E-SPART Analyzer: Its Performance and Applications to Powder and Particle Technology Processes

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Abstract

The characterization of electrostatic charge and aerodynamic size properties of particles and powders is of critical importance in many electrokinetic processes and research applications. Some of the major particle and powder technology processes that employ electrokinetics of particles are: 1) electrophotography, including laser printing and ink jet printing, 2) powder coating and electrosprays, 3) electrostatic beneficiation of coal and minerals and electrostatic precipitators, and 4) lung deposition of inhaled pharmaceutical aerosols. In these processes, dispersion, transport, and deposition of particles depends significantly upon the electrokinetic behavior of the particles, determined by (1) the aerodynamic diameter—a parameter that includes the particle size, shape, and density, (2) electrostatic charge—both the magnitude and polarity, and (3) fluid flow and electrical fields surrounding the particles.

There are a number of instruments that can be used to characterize the aerodynamic size distribution of particles. Likewise instruments are available to estimate the net average electrostatic charge of particles sampled. However, choice of instruments for real-time simultaneous measurements of aerodynamic diameter and electrostatic charge distributions of particles on a single particle basis is limited. The Electrical Single Particle Aerodynamic Relaxation Time (E-SPART) analyzer can be used for simultaneous characterization of particle size distribution in the range from submicron to 100 μm and particle charge distribution in the range from 0 to their saturation charge levels. We present a brief description of the principles of operation of the analyzer, its operational range, its advantages, and limitations. Application of the E-SPART analyzer to some powder technology processes is also briefly discussed, citing current research needs in these processes with examples of experimental investigations. In many of these processes, the E-SPART analyzer can be used to optimize the particle and powder technology processes involving electrokinetic properties of particles.

1. Introduction

Electrokinetic properties of the particles play a significant role in many technology processes. Table 1 shows typical ranges of particle size and electrostatic charge involved in some of these processes. Performance optimization of these processes often require measurement of both particle size and charge simultaneously on a single particle basis. It is also desired that such measurements be made in situ and in real-time. The Electrical Single Particle Aerodynamic Relaxation Time (E-SPART) analyzer meets some of these requirements and has been used for measuring the aerodynamic diameter and electrostatic charge distributions of particles on a single particle basis in many of these applications. The instrumental method employed in this analyzer is non-invasive, and the measurement of particle size is independent

<table>
<thead>
<tr>
<th>Application</th>
<th>Size (d, in μm)</th>
<th>Charge-to-mass ratio (μC/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pharmaceutical aerosol</td>
<td>0.2 to 10</td>
<td>0.1 – 10</td>
</tr>
<tr>
<td>Electrophotography</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A) Past</td>
<td>8 – 14</td>
<td>8 – 10</td>
</tr>
<tr>
<td>B) Present</td>
<td>6 – 10</td>
<td>15 – 20</td>
</tr>
<tr>
<td>C) Future trend</td>
<td>4 – 8</td>
<td>20 – 30</td>
</tr>
<tr>
<td>Powder coating</td>
<td>5 – 50</td>
<td>0.1 – 20</td>
</tr>
<tr>
<td>Coal and mineral beneficiation</td>
<td>5 – 1000</td>
<td>0.01 – 10</td>
</tr>
<tr>
<td>Electrospray</td>
<td>5 – 100</td>
<td>0.01 – 10</td>
</tr>
</tbody>
</table>

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of the refractive index and chemical composition of the particle. Since charged particles often deposit on the inner walls of the sampling tube during sampling and measurements because of the space charge and image forces, in-situ characterization is preferred for charged particles. The E-SPART analyzer can be adapted to perform remote measurement of the size and charge on a single particle basis, and to study the particle trajectories as well. Remote, non-invasive, in-situ measurements allow an understanding of the behavior of charged particle clouds where representative sampling is difficult and causes significant perturbations of the process conditions.

2. E-Spart analyzer

2.1 Principles of operation

The operational principle of this instrument depends upon the phenomenon that when an airborne particle is subjected to an oscillatory external force, such as an acoustic excitation, the resultant oscillatory motion of the particle lags behind the external driving field. This phase lag \( \phi \) relates to the aerodynamic diameter \( d_a \) of the particle. To determine this phase lag, the analyzer uses a differential laser Doppler velocimeter (LDV) to measure the motion of individual particles subjected to a combination of an acoustic excitation and a superimposed DC electric field. The DC electric field is used to measure the electrical migration velocity of the charged particles.

The particles are sampled in a laminar flow field through the LDV sensing volume. As each particle passes through the sensing volume, it experiences the acoustic excitation and the superimposed DC electric field in a direction perpendicular to the direction of the laminar air flow sampling the particles. The aerosol is sampled vertically downward whereas the acoustic and electric excitations are applied in a horizontal direction. A typical sampling configuration of the E-SPART analyzer is shown in Fig. 1. An acoustic field induces an oscillatory velocity component of the particle in the horizontal direction. The inertia of each particle causes a phase lag \( \phi \) of the oscillatory motion of the particle with respect to the driving field. Fig. 2 shows two configurations of external field applied in the relaxation cell (Fig. 1) for the measurements of \( d_a \) and \( q \). The LDV measures the oscillatory velocity component (in the horizontal direction) of the particle and a microphone measures the acoustic field. The phase lag of the particle motion with respect to the driving field is measured by the signal processor and converted to aerodynamic diameter by using a personal computer. The computer stores the aerodynamic size data for the particles sampled and provides the measured size distribution (Fig. 3). In some E-SPART analyzers, no acoustic drive is used; instead an AC electric field drives the charged particles. The process of size measurement is identical to the acoustic system.

The measurement of charge is performed by employing either: 1) a DC electric field superimposed upon the acoustic field, or 2) an AC electric field replacing the acoustic field, as shown in Fig. 1. The
Fig. 2 E-SPART measurements of aerodynamic diameter \(d_a\) and electrostatic charge \(q\) with (1) acoustic plus DC electric or (2) AC electric excitation of particles. Acoustic field forces the particle in an oscillatory motion and the DC electrical field imparts an electrical migration velocity component \(v_{\text{e}}\), the magnitude and direction of which will depend upon the polarity and magnitude of the electrical charge \(q\). With acoustic drive, the aerodynamic diameter \(d_a\) can be measured for both electrically charged or uncharged particles by determining the phase lag \(\phi\) (Fig. 2). With an AC electric field as the driving force, the measurement process is applicable only to electrically charged particles. If a particle is charged, it experiences an oscillatory motion due to the applied AC electric field. The aerodynamic diameter \(d_a\) is measured from the phase lag \(\phi\) and the electrostatic charge \(q\) is determined from the ratio of the amplitude of particle motion to the amplitude of electric drive. The advantage of AC excitation is the minimization of sampling loss since there is no steady electrical migration velocity. A unidirectional migration velocity caused by the DC electric field may deflect the highly charged particles away from the LDV sensing volume.

2-2. Particle motion in an acoustic field

For a small particle—Reynolds number \(Re_p < < 1\), Stokes’ law describes the force of resistance for spherical particles moving in a viscous medium:

\[
F_r = 3\pi \eta d_p \left( v_p - u_\theta \right) / C_c,
\]

where

- \(F_r\) = force of resistance
- \(\eta\) = fluid viscosity
- \(d_p\) = particle diameter
- \(v_p\) = particle velocity (time dependent)
- \(u_\theta\) = fluid velocity (time dependent)
- \(C_c\) = Cunningham slip correction factor.

The Cunningham slip correction factor can be computed by using the semi-empirical equation.
where
\[ \lambda_g = \text{the mean free path of air molecules (0.065 \mu m)}. \]

An equation describing the motion of a particle of mass \( m_p \) in a sinusoidal acoustic field can be written as
\[ m_p \frac{dv_p}{dt} + 3 \pi \eta d_p (v_p - u_g)/C_c = F(t), \]
where
\[ m_p = \text{particle mass} \]
\[ t = \text{time} \]
\[ F(t) = \text{any external force}. \]

In the SPART analyzer, particles are drawn vertically into the sensing volume where they experience a horizontally directed excitation. If an acoustic field is used,
\[ u_g = U_g \sin \omega t, \]
and, in the absence of any external field,
\[ F(t) = 0. \]

If we momentarily neglect some of the correcting terms, the equation of motion of a particle can be written as:
\[ \tau_p (dv_p/dt) + v_p = U_g \sin \omega t, \]
where
\[ \tau_p = m_p C_c / 3 \pi \eta d_p, \]
\[ \tau_p = m_p B \]
where \( \tau_p \) is the relaxation time and is the product of particle mass and its mechanical mobility, \( B \), given by
\[ B = C_c / 3 \pi \eta d_p. \]

The steady state solution of Equation 6 for \( t >> \tau_p \) is
\[ V_p(t) = U_g \sin(\omega t - \phi) / (1 + \omega^2 \tau_p^2)^{1/2}, \]
where the phase lag \( \phi \) of the particle with respect to the acoustic field surrounding the particle is given by
\[ \phi = \tan^{-1} \omega \tau_p. \]

Equation (11) is an approximation and can be used for \( \phi < 65^\circ \). A more accurate relationship used in the E-SPART measurements is discussed later.

The ratio of the amplitude of particle velocity \( V_p \) and the amplitude of the gas motion due to the acoustic field can be written as
\[ V_p/U_g = 1/(1 + \omega^2 \tau_p^2)^{1/2}. \]

Equations (11) and (12) show that the measurement of either the phase lag of the particle motion relative to the motion of the gas, or the velocity amplitude ratio of the particle in the acoustic field can be used to determine the relaxation time \( \tau_p \) or the aerodynamic diameter of the particle. For a spherical particle of density \( \rho_p \), the relaxation time \( \tau_p \) can be written in terms of particle diameter \( d_p \),
\[ \tau_p = \rho_p d_p^2 C_c(d_p)/18 \eta. \]

For a particle of any shape, \( \tau_p \) can be written as
\[ \tau_p = \rho_0 d_p^2 C_c(d_p)/18 \eta, \]
where \( \rho_0 \) represents unit density (1000 Kg/m^3). The Cunningham slip factor \( C_c \) is represented as a function of \( d_p \) in Equation (12) and as a function of \( d_a \) in Equation (13), respectively.

Fig. 4 shows the relative phase lag with respect to the external drive as a function of the aerodynamic diameter of the particle for several drive frequencies. We have assumed Stokes' law (Equation 3) to be valid in the entire range of phase lag \( \phi \) from 0 to 90 degrees. As phase lag increases, the pressure-force caused by the acoustic compression of the gas increases. The effective mass and the effective mechanical mobility of the particles must be considered, and appropriate correction to the Stokes' equation becomes necessary. Therefore, when an acoustic excitation is used for measuring the aerodynamic diameter \( d_a \) or the relaxation time \( \tau_p \) of a particle, it is necessary to use the correction terms for large values of \( \phi \). Equation 3 is modified by replacing mass \( m_p \) and the mechanical mobility (\( B = C_c / 3 \pi \eta d_p \)) with the effective mass of the particle \( m_p' \) and the effective mobility (\( B' \)) of the particle, respectively. The
Fig. 4 Phase lag of the particle motion with respect to the acoustic drive plotted as a function of aerodynamic diameter for different drive frequencies. The phase lag has been calculated from Stokes' law (appropriate corrections to Stokes' law become necessary when $\phi$ is greater than $74^\circ$).

Phase lag of the particle $\phi$ of Equation 11 is replaced by the corrected phase lag $(\phi - \theta)$, given by:

$$ (\phi - \theta) = \tan^{-1} \left( \frac{3(\alpha - 1)\xi(\xi + 1)}{2(\alpha + 3/2)\alpha \xi^2 + 3/2 \xi^2 + 9/2 \xi^2 + 9/2 \xi^4} \right) $$

where

$$ \theta = \tan^{-1} \left( \frac{2 + \xi}{\xi(\xi + 1)} \right) $$

$$ \alpha = 2p_p/p_g $$

$$ \xi = \frac{2}{dp} \sqrt{2\gamma/\omega} $$

Fig. 5 shows the relative phase lag $\phi$ (top curve) derived from Equation 11 and $(\phi - \theta)$ derived from Equation 15 as a function of $d_a$ for acoustic drive frequency of 100 Hz. The lower curve $(\phi - \theta)$ shows the influence of the correction term, where maximum phase lag is $74^\circ$ occurring at 75 $\mu$m diameter at 100 Hz drive frequency. To operate the analyzer over a wide size range, it is necessary to use more than one frequency of excitation either in tandem inside a single relaxation chamber, or simultaneously in more than one relaxation chamber connected in series. To cover size range from submicron to 70 $\mu$m in diameter the relaxation cells have been operated at different frequencies, 24 kHz (for 0.3 to 4.0 $\mu$m) and 1.0 kHz (for 2.0 to 20.0 $\mu$m), 444 Hz (5 to 30 $\mu$m), and 111 Hz (15 to 70 $\mu$m). Integration of experimental data arising from the overlapping ranges is accomplished by using test aerosols of known concentration and combining the calibration with an appropriate software package.

Fig. 6 shows the amplitude ratio $V_p/U_g$ plotted as a function of $d_a$ for different drive frequencies. These plots represent Equation 12. The effects of correction terms are negligible on amplitude ratio expression. As noted earlier, measurement of the aerodynamic diameter distributions can be performed either from the phase lag or from the velocity amplitude ratio measurements. It appears that for any given frequency of excitation, the operational range of size measurements can be extended if the measurement of phase lag $(\phi)$ is used to determine $d_a$ at the lower half of the particle size range and amplitude.
ratio ($V_p/U_g$) is used to determine $d_a$ at the larger half of the size range.

### 2.3 Particle Motion in a DC Electric Field

Along with the acoustic excitation, a DC electric field ($E$) is also applied in the same direction for measuring electrostatic charge $q$ of the particle. The constant electric field ($E$) applies an electrostatic force on a charged particle which can be expressed as $F_e = qE$ where $q$ is the particle charge. A particle of diameter ($d_p$) with $n$ elementary charges will move with an electrical migration velocity ($V_e$) given by

$$V_e = neEC_0/3\pi \eta d_p,$$

where $e$ is the elementary charge. As shown in Fig. 2, two alternative modes are used for size and charge measurements. If acoustic and DC electric fields are used, the oscillatory acoustic velocity component $V_p\sin(\omega t - \phi)$, is superimposed on this electrical migration velocity $V_e$ of the particle. For each particle, $V_e$ is determined to calculate $n$, the number of elementary charges, after the aerodynamic diameter ($d_a$) of the particle is computed from the measured phase lag $\phi$. The analyzer also recognizes the direction of $V_e$ which depends upon the polarity of the charge $q$ of the particle. Thus, from the direction and magnitude of $V_e$, the polarity and magnitude of particle charge are recorded by the analyzer for each particle whose diameter has been measured. The analyzer also records the number of uncharged particles for each size channel. Currently, E-SPART measurements are made using an acoustic and a DC electric drive; $d_a$ is determined from $(\phi - \theta)$ and $q$ from $V_e$. Alternatively, $d_a$ can be determined from the measured values of $V_p/U_g$, as shown in Fig. 2. Similarly, $d_a$ and $q$ can be measured by applying an AC electric drive, as described below.

### 2.4 Motion of a Charged Particle in an AC Electric Field

In this configuration, an AC electric field, $E_0\sin\omega t$ is applied (Fig. 2) across the two electrodes replacing the acoustic transducers. It is necessary, however, that the particles be electrically charged in order to make size and charge measurements. A charged particle, transiting the LDV sensing volume, will experience an oscillatory electric field, $E_0\sin\omega t$, therefore, an external force,

$$F(t) = qE_0B\sin\omega t,$$

where $u_e = 0$.

The electrical mobility $Z$ is expressed as

$$Z = qB.$$  

The Equation 3 can be written in terms of $Z$,

$$\tau_p dv_p/dt + v_p = ZE_0\sin\omega t,$$

where $E_o = V_o/d$.

The steady state solution for $t > > \tau_p$,

$$v_p(t) = ZE_0 \sin(\omega t - \phi)/(1 + \omega^2 \tau_p^2)^{1/2},$$

where $\phi$ has the same expression as Equation 11 and the amplitude ratio has the similar form of Equation 12.

$$\varphi = \tan^{-1} \omega \tau_p$$

$$V_p/E_o = Z/(1 + \omega^2 \tau_p^2)^{1/2}$$

$$= qC_0/3\pi \eta d_a(1 + \omega^2 \tau_p^2)^{1/2}.$$  

Equations 24 and 25 show that for a charged particle, the aerodynamic diameter $d_a$ can be determined from the measured value of the phase lag $\phi$ in a manner similar to the acoustic E-SPART analyzer. The relationships between $\phi$ and $d_a$ for different frequencies are shown in Fig. 4. The measurement of aerodynamic diameter $d_a$ is independent of the driving field amplitude $E_o$ and the magnitude of the particle charge $q$. Contributions from correction terms are negligible, unlike the case of acoustic drives where the gas is
Subjected to compression and rarification. Once $d_90$ of the particle is determined from $\phi$, the analyzer then calculates the electrical mobility $Z$ or the electrostatic charge $q$ of the particle. The polarity of the charge is determined by noting if the overall motion of the charged particle is “in phase” or “180° out of phase” with respect to the electric field.

### 2.5 Instrument operation

The experimental arrangement of an E-SPART analyzer is shown in **Fig. 3**. A personal computer is used for operating the E-SPART analyzer with a menu driven program designed to allow the operator to select the various options. Features include sampling time, maximum count per channel, and data storage and retrieval routines. In a typical operational mode, the instrument provides the aerodynamic size distribution of the sampled particles, the electrostatic charge distribution for any of the size channels selected by the operator, and a table showing the particle count versus the magnitude of the electrostatic charge for that given size channel. **Table 2** shows a portion of a typical “summary data printout” of an E-SPART analyzer. Particle counts are separated, one for positively charged particles and the other for negatively charged particles. For a given size, the computer calculates the net average electrostatic charge for all the particles counted in that particular size channel and the charge-to-mass ratio for that particular size. The operator can choose any size channel for obtaining the charge distribution for that channel. A summary of data provides the total number of particles counted with the average charge calculated for a given size channel for both positively and negatively charged particles. The software has the capability to provide the following information:

#### A. Size distribution
1. Size frequency distribution plot, $dN/d \log d_a$ vs. $d_a$.
2. Cumulative numbers distribution, $N(d_a)$ vs. $d_a$.
3. Volume distribution, $dV/d \log d_a$ vs. $d_a$.
4. Cumulative volume distribution, $V(d_a)$ vs. $d_a$.
5. Count median aerodynamic diameter (CMAD) in micrometers.
6. Mass median aerodynamic diameter (MMAD) in micrometers.
7. Geometric standard deviation (dimensionless).

#### B. Charge distributions
1. Charge distribution for a given size, $n(d_a)$ vs $q$(femto Coulomb/particle).
2. Table showing charge distribution for a given size.
3. Charge-to-mass ratio ($q/m$) distribution for a given size ($d_a$).
4. 2-D plot showing $n(d_a)$ and $q/m$ vs $d_a$.
5. 3-D plot showing $n(d_a)$ and $q/m$ vs $d_a$.
6. Table showing summary of charge distribution for all size channels: channel number, size ($d_a$), number of particles counted in that size channel with $+ve$ and $-ve$ charge, charge-to-mass ratio for positively charged and negatively charged particles, and the net average charge-to-mass ratio for that size channel (see **Table 2**).

#### 2.6 Range of operation

**A. Size Measurements:** The prototype E-SPART analyzer was operated in a range 0.3 to 70 $\mu$m in aerodynamic diameter. **Fig. 7** shows the cumulative number distributions of aerosol containing fairly monodisperse polystyrene latex spheres (PLS) of 0.8 $\mu$m diameters as measured by the E-SPART analyzer operating at 25KHz. **Fig. 8** shows the cumulative volume distributions of aerosol containing bis-ethyl hexyl sebacate (BES) droplets of uniform size with diameters 3.0, 10.0, 20.0 and 30.0 $\mu$m in diameter as measured by an E-SPART analyzer operating at 444 Hz and 111 Hz, respectively. Also shown in **Fig. 8** is a cumulative volume distribution of a dry powder containing polystyrene particles of average...
The number distribution is compared with the number distribution measured by a Coulter counter. Fig. 10 shows cumulative number distributions of two monodisperse test aerosols containing BES droplets of 19.0 and 29.0 \( \mu m \) diameters and a polydisperse dry powder paint of average particle diameter 52 \( \mu m \). The measurements were taken by using an AC drive. The BES droplets were generated by using a Vibrating Orifice Aerosol Generator which produces charged droplets. Fig. 10 shows that measurements of size distribution can be performed with an AC drive replacing the acoustic drive.

B. Mass Measurements: For each particle, the aerodynamic diameter \( d_a \) and the charge \( q \) are determined in the E-SPART analyzer and the average value of charge-to-mass ratio is computed. For a spherical particle of diameter \( d_p \) and specific gravity \( \rho_p \), we can write an approximate relationship:

\[
q \approx d_a \rho_P \frac{P_a}{P_p}.
\]

The mass \( m_p \) of the particle can be computed from the measured value of \( d_a \), if \( \rho_p \) is known.

Thus,

\[
m_p (d_a) = \frac{1}{6} \pi d_a^3 (\rho_p) -\frac{1}{2}.
\]

C. Charge Measurements: The desired range of measurement of electrostatic charge on each particle is from zero charge to its saturation value with positive or negative polarity. The saturation charge-to-mass ratio for tribocharged, dielectric solid particles varies inversely with particle diameter (Equations 29, 30). Fig. 11 shows the variation of the charge-to-mass ratio of a toner sample measured as a function of aerodynamic diameter. The data show that the analyzer can measure particle charge up to their saturation limits.

D. Count Rate: The E-SPART analyzer can be used to measure aerodynamic size and electrostatic charge distribution of particles in real time and on a single particle basis. The measurement of size and charge (magnitude and polarity) is simultaneous and noninvasive. The method permits continuous sampling or in-situ measurements. The maximum particle count rate depends upon the frequency of operation -- from 10 particles/s to 2,000 particles/s depending on the size range of operation, from 70 \( \mu m \) down to 0.3 \( \mu m \) in aerodynamic diameter. Further extensions
Fig. 10 Cumulative number distribution of BES droplet aerosols for two different sizes: 19 \( \mu \text{m} \)-dia and 29 \( \mu \text{m} \)-dia, and a powder paint with 52.0 \( \mu \text{m} \) MMAD measured by an E-SPART analyzer using AC electric drive.

![Cumulative number distribution](image)

Fig. 11 The charge distribution of a tribocharged and corona charged toner sample as measured by an E-SPART analyzer. The solid line shows the saturation charge calculated from the Gaussian and Pauthenier limits, respectively. The experimental data show the E-SPART can measure particle charge to its saturation limit. Particles smaller than 7 \( \mu \text{m} \) dia acquired higher charge than the values predicted by the Pauthenier equation, whereas larger particles acquired charge-to-mass ratio less than the predicted values.

of this range and count rates are possible, but require critical control of the sampling process and instrument operation.

3. Applications

Fig. 12 shows some of the particle technology applications where particle size and charge measurements play important roles in process characterization and control. The following is a brief description of E-SPART analyzer applications.

![Different industrial applications](image)

3.1 Electrophotography

Electrophotographic processes as applied to copiers and laser printers, employ electrostatically charged toners as the imaging material. For example, in a copying machine, a photoconducting surface is charged by using a corona charger to record a latent image of the original document and the charged toner particles are used to develop the image on the surface of a paper or a film. The charge properties of toners are determined by the size and shape, composition, and concentration of toners in the developer. Although the physics of the charging process are not completely understood, empirical approaches based partly on theory and partly on trial and error have been successful in optimizing the process variables to meet the increasing demand of image quality, color balance, cost, and size reduction of the copying and printing devices. Experimental approaches require both basic and applied research supported by accurate quantitative measurements.5-7)

Perhaps the two most critical parameters of toners are their size and charge distributions. For example, higher resolution can be obtained when toner size is decreased. Early copying machines used toner 8-14 \( \mu \text{m} \) in diameter (see Table 1); currently, the majority of office copiers use toners in the 6-10 \( \mu \text{m} \) range, however, for higher resolution use of toner 4-6 \( \mu \text{m} \) in diameter (microtoners) has been suggested. The use of microtoners may have some problems: 1) toner q/m values increase (q/m is proportional to 1/d), which adversely affect toner mass transfer to the latent image development since the mass of toner
deposited per unit area is proportional to $1/(q/m)$; 2) dust problems caused by uncharged fine particles; 3) cleaning residual toners from the photoconductor may become very difficult; and 4) the presence of “wrong-sign” toner could contribute more to background development compared to using large-size toner.

In electrophotographic processes, toners are charged by triboelectrification. The size and charge distributions of a positive toner sample measured by the E-SPART analyzer are shown in Figs. 13 and 14. The net charge $q$ on a particle increases as the particle diameter $d_a$ increases ($q \propto d_a^2$), however, the charge-to-mass ratio decreases with increasing diameter since $m$ is proportional to $d_a^3$. Fig. 15 shows charge distributions for three particle sizes for a negative toner sample. The maximum surface charge density is limited by the electric field which produces ionization of the gas surrounding the particles. This charging limit, called Gaussian limit, can be approximated for air, as

$$Q_s = 2.64 \times 10^{-5} \text{C/m}^2$$

Equation (30) shows that $(q/m)$ is inversely proportional to $d_p$. This relationship is an approximate one, since the ionizing field not only depends on the surface charge density, but also on the curvature of the surfaces or the particle diameter. Fig. 11 shows the variation of $(q/m)$ of a tribocharged black toner sample as a function of $d$ as measured by an E-SPART analyzer.

### 3.2 Powder coating

In this process, a dry powder is fluidized, electrostatically charged, and then sprayed over the workpiece for uniform coating. Next, the workpiece, coated with powder, is heated and the powder melts and adheres to the surface. The advantage of electrostatic powder coating is that the coating process quickly produces a chemically resistant, durable painted surface. The paint thickness can be easily varied, and since no solvent is used the process eliminates the environmental pollution caused by the emission of volatile organic compounds (VOC) used in solvent-based painting processes. Due to the elimination of VOC, the process is now widely used in the US, Europe, and Japan for coating metal and plastic surfaces for products ranging from appliances to automobiles. Powder coating in the automotive industry is limited mostly to painting of internal surfaces and to external clear coats. Most of the external surface coating is still performed by solvent-based painting. To date, the surface finish achieved by solvent-based coating is more glossy and better weather resistant; however, with research and advancements in powder coating, it is conceivable that the solvent-based
Fig. 16 Aerodynamic diameter and electrostatic charge-to-mass ratio distributions plotted for a powder paint after tribocharging. The charge distributions show bipolar charging of the particles.

process will eventually be replaced by the dry electrostatic process. The quality of powder coating is being improved to eliminate the so-called “orange peel” effects from the painted surface so that auto industries can use this process. The demand for powder coating is rising, primarily because of its environmental safety, operational efficiency, labor cost reduction, and the high quality durable painting it produces.

Adjustments for achieving high quality powder coating involve 1) the production of powders in the desired particle size range, 2) fluidization of powders, 3) pneumatic conveying of powders to the charger, 4) electrostatic charging and spraying of the powder, 5) coating of the powder on the work surface, and 6) heat treatment and bonding of the paints to the work surface.

In-situ measurements of particle size, charge, and particle trajectories around the work surface are of importance in powder coating research. The particles are charged either by corona charging or by tribocharging. Both methods have certain advantages and disadvantages in producing the desired charge-to-mass ratio distribution of the particles. For example, in a corona charger, the charging process is inefficient but predictable and controllable and produces a charge distribution of particles which is primarily unipolar. In contrast, the tribocharging process is efficient but unpredictable, and it produces a bipolar charge distribution of powders. In both cases, there is a complex interaction of the fluid flow field with the local electric field during the deposition process. Corona charging is more widely used in powder coating than tribocharging. In corona charging, the limiting value of the surface charge, known as the Pauthenier limit, can be expressed as:

\[ Q_{\text{max}} = \pi \varepsilon_0 [1 + 2 \left( \frac{\varepsilon_r - 1}{\varepsilon_r + 1} \right)] d^2 E \]  

where \( \varepsilon_0 \) is the permittivity of the free space, \( \varepsilon_r \) is the relative permittivity of the powder, \( d \) is the particle diameter, and \( E \) is the electric field. The maximum charge on a particle is limited by the field strength \( E \) but its maximum value is still limited by the ionization of the medium, expressed as the Gaussian limit.

Fig. 10 shows a size distribution of a powder paint taken by an E-SPART analyzer. Fig. 16 shows electrostatic charge distribution of a powder paint after tribocharging. The particles, when tribocharged, acquired a bipolar charge distribution, as shown in Fig. 16. The upper half of the plot shows (1) charge-to-mass \((q/m)\) ratio (broken line) and particle counts plotted as a function of \( d_p \) for positively charged particles. The lower half of the plot represents negatively charged particles.

### 3.3 Coal beneficiation

In the electrostatic beneficiation process\(^8\,^9\), the coal is first pulverized into a fine powder -- in the size range 5–1000 \( \mu \)m in diameter. The powder is then electrostatically charged by contact and triboelectrification. Once these coal particles come in contact with such metals as copper, the organic coal particles become positively charged and the pyrites and inorganic mineral particles become negatively charged. When charged particles pass through an electrostatic separator consisting of two parallel plates across which a high voltage is applied, the powdered material separates on the basis of particle charge and its polarity. The organic coal particles are attracted toward the negative plate, whereas the pyrites and mineral fines are attracted toward the positive plate.

Size reduction is very critical because particles must be small enough for selective liberation of pyrites and minerals from coal yet large enough for minimizing the energy needed for grinding the particles into fine powders. Electrostatic beneficiation provides a method of dry coal cleaning, avoiding potential stream pollution that occurs in wet cleaning.
One crucial aspect of dry beneficiation is the understanding of the electrophysical properties of powdered coal needed to enhance bipolar charging of coal and mineral particles for efficient separation. In this application, the measurement and control of electrostatic charge and particle size distributions are important for optimization. Fig. 17 shows the charge distributions of pulverized coal and mineral particles. The particles are bipolarly charged, and once these particles are separated, the major mass fraction of the positively charged particles should contain coal and the negative particles should contain minerals.

3.4 Electrostatic spray deposition of pesticides

Pesticides and herbicides are sprayed on plants and vegetation. Electrostatic spray has been successfully used for achieving a better coating of spray on the leaf surface and minimization of soil and water contamination.\(^{10, 11}\) It has been found that electrostatic spraying improves the deposition efficiency and reduces loss and thereby minimizes the amount of material needed to coat the surface. Further, the coating can penetrate dense plant foliage canopies and form an even distribution of small droplets on top of the foliar surface as well as leaf undersides within the lower portion of the canopy. As in powder coating applications, the particle size and particle charge both play a very significant role in electrostatic spray process in agriculture. In-situ measurement and control techniques are needed for efficient foliar surface coating and minimization of any soil, and groundwater contamination.

In spraying liquid herbicides or pesticides, generally air-atomizing nozzles are used, aided by electrostatic induction charging. Induction charging has the advantage that the voltage requirement for charging is generally low, typically below 1,000 volts DC with current requirement less than 100 \(\mu\)A. The droplet size for optimum coating is kept below 100 \(\mu\)m in diameter and preferably above 30 \(\mu\)m in diameter to minimize complete drying and causing air pollution. In induction charging, the droplets can acquire high electrostatic charge with a charge-to-mass ratio close to the charge saturation limit.

3.5 Lung Deposition of Pharmaceutical Particles

Deposition of inhaled pharmaceutical particles in the human respiratory tract depends primarily upon: 1) the aerodynamic size distribution of particles, 2) the breathing pattern, and 3) the airway geometry. It has also been found that many physical properties of the particles, such as shape, hygroscopicity, and electrostatic charge, have significant influence on particle deposition within the human lung.\(^{12 - 14}\)

For the appropriate therapeutic effect, it is necessary that the pharmaceutical aerosols (particle size, ranging from submicrons to 10 \(\mu\)m) deposit accurately in the targeted sites of the lung and in acceptable quantities. Since direct measurements of the deposition pattern of the inhaled pharmaceutical aerosols inside a human lung is not possible with currently available instrumentation, both physical and mathematical models are extensively used to study the lung deposition pattern. Such models are used to improve targeted deposition of the inhaled aerosol by adjusting the particle size distribution and the breathing pattern. The possibility of increasing the total deposition and shifting of the deposition to a particular portion of the respiratory tract by controlling the electrostatic charge or by manipulating hygroscopic growth of the particles has been suggested by many investigators. In-situ measurement of particle size and electrostatic charge distributions in real-time within a physical lung model provides a means to make observations of the particle deposition pattern in a simulated flow field environment. Fig. 18 shows the change in the fractional deposition efficiency of the particles in a lung model as a function of electrostatic charge. The experimental data shows that by increasing electrostatic charge it is possible to target particles in the smaller airways of the lung when particle size and the breathing patterns are both controlled.
Fig. 18 Calculated values of lung deposition fraction of inhaled particles as a function of aerodynamic diameter plotted for different magnitude of electrostatic charge. The computation was based on a physical lung model.

4. Summary

The above examples of powder and particle technology processes show that characterization of electrokinetic behavior of particles often requires simultaneous measurements of their size and electrostatic charge on a single particle basis. Such characterization also requires appropriate sampling or in-situ measurements to minimize sampling losses. The ESPART analyzer can be conveniently used in a number of such applications.

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Nomenclature

\begin{align*}
C_c &= \text{Cunningham Correction factor, dimensionless} \\
d_a &= \text{aerodynamic diameter of particles, m} \\
d_p &= \text{particle diameter (geometric), m} \\
E &= \text{electric field, Vm}^{-1} \\
e &= \text{electronic charge, C} \\
F_r &= \text{force of resistance, N} \\
F(t) &= \text{external force, N} \\
m_p &= \text{particle mass, Kg} \\
n &= \text{number of elementary charge} \\
N &= \text{number of particles} \\
q &= \text{electrostatic charge, Coulomb} \\
R_{ep} &= \text{particle Reynolds number, dimensionless} \\
t &= \text{time, s} \\
ug &= \text{gas velocity, ms}^{-1} \\
V &= \text{volume, m}^3 \\
V_p &= \text{particle velocity, ms}^{-1} \\
Z &= \text{electrical mobility, m}^2\text{s}^{-1}\text{v}^{-1} \\
\eta &= \text{viscosity of the medium, Kg m}^{-1}\text{s}^{-1} \\
P_g &= \text{gas density Kg m}^{-3} \\
P_o &= \text{unit density} \\
P_p &= \text{particle density Kg m}^{-3} \\
\tau_p &= \text{relaxation time, s} \\
\lambda_g &= \text{mean free path of gas, m} \\
\omega &= \text{frequency in radians/s} \\
\phi &= \text{phase lag, radians} \\
\theta &= \text{correction term to phase lag } \phi, \text{ radians} \\
\nu &= \text{kinematic gas density (} \eta/P_g \text{)} \\
\varepsilon_o &= \text{permittivity of free space, F m}^{-1} \\
\varepsilon_r &= \text{relative permittivity, dimensionless}
\end{align*}

References

4) M. K. Mazumder, R. E. Ware, and W. G. Hood, "Simultaneous Measurements of Aerodynamic


