Control of Liquid Electrophoretic Toner Supplies

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Abstract

In high volume liquid toner printers, a liquid toner supply should be continuously replenished. We provide a simple process physics diagram relating toner properties to developed mass and printed density. We describe three toner control and replenishment methods that have been used in previous products. We show print density and toner property data from a long print test using an experimental set of inks. We use regression analysis to analyze the adequacy of the three known replenishment methods. The analysis shows ink to ink differences and also identifies cases in which the known replenishment methods are insufficient to maintain constant output print quality.

Liquid Toner Development

In this paper we discuss print density variations caused by variations in the properties of liquid electrophoretic toners. These toners consist of charged particles dispersed in a liquid carrier. In electrophotographic, ionographic, and electrographic printers, the liquid toner is brought into contact with a surface bearing an electrostatic latent image. Charged toner particles are attracted to and develop the electrostatic latent image [**1, 2**]. Like xerography using dry toner, the developed mass per unit area (DMA) depends on the electric field near the electrostatic latent image and on the toner particles' response to that field. Like dry toner xerography, the final print density depends on the DMA, the toner particle's pigment loading and the paper's surface properties. Unlike dry toner xerography, the response of liquid toners depends on the chemical charging of the toner particle [**3**] and on the particle's electrophoretic mobility in its carrier liquid [**4**]. The development process includes charge transport by both toner particles and counter-ions [**5**] and is also influenced by fluid flow in the development and metering zones [**6, 7**]. Figure 1 (at the end of the paper) shows a process physics diagram for the factors influencing the reflective optical density (ROD) in solid areas of the print. The direction of cause and effect is from right to left. That is, the value of each parameter is influenced by those parameters connected to it from the right and influences those parameters to its left to which it is connected. For example, DMA is effected by surface voltage, development geometry and ink; and DMA effects ROD.

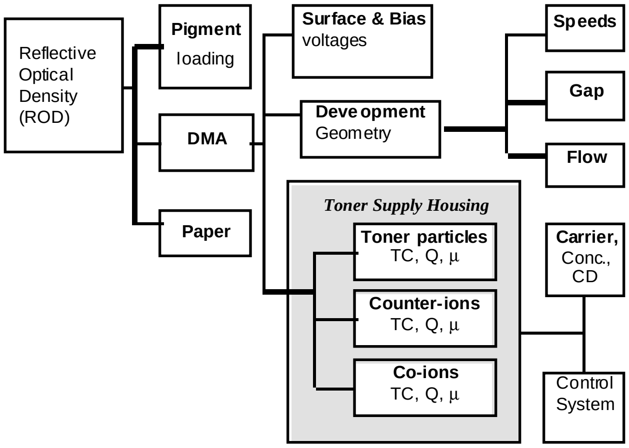

Figure 1. Process physics diagram for factors effecting the print density.

Liquid Toner Replenishment Strategies

As shown in Figure 1 and in reference 5, liquid toner development depends on Ni, μi, and Qi, where i = 1 for toner particles, i=2 for counter-ions, and i=3 for ions of the same sign as the toner particles. Ni is the number of each species per unit volume, μi is the mobility of each species, and Qi is the charge of each species. Maintaining a constant ROD requires keeping these quantities constant. These quantities are not all independent [3], but depend on the chemical equilibria between toner particles and charge director molecules. During a long print run the toner is consumed and has to be replaced. It is possible to wait until the toner level drops below a critical level, then to fill the toner supply housing with toner of the same composition as the original toner, an approach which we call *Strategy 1.*

One difficulty with Strategy 1 is that carrier and toner particles may be consumed at different rates. To minimize the cost of removing and reclaiming the carrier liquid from the paper, liquid electrophoretic print engines use reverse rolls [**6**] to minimize carryout. Excess carrier removed by the reverse roll returns to the liquid toner supply housing. This may lead to a continuous decrease in TC, the toner solids concentration, between fill ups. At some point, there is not enough toner to completely develop the latent electrostatic image and ROD begins to drop. In a modification of Strategy 1, ink is added frequently, for instance, when the total ink supply volume has dropped by a small fraction of its initial volume. Still, if TC in the developed image is greater than TC in the added ink, TC in the ink supply housing will drop.

This leads to *Strategy 2:* the ink supply is replenished by independent additions of carrier fluid and/or a toner that is more concentrated than the toner in the supply housing. The more concentrated toner is usually called "concentrate," or "toner concentrate." Replenishment Strategy 2 requires two sensors, one for toner supply volume and one for TC. The toner volume sensor can be a float valve in the supply housing. The TC sensor measures the attenuation of light by toner flowing through a narrow gap between transparent windows. The two replenishment rules of Strategy 2 are

➢*When toner volume drops, add carrier.*

➢*When TC drops, add concentrate.*

If the concentrate TC is less than the average developed image TC, Strategy 2 can lead to continuous growth of the ink supply volume. The volume sensor should also have a high level, so excess toner can be removed.

A possible problem with strategy 2 is that toner particles and counter-ions may be consumed at different rates. This may happen because counter-ions are preferentially attracted to background areas of the electrostatic latent image and repelled from image areas. For print jobs that are mostly text the image area may be only 4% of the total area and counter-ion depletion may be very much greater than toner particle depletion. Changes in the ratio of counter-ions to particles will change the chemical equilibria and cause changes in the toner's charge and the number of counter-ions.

Note that replenishment strategy 2 may fail quickly for text jobs but work better for printing halftoned photographic images, where area coverage is often 30-50% of the total area. This leads to a modification (designated *Strategy 2a*) in which the charge director concentration in the concentrate is different from the charge director concentration in the initial ink supply. In this strategy, the concentrate's ratio of charge director to toner particles is chosen to equal the average ratio in developed images. If deviations in the ratio of charge director to toner particles in the developed image are not too great and if a deviant image is not printed for too long, the variations in DMA may not be significant. This strategy has been used in the Savin 870 copier and other commercial printers and is reported to be quite satisfactory [8].

Strategy 3 uses another approach to maintaining a constant ratio between charge director and toner particles. Carrier, concentrate and/or a concentrated charge director solution can be added independently to the toner supply housing. The concentrated charge director solution is usually just called "charge director." Strategy 3 requires a sensor for toner conductivity. Because the conductivity of liquid toner is very low, typically 10-100 picoSiemens/cm, special sensors have to be used [9]. Along with the replenishment rules used by Strategy 2, Strategy 3 adds,

➢ *If conductivity is low, add charge director.*

To avoid fluctuations toward high conductivity, Strategy 3 usually replenishes with toner concentrate which is either uncharged or is charged at a level below that in the toner supply housing.

Note that conductivity, σ, does not appear in Figure 1. σ is a sum of properties which do appear in Figure 1:

$$\sigma = (N\,Q\,\mu)\ \text{toner} + (N\,Q\,\mu)\ \text{counter-ion} + (N\,Q\,\mu)\ \text{co-ion}$$

Keeping all conductivity components constant will keep development constant but conductivity might stay constant while its components vary. If Strategy 3 successfully controls *both* TC and σ, then development should remain constant.

Strategy 3 was developed at Savin in the mid 1980s [10] and is practiced under license from Savin by the Electropress®. The Electropress® is a very high volume press printing a 20 inch wide web of paper at 100-300 feet per minute [11]. Carrier is supplied to the toner supply housing from 55 gallon barrels. Concentrate is supplied from 5 gallon cans. Charge director is supplied from one pint bottles. In an 8-10 hour shift it is generally necessary to replace the carrier barrel and the concentrate can twice. Under these conditions the toner supply can last for months. The toner supply is usually replaced with fresh toner only if it is contaminated by external agents.

Whichever replenishment strategy is chosen, the design of the control system also includes selection of tolerances for the sensed parameters. That is,

- In Strategy 1, 2 or 3, how far may the toner supply volume drop before toner or carrier is added?
- In Strategy 2, 2a or 3, how far may TC drop before concentrate is added?
- In Strategy 3, how far may conductivity drop before charge director is added?

If tight tolerances are chosen, then sensors should be accurate (expensive) and the addition hardware should operate frequently and precisely (expensively). If loose tolerances are chosen, larger variations in print density are expected.

Toner Variations and Print Variations

To determine the best replenishment strategy for a particular ink, a particular development system, and a particular mix of customer jobs, we need to quantify the relations between toner variations and print density variations. Once these relations are known, we can determine not only the replenishment strategy but also sensor accuracies and component tolerances.

Because TC and σ are incomplete measures of the toner, we also measured toner particle mobility, μtoner [4], and total toner charge density, ρ [12], where

$$\rho = (N\,Q)\ \text{toner} + (N\,Q)\text{counter-ion} + (N\,Q)\text{co-ion}$$

Of course, ρ, μtoner and TC will all be highly correlated with σ. It is variations of one measure, independent of the others, that may show extra information about the toner.

We have measured variations in these toner properties for a set of four experimental toners, Cyan, Magenta, Yellow and Black, which we will call toner Set A. We printed Toner Set A in an experimental electrographic printer, using roll-fed dielectric paper from Rexham. Each roll of paper is 167 m^2, equivalent to about 2800 8.5x11' prints. After the toner set was installed "color bars" prints [13] were run to insure that the machine was functioning properly and that xerographic parameters were set to give proper density and color. A pictorial test print was then run in a production simulation mode with groups of 10 prints made continuously for 7 to 8 hours per day until the run was finished. At the beginning and end of each roll of paper, a color bars target was produced and the densities of the primary colors were determined using an X-Rite Model 938 spectrodensitometer. Throughout the course of the experiments, toner replenishment was conducted using Strategy 2, that is with Isopar G added to maintain volume and a charged toner concentrate added to maintain developer optical density. 20 rolls of paper were printed over a period of several weeks. Toner samples were withdrawn at each roll change and particle size, toner concentration, toner conductivity, toner mobility, and total bulk charge were determined. The mass of the supply sump and the various additive sumps were recorded to allow mass balance to be established.

Figure 2 shows the density of the primary color bars as a function of the number of rolls of paper printed. All four primaries lose density as the run progresses. The slope of this degradation varies from –0.0033 for Y to –0.0089 for M. Simple linear regressions of ROD vs. Roll number give R^2 of 55% to 89%. Since the main target, a floral pattern, does not use exactly the same amount of each of the four primaries it might be expected that the total mass of toner used would provide a better predictor. However, regression against the total number of grams of toner consumed does not improve the R^2. An alternative to this “use” explanation of toner degradation correlates performance with physical properties of the toner. Such an approach will also allow us to examine the validity of the models put forward above.

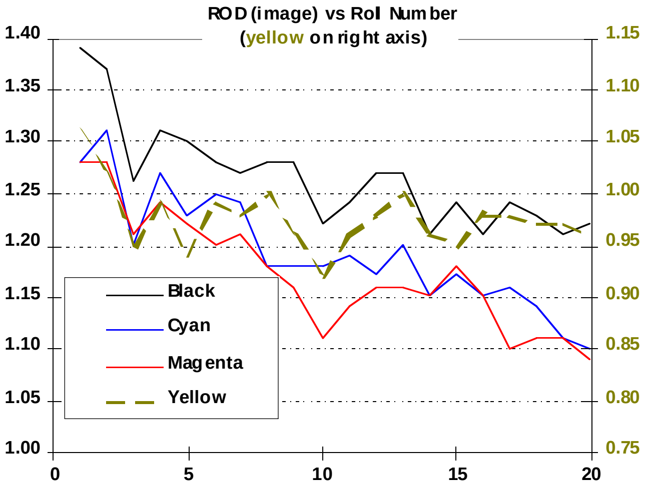

Table I shows the slopes from a multivariate linear (multilinear) regression of each ROD against its toner’s conductivity, toner mobility, toner charge and bulk toner charge density. These multilinear regressions only explain about 50-65% of the observed variance in ROD. No single parameter’s slope has the same sign for all of the four colors nor do they have the same rank order of importance. While these regressions do not fit all the data, the residuals are not systematic. Table II shows that Black ROD significantly correlates with conductivity and mobility.

Table I. Regression slopes for RODs from Figure 1

	Cyan	Magenta	Yellow	Black
Conductivity	-.0024	-.0002	-.0008	.0023
Mobility	-.0001	-.0014	-.0014	.0017
Concentration	.0391	-.0641	.0088	-.0720
Bulk Charge Density	-.0039	-.0524	-.0689	.0074

Table II. Statistical significance of variables effecting Black ROD

	Coefficient	Std. Error	t-Statistic	Prob.
Conduct.	0.0023	0.0016	1.3951	0.1833
Mobility	-0.0720	0.0261	-2.7621	0.0145
Bulk Charge	0.0074	0.0388	0.1903	0.8517
TC	1.2941	0.1159	11.166	0.0000

Table III. P test values for ROD regression coefficients

	Cyan	Magenta	Yellow	Black
Conduct.	.0203	.6989	.0984	.1833
Mobility	.9644	.4283	.1234	.2235
Concentration	.4586	.0870	.6170	.0145
Bulk Charge Density	.8677	.1544	.1248	.8517

Further insight into the significance of the variables is provided by examination of the P test values associated with the hypothesis test that each of the coefficients is equal to zero (Table III). Only four of the coefficients estimated can be held to be different from zero at a 90% confidence level. Conductivity and toner concentration are the variables most likely to be effective in controlling print ROD.

This analysis suggests that ~60% of the observed ROD variation can be attributed to changes in the physical parameters we have measured and analyzed. The most significant variables are Bulk Charge Density and Conductivity. Control of these, by conductivity control, is the goal of replenishment Strategy 3. Data on a system controlled under Strategy 2 suggests that a significant reduction in print quality variability may be obtained by adding conductivity control to volume and concentration control. The remaining ROD variations suggest that even the most complete replenishment strategy we know may be insufficient to keep output print quality completely constant.

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13. A color bars target is a target which has full width stripes, across the process direction in each of the four primaries, red green and blue composed as secondary overlays of 100% area of coverage bars, and a three color black similarly composed of yellow over magenta over cyan.

Biographies

Ed Caruthers has a Ph.D. in theoretical Solid State Physics, from the University of Texas, at Austin, 1973. He has worked in the area of liquid electrophoretic printing at DuPont (1985-1987), DX Imaging (1987-1991), AM Graphics (1991-1992), and Xerox Corp. (1993-present). Previous papers for IS&T's 8th and 10th NIP meetings concerned liquid ink formulation, toner charging mechanisms, electrophoretic development, metering, transfer, and image quality.

George Gibson is a Technical Manager in the Joseph C. Wilson Center for Research and Technology. Prior to joining Xerox in 1993 he was the Manager of Toner Development Manufacturing at AM International. Prior to that he was employed by Savin Corporation as Manager of Toner Development. He has presented a number of papers in the area of liquid toner, non-aqueous and aqueous colloids and holds 24 U.S. patents. He received his B.A. and M.S. in Chemistry from Binghamton University (formerly the State University of New York Center at Binghamton).