Quantitative Charge Spectrometer

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Abstract

The measurement of the actual toner charge distribution, for both positively and negatively charged particles, in an electrophotographic development system would be useful in evaluating and optimizing the development system. We report the development of a charge spectrometer for a contact monocomponent development system, which quantitatively measures the charge distribution for the toner particles, as well as the percentage of wrong-sign toner.

Introduction

As it has become clear that wrong-sign toner (WST) particles in electrophotographic development systems are responsible for image defects, efforts to measure and understand toner charge distributions have increased. WST particles have been shown to be indirectly responsible for background development[1–3] and directly responsible for edge raggedness.[4] Low-charged wrong- (and right-) sign toner particles can create toner dust inside a copier or laser printer, leading to reliability problems.

Other motivations for measuring toner charge distributions exist. For example, it is known that it would be advantageous to lower the average toner charge-to-mass ratio, Q/M, in development systems.[5] Attempts to lower Q/M usually result in increased amounts of WST. Therefore, lowering Q/M requires narrowing the toner charge distribution, which requires understanding the source of and minimizing the amount of wrong sign toner. Furthermore, the study of toner charging is but one example of the unsolved insulator electrostatic charging problem.[5,6] Recent advances in the theory of insulator charging, by studying toner-carrier charging properties,[7,8] further motivates the desire for a tool that can characterize quantitatively the charge distribution of toner particles.

It is the purpose of this report to describe a quantitative charge spectrometer (QCS) that measures for the first time (to our knowledge) the amount of WST and Q/M quantitatively, as determined by independent techniques. This QCS mates a new toner injection system to a known charge spectrometer[5,9,10] that utilizes laminar air flow and crossed electric fields. The injection system is specifically designed for a contact monocomponent development system, although its principle is extendable to other monocomponent systems.

In recent years there have been many attempts to measure toner charge distributions, reviewed in Ref. 5. These include:

1. Incremental blowoff,[11]
2. Laminar air flow, crossed electric fields, collection of toner on the side walls,[12-15]
3. Laminar air flow, crossed electric fields, collection of toner on the bottom plate (used here),[9,10,15,17]
4. Gravity, crossed electric fields, photographic detection under chopped laser illumination,[18,19]
5. Laminar air flow, electric fields, and gravity,[19]
6. Millikan oil drop,[20,21] and
7. Doppler velocimeter used to measure the velocity of toner particles subjected to a dc electric field and an ac acoustic pulse.[22]

Although all of these techniques have successfully measured properties of the toner charge distribution, none that we know of can claim to be quantitative, in the sense that the calculated Q/M from the charge spectrometer data equals the measured Faraday cage measurement. The primary difficulty, we believe, is in the collection of the toner particles and their injection (without loss or alteration of their charge) into a charge-measuring device. Therefore we focused our attention on a new injection system, which we report here.

This article is organized as follows. The principles of operation of the charge spectrometer are reviewed in the next section. The new particle injection system and its qualification tests are then described. Our results are summarized in the final section.

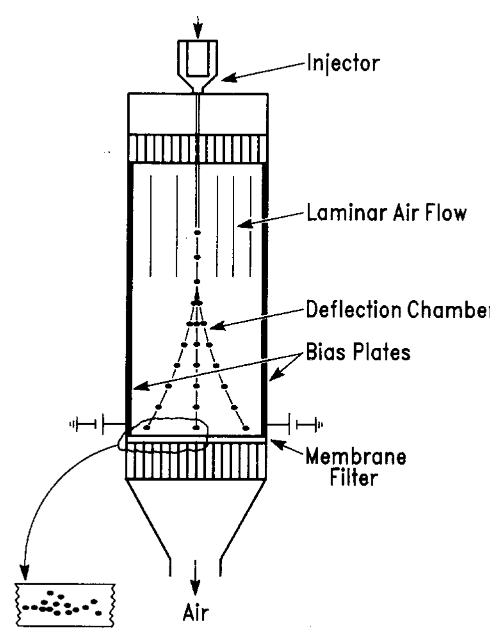

Figure 1. Schematic of the charge spectrometer,[9,10] showing an injector and the laminar air flow chamber in which a crossed electric field causes the toner to move horizontally proportional to Q/d.

Principles of Operation

Figure 1 shows a schematic representation of the quantitative charge spectrometer (which differs from a previously reported charge spectrometer[9,10,16,17] only by the injection system). Its operation may be broken down into three steps: injection, deflection, and collection.

In Step 1, charged toner is removed from a developer and is injected into a laminar flow chamber. Injection systems described in the literature include holding the carrier in a magnetic chuck[9] or a miniature blowoff cage[10] and blowing with air, vibrating toner off the carrier,[23,24] or using an insulative fur brush to separate mechanically toner from a photoreceptor.[18] Our new particle injection system is described in the third section.

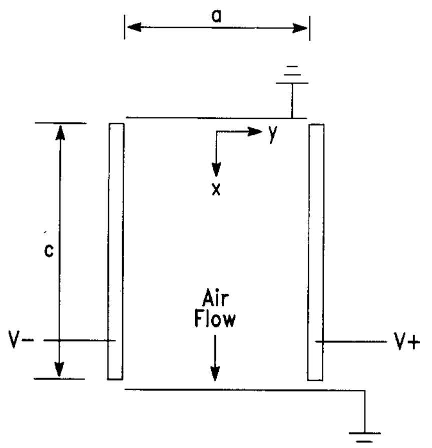

Figure 2. Detail of the electrostatics of the air flow chamber.

In Step 2, the toner enters the laminar flow chamber, which has two bias plates. Applying a potential between the plates, as shown in Figure 2, creates an electric field. For an infinite parallel plane the electric field strength is just $E = V/D$ where V is the applied voltage difference and D is the plate separation. For the chamber geometry shown in Figure 2, which has plates of finite dimension in the x-axis and y-axis and assumed infinite dimension in the z-axis, the deflection electric field is given by:[16]

$$E_y = \frac{-4V}{c} \sum_{\text{odd } n=1}^{\infty} \frac{\sin(n\pi x/c)\cosh(n\pi y/c)}{\sinh(n\pi c/2a)}, \tag{1}$$

where c is the height and a is the width of the chamber. The deflection force experienced by a charged particle with charge q in an electric field is:

$$F_e = qE_y. \tag{2}$$

The viscous drag force experienced by spherical particles is described by Stokes' law (for Reynolds number < 0.5):

$$F_{drag} = 3\pi\mu d v_y, \tag{3}$$

where d is the particle diameter, v_y is the particle velocity in the y direction, and μ is the viscosity of air. Equating the deflection force (Eq. 2) and the viscous drag (Eq. 3), it is easily shown that Q/d is proportional to the deflection distance of the particle, y, which is the time integral of v_y

$$y = \int v_y dt = \frac{Q}{d}\frac{1}{3\pi\mu}\int E_y dt. \tag{4}$$

At the bottom of the laminar flow chamber, the deflected toner particles are captured by a membrane filter.

In Step 3, the toner that has collected on the membrane filter is measured individually for its diameter and deflection distance, using an automatic image analysis system. The image analysis system used to analyze the sample consists of a microscope with a camera. The camera output is digitized and fed into a computer. The stage on which the membrane filter rests has an x-y movement that is computer controlled. The microscope focus is also computer controlled. The system scans the filter membrane frame by frame, counting and sizing particles. The tabulated results of particle counts, diameters, and associated deflection distances can then be plotted; an example is shown in Figure 3. In Figure 3, the deflection has been related to Q/d, using Eq. 4, and the percentage of particle counts is plotted as a function of Q/d for a range of toner particle diameters. The data show both right-sign (negative) and wrong-sign (positive) toner particles. The peak value of Q/d is approximately independent of d under the conditions of this experiment. (These data comprise the -325-V bias run for Test 2; see the fourth section below.)

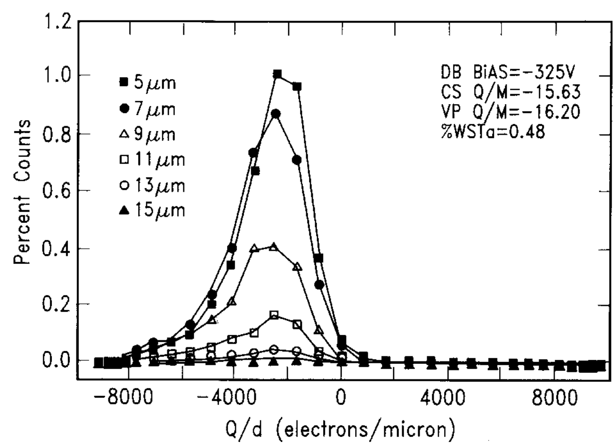

Figure 3. Typical data taken from the quantitative charge spectrometer. Note that the vacuum pencil (VP) Q/M approximately equals the Q/M calculated from the charge spectrometer (CS) data. The percent wrong-sign toner by area (%WSTa) is also shown. Shown are the percentage counts versus Q/d for 6 toner diameters.

New Particle Injection System

The function of the injection system is to obtain a representative sample of charged toner particles. To assure that the sample is representative, the injector needs to strip toner completely at the injection location and deliver these particles into the deflection chamber with minimal loss. In addition, it cannot impart additional charges to the toner that may occur from collisions with the surfaces of the injector.

To achieve these objectives, we have designed a new particle injection system that strips toner from the roller of a contact monocomponent development system with near 100% efficiency, using a high velocity air stream that entrains the toner. The air flow is driven by a 95-psi pressure drop between the inlet and exit of the injector tube (see Figure 4). Air flow is nearly straight with smooth transitions in tube diameter to minimize the collision of toner particles with the injector tube walls. It comprises a 32-µm diameter tube region with a small (< 250 µm long) opening in the side of the tube that allows toner to enter the air stream. The tube diameter gradually widens to 250 µm and stays at that diameter for most of its length. Near the injector exit location, the tube diameter widens gradually to 2.17 mm where the injector air flow enters the chamber.

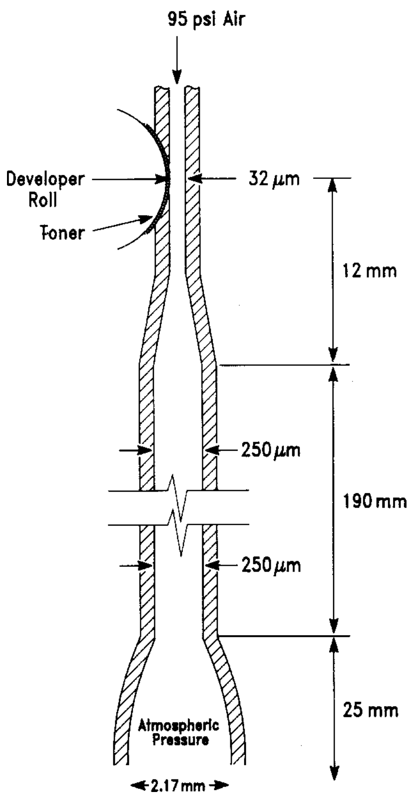

Figure 4. Schematic diagram of the new injection system.

As noted earlier, high air velocities are needed to strip the toner particles from the roller. To determine under what conditions toner stripping occurs, let us examine the forces existing at the stripping location. For simplicity let us assume that the force holding the toner to the roll is electrostatic. The electrostatic adhesion force F_a may be described by the following equation:

$$F_a = qE = q\frac{\sigma}{\epsilon_0} = \frac{q}{\epsilon_0}\frac{M}{A}\frac{Q}{M}, \quad (5)$$

where q is the toner charge, ϵ_0 is the permittivity constant σ is the charge/unit area, M/A is the developed mass/unit area, and Q/M is the average charge-to-mass ratio. For an average 8-µm diameter toner with a Q/M = -15 µC/g and an M/A = 0.7 mg/cm^2, we get an electrostatic adhesion force F_a = 4.8×10^{-8} N.

Let us examine the shear forces on the toner particle. Assume fully developed laminar flow. The shear τ is related to the radial distance from the center of the tube, r, and the derivative with respect to distance along the tube axis (d/dS) of the pressure P (neglecting hydrostatic pressure)

$$\tau = -\frac{rdP}{2dS}. \quad (6)$$

By definition τ is $\mu\, dv/dr$, where μ is viscosity and v is the air velocity. Solving for v by assuming dP/dS is constant at a cross section, integrating v over a cross section to get the total flow, calculating the average velocity, using

$$dP/dS = v_a 8\mu / r_0^2,$$

we finally get

$$\tau = v_a 4\mu / r_0. \quad (7)$$

Substituting appropriate numbers, we find the average shear force on an 8-µm particle to be approximately

$$F_{\text{shear}} = \tau \times A \simeq \tau \times \pi r_t^2 = 6.6 \times 10^{-8}\,\text{N}.$$

Let us now examine the force contribution due to air momentum transfer. Again, simplifying assumptions will be necessary to allow the problem to be solved analytically. Let us assume that the particle projects into the air stream and is isolated (the actual case is that the toner particle is shielded by being recessed as shown in Figure 5). Let us assume that the air is deflected 45 degrees. We derive the force pushing the particle, F_m, as follows:

$$F_m = \frac{d(momentum)}{dt} = M\frac{d\bar{v}}{dt}, \quad (8)$$

where M is the unit mass of air changing direction and $\bar{v}$ is the change in velocity. Substituting the appropriate numbers we get: $F_m = 1.8 \times 10^{-5}$ N.

Due to the simplifying assumptions (electrostatic adhesion, incompressible laminar flow, etc.), only estimates of the forces are possible. However, the above calculations are useful for identifying the forces involved in toner stripping. In summary, we estimate the forces of adhesion to be $F_a = 4.8 \times 10^{-8}$ N and the shear and momentum forces to be $F_{\text{shear}} = 6.6 \times 10^{-8}$ N, and $F_m = 1.8 \times 10^{-5}$ N, respectively. As can be seen from the calculations, toner stripping forces exceed the adhesion force and toner stripping should occur. Because the toner is located in a recessed region (see Figure 5), rather than directly in the airstream as assumed for calculations at the stripping location, we expect the momentum forces to be much lower than calculated, because the tube walls act as shields to prevent air from hitting the toner directly. It would be desirable to utilize the force derived from the momentum transfer (because it is 3 orders of magnitude larger than the adhesion force) to improve stripping efficiency. In practice, however, we find that for the toner to project into the opening of the tube a significant amount, the length of the opening becomes very large. This causes the stripping of a larger area of toner from the developer roll and is undesirable from a charge density standpoint, which we will discuss later. From the qualitative examination of these force equations, we learn that higher air velocity causes greater forces to push the toner, while a lower toner Q/A reduces the electrostatic adhesion force holding the toner to the roll. It can also be seen how charge selectivity can occur, because higher charged particles have a greater adhesion force holding them to the surface of the roll.

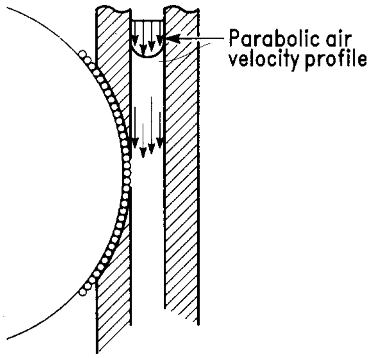

Figure 5. Details of the injection system where the developer roll with toner on its surface is inserted.

Assuming that the toner is entrained in the airflow, it must be transported into the deflection chamber. The tube then expands smoothly into a 250-μm diameter tube. This expansion into a larger diameter tube reduces the pressure drop required to drive the air flow. If we examine the forces on a cloud of charged toner as it traverses the 250-μm tube region, we find that there is a repulsive force that has the effect of driving the charged toner particles into the injector tube walls. We can calculate this repulsive force if we know the charge density of this toner cloud. The repulsive force is derived using Gauss's law to calculate the electric field for a cylinder of space charge. The volume space charge density ρ is assumed to be uniform for simplicity. The repulsive electric field E_r is

$$E_r = r_0 \frac{\rho}{2 \epsilon_0}, \tag{9}$$

and the repulsive force F_r is

$$F_r = Q\rho \frac{r_0}{2 \epsilon_0}, \tag{10}$$

where Q is the toner charge. To limit the amount of toner that hits the wall we find that we must keep the charge density low, the tube diameter small, and the flow velocity large. With a high flow velocity, the toner quickly traverses the tube length. This reduces the time for the toner to drift toward the tube walls under the influence of the electrostatic repulsion force. The flow velocity can be made larger by reducing the tube diameter. However, eventually we must expand the diameter to reduce the velocity of the air to match the deflection chamber velocity, as will be discussed next.

When the injector air flow enters the deflection chamber of the charge spectrometer, the exit velocity must match that of the chamber. This is a requirement for two reasons. If the velocity exceeds the chamber velocity by a large margin, the air exiting the tube will expand. This will cause the line width or zero spot to be very large and hence cause a loss of resolution in the charge measurement. The other reason is that the calculation of the *Q*/*d* assumes that the velocity of the particles traveling in the air stream is constant and of a known value equal to the chamber air velocity. The chamber air velocity is set at 100 ft/min. A lower chamber velocity is possible, but this would require a reduction in the exit velocity of the injector (lower velocity decreases the centering force and hence is not desired). A higher chamber velocity is limited by two factors. The first factor is that the blower can draw only a little over 100 ft/min, given the pressure drop caused by the filter membrane used to trap the toner. The other limitation is that the flow must be laminar and hence we must have a reasonable Reynolds number ($R_c \approx 2400$ for 100 ft/min).

In principle we would like to operate the injector at the highest possible flow rate and velocity because stripping efficiency increases and losses in transport are minimized. An increased stripping efficiency and a decreased transport loss would reduce charge selectivity. However, in practice we are limited by the exit velocity constraint.

Examination of the injector nozzle after numerous charge spectrometer runs reveals that there is no buildup of toner in the small- and medium-size tube regions (32-μm and 250-μm diameter, respectively). However, because the air velocity needs eventually to match the chamber velocity, there is buildup of toner at the transition between the 250-μm region and the 2.17-mm exit tube diameter. This is because the toner repulsion force increases, as shown in Eq. 10, as the tube radius increases. We can visualize this by noting that when the toner is in the narrow portion of the tube, the charge is stretched out in a thin line. When the toner reaches the expansion zone in the tube, the air velocity slows and the traversing toner is flattened into a short cylinder of charge, resulting in a higher repulsion force. To measure the effect of this buildup and other possible charge selectivity problems, we performed independent measurements of the average Q/M taken from the development roll, using a vacuum Faraday method. The average Q/M from the charge spectrometer is obtained by dividing the total charge collected by the total mass collected. Another independent measurement is a particle size analyzer (Coulter Counter) determination of the size distribution. This information is also determined by the image analysis system. The results of these comparisons are discussed in the next section.

Qualification Tests

To qualify the new injector design, a series of three tests were performed. These were:

1. Simulated "black" and "white" development conditions,
2. Varying doctor blade bias, and
3. Toner with "high" and "low" background development.

These tests were selected because 1 and 2 provide a test of variable Q/ M, and 2 and 3 provide a test of variable WST concentration (based on vacuum pencil measurements and observations of background development).

Test 1: "Black" and "White" Conditions.

In the process of printing a solid black page, toner on the developer roll of a nonmagnetic monocomponent contact system[25] passes under the doctor blade only once before it is developed on the photoconductor, whereas during the course of printing a solid white page, toner is not transferred to the photoconductor and therefore stays on the developer roll and passes under the doctor blade multiple times. This difference has two distinct, though related, effects. First, in the case of a white page, the toner experiences many more charging events than it does in the case of a black page. Second, because the mechanical interactions between the toner, developer roll, and doctor blade are greater in the case of a white page, larger particles tend to be rejected by the doctoring process. Typically, the toner for a white page has an average Q/M of –14 to –16 μC/g (vacuum pencil measurements) and a median particle diameter of 8 μm (Coulter Counter measurements). For a black page, the average Q/M is –8 to –10 μC/g with a median particle diameter of 10 μm.

For benchtop testing purposes, we allowed the toner to stay on the developer roll for either one or twenty revolutions, corresponding approximately to "black" and "white" printing conditions, respectively. Vacuum pencil and Coulter Counter measurements confirmed these benchtop conditions, producing approximately the same average Q/M and size distributions as found during actual printing conditions. A standard, unmodified IBM 4019 LaserPrinter developer cartridge was used in this set of experiments.[25] It was mounted on a developer test stand, supplied with the appropriate relative bias voltages (developer roll, ground; doctor blade, –325 V; toner adder roll, –125 V). The developer cartridge was then mounted on the charge spectrometer, and a series of lines were generated. These lines were analyzed in the previously described manner with the automated image analysis system.

Our data are shown in Figures 6-8. Figure 6 shows comparisons of Q/M as measured by the vacuum pencil and as calculated from the charge spectrometer data. The line with a 1:1 slope (shown) represents perfect agreement. As can be seen, the data indicate that this quantitative charge spectrometer can accurately measure Q/M up to about –16 μC/g. Size distribution of the toner on the roller for "black" and "white" conditions, shown in Figure 7, can be compared with Coulter Counter data shown in Figure 8. The quantitative charge spectrometer can detect the shift in size distribution from the "black" to "white" conditions. Finally, the *Q/d* distribution, summed over all *d*, is shown in Figure 9. The "black" condition clearly has more toner at lower Q/M, although the amount of WST appears the same for both conditions.

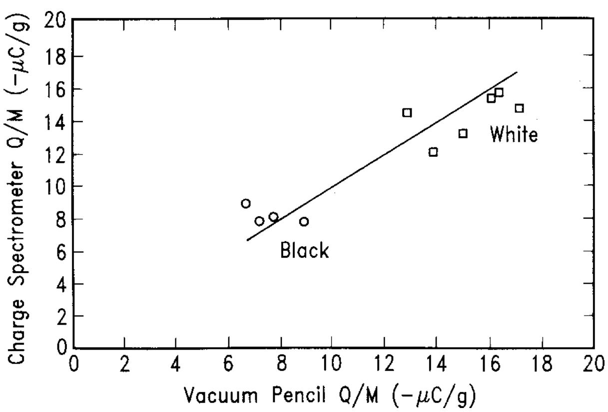

Figure 6. Charge spectrometer Q/M versus vacuum pencil Q/M for the "black" and "white" condition (see text).

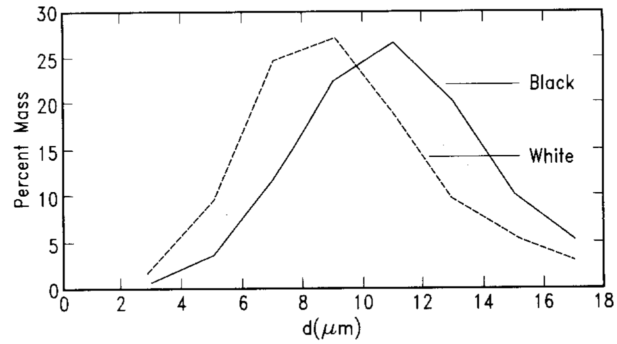

Figure 7. The size distribution of the toner as determined by the QCS for the "black" and "white" conditions.

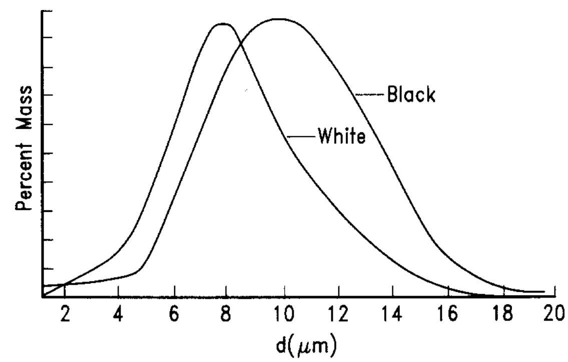

Figure 8. The size distribution of the toner as determiend by Coulter Counter for the "black" and "white" conditions.

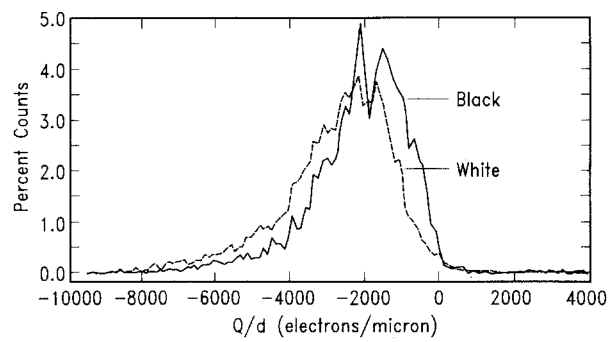

Figure 9. The Q/d distribution summed over all toner diameters for the "black" and "white" conditions.

Test 2: Doctor Blade Bias Variations.

By varying the doctor blade bias, with respect to the developer roll, from +250 to –500 V, the average Q/M on the developer roll can be varied from approximately –5 to –18 μC/g with significantly more background development as the bias becomes positive. This gives us the ability to test the charge spectrometer's accuracy and repeatability over a wider range of Q/M values than in Test 1, while observing changes in the amount of WST (assuming WST determines background development). In this set of experiments, the developer roll was grounded, the toner adder roll held at –125 V with respect to the developer roll, and the doctor blade bias was set to one of five different voltages: +250 V, +125 V, 0 V, –325 V and –500 V, all with respect to the developer roll. The developer roll was then turned for twenty revolutions at 3.2 ips (the "white" condition).

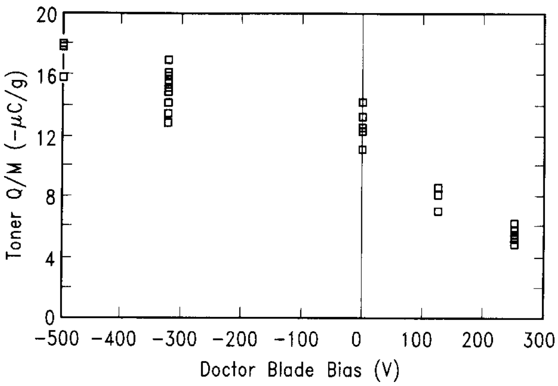

Figure 10. Q/M determined by the QCS as a function of the doctor blade bias.

Figure 10 shows Q/M versus doctor blade bias, and Fig. 11 shows Q/M calculated from the charge spectrometer data compared to Q/M measured directly with a vacuum pencil. Again, the charge spectrometer accurately determines Q/M up to about –16 μC/g; there may be a little roll-off at –18 μC/g. The percentage of WST (by area) versus doctor blade bias is shown in Figure 12. Percentage of WST by area is used because it is more indicative of a change in reflectance on paper. Clearly, as the doctor blade bias becomes more positive, the amount of WST dramatically increases. Size distribution shifts only slightly with bias, becoming slightly smaller (by ≈ 0.1 μm) as the bias is changed from 0 to –500 V. The *Q/d* distribution, shown in Figure 13, clearly shows the shift of *Q/d* and an increase in the amount of WST as the bias is changed. The amount of WST is compared with direct measurements of background development in the next test.

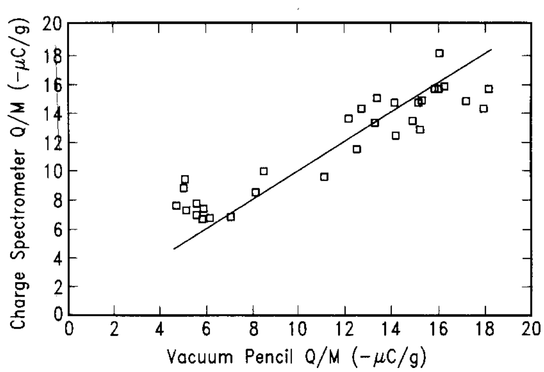

Figure 11. Comparison of Q/M for the QCS and vacuum pencil as a function of doctor blade bias.

Test 3: High- and- Low-Background Development Toner

Having shown that the new charge spectrometer injector system works at an acceptable level for detecting gross changes in the average Q/M and particle size, an attempt was made to distinguish subtle differences. Toners were obtained that had very similar vacuum pencil Q/M values but varied by a factor of 2 or 3 in terms of the amount of background development (BD) produced. One of the toners had a BD level of 3 mg/page on the photoconductor, and the other had a BD level of 8 mg/page. Both toners had vacuum pencil Q/M values in the range of –14 to –16 μC/g for the simulated "white" printing condition described previously.

Standard, unmodified IBM 4019 LaserPrinter developer cartridges were filled with these toners. The BD levels were tested, using two separate techniques. First, the 4019 LaserPrinter was "crash stopped" (i.e., the cover was opened) during the printing cycle of a solid white page. The M/A on the photoconductor was measured by a vacuum lift-off technique. Next, print samples were generated on the 4019 LaserPrinter, and optical density (OD) measurements were made of the background. These measurements showed that the BD levels of the two toners were different by a factor of 2-3.

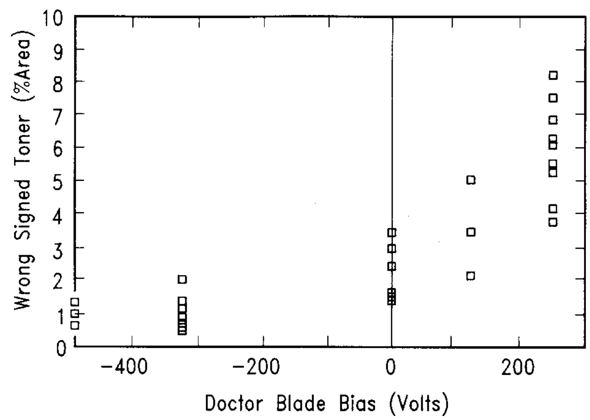

Figure 12. Percentage of WST as a function of the doctor blade bias as determined by the QCS.

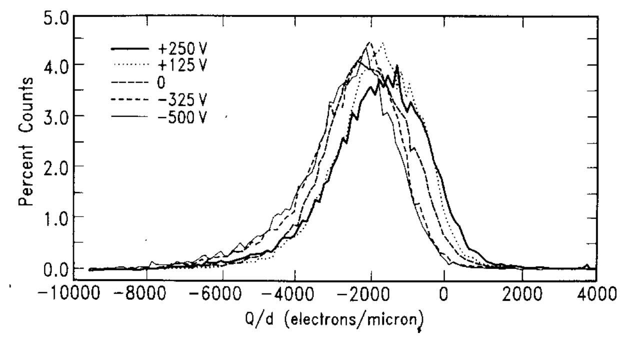

Figure 13. The Q/d distribution (summed over all toner diameters) as a function of the doctor blade bias.

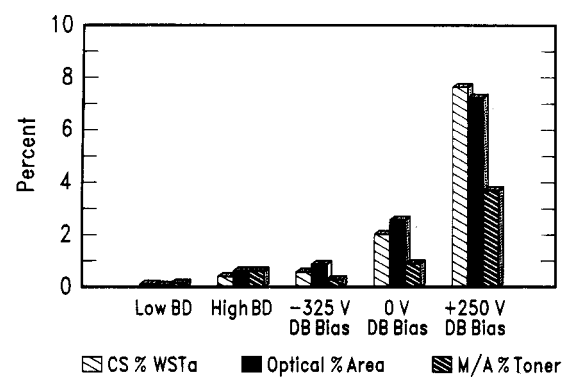

Figure 14. Comparison of (1) the percentage of WST as determined by the QCS, (2) the optically determined percentage area of coverage from a print, and (3) the percentage M/A (M/A on the photoreceptor as compared with M/A on roller times the speed ratio) for 3 doctor blade biases and 2 toners with differing background development.

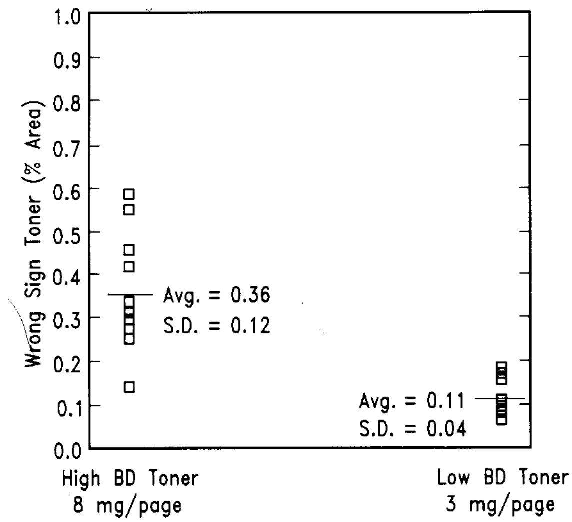

Figure 15. All the measurements of the percentage of WST for the high and low background development BD toner. The average and standard deviation are shown.

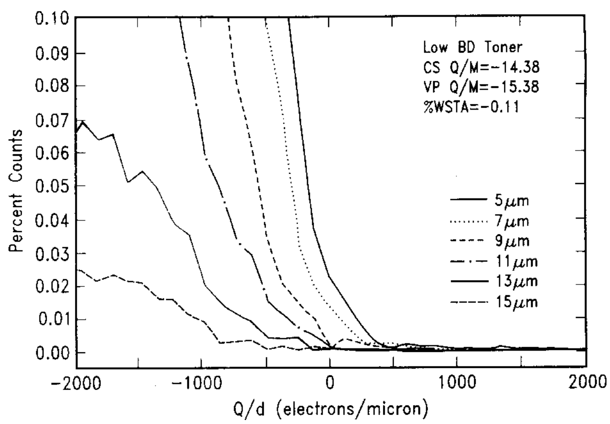

Figure 16. Detail of the Q/d distribution for the low-BD toner.

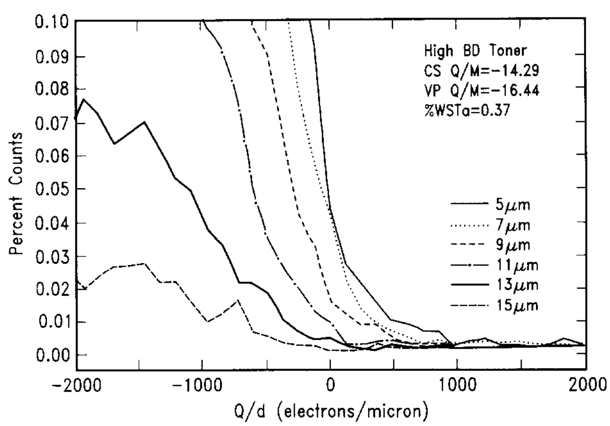

Figure 17. Detail of the Q/d distribution for the high-BD toner.

These toners were then run on the charge spectrometer. The charge spectrometer confirmed that the average Q/M values were virtually indistinguishable and did show a difference in the amount of WST. The high-BD toners exhibited a WST percentage of 0.36%, whereas the low-BD toners exhibited a WST percentage of 0.11%, the same factor of 3 difference detected by the OD and M/A methods (Fig. 14). The optical percentage area is the area covered by the toner divided by the total area, as determined by the image analysis system. The M/A percentage toner is the M/A of the toner on the photoreceptor for a white page divided by the M/A on the roller times the speed ratio of 1.6. Included in Figure 14 are similar measurements for the doctor blade bias test (Test 2), which shows quantitative agreement between the amount of WST as measured by the charge spectrometer and background development as measured by OD measurement. Semiquantitative agreement with M/A on the photoreceptor is obtained. (It is noted that this measurement involves such small amounts of toner mass that equilibration of the toner with the RH in the laboratory is required after each vacuum pencil measurement.) Figure 15 shows the range of values obtained for multiple measurements of the low-and high-BD toners and their average and standard deviation (SD). An expanded view of the *Q/d* distributions near zero *Q/d* is given in Figures 16 and 17 for the low- and high-BD toners, clearly showing that the change in the amount of WST is due to a subtle change in the tails of the distributions.

Conclusions

A new injection system has been described for the charge spectrometer. This new injection system strips toner from a roller, using a high velocity air stream that entrains the toner. The air flow is driven by a 95-psi pressure drop between the inlet and the exit of an injector tube of varying diameter.

With this new injection system, we have been able to measure Q/M and the percentage of WST quantitatively for the first time, to our knowledge. Three tests that qualified the instrument were described. The first test simulated black and white printing. The quantitative charge spectrometer was able to detect both the difference in Q/M and the shift of particle size, as determined by independent techniques. In the second test, the doctor blade bias was varied. In this case the quantitative charge spectrometer detected not only the change in Q/M, but also a change in the percentage of WST. In the third test, two toners with the same Q/M, but differing background development, were tested. The charge spectrometer detected a difference in the amount of WST, which quantitatively correlated with the amount of background development as determined by independent techniques.

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