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Droplet Charging for Wet Scrubbers

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ABSTRACT

Water droplet charge/mass of wet scrubbers was measured over the direct charging applied potential range of 0–20 kV, 30–70 pounds per square inch gauge (206.8–482.6 kPa) water pressure, and with spiral, impingement, and whirl nozzles. The measured charge/mass ranged from ~0.0005 to 0.2 microcoulomb/gm and was directly related to the applied voltage. The water charge/mass was a function of the spray nozzle, with the smaller orifice lower-flow nozzles having the higher charge/mass.

INTRODUCTION

Coulombic forces for the electrostatic collection of aerosol particles in charged droplet scrubbers are dependent upon the droplet electrostatic charge. This paper presents the results of measurements of the water droplet charge/mass as a function of applied potential, water pressure, nozzle type, and water conductivity. Electrostatically augmented wet scrubbers using electrostatically charged droplets have been reported by Penney,[1] Eyraud et al.,[2] Pilat et al.,[3] and Lear et al.[4] The electrostatic fractional collection efficiency $\eta_{coulombic}$ of a single spherical charged drop for aerosol particles charged to the opposite polarity was reported by Kraemer[5] and Kraemer and Johnstone[6] to be described by eq 1

$$\eta_{coulombic} = \frac{4C_c q_p Q_d}{3\pi^2 \mu_g D_d^2 U_d \varepsilon_o} \qquad (1)$$

where C_c is the particle Cunningham Slip Correction factor, q_p is the particle charge, Q_d is the droplet charge, μ_g is the gas viscosity, D_d is the drop diameter, U_d is the drop velocity with respect to the gas, and ε_o is the permittivity of free space (vacuum). Prem and Pilat[7] reported particle collection efficiencies for single charged drops numerically calculated (Runga-Kutta) including inertial impaction, Brownian diffusion, and electrostatic forces. Experimental measurements of the single-drop particle collection efficiency have been reported by Wang et al.[8] with single 137–500-μm-diameter monodisperse drops (moving at their terminal gravity settling velocity and with electrically neutral surroundings) charged to $\sim 10^{-12}$ coulomb/drop collecting 0.2-μm-diameter aerosol particles charged to opposite polarity are in general agreement with Kraemer's single-drop particle collection efficiency equation. The overall particle collection efficiency $\eta_{overall}$ of a spray droplet wet scrubber can be calculated using the equation reported by Kleinschmidt[9] and shown here

$$\eta_{overall} = 1 - \exp(-f\eta_{singledrop}) \qquad (2)$$

where f is the fraction of gas swept by the multiple drops and $\eta_{singledrop}$ is the particle collection efficiency of a single drop. Pilat et al.[3] reported that the measured overall particle collection efficiencies for pilot plant electrostatic spray droplet scrubbers using multiple droplets are considerably lower than the collection efficiencies calculated using the Kleinschmidt's equation (eq 2) and the single-drop collection efficiencies calculated using Kraemer's equation (eq 1). This is probably caused by the reduction in the single-drop effective electric field (as experienced by the charged aerosol particle) caused by the presence of other charged drops (all the drops were charged to the same polarity) surrounding the single charged drop. Vaaraslahti et al.[10] reported on the natural charging of water droplets during spraying and the effects of the spray nozzle material, liquid feed rate, and solute concentration.

IMPLICATIONS

The magnitude of the electrostatic charge on aqueous droplets has been reported to be related to the aerosol particle collection efficiency of both charged and uncharged droplets in wet scrubbers. This paper presents measured electrostatic charge/mass of water drops sprayed from commercially available nozzles and charged by direct charging (direct current power supply connected directly to the liquid just upstream of the nozzle).

EXPERIMENTAL PROCEDURES

Apparatus

The liquid water spray droplets were generated using an electrically insulated water tank (pressurized with air),

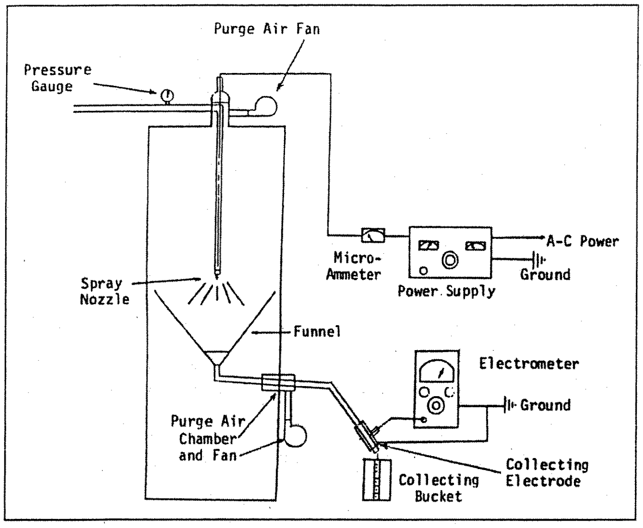

Figure 1. Water spray droplet charge measurement apparatus.

nonconductive polyvinylchloride (PVC) piping between the tank and the spray nozzle, and a 50-kV direct current (DC) power supply connected to an electrode inside the pipe adjacent to the spray nozzle. The spray tower was a 14′ high × 3′ × 3′ (4.27 m × 0.91 m × 0.91 m) Lucite chamber (constructed for research on charged droplet wet scrubbing of aerosol particles). The voltage and current meters on the Hipotronics 50-kV power supply and a microammeter located between the power supply and the spray nozzle provided the electrical current and voltage readings. Figure 1 shows the water charge to mass measurement apparatus. Table 1 presents the nozzle parameters of material, nozzle type, spray cone angle, nozzle orifice diameter, water flow at 70 pressure per square inch gauge (psig) (482.63 kPa), and the surface area and volume drop median diameters (the drop diameter data were furnished by the nozzle manufacturers).

Measurements

The water charge/mass ratio was measured using a 2.5-ft (0.762-m)-diameter funnel to collect the droplets, a Keithley Model 602 electrometer to measure the electrical current, and a graduated cylinder to measure the volume of liquid collected (in the 1–10 L range) over recorded time periods (in the 1–3 min range). With the water flow off and the DC power supply on, the background current was measured before each test. A grounded steel enclosure around the charge measuring system shielded against the interfering influence of outside electric fields. The Keithley electrometer was periodically checked with a Keithley Model 261 picoampere source. The Hipotronics 50-kV power supply voltage meter was checked with a Fluke multimeter and found to have a maximum error of ±100 V. Water conductivity was measured with a Labline conductivity meter (the water conductivity was adjusted using sodium carbonate [Na_2CO_3]). The liquid specific gravity was measured with a 50-mL class A volumetric flask weighed on a Mettler balance. Tests were conducted using Seattle's domestic water supply for each of 11 nozzles with water pressures (measured at the spray nozzle) of 30, 40, 50, 60, and 70 psig (206.8, 275.8, 344.7, 413.7, and 482.6 kPa) and positive polarity voltages of 0, 1, 2, 3, 5, 10, and 20 kV.

The liquid charge to mass ratio was obtained from the measured data using eq 1

$$\frac{q}{m}, \frac{\text{coulomb}}{\text{gm}} = \frac{(\Sigma I, \text{amp})(t, \text{sec})}{(V, \text{mL})(\rho, \text{gm/mL})} \quad (3)$$

Table 1. Spray nozzle parameters.

Nozzle	Material	Type	Cone Angle (°)	Orifice Diameter (in.)	Orifice Diameter (cm)	Flow 70 psig (gal/min)	Flow 70 psig (L/min)	Median Drop Diameter (μm) Surface Area	Median Drop Diameter (μm) Volume
Bete TF6FCN	Teflon	spiral	full 90	0.094	0.24	1.8	6.8	110	140
Bete TF6FCN	steel	spiral	full 90	0.094	0.24	1.8	6.8	110	140
Bete TF6FC	steel	spiral	full 120	0.094	0.24	1.8	6.8	94	120
Bete L80	Teflon	spiral	full 90	0.08	0.2	1.4	5.3	95	120
Bete L80	steel	spiral	full 90	0.08	0.2	1.4	5.3	95	120
Bete P80	steel	impinge	full 90	0.08	0.2	1.4	5.3	150	160
Bete CW10080F	steel	whirl	full 80	0.086	0.22	1.3	4.9	170	210
Bete WL 1/2 80	Teflon	whirl	full 80	0.055	0.14	0.65	2.5	130	170
Bete WL 1/280X	Teflon	whirl	square	0.055	0.14	0.65	2.5	140	180
Spray S LN26	brass	whirl	hollow 72	0.086	0.22	0.62	2.4	—	305
Spray S LN22	brass	whirl	hollow 74	0.076	0.19	0.6	2.3	—	260

where I is the current, t the liquid sampling time, ρ the liquid density, and V the volume of water collected during time t.

RESULTS

Applied Voltage

The charge/mass of fresh water (conductivity in the 50–60 microSiemens/cm range) is directly related (charge/mass increases with increasing voltage) to the applied DC voltage as is shown in Figure 2 for Spray Systems brass nozzles and Bete Teflon and steel nozzles at water pressure of 70 psig (482.63 kPa). The metal (steel) Bete nozzle has a slightly larger charge/mass than the Teflon Bete nozzle of the same type and size. The nozzles with the smaller orifice diameters and lower flow rates (Spray Systems LN26 and Bete L80) appear to provide larger charge/mass ratios.

Water Pressure

At constant voltage, the charge/mass decreases a little with increasing pressure as is shown in Figure 3 for a Spray Systems Brass LN26 nozzle over the 30–70 psig (206.8–482.6 kPa) pressure range at voltages of 0, 2, 5, 10, and 20 kV. However, with no applied voltage, the charge/mass increases with increasing pressure (increasing liquid flow rate) in agreement with measurements reported by Vaaraslahti et al.[10]

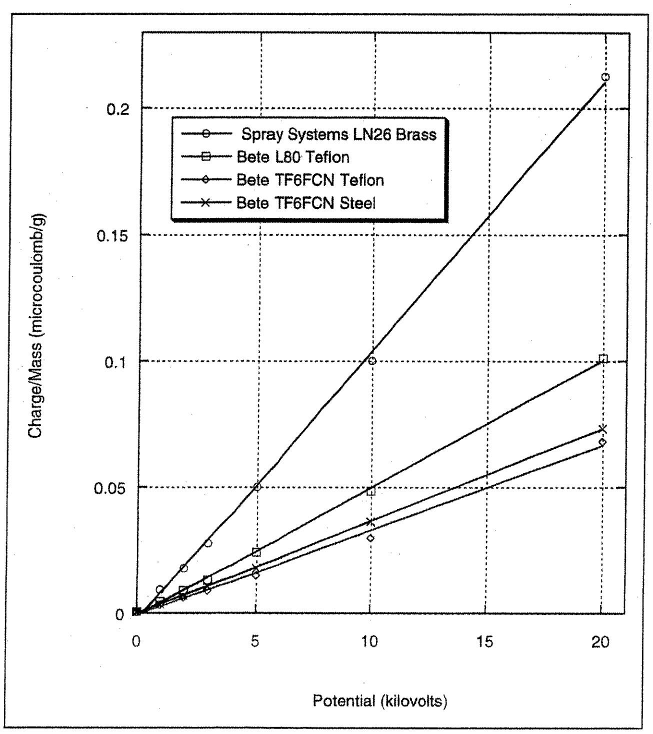

Figure 2. Charge/mass as function of applied potential (kV).

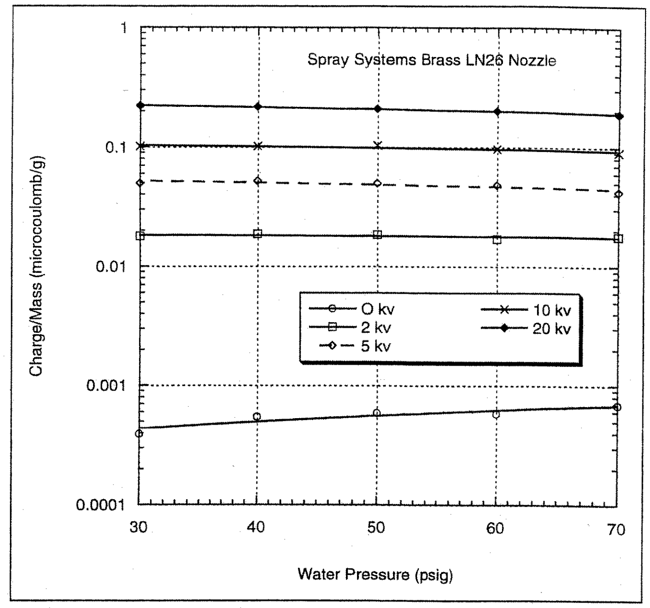

Figure 3. Charge/mass as function of water pressure.

Water Conductivity

Three nozzles (Bete L80 Teflon, Bete L80 Steel, and Bete TF6FCN Teflon) were tested with various water conductivities (60, 3300, and 12,000 microSiemens/cm). The water conductivity was adjusted using Na_2CO_3. As shown in the Figure 4 graph of the charge/mass versus voltage, the water conductivity did not have much effect.

DISCUSSION

For a spherical droplet, the total drop charge is given by

$$q = Q_{ac}4\pi r^2 \tag{4}$$

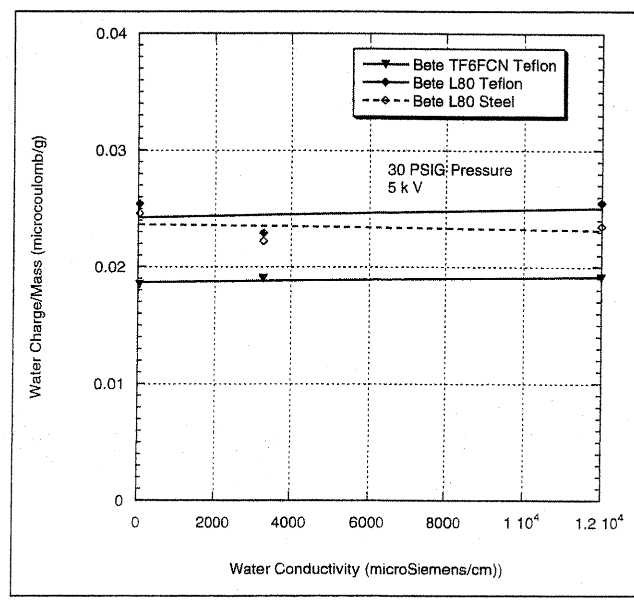

Figure 4. Charge/mass as function of water conductivity.

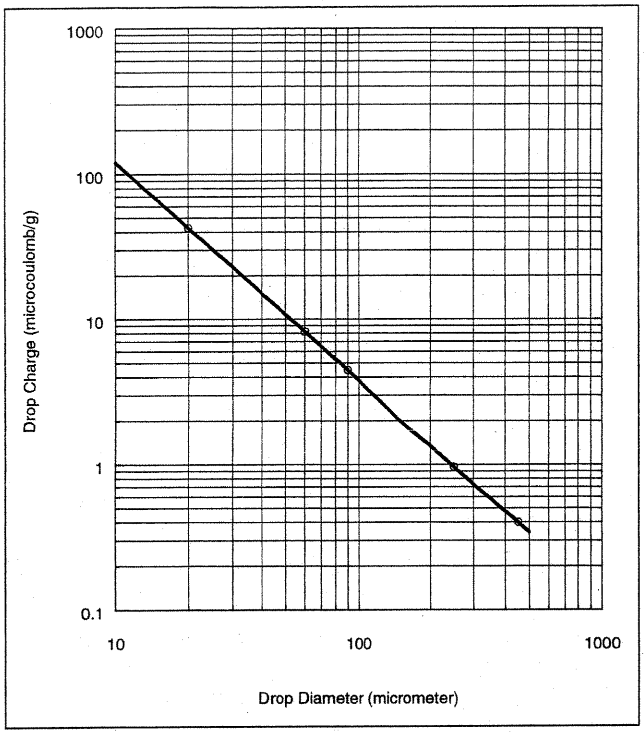

Figure 5. Rayleigh charge limit for water drops.

where r is the drop radius and Q_{ac} is the drop surface charge density (coulomb/cm^2). The drop charge/mass ratio for a spherical drop can be expressed as

$$\frac{q}{m} = \frac{Q_{ac} 4\pi r^2}{4/3\pi r^3 \rho} = \frac{3Q_{ac}}{r\rho} \tag{5}$$

where ρ is the liquid drop density. For drops formed with equal surface charge density Q_{ac}, the charge to mass is inversely proportional to the drop radius. This may be a factor for the various spray nozzles having different curves for the charge/mass as a function of applied potential as shown in Figure 2.

The Rayleigh limit electrostatic charge for liquid drops is given by

$$\text{Rayleigh limit } \frac{q}{m} = \frac{\sqrt{[2\pi\gamma\varepsilon_o D_d^3]}}{[(\pi\rho_d D^3)/6]} \tag{6}$$

where γ is the liquid surface tension (dyne/cm). The Figure 5 graph of the Rayleigh charge limit versus drop diameter shows that a 100-μm-diameter water drop has a Rayleigh limit of $\sim 4 \times 10^{-6}$ coulomb/g or 4 microcoulomb/g. As is shown in Figure 2, the maximum drop charge/mass measured was ~0.2 microcoulomb/g, which implies the drops were charged to somewhat below their Rayleigh limit.

Liquid drops can also be electrostatically charged inductively. Pilat et al.[3] reported a measured 0.57 microcoulomb/g water charge/mass ratio using 5 kV inductance charging, 103 psig (710 kPa) water pressure, and a Spraying Systems 7N4 brass nozzle (50-μm number median droplet diameter). Higashiyama et al.[11] reported water charge/mass ratios in the 0–0.235 microcoulomb/g range using a water pressure of 3000 kPa (435.1 psig) to form drops in the 10–120-μm-diameter range and inductive charging with a 3-cm i.d. ring electrode and 0–1.6 kV voltages.

CONCLUSIONS

The findings of this research are:

(1) Water charge/mass increases with increasing applied potential.
(2) Water charge/mass is a function of the spray nozzle, with smaller orifice lower-flow nozzles having higher charge/mass.
(3) Water conductivity has little effect on charge/mass with applied potentials.
(4) Metal nozzles provide greater water charge/mass than Teflon nozzles.

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APPENDIX A

Nomenclature

C_c = Cunningham slip correction factor for particle
dp = diameter of particle
D_d = diameter of drop
f = fraction of gas swept by the drops
I = electrical current
m = mass
q_p = electrostatic charge on particle (coulomb)
Q_d = electrostatic charge on liquid drop (coulomb)
Q_{ac} = drop surface charge density (coulomb/cm^2)
r = drop radius
t = time
U_d = velocity of drop with respect to gas
V = liquid volume
ε_o = permittivity of free space (vacuum)
γ = liquid surface tension (dyne/cm)
$\eta_{coulombic}$ = charged single-drop collection efficiency for oppositely charged particles
$\eta_{overall}$ = overall particle collection efficiency of spray droplet scrubber
$\eta_{singledrop}$ = particle collection efficiency of single droplet
μ_g = gas viscosity
ρ = liquid density

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