A Laser-Optical-Sheet Based Technique for Monitoring Particle Charge Distributions

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Abstract

A system utilizing a coherent sheet of light obtained by a pulsed laser and appropriate optical components was developed to monitor a charged particle stream as it passes through an electric field. The deflection patterns of narrowly sized quartz particles (74 x 53 μm) were photographed and analyzed by a densitometer. The deflection and dispersion of a spot, representing a group of particles, can be used to determine the average charge and charge distribution in the particle stream. The results demonstrate the efficacy of this technique for determining the charge distribution of a particle stream. Such a device has the potential for monitoring particle charge in continuous airborne particulate streams.

1. Introduction

The prediction and control of electrostatic charge in a particle stream is important in various processes including electrophotography [1], electrostatic powder coating [2], electrostatic precipitators [3], electrostatic separation [4, 5], powder handling [6], etc. Therefore, it is often desirable to measure the electric charge distribution of a particle stream rather than only the average charge-to-mass ratio. Such measurements are often required on a suite of particles rather than for individual particles. Further, a technique that can provide a rapid analysis, yet be simple in operation would be particularly useful for on-line monitoring.

The classical method uses a Faraday cup or “pail” coupled to a suitable monitoring circuit to measure the surface charge of an individual particle or the average charge for a group of particles [7, 8]. Based on the Faraday cup approach, the “blow-off” tribo method was developed [9] and improved [10] for measuring the average electric charge on a known amount of toner particles in electrophotography. Inculet [5] suggested using a Faraday cage-type instrument, called a “Separation Tower”, to perform charge-to-mass ratio measurements. With this method, the average, net charge on some amount of particles is measured, but the magnitude and the sign of the charge on individual particles cannot be determined. Thus, this method is incapable of detecting a bipolar charging system, which is sometimes observed for powders.

Another approach for measuring the charge on the surface of a particle or droplet is based on Millikan’s oil droplet experiment [11]. Several modified Millikan’s apparatuses were used to measure the electric charge on a single particle [12-17]. The basic principle of Millikan’s approach is rather simple. However, the charge measurements are tedious and time-consuming, because the particles must be measured, one at a time, to obtain a statistically meaningful distribution. Moreover, it becomes more difficult to trace each particle as the particle size decreases. As such, it is primarily used as a research tool and is not commercially available or suitable for industrial applications.

Charge spectrometers, commonly used in investigating the electrical behavior of commercial electrophotographic powders, have been used to measure the distribution of toner charge indirectly [18-21]. The spectrometer is particularly powerful because it can directly measure the amount of charge on toner particles. However, the concentration of toner particles must be kept low enough to minimize the number of touching particles but large enough to provide a statistically meaningful number of counts. Particle clusters or agglomerates would provide incorrect information about the particle size and electric charge. Another problem is that the collecting filter must be grounded to prevent the charge on the captured toner particles from distorting the trajectory of incoming particles. However, grounding the filter distorts the electric field at the
Several methods have been used for determining the charge distribution of an aerosol. Most of these methods are based on the measurement of the electrical mobility distribution of monodisperse or size-classified particles. Instruments used for measuring electrical mobility include the Millikan cell [25-28], parallel-plate electrical mobility spectrometer [29-33], and concentric electrical mobility analyzer (e.g., electric aerosol analyzer and differential-mobility analyzer) [34, 35]. A commercially available electrical aerosol analyzer and a differential mobility analyzer with a concentric configuration were developed mainly for particle-size measurement. However, if the particle size is determined by an independent method, such as an optical particle counter, these devices can also be used for the determination of the particle charges [34, 35].

An apparatus, utilizing a laser-based Phase Doppler Particle Analyzer (PDPA) for monitoring the particle component velocities, size, and number density, was developed to determine the charge on small particles [36]. This method provides high-speed data collection on a particle-to-particle basis. However, the major drawback of this approach is the high cost and complexity of the system.

A review of existing charge measurements shows that either the methods are only related to the average charge-to-mass ratio or the methods with charge distribution measurement have certain disadvantages, discussed above. In this paper, a new technique is developed which allows the charge distribution of a particle mixture to be analyzed. For this study, the electrostatic charge on narrowly sized quartz particles was analyzed. This approach is presented and discussed, along with the results from the initial tests.

2. Experimental Approach

The basic principle of this new approach is based on the deflection of charged particles by an electric field. This approach is similar to the others in which particles are introduced into a laminar air flow stream across which an electric field is applied. The deflected distance of the particle is then a function of the charge on the particle. However, in the current approach, the trajectory of the entire particle stream in the electric field is recorded as it passes through a laser sheet, as opposed to tracing individual particles or collecting samples on the electrodes or in specially designed trays as in other techniques [5, 18-21]. This provides a means to estimate the electric charge distribution of a particle stream directly.

3. Test Set-Up

A Surelite I pulsed argon laser (Continuum) and necessary optical components including a mirror, prism, spherical lens, and cylindrical lens, were used to generate a laser sheet [37], shown in Figure 1. A schematic representation of the experimental set-up is given in Figure 2a. The test chamber (95 x 95 x 400 mm) was constructed out of 9 mm Plexiglas, with copper plates (75 x 75 x 150 mm) attached to two sides. The plates were connected to a DC power supply to vary the potential and polarity on the plates. The bottom of the separation chamber was open to the atmosphere. A slit was cut in the Plexiglas to allow the laser sheet to pass through the opening, eliminating the reflection in the chamber. The sheet was projected at 45° to the vertical plane. Figure 2b shows the change of spot shape in the laser sheet due to the electric force, which will be discussed later.

Crystalline quartz particles (U.S. Silica) were first wet screened at 25 μm (500 mesh), followed by dry screening. Narrow size fractions (74 X 53 μm) of the screened quartz were used for the charging experiments. The quartz sample was essentially pure SiO₂. The particles were tribocharged by contacting with a copper plate, attached to a vibrat-
ing feeder, and fed into the top of the test chamber through a copper funnel. The particles fell freely through the chamber and were illuminated by the laser sheet. Photographs of the particle stream at different applied potentials were taken using a 35 mm still camera, which was placed perpendicular to the electric field.

Correct film exposure was determined by finding the proper combination of laser power, diaphragm opening (f-stop number), and exposure time (shutter speed). The Surelite I pulsed argon laser has a frequency of 20 Hz, which means a light pulse is generated every 0.05 seconds. Thus a long exposure time is required to eliminate the bias caused by the frequency of the pulsed laser. After the initial trials with different combinations of laser power, f-stop number, and exposure time, a laser power of 0.125 watts, f-stop number of 16, and exposure time of 0.5 seconds were selected. These settings provided the most consistent photographs of the particle stream. In all cases, 100 speed, black-and white Kodak film was used. Each negative frame was scanned with a Personnel Laser Densitometer to determine the optical density patterns on the frames resulting from the motion of particle in the electrical field. Image analysis was then performed on the scanned picture using the software package ImagequaNT (Molecular Dynamics, Inc.) from which the peak heights and peak positions were determined. This approach is commonly used in biotechnology research for displaying a scanned image and identifying cells based on the differences in optical density.

3. Results and Discussion

Figure 3 shows the change in the dispersion pattern with the applied potential for the quartz particles after contacting the copper plate. When no electric field was applied, the particles fell along the center line of separation chamber with almost no dispersion, as indicated by the spot in Figure 3a. When a positive voltage (i.e., 3.0 kV) was applied to the left electrode, the spot shifted slightly to the left side as shown in Figure 3b. This indicated that the particles carried more negative charges.

Davies [38] suggested that the sign of the charge that a particle or material will develop after contact is determined by the differential in work function between the particle and contact media. The work function, \( \phi \), is defined as the difference in potential between the Fermi level and a free electron state, where the Fermi level is the energy level at which 50% of the electron states are filled. When two
Materials with dissimilar work functions are contacted, the material with the higher work function gains electrons, producing a negative charge. The material with the lower work function loses electrons, producing a positive charge. This transfer occurs because the Fermi levels of materials in contact must equilibrate. Since the work function of quartz particles is higher ($\Psi = 5.0$ eV) than that of copper ($\Psi = 4.38$ eV), the quartz particles should charge negative, according to the solid state electron transfer theory.

As the applied potential was increased to 4.5 kV, the spot was more dispersed and moved more towards the left positive plate. No particles were found at the right side (Figure 3c). At higher applied potentials, the spot became narrower, and the particles were distributed between the copper plates (Figures 3d-3f). It can be seen that the

Fig. 3 Photographs of quartz particles (74 x 53 $\mu$m) on the laser sheet intersecting the chamber cross-section at an angle of about 45° at the bottom of the electric field after tribocharging by contact with a copper plate: (a) 0 kV; (b) 3.0 kV; (c) 4.5 kV; (d) 6.0 kV; (e) 7.5 kV; (f) 9.0 kV.

Fig. 4 Photographs of naturally charged quartz particles (74 x 53 $\mu$m) on the laser sheet intersecting the chamber cross-section at an angle of about 45° at the bottom of the electric field: (a) 0 kV; (b) 3.0 kV; (c) 4.5 kV; (d) 6.0 kV; (e) 7.5 kV; (f) 9.0 kV.
higher the applied potential, the greater the distribution of particles between the two plates. This occurs because the electric force is proportional to the applied potential for a given charged particle. It was found that some particles remained in the center of the chamber. One explanation for the lack of charging would be insufficient contact between the particles and copper plate while feeding. It was also observed that some particles actually deflected toward the right negative side, indicating a positive charge on the particles. This has also been found for silica particles tribocharged with copper [39]. Investigation of this phenomenon is continuing.

Figure 4 shows the change in the dispersion pattern with applied potentials for the quartz particles that were naturally charged. In this case, the particles were passed over a quartz spatula and through a glass funnel as opposed to contacting with copper. When no electric field was applied, the particles fell along the center line of separation chamber (Figure 4a), as in Figure 3a. When 3 kV was applied to the left electrode, no significant shift of the spot was observed, only some dispersion of the spot along the center separator line. As the applied potential was increased to 4.5 kV, the spot was more dispersed towards both ends (Figure 4c). At higher applied potentials, the spot became narrow, and the particles were evenly distributed between the separator plates (Figures 4d-4f). This indicates that the naturally charged particles carry about the same amount of positive and negative charges.

As noted in the previous section, each negative frame was scanned with a densitometer and then subjected to image analysis. Optical density curves as a function of horizontal position in the chamber were obtained. A typical dispersion pattern as a function of the applied potential for the quartz particles is plotted in Figure 5. The x-axis in the figure is the actual distance along the separator chamber in the horizontal direction. The origin is defined as the center of the chamber.

With no applied voltage, the optical density versus distance curve was normally distributed about the center of the chamber. As the positive voltage was increased to 3 kV, the curve shifted to the anode (left side). This indicates that the spot, as shown in Figure 3b, represented a group of particles having approximately the same negative electric charge. The peak decreased and the curve broadened as the voltage was increased to 4.5 kV and 6.0 kV. Also, the optical density at the left end increased, whereas the optical density at the right end remained unchanged. This demonstrates that the majority of the silica particles acquired a negative charge. This is in agreement with that expected based on the material work functions and was also recently reported by Ban et al. [40]. They found that silica particles obtained under a gas flow after contacting with a copper loop showed negative charges on the majority of the silica particles. In their work, the electric charge was measured by PDPA.

Several replicate tests were made to determine the reproducibility of the results. Figures 6a and 6b give several optical density versus distance curves at a given voltage. As can be seen, the curves were reproducible.

The naturally charged quartz particles (Figure 4) were also analyzed to determine the effectiveness of the charging apparatus. The optical density curves as a function of distance for various electric fields are shown in Figure 7. Comparing Figures 5 and 7, it can be seen that the response to the applied potential was different. The optical density versus distance curve are normally distributed at all voltages for the naturally charged particles. No peak shifts were observed, and the change at the each end was minimal. Broadening of curves was also found, but each curve was symmetric about the center of the separation chamber. As expected, particles charged by contacting with copper are more sensitive to the potential than particles naturally charged. The different behavior can be explained with the difference in the charging system.
5. Conclusions

A system using a coherent sheet of light, which was obtained by a pulsed laser and appropriate optical components, was designed to visualize particles and monitor the charge distribution of the particles after passing through an electric field. The particles passing through the laser sheet create a spot, which represents a distribution of particles. The average charge of the particles can be estimated by the deflection of the spot toward one of the electrodes. The dispersion shape of the spot provides information about the electric charge distribution in the particle stream, e.g., a wide spot indicates a broad charge distribution in the particle stream. An asymmetrical shape of the spot indicates that the particles are preferentially charged. It was shown that after contacting with a copper plate, a majority of sieved quartz particles (74 × 53 μm) were found to be negatively charged. On the other hand, the charge distribution of naturally charged particles was normally distributed under all voltages, indicating that the particles carried equal positive and negative charges. This technique was also shown to be very reproducible. Compared to other charge or charge distribution measurement techniques, this technique is relatively simple and fast, and is also suitable for on-line charge monitoring.

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