Determination of Particle Charge to Mass Ratio Distribution in Electrostatic Applications: A Brief Review

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***Abstract*— Charge to mass ratio is a critical parameter that needs to be determined in order to accurately predict behavior of a charged particle exposed to inertial, electrical and gravitational forces. The effectiveness of various electrostatic applications depends directly on this parameter. Much theoretical and experimental research has been devoted to assess the value of the average charge to mass ratio. However its complex nature limits our ability to accurately determine its value when particles of varying size are present. In this work a brief overview of the scientific literature that explores measurement techniques for determination of charge to mass ratio distribution is presented. Important observations and key aspects regarding these techniques are outlined and suggestions offered of what is needed to determine this parameter as a function of particle size.**

***Index Terms*—Electrostatic devices, electrostatic measurements, electrostatic processes, spraying, coating.**

I. Introduction

Charge to mass ratio (*Q/M*) is a critical parameter that needs to be determined in order to accurately predict behavior of a particle exposed to inertial, electrical and gravitational forces. Many electrostatic processes depend directly on this parameter. Much theoretical and experimental research has been devoted to assess the value of charge to mass ratio of both solid particles and liquid droplets. However, complex nature of the process limits our ability to make accurate measurements. Therefore, this phenomenon is still a subject of ongoing study.

In this work, issues related to prediction of *Q/M* are discussed and a number of measurement techniques are briefly outlined to evaluate their applicability to electrostatic applications and predict their limitations. The following sections give a summary of the theory and an overview of the scientific literature concerning this matter. Special attention has been devoted to techniques that tend to concentrate on the stochastic nature of the drop charge distribution.

II. THEORETICAL CONSIDERATIONS

In electrostatic applications, several charging mechanisms may be employed. These include corona, tribo, conduction and induction charging with the latter two being predominant.

Conduction charging refers to the process in which a voltage is directly connected to the conductive or semi-conductive material undergoing atomization. Charge flows from the voltage supply to the material due to the presence of the electric field formed between the voltage supply and an adjacent ground.

Induction charging refers to the process in which a voltage is connected to an electrode which is placed adjacent to a grounded material undergoing atomization. Here an electric charge opposite in polarity to the supply flows from the ground to the material surface as induced by the applied electric field. As a particle separates from the bulk material, it retains charge.

If we assume that the surface charge density is equal for all the particles, a reasonable conclusion would be that the particle charge is proportional to the particle surface area. Since the surface area is directly proportional to the square of particle diameter, this would imply that the particle charge to mass ratio is inversely proportional to the particle diameter. The expected value of charge to mass ratio is:

$$\frac{q_E}{m} = \frac{\sigma \cdot S}{\rho V} \sim \frac{1}{D} \qquad (1)$$

where q_E is the expected charge of the particle, m is the particle mass, ρ is the liquid density, σ is the surface charge density, S is the surface area, V is the particle volume and D is the diameter of the particle. This theoretical assumption will be referred to as surface area theory.

The amount of charge that each individual drop can carry is limited. There are essentially two physical mechanisms limiting the charge that can be retained on the droplet surface. If a drop is charged so that the inward stress due to surface tension cannot balance the outward stress due to the electric field, disintegrations of a drop occurs. This is known as Rayleigh limit:

$$\frac{q_R}{m} = \frac{12\sqrt{2}}{\rho}\sqrt{\frac{\varepsilon\,\gamma}{D^3}} \qquad (2)$$

where q_R is the Rayleigh charge limit, ε is the electrical permittivity and γ is the surface tension of the liquid.

In a further mechanism an avalanche ionization process and localized electrical discharge can occur at the surface of a charged drop when the drop charge exceeds the limit known as Paschen limit:

$$\frac{q_P}{m} = \frac{12\varepsilon_0 V_p}{\rho D^2} \qquad (3)$$

where q_P is the Paschen charge limit and V_P is the surface potential.

These limits inform us about the maximum charge to mass ratio that the particle can have, and nothing about the probability that it has any given charge to mass ratio below that limit.

To date, there is no systematic theory that would correlate probable particle charge-to-mass ratio and particle diameter.

III. Measurement Techniques and Results

In his study [1], Brown divided all the measurements of charge to mass ratio into two basic categories: static and dynamic. Methods involving direct charge measurement are referred to as static methods. Dynamic methods calculate the charge to mass ratio by observing the particle motion parameters in the presence of external electric field.

A. Static Methods

The basic instrument for measuring electric charge is the Faraday cup. This consists of a shielded and isolated inner container which is completely surrounding the charged object. On the inner wall of the container charge of the opposite polarity is induced. The cup is connected to an operational amplifier circuit. The magnitude of the charge can be determined directly from the voltage and capacitance of the operational amplifier. By dividing the total collected charge by the number of particles sampled, the average particle charge can be obtained. Faraday cup techniques were used by a number of authors [2]-[4].

Anestos et al. [5] investigated the dependence of the charge to mass ratio of the spray stream on fluid and atomization parameters. A flat sheet target was used for the investigation. A small opening in the center of the target allowed part of the spray to pass through to a collector. The current to the collector was measured with an electrometer, while the total current to the sprayed surface was measured with a microameter. The spray was allowed to pass through the opening for a period of one minute and then the weight of the fluid collected was measured. From the measurements of the collected mass and the current, the average charge to mass ratio was determined. The spray gun could be moved vertically and horizontally, so that sectors of the entire spray pattern could be scanned by the collector. The apparatus used in order to measure the size and number density of the sprayed paint particles consisted of a grounded metal disc with the front surface coated with gelatin. The disc was rotating behind the target. Paint droplets produced spots in the gelatin and their size could be accurately measured by photographs, knowing the ratio between the actual diameter and the spot diameter.

Maximum specific charge (due to Rayleigh limit) that the spray stream can have is much higher than the specific charge which was measured experimentally. From the size distribution, an estimate was made for the maximum charge the spray stream could attain. The maximum charge was calculated for the 24 groups of the 420 drops whose size was measured. Even the peak measured specific charge was only 1/8 of the maximum possible specific charge.

Increasing the fan air velocity and mass of fluid delivery was seen to flatten out the charge distribution among the particles. This was an expected result. The experiment also showed that there is an optimum value of conductivity at which the specific charge of the spray stream exhibits a maximum.

Jones and Thong [6] discussed the electrical dispersion of a jet of kerosene into a spray of monodisperse droplets. Pressurized air was used to force the liquid from the reservoir through a fine stainless steel capillary to which a high voltage is applied. This generated a conical spray of fine droplets which were deposited on the grounded plate. The flow system was designed to form a steady flow. The *Q/M* ratio was calculated as a ratio of total current measured at the plate and total liquid flow. This *Q/M* ratio was found to be inversely proportional to the radius, and size of the particles ranged from 40µm to 120µm. This agrees well with the surface area theory.

Tang and Gomez [7] performed an experimental investigation on the feasibility of using an electrospray to produce monodisperse droplets of water in the diameter range 2-10µm. Because of the high surface tension of water, the establishment of stable sprays required the use of a sheet flow of carbon dioxide to prevent breakdown in the gas surrounding the spray and its destabilizing consequences on the electrospray performance. The experimental setup consisted of a stainless steel capillary charged at a high electric potential, and a grounded electrode positioned perpendicularly to the capillary. The droplet charge level was determined by measuring the total current collected by the ground electrode. Since an electrospray operating in cone-jet mode generates a very narrow size distribution, the volume charge density of the electrospray was well represented by a mean value calculated from the ratio between the total electric current and the total liquid flow rate. Authors concluded that the volume charge density varies with the inverse of the droplet diameter. This also agrees well with the surface area theory.

Ye and Domnick [8] presented a numerical method for the calculation of the electric field with space charge in electrostatic powder coating with a corona spray gun and used a suction-type Faraday cup apparatus to measure the Q/M ratio. The suction tube with a diameter of 10 mm was mounted in the centre of the target. The spray gun could be moved in a horizontal direction. Particles with full size distribution were sprayed.

Their calculated charge-to-mass profile based on Pauthenier theory [9] showed a good agreement with the experiment for the particle radius less than 60µm. This is a good agreement with surface area theory. For particles with larger diameter, the experimental charge-to-mass values stayed constant which differs from the theory. They concluded that this was probably due to the experimental uncertainty for the large particles. From the obtained results, it was evident that the sensitivity of this instrument decreased with increasing mean particle diameter.

B. Dynamic Methods

Johnston [10] described a semi automatic method for determination of the distribution of the magnitude and polarity of the charge on airborne dust. The aerosol is sampled through an electrified electrode with the flow split perpendicular to the electric field direction. Flow rates through both exit parts need to be approximately the same. This is achieved by connecting one to a vacuum line and the other to an optical particle counter which counts the numbers of particles in a selected size range. His plotted data shows linear dependence of the particle charge on particle diameter. This implies that the *Q/M* ratio is inversely proportional to the square of radius. Particles diameter was measured in the range between 0.5µm and 8µm.

Gillespie and Langstroth [11] measured electric charges on the aerosol particles. A sheet of air drew the particles through a transverse electric field between two microscope slides. Since the charge and size of a particle determined the distance of travel in the direction of air flow before deposition on a slide, a microscopic assessment of the number and sizes permitted calculation of the charge distribution. The relationship between particle charge and particle radius was linear which infers that *Q/M* was inversely proportional to the square of radius. All the measured particles had a radius below 2μm.

Pfeifer and Hendricks [12] developed a relationship between droplet *Q/M* ratio and droplet radius for electro hydrodynamically sprayed droplets. Probability distributions of the *Q/M* ratio and the droplet radius were derived as modified Maxwell-Boltzmann functions under the assumption that the unstable liquid mass disrupts into equally sized and charged particles so that the system energy tends toward a minimum value. Particle *Q/M* ratio was found to be inversely proportional to the particle radius to the power of 1.5. Experimental verification showed good agreement for octoil and glycerine and relatively good agreement with Krohn's data for Wood's metal [13] where the radius exponent was 1.7. In these data particle radii were between 0.5μm and 10μm.

Juan et al. [14] investigated the distributions of charge and diameter of drops emitted from electrified liquid cones in the cone-jet mode. The liquid came from a reservoir at high pressure through a stainless steel needle which is charged to several kilovolts. The Taylor cone produced at the tip of the needle generates a cloud of charged droplets inside a stainless steel chamber. Two of the opposing openings are sealed with glass windows in order to provide optical access. One opening was for the microscope and the other for the illumination of the Taylor cone with a continuous light source. Facing the needle is the sampler. A differential mobility analyzer (*DMA*) first samples the spray drops, selects those whose electrical mobility is within a narrow band, and either measures the associated current or passes them to a second *DMA* instrument (aerosizer) through an orifice by pumps. When the current through the cone is measured, the spray chamber and the sampling tube are connected directly to an electrometer. The current is monitored at the end of each run to ensure that the conditions remain unchanged during the experiment. The mobility of the drops could be measured in the *DMA*. Droplet charge was then uniquely determined by measuring droplet mobility and droplet diameter. For a given cone-jet parameters, the distribution of charge for the main (primary) drops is 2.5 times broader than the distribution of diameters, and ratio of maximum and minimum charge is 4. Particle diameters were in the range of 0.65μm to 1.35μm. It is stated that the charge of a droplet is proportional to it's diameter to the power of 3 which means that the charge to mass ratio is not a function of particle diameter.

Chen et al. [15] summarized the literature data on particle *Q/M* in gas-solids fluidized beds directly measured after steady state conditions have been reached. They showed that the experimental values were consistently lower than the maximum *Q/M* predicted by Paschen's limit. They explained that this was likely associated with low operating gas velocities used in most experiments, which limited the build up of charge on particles, as well as with the leakage of charges from the fluidized bed through the wall.

Orme et al. [16] observed the formation of highly uniform charged molten metal drops from a capillary stream. The conductive molten liquid was grounded and a positive periodic potential was applied to the charging electrode. Molten metal droplets were charged by electrostatic induction. The molten metal jet passed through the charge electrode that surrounded the jet at the point of droplet formation. As drops were formed from the continuous column of molten metal, a negative charge was induced on the drop.

Charged droplets passed through the space between the deflection electrodes and were deposited on the substrate. *Q/M* ratio of the droplets was determined by measuring the deflection of the droplets trajectories. This ratio was inversely proportional to the square of radius. Size of the particles ranged from 375μm to 400μm. The authors showed excellent agreement between their experimental values and Schneider's theoretical predictions [17].

Kulon, Malyan and Balachandran [18] used a noninvasive method of measurement of the charge level on a population of particles by combining the Phase Doppler Anemometry technique and high-resolution computer-controlled traversing system**.**

The Phase Doppler Anemometry technique is a nonintrusive optical method for simultaneous measurement of the size as well as the velocity of spherical particles. The principle of the Phase Doppler Anemometry is based on light scattering from two-plane light beams incident on the particle. Measurement region within the spray is formed by the intersection of the laser beams. Each pair of beams is coherent and polarized so that when they intersect an interference pattern of light and dark fringes is formed. The phase shift between the signals from different detectors is proportional to the size of the spherical particle.

The velocity measurement is based on the Doppler Effect. When two coherent and polarized laser beams intersect an interference pattern of light and dark fringes is formed. As a droplet passes through the measurement region it scatters light at a frequency based on its velocity normal to the fringes and the spacing of the fringes. A receiving device measures the frequency of this scattering signal and the spacing of the fringes is known based on the wavelength of the laser light and the angle between the beams. Knowing the Doppler frequency, frequency of the scattered signal and the spacing of the fringes, the particle velocity can be calculated.

The PDA system was used to track the motion of charged particles in air in the presence of a dc electric field within the space between the parallel-plate electrodes.

Charged particles exposed to the external electric field and situated in a viscous medium experience two types of forces exerted on them: external electrical force and drag force as a result of a relative motion of a particle in the air. After the relaxation time, a particle attains mechanical equilibrium and reaches a steady state velocity relative to the medium. By equating drag resistance force and the electrical force in the direction of the particle drift velocity, knowing the size and motion parameters the charge on an individual particle can be calculated.

It should be noted that space charge contribution to the overall electric field was not considered. The particle charge, as expected, was seen to increase with increasing particle size. Their experimental results showed that an average charge-to-mass ratio is 0.24μC/g. Radius for all the particles was below 4μm. Charge to mass ratio is inversely proportional to the square of radius. Radius exponent in this dependency is greater than expected.

Gemci et al. [19] described an experimental setup to obtain the individual droplet charge to mass ratio based on the measurements of the drop size and velocity by Phase Doppler Interferometer. Drops were accelerated to terminal velocity in a known uniform electric field after they had passed through a small hole in the deposition electrode. The phase Doppler Interferometer system was positioned to measure sizes and velocities of individual drops passing through the region beyond the grounded electrode.

Particles reach the equilibrium state and terminal velocity when electrical, gravitational and viscous drag force are in balance. Equating forces acting upon a particle yields the particle charge. The charge to mass ratio of each individual drop is computed. The distribution of charge to mass ratios is well correlated with the Paschen charge limiting theory. A line that marks the upper limit of the distribution coincides well with the Paschen line and all drops in the measured distribution have charge to mass ratios below but within one order of magnitude of the Paschen maximum. It should be noted that the space charge density effect on the overall electric field is not considered. Charge to mass ratio is inversely proportional to the square of radius which means that the radius exponent is greater than our assumed value.

Mazumder et al. [20]-[21] applied a laser-beam instrument called the electrical-single particle aerodynamics relaxation time (E-SPART) analyzer for measuring aerodynamic size and electrostatic charge distribution of particles in real-time and on a single particle basis. Direct application of this was used to characterize toner particles in electro-photography. As the particle passes through the sensing volume located at the centre of the relaxation chamber in the direction normal to the plane containing two laser beams it experiences acoustic excitations that cause particle oscillations. If the particle is charged it experiences another velocity component due to the presence of dc field. From the values of phase lag and electrical migration velocity particle charge is calculated. The main disadvantage of this technique is limited time resolution. Average count rate is around 100 particles per second. Size distribution ranged from 2μm to 20μm and charge-to-mass ratio was below 20μC/g. Charge to mass ratio is inversely proportional to the square of radius. Radius exponent is greater than expected value.

Q/M ratio distribution measured by E-SPART at the downstream of the lung model [22] was, also, inversely proportional to the square of radius.

Wong and Shrimpton [23] determined the electrical charge distribution amongst the drops by post-processing Phase Doppler Anemometry data for electrostatically atomized liquid sprays. Extending the technique of Schwar et al. [24], a method was developed of defining mean and root mean square drop charge by post processing method of data obtained from Phase Doppler Anemometry measurements. Axial and radial velocities and diameters of individual drops are available for a set of measurement locations.

Reasonable assumptions were made in order to investigate the relationship between the drop charge and the droplet diameter. It is assumed that droplet charge of the m^{th} drop size class varies with diameter such that:

$$q_m = AD_m^n \tag{4}$$

where q_m is the drop charge of the m^{th} drop size class, D_m is the diameter of the m^{th} drop size class,
A is parameter constant for all the drops and n is real number constant for each drop size class.

By equalizing the radial components of the forces acting on the droplet with the above given assumption, one can graphically obtain values of the unknown parameter n for each measured point. To obtain an estimate of A relative and actual volumetric spray specific charges are compared. With obtained estimates for n for each data point and estimate for

A for each data set, all drops are re processed for all measurement locations, for each data set to find the mean and standard deviation of drop charge as a function of size.

Following this method, it is found that drop charge does not exceed Rayleigh limit for nearly all mean charges. As no explicit limit is imposed during post processing, this confirms the applicability of the proposed method.

Processed data show that the values of the drop charge are proportional to droplet diameter to the power of exponent which varies in range of 2.1 to 2.9 for the spray of specific charge 1.2C/m^3. The lower limit of this range agrees well with surface area theory and the upper limit with that of the results reported above [14].

IV. Conclusion

In this work a brief overview of scientific literature that explores measurement techniques for determination of charge to mass ratio distribution in electrostatic applications is presented. Important observations and key aspects regarding these techniques are noted. It is shown that the conflicting results exist for the dependence of charge to mass ratio on particle size and it is suggested that this area needs further experimental and theoretical research.

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