 332,000% for 0.05-μ diameter particles of four electron units of positive charge per particle (9.78×10^{-3} C/gram particles). Kraemer and Johnstone's calculations of the single droplet collection efficiency considered only the forces of fluid resistance and of electrostatics (the inertial and Brownian diffusion forces were assumed negligible).

Sparks (1971) calculated the efficiency of charged droplets for collecting charged particles of opposite polarity. The calculations involved solving the equation of particle motion for a gas flowing around a sphere as reported by Sparks and Pilat (1970). The Runge-Kutta numerical solution for particles (charged to negative polarity in a corona of 1000 V/cm) flowing near a 200-μ diameter droplet (charged to positive polarity in a corona of 1000 V/cm) included the forces of Brownian diffusion, inertia, and electrostatics. The calculation results, shown in Figure 1, predict a single droplet collection efficiency of about 275% for 0.05-μ diameter particles with 200-μ droplets with an undisturbed fluid velocity of 100 cm/sec (note that the settling velocity of 200-μ water droplets in air at 20°C and atmospheric pressure is about 70 cm/sec).

Experimental Measurements

Electrostatic Droplet Spray Apparatus. The 140-acfm double chamber electrostatic droplet spray scrubber is shown schematically in Figure 2. A dioctyl phthalate aerosol was generated by injecting the DOP into an electrically heated aluminum tube, 1.5 in. in diameter and 18 in. in length. The DOP condensation aerosol passed through a blower, a corona charging section, and into the first scrubber chamber. The scrubber chamber and ducts were constructed of ¼ in. thick Lucite. The corona charging sections on both chambers consisted of a single 12-gauge steel rod mounted horizontally in the middle of the rectangular inlet ducts with ground strips of copper and

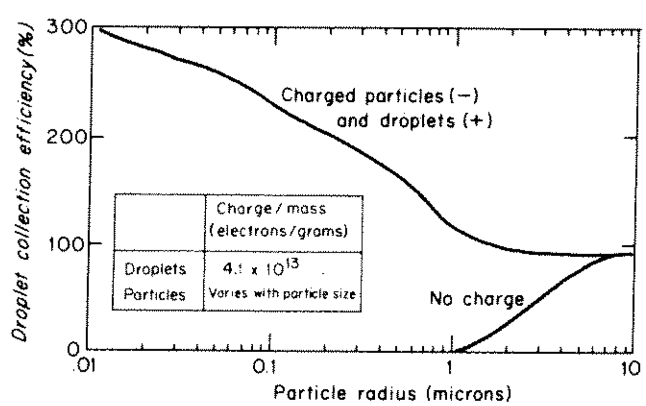

Figure 1. Calculated particle collection efficiencies for a single 200-μ diameter droplet with a 100-cm/sec undisturbed fluid velocity

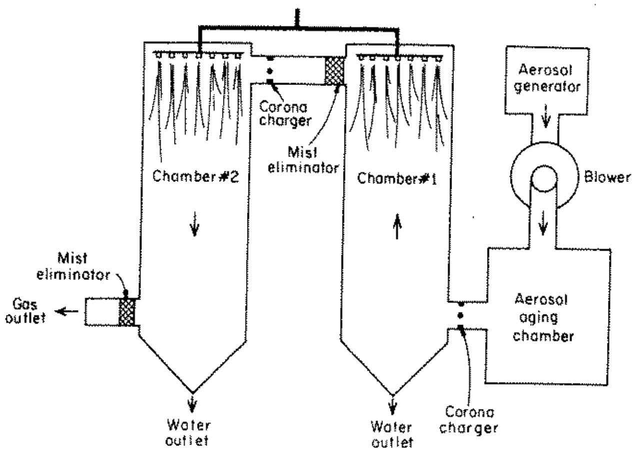

Figure 2. Schematic of electrostatic droplet spray scrubber

charged to 27,000 V. The first chamber (60 in. high by 24 in. wide, rectangular) was countercurrent and had a water flow of 1.2 gal/min with 20 spray nozzles. The second chamber (45 in. high and 20 in. in diameter, cylindrical) was cocurrent and had a water flow of 1.0 gal/min with 13 spray nozzles. The spray nozzles were Spraying Systems Fogjet 7N4 nozzle tips. The water droplets were inductively charged positively with a 5-kV power supply.

Measurement Techniques. The particle mass concentration and size distribution were simultaneously measured at the inlet (upstream of the charging section on the first chamber) and outlet of the electrostatic scrubber using Mark III University of Washington Source Test Cascade Impactor. These cascade impactors are similar to those reported by Pilat et al. (1970) and are commercially available under a licensing agreement with the University of Washington. The DOP aerosol mass concentration at the inlet to the electrostatic scrubber was typically about 0.15 grains/acf. The particle size distributions at the scrubber inlet to chamber 1 and outlet from chamber 2 are shown in Figure 3.

The size distribution of the water droplets was measured by collecting the droplets on greased (melted petroleum jelly) glass slides and photographing them as described by Pigford and Pyle (1951). The droplet images on the photomicrographs were sized with a Zeiss particle size analyzer. As the water droplets form hemispheres on the greased slides, a conversion factor of 1.26 was used to correct the flattened diameter to the real droplet diameter. About 700 droplets were sized for each distribution measured. The droplet size distributions at 103 psig and at

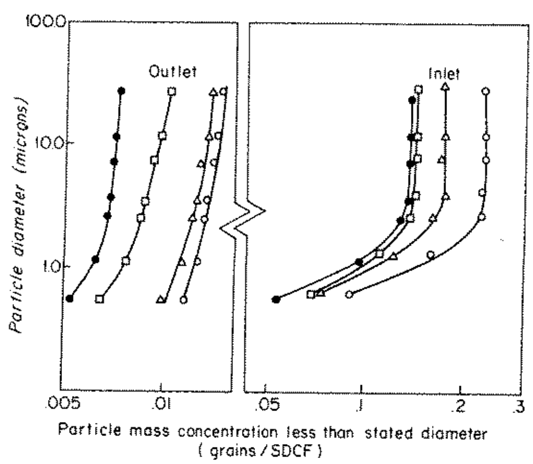

Figure 3. Size distributions of dioctyl phthalate aerosol particles at electrostatic droplet spray scrubber inlet and outlet

charged (5000 V) and uncharged conditions are shown in Figure 4.

The electrostatic charges of the aerosol particles and the water droplets were measured with a similar device which basically consisted of a sample collection section and a charge measuring circuit. The aerosol charge analyzer involved a 1-in. diameter Gelman filter holder with a Type A glass fiber filter to collect the particles. The filter holder and nozzle (for isokinetic sampling) was electrically insulated from a grounded aluminum shield which protected the filter holder from external electric fields. The electrostatic charge measuring circuit included a 1000-pF capacitor and an operational amplifier circuit. The aerosol charge to mass ratio was obtained by monitoring the current for a recorded particle sampling time and then weighing the filtered particles. The aerosol charge was typically about 5.3×10^{-5} C/g (3.6×10^{14} electron units/g) in the first scrubber chamber.

The droplet charge analyzer included a 3-in. square droplet collector (packed with aluminum shavings) connected to a grounded microammeter (10^{-7}–10^{-8} A). The droplet charge analysis consisted of placing the collector in the spray droplets, monitoring the current and sampling time, and weighing the amount of water collected. The droplet charge with a 5000-V inductance charge was typically 5.6×10^{-7} C/g (3.8×10^{12} electron units/g).

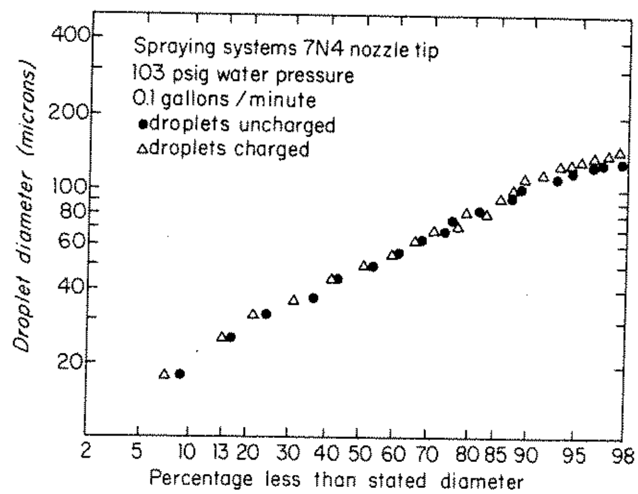

Figure 4. Size distribution of water spray droplets

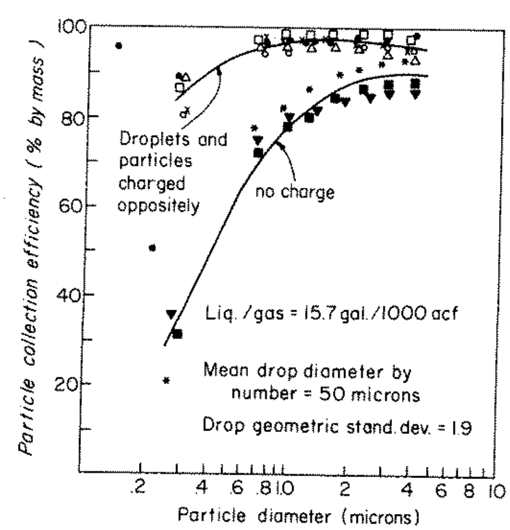

Figure 5. Particle collection efficiency of electrostatic spray droplet scrubber as function of particle size

Results. Simultaneous measurements of the aerosol size distribution and mass concentration at the inlet and outlet of the electrostatic droplet spray scrubber showed that the overall particle collection efficiency increased from 68.8% at uncharged conditions to 93.6% at charged conditions. Four particle collection efficiency tests were performed at the electrostatic charged conditions and three tests at the uncharged conditions. Each different symbol for the points in Figure 5 represents a separate collection efficiency test. As shown in Figure 5, the collection efficiency for the 0.3-μ diameter particles increased from 35% at uncharged conditions to 87% when charged.

Discussion. In general, the measured increase in the scrubber overall particle collection efficiency from 68.8% at uncharged conditions to 93.6% at charged conditions agrees with the trend of the theoretically calculated single droplet collection efficiencies shown in Figure 1. These calculations show that the single droplet collection efficiencies for 1-μ diameter particles increase from about 1% at uncharged conditions to about 160% at charged conditions.

The scrubber overall particle collection efficiency E_o may be calculated from the single droplet collection efficiency E_d using an equation reported by Kleinschmidt (1939)

$$E_0 = 1 - e^{-fE_d} \quad (1)$$

where f is the fraction of gas swept by the droplets and is given by

$$f = \frac{3\,HL}{4\,RG} \quad (2)$$

where H is the distance the droplets travel with respect to the gas, R the droplet radius, and L/G the liquid to gas loading ratio.

Although the charging conditions, the relative velocity between the gas and the drops, and the droplet diameters are not the same for the calculated single droplet and the measured overall scrubber cases, a calculation of the overall efficiency using Equation 1 will serve to better illustrate a comparison between the measured and calculated results. Let us assume the distance the droplets travel with respect to the gas is 1 ft (this parameter was not measured). With a liquid-to-gas ratio of 15.7 gal/1000 acf, a droplet diameter of 50 μ (number diameter from Figure 4), and a 1-ft distance the droplets travel with respect to the gas, the fraction of gas swept, using Equation 2, is 19.22. If we use the single droplet collection efficiencies of 0.01 at uncharged and 1.6 at charged conditions and Equation 1, scrubber overall collection efficiencies of 17.4% at uncharged conditions and of near 100% for charged conditions can be calculated.

The calculated increase in the scrubber overall collection efficiency from 17.4% to near 100% is somewhat larger than the measured increase from 68.8–93.6%. This difference is probably due to the differences in the conditions between the theoretical and measured cases and to weaknesses in the theoretical model. Although the calculated results presented in Figure 1 include the mechanisms of Brownian diffusion, inertial impaction, and electrostatic forces, they do not include the effects of space charge (electric field caused by the presence of charged droplets and aerosol particles). The problem of calculating the effects of the electric field space charge is complex because the electric field strength and direction are dependent upon the location in the scrubber chamber and upon the droplet and aerosol charge and concentration distribution. However, in general it appears that the space charge will reduce the scrubber overall particle collection efficiency by two mechanisms: reduction of the single droplet particle collection efficiency by modifying the particle trajectory near the droplet, and by reduction of the droplet concentration in the scrubber as the charged droplets will be repelled by their like charges and migrate toward the scrubber chamber walls. Also, the theoretical model assumes that all particles that touch the droplet surface are collected. However, this does not probably occur, especially with particles such as dioctyl phthalate which are essentially not soluble in water.

In conclusion, it appears that electrostatically charging the droplets and particles to opposite polarity can substantially increase the particle collection efficiency of spray scrubbers, but more study is needed to obtain additional knowledge concerning this particle collection phenomenon.

Acknowledgment

The assistance of Blaine Sorenson, Arn Thoreen, and Gary Raemhild with the experimental measurements are appreciated.

Literature Cited

Cottrell, F. G., U.S. Patent 895,729 (1908).

Coulomb, C. A., "Seven Papers on the Discovery of the Inverse Square Law of Electrostatics," *Memoires de L'Academie Royal des Sciences*, Paris, 1785.

Eyraud, C., Joubert, J., Morel, R., Henry, C., Roumesy, B., "Study of a New Dust Collector Using Electrostatically Sprayed Water," *Proc. Part I, Inter. Clean Air Congr.*, London, Oct. 4–7, pp 129-130, 1966.

Hanson, D. N., Wilke, C. R., "Electrostatic Precipitator Analysis," *Ind. Eng. Chem., Process Des. Develop.*, **8**, 357–64 (1969).

Kleinschmidt, Z. Z., 1939.

Kraemer, H. F., "Collection of Aerosol Particles by Charged Droplets," PhD Dissertation, Univ. of Illinois, Urbana, Ill. 1954.

Kraemer, H. F., Johnstone, H. F., "Collection of Aerosol Particles in the Presence of Electric Fields," *Ind. Eng. Chem.*, **47**, 2426–34 (1955).

Oglesby, S. J., Nichols, G. B., "A Manual of Electrostatic Precipitator Technology," Vol. I (NTIS No. PB-196-380), Vol. II (NTIS No. PB-196-381), Reports from Southern Research Institute, Birmingham, Ala., to Environmental Protection Agency, 1970.

Penney, G. W., "Electrical Liquid Spray Dust Precipitator," U.S. Patent 2,357,354 (1944).

Pigford, P., Pyle, C., "Performance Characteristics of Spray-Type Absorption Equipment," *Ind. Eng. Chem.*, **43** 1649–66 (1951).

Pilat, M. J., Ensor, D. S., Bosch, J. C., "Source Test Cascade Impactor," *Atmosph. Environ.*, **4**, 671–9 (1970).

Sparks, L. E., Pilat, M. J., "Effect of Diffusiophoresis on Particle Collection by Wet Scrubbers," *ibid.*, pp 651–60.

Sparks, L. E., "The Effect of Scrubber Operating and Design Parameters on the Collection of Particulate Air Pollutants," PhD Dissertation, Univ. of Washington, Seattle, Wash., 1971.

White, H. J., "Industrial Electrostatic Precipitation," Addison-Wesley, Redding, Mass., 1963.

Received for review January 22, 1973. Accepted November 21, 1973. Work supported in part by a research grant from the Reynolds Metals Co., Longview, Wash.