The Effect of the Finite Size Inlet Tube in the Charge Spectrograph on the Measured Charge Distribution*

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Abstract

The measurement of the toner charge distribution of two component developers and other samples of charged toner has greatly increased our ability to understand xerographic responses, in particular background development. The toner charge distribution can be measured with the Xerox charge spectrograph or other similar devices. In our device, the inlet tube which introduces the toner to the analyzing electric field has a small, but finite, size which causes the toners entering the dispersion field to have a spatial distribution. This results in a measured toner charge distribution which is the product of the actual charge distribution and the spatial distribution of the inlet tube. The spreading due to the inlet tube does not affect the average value of the measured charge distribution; but, does affect the width of the measured charge distribution and associated quantities, such as the measured amount of wrong sign toner and the estimate of the amount of wrong sign toner in the actual toner charge distribution. The analysis provides guidelines for use of the spectrograph in a manner which will minimize the impact of the spatial distribution on the use of charge distribution data in interpreting xerographic results.

Introduction

In this report we will present results from a study to characterize the performance of the Xerox charge spectrograph. The toner charge spectrograph has been previously described.[1] To obtain the distribution of the charge of the toner particles in a sample of xerographic developer, a small quantity of the developer is placed in a magnetic "chuck." A fine air stream is used to dislodge the toner particles from the carrier beads thus forming a powder cloud of charged toner particles above the inlet tube of the instrument (Figure 1). Toner particles from this cloud are entrained in the air stream entering the inlet tube and are carried into the analyzing chamber. The air flow through the inlet tube is carefully matched to the air flow through the analyzing section of the instrumentation in order to prevent turbulence. When the toner particles in the inlet air stream enter the analyzing section, the toner particles are displaced by an electric field perpendicular to the air stream. The toner particles are eventually trapped on a filter at the bottom of the instrument. The displacement of a toner particle is dependent on the electric field strength and the ratio of the particle's charge to its radius, *q/r,* or equivalently, the charge to diameter ratio *q/d.*

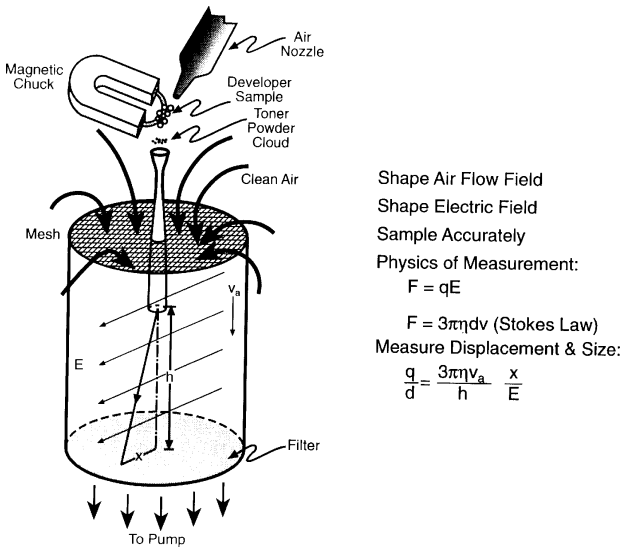

Figure 1. Diagram of the charge spectrograph measurement. An air stream from the air nozzle removes toner from the developer sample held in the magnetic chuck. The toner forms a powder cloud above the inlet to the measuring chamber. Air flow through the chamber pulls the toner into the chamber where it is dispersed by the electric field, E. The q/d of a toner particle is proportional to the displacement of the toner particle, x.

The toner particles captured by the filter form a "smear" which is representative of the *qld* distribution of the toner particles in the air stream, and by inference, in the developer. The location of the toner particles on the filter is determined using an automatic image analysis system which has been programmed to measure the displacement of the toner particle from a zero line as well as the size of the toner particle. Using the parameters of the spectrograph, the displacement is converted to the *q/d* value for the particle, $q/d = (3\pi\eta v_a /h)(x/E)$, where η is the viscosity of air, v_a, the air speed; *h*, the distance from the inlet tube to the filter; *x*, the displacement on the filter in the direction of the electric field; *E,* the strength of the electric field. The output of the image analysis is the number distribution of toner particles having a given *q/d* and *d.* If one is not particularly interested in the toner size information, the filter can be scanned by a microdensitometer to obtain the optical density as a function of displacement. This can be converted to optical density as a function of *q/d* providing an alternative measurement of the charge distribution of the toner particles. It is convenient to

represent the output of the image analysis as the number fraction of particles with a given *q/d* and *d, n(q/d,d).*

A quantity of interest in xerographic development is the charge-to-mass ratio of the toner particles. Previously this quantity has been measured by the total blow off technique.[2] In this toner charge characterization method the total quantity of toner charge in a developer sample is obtained along with the total mass of toner in the sample. The charge to mass ratio, q_{total}/m_{total}, is equivalent to the ratio of the charge of an average toner particle to the mass of an average toner particle, or *q/m.*

In analogy with the blow off measurement, the quantity, *q/m* can be obtained from the charge spectrograph measurement by calculating the average charge, *q*, and correspondingly the average mass, *m.* We have generally found that *q/m* calculated from the charge spectrograph measurement is less than the *q/m* measured from the total blow off method (Figure 2a). We believe this is due to two factors, namely, the image analysis oversizes the non-spherical toner particles, measuring the resting cross sectional area; and, the low pressure air stream does not effectively recover the higher charged, smaller size toner particles in the developer. If one compares the average charge per particle calculated from the charge spectrograph measurement with that obtained from the total blow off measurement and a toner size measurement $(q_{BO}) = (q/m)(\pi\rho_t d^3/6)$, one finds good agreement between the two developer charge characterization techniques[3] (Figure 2b).

Results and Discussion

The effect of the finite size aperature is now examined. In the ideal spectrograph, all the toner particles enter the analyzing section along the center line of the instrument. In the actual instrument there is a finite size to the inlet tube allowing some of the toner to enter off axis. For our instrument, the inlet tube is approximately 2.2 mm in diameter at the outlet end. In addition, there is a constriction in the tube to create a *venturi* effect to minimize the possibility of toners contacting the walls and possibly modifying their charge and/or sticking to the sides of the inlet tube. The diameter of this constricted region is approximately 0.4 mm. While most of the toner particles do travel down the center of the inlet tube, we find the toner particles are deposited in a circle of approximately 2.2 mm diameter in the absence of an electric field. Thus the position of the toner particles on the substrate depends on their position in the inlet tube plus the displacement due to the electric field or

$$x - kE\frac{q}{d} + u, \text{ where } k = \frac{h}{3\pi\eta v_\alpha}$$

For our spectrograph, k = 1.06×10^9 cm^3/(volt coul) with *E* in volt/ cm. If we let the distribution of toner particles with *q/d* in the developer sample be *G(q/d)* such that

$$\int_{-\infty}^{\infty} G(q/d)\,d(q/d) = 1;$$

and, let the spatial distribution of the toner particles at the exit of the inlet tube be *g(u)* such that

$$\int_{-\infty}^{\infty} g(u)\,du = \int_{-R}^{R} g(u)du = 1,$$

then, the fraction of toner particles on the filter between *x* and *x* + *dx* is

$$dN = F(x)dx \text{ such that } \int_{-\infty}^{\infty} F(x)\,dx - 1.$$

Hence,

$$1 = \int_{-\infty}^{\infty} F(x)\,dx = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} G\left(\frac{q}{d}\right)g(u)d\frac{q}{d}du =$$

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{1}{kE}G\left(\frac{x-u}{kE}\right)g(u)dudx$$

and $$F(x)\frac{1}{kE}\int_{-\infty}^{\infty} G\left(\frac{x-u}{kE}\right)g(u)du.$$

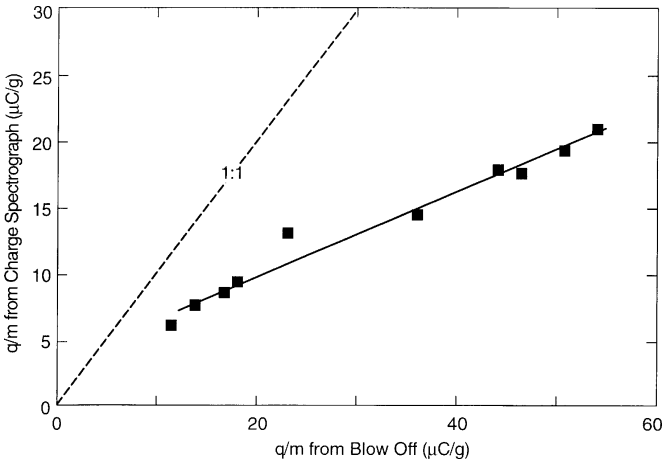

Figure 2a. The charge-to-mass ratio calculated from the charge spectrograph measurement versus the charge-to-mass ratio obtained from the total blow-off measurement. In the charge spectrograph measurement the image analysis overestimates the toner diameter which makes the calculated mass too large. A smaller effect in the charge spectrograph measurement is that not all the toner is removed by the air stream which reduces the calculated charge. The result is the q/m calculated from the charge spectrograph measurement is low compared to the total blow-off q/m.

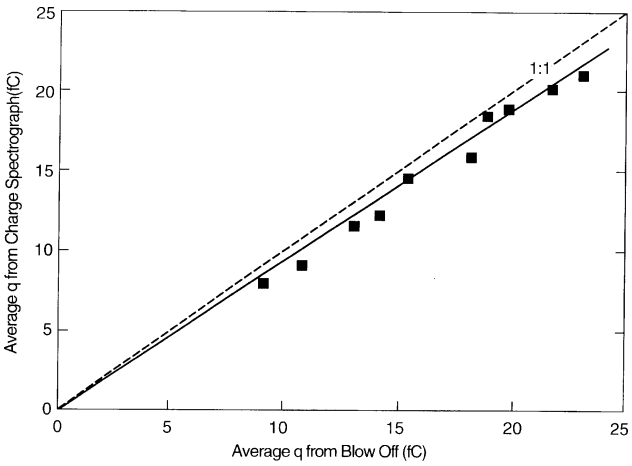

Figure 2b. The average charge per particle, q, calculated from the charge spectrograph measurement versus the average charge per particle calculated from the total blow-off measurement. The calculation of the total charge minimizes, but does not eliminate, the effect of the errors introduced by the charge spectrograph measurement. There is much better agreement between the two measurement techniques.

For a toner sample having $G(q/d)$ and a charge spectrograph with a spatial distribution $g(u)$ at the exit of the inlet tube, the expected position of the toner particles on the filter is

$$\langle x\rangle = \int_{-\infty}^{\infty} xF(x)dx$$

$$= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left(kE\frac{q}{d}+u\right)G\frac{q}{d}g(u)d\frac{q}{d}du$$

$$= \int_{-\infty}^{\infty} kE\frac{q}{d}G\left(\frac{q}{d}\right)d\frac{q}{d}\int_{-\infty}^{\infty}g(u)du + \int_{-\infty}^{\infty}G\left(\frac{q}{d}\right)d\frac{q}{d}\int_{-\infty}^{\infty}ug(u)du$$

$$\langle x\rangle = kE\left\langle\frac{q}{d}\right\rangle.$$

This result shows that the expected position of the toner particles on the filter is not changed by the finite width of the inlet tube. Changing the applied analyzing electric field will change the position of the toner particles on the filter. The mean q/d obtained from the displacement on the filter will be independent of the strength of the electric field; but the width of the distribution will be affected as we will show shortly.

We have measured the charge distribution of a developer sample at several electric field strengths. The details of the developer materials and sample preparation are not important for this work. The developer was chosen to have a narrow charge distribution and a q/d which enabled measuring at different field strengths keeping the "smear" within the allowable position of the spectrograph. As expected, the mean (and mode) of the distribution were independent of electric field strength as shown in Table I and Figure 3.

Table I. Data for toner charge distribution measurements at different analyzing electric field strengths

E(volts/cm)	<q/d>	HWHM*	% Wrong Sign Toner
25	0.95	0.44	1.11
50	1.02	0.27	0.89
75	1.00	0.24	0.76
100	1.03	0.21	0.89
175	1.05	0.20	0.74

* **H**alf **W**idth of the distribution at **H**alf of the peak **M**aximum.

The curves in Figure 3 and the data of Table I show that while the mean value is independent of the electric field strength, the widths of the measured charge distributions are not.

The width of the measured distribution curve can be obtained by calculating the variance of the displacement of the toner on the filter.

$$\mathrm{var}(x) = \int_{-\infty}^{\infty}\left(x-\langle x\rangle\right)^2F(x)dx$$

$$= \int_{-\infty}^{\infty} k^2E^2\left(\frac{q}{d}-\left\langle\frac{q}{d}\right\rangle\right)^2G\left(\frac{q}{d}\right)d\frac{q}{d}\int_{-\infty}^{\infty}g(u)du$$

$$+\int_{-\infty}^{\infty}G\left(\frac{q}{d}\right)d\frac{q}{d}\int_{-\infty}^{\infty}u^2g(u)du$$

$$+2\int_{-\infty}^{\infty}kE\left(\frac{q}{d}-\left\langle\frac{q}{d}\right\rangle\right)G\left(\frac{q}{d}\right)d\frac{q}{d}\int_{-\infty}^{\infty}ug(u)du$$

$$= k^2E^2\,\mathrm{var}\left(\frac{q}{d}\right)+\mathrm{var}(u)$$

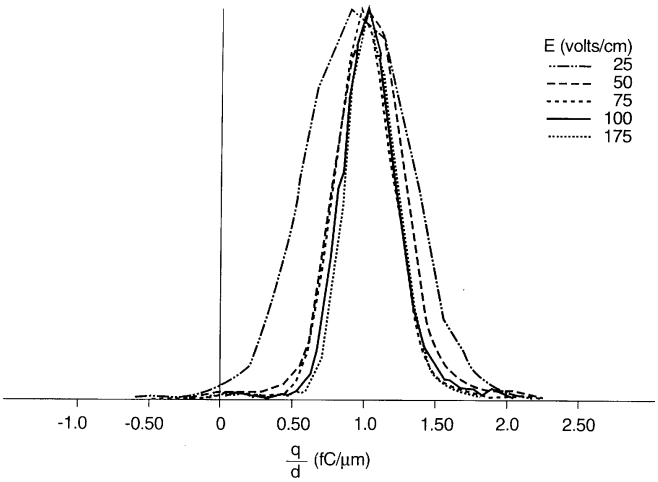

Figure 3. Charge distribution curves obtained for different values of the dispersing electric field, E, in the charge spectrograph. The mean of the charge distribution is independent of the strength of the electric field; but, the width of the charge distribution is dependent of the strength of the electric field; but, the width of the charge distribution is dependent on the field strength.

If the "smear" distribution and the charge distribution are approximately Gaussian then the variance is σ^2 and related to the half width at half maximum, HWHM (= 1.18 σ), which can be obtained from the curves in Figure 3. Thus,

$$\sigma^2_{meas}(x) = k^2E^2\sigma^2_{q/d} + \mathrm{var}(u)$$

$$\sigma^2_{meas_{q/d}} = \sigma^2_{actual_{q/d}} + \frac{1}{k^2E^2}\mathrm{var}(u)$$

Using the HWHM for the distribution and noting that the HWHM of the spatial distribution is the radius of the inlet tube, one obtains

$$HWHM^2_{meas\,q/d} = HWHM^2_{actual\,q/d} + \frac{1}{k^2E^2}R^2$$

Using the data in Table I (obtained from the curves in Figure 3) one can plot the measured HWHM^2 versus E^{-2}, which from the above equation is a linear function in E^{-2}. The intercept in this plot is the true width of the charge distribution; the slope of the line should be related to the size of the inlet tube. Figure 4 shows a plot of HWHM^2 actual versus E^{-2}. As expected the data are linear. The linear regression results are listed in Table II.

Table II. Linear regression results for HWHM^2 vs E^{-2}

Index of determination	0.998
Slope	0.0100 ± 0.0002
Intercept (HWHM^2 actual)	0.037
Standard Error of Estimate	0.0031

From the slope, one can calculate R=1.06 mm, which is the approximate radius of the glass formed inlet tube.

Another parameter, which can be obtained from a measurement of the charge distribution of toner in a developer, is the amount of wrong sign toner. Background development is related to the amount of wrong sign toner in the developer. The amount of wrong sign toner in the

developer is obtained from the toner charge distribution, *G(q/d)*

$$WST = \int_0^{\infty} G\left(\frac{q}{d}\right) d\frac{q}{d} \text{ or } WST = \int_{-\infty}^{0} G\left(\frac{q}{d}\right) d\frac{q}{d}$$

depending on whether the proper or desired polarity of the toner is negative or positive, respectively. The measured amount of wrong sign toner on the filter is dependent on the convolution of the width of the inlet tube and the toner charge distribution. Assuming a developer sample with negatively charged toner as the desired polarity, the measured amount of wrong sign toner on the filter is:

$$WST_{meas} = \int_0^{\infty} F(x)dx$$
$$= \int_0^{\infty} dx \int_{-\infty}^{\infty} \frac{1}{kE} G\left(\frac{x-u}{kE}\right) g(u)du$$

As we have previously shown, the width of the measured toner charge distribution is larger than the actual toner charge distribution due to the width of the inlet tube. Thus, the measured amount of wrong sign toner will usually be somewhat larger than the actual wrong sign toner present in the developer sample.

The amounts of wrong sign toner measured for the model developer at different electric field strengths are shown in Table I. As mentioned earlier this developer was chosen to have a narrow toner charge distribution and a *q/d* which would permit the charge distribution to be obtained at different electric fields without instrument limitations. As a consequence there is little wrong sign toner present; however, there is a trend in the data in Table I for the wrong sign toner to decrease as the analyzing electric field increases and the measured charge distributions to become narrower or sharper.

In summary, we have shown that the charge spectrograph yields the same result as the total blow off measurement for the charge of an average particle in a developer sample. In addition the charge spectrograph provides information about the distribution of toner charge in a developer sample. However, care must be used when interpreting the measured charge distributions since the finite size of the inlet tube contributes to a broadening of the measured charge distribution. The broadening of the measured charge distribution due to the finite size of the inlet tube can be minimized by using the smallest feasible inlet tube opening and measuring the charge distribution at the highest possible electric field permitted by the design of the instrument.

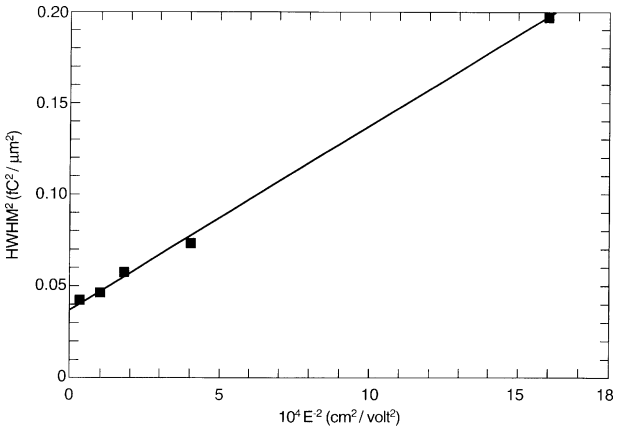

Figure 4. The square of the half-width-at-half-maximum, HWHM, of the charge distribution versus the reciprocal of the square of the strength of the dispersing electric field in the charge spectrograph.

References

1. Lewis, R., Connors, E., and Koehler, R., "A Spectrograph for Charge Distributions in Xerographic Toner," *4th Inter. Conf. on Electrophotography*, Washington, DC (1981).
2. Schein, L. B. and Cranch, J., *J. Appl. Phys.* **46**, 5140 (1975).
3. Gutman, E. J., "Comparison of the Blow Off Tribo and the Charge Spectrograph Measurement of Toner Charge," *SPSE 35th Annual Conference*, Rochester, NY (1982).

* This paper was originally printed as a poster paper in the original proceedings, and the figures were handed out at the Conference. The author has provided the figures for this publication.