A Novel High Field Electrophoretic Cell for Characterisation of Concentrated Liquid Toners

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Abstract

It is well known that the electrical properties of liquid toners used in electrophotography significantly influence the quality of printed images. Electrophoresis, being the main driving force in liquid immersion development processes (LID), has been extensively studied by researchers elsewhere. The most important electrical characteristics of conventional liquid toners used in LID are conductivity, electrophoretic mobility and charge to mass ratio. Although the physical origins of these parameters in liquid toners are well understood, methods and commercial equipment available for measuring these properties are limited. The majority of methods that have been developed, suit toners of low viscosity and low solid content. In the past decade, there has been increasing attention to new liquid toners with higher solid content and increased viscosity. These toners are opaque and therefore, the traditional optical methods for measuring particle transient time in low concentration dispersions are unsuitable for these highly concentrated liquid toners. This paper will introduce a new method of measuring the electrical properties of liquid toners and will discuss its potential application in liquid electrophotography.

Introduction

The main physical mechanism behind any electrophotographic printing process utilizing liquid developers is based on electrophoresis of charged toner particles in a carrier fluid. Consequently, critical functional performance metrics, such as development and transfer efficiencies, image resolution and uniformity etc., depend considerably on electrical properties of the liquid developers used. The most important electrical characteristics of conventional liquid toners are known to be conductivity (σ), electrophoretic mobility (μ) and charge to mass ratio (Q/M). Although the physical origins of these characteristics are relatively well understood, methods for measuring these properties are limited. Two of the major limitations are addressed in the following discussion.

Electrophoretic Mobility

Mobility of toner particles in non-aqueous dispersions is often determined from measurements of particle drift velocity under a constant electric field. In order to register velocity of toner particles, light transmission methods are traditionally used. These methods are represented by modern commercial devices produced by Coulter Electronics (Delsa), Malvern Instruments (Zetasizer) and by a relatively new optical technique called Phase-Analysis Light Scattering (PALS).[1] All three methods are based on Laser Doppler Velocimetry (LDV) and require the toner sample to be transparent to light. Conventional liquid toners therefore are by necessity diluted to carry out the measurement of toner mobility.

There exist other methods of measuring electrophoretic mobility of toner particles. These are mostly based on determining the time required by toner particles to travel between two electrodes upon application of a DC voltage.[2-5] In all these methods, the total current is measured over a set period of time of voltage application. The information on total current, however, does not allow one to distinguish the current flow of toner particles from that of other charge carriers often referred to as excess ions, counter-ions or micelles that are present in the non-aqueous dispersion. The problem arises from the fact that conventional non-aqueous liquid toners comprise of a substantial amount of charge control agent that upon dissociation introduce additional charge carriers not associated with marking particles.

In order to distinguish the current flow associated with toner particles from that associated with other charge species, a number of techniques have proposed using optical methods to sense the movement of marking particles while simultaneously measuring total current transient. However, these methods also rely on transparency of the toner to the laser light beam and therefore, only diluted toner samples could be analysed.

The authors of Ref. [6] reported about simultaneous measurements of current and mass transients associated with deposition of toner particles undergoing electrophoresis. Although this technique was originally presented as a tool for determining Q/M values for liquid toners, it could potentially allow the derivation of toner particle mobility. The difficulty however, is in that the structure of the toner holding chamber is not suitable for liquid toners of high concentration and viscosity. The considerable inertia of the balance used for recording the changes in the weight of the toner deposit during the plate-out experiments would limit the sampling rate to milliseconds, which would make it difficult to isolate the motion of toner particles from other charge species.

In the mid 80s, Indigo Ltd. introduced their Mobility Analyser, which utilized both electrical current and light transmission transient techniques for determining toner particle motilities. However, as in the Malvern Zetasizer, the analysed toner samples need to be transparent to light.

Recently, a new method for measuring electrophoretic mobility of undiluted liquid toners, called Electro-kinetic Sonic Amplitude (ESA) was introduced to the market.[7] This method became quite popular for the express control of toner samples. However, it uses very high frequency AC signal and relies to a great extent on a number of theoretical principles in order to convert the measured ESA signal into electrophoretic mobility values. It therefore becomes quite difficult to directly apply the results of high frequency measurements to the actual DC electrophoresis of toner particles occurring during image development in a typical electrophotographic process.

Conductivity of Electrophotographic Toners

Conductivity of liquid toners is traditionally measured using a Scientifica 627 Conductivity Meter. In this device, toner particles are subjected to a low voltage and a low frequency sine wave creating an AC current proportional to the toner conductivity. Some other methods for measuring electrical conductivity of liquid toners using DC signals have been reported elsewhere,[8] however in practice, there appears to be no real alternative to the Scientifica apparatus.

Recently, a number of new printing technologies in the area of digital printing have been disclosed.[9-14] These technologies use toners of high particle concentrations ranging from 5 to 40%. These toners, however, are characterised by particle mobility in the range 10^{-10}-10^{-12} $m^2V^{-1}s^{-1}$, which is substantially lower than that of conventional liquid toners and approaching the detectable limit of most mobility measuring methods. These low particle mobility values are mainly caused by considerable viscosity build-up associated with the increased particle to particle interactions in highly concentrated toners (that is why these toner systems are often called high viscosity toners or HVT). To achieve good image density with these new toners, comparable with that for conventional liquid toners, electric fields on the charged toner particles are required to reach 10^6-10^8V/m to compensate for the low electrophoretic mobility.

The other important factor to consider is that the mobility of this new type of high concentration toners is known to substantially change with the level of solid content and therefore, when diluted these toners exhibit a different mobility to the undiluted sample.

Liquid toners having high particle concentration are usually considerably more viscous than conventional liquid developers used in LID. The attempts at measuring conductivity of an undiluted HVT sample using a toner sample probe of a Scientifica Conductivity Meter usually result in ambiguity of the results due to highly unstable readings.

These circumstances initiated the design and construction of a new method for measuring the electrical properties of electrophotographic toners, accounting for the following major factors:

- The method should allow measurements of undiluted toner samples with solid content ranging from a value as low as for conventional liquid toners to as high as that of lithographic printing inks.
- The toner holding chamber should be designed to allow the application of a large range of electric field across a toner sample. This should produce sufficiently high current values for both low concentration and high concentration toners.

Experimental Approach

Device Schematics and Principle of Operation

A schematic diagram and picture of the High Field Toner Cell (HFTC) device being described in this paper are depicted in Figures 1 and 2.

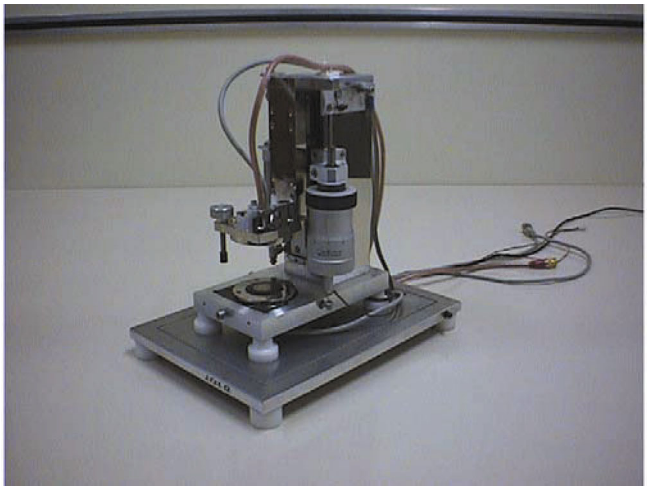

Figure 1. Photograph of an HFTC apparatus

The HFTC includes two parallel electrodes spaced apart at a selected gap in the range between 5µm and 10mm. The gap setting is supported by a precision control mechanism. The electrodes are made from glass plates coated with ITO on the side contacting the toner sample during the measurements. The plates are therefore transparent to light, while still acting as electrodes. The HFTC also includes a means of providing an electric field between the first electrode and the second electrode (bipolar high voltage power supply), means to measure a displacement current (logarithmic low noise current amplifier), and two optical density measuring devices adapted to measure the change in optical density in the cell adjacent each electrode (LED-detector couple).

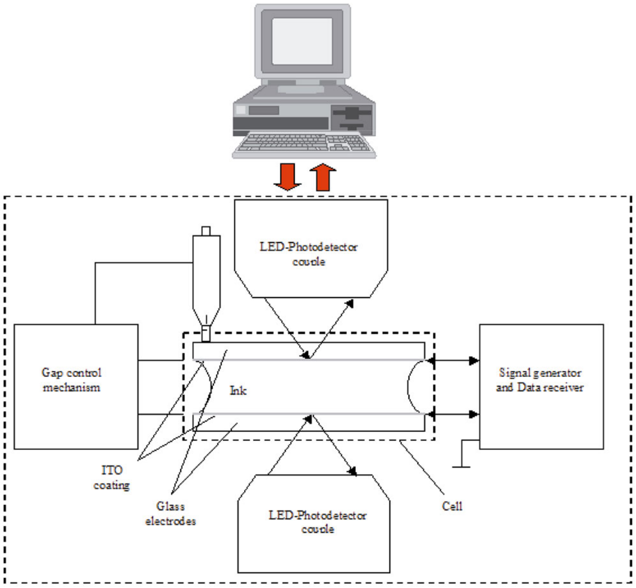

Figure 2. Schematic diagram of HFTC

A measurement test run includes the following major steps. A voltage signal of any required profile is firstly formed on a personal computer using a special plotting routine and then sent to a high speed controller where all input and output data are stored in a memory bank. A test run is then triggered, while voltage is being applied to the cell, current and optical responses are being synchronously received by the input buffer for further processing. This arrangement of data communication enables the achievement of minimal delay times for data exchange and ensures accurate synchronisation of the voltage and current measurements independent of the time required for data processing. Such a setup enables sampling rates as low as 5µs, bringing the total number of data point per run to several millions.

Technical Characteristics of HFTC

The current version of the HFTC has been evaluated for reproducibility, robustness and accuracy with a variety of toner formulations. The results of this system assessment suggest the following range of technical characteristics. These will be refined with further development of the HFTC technique:

Toner Sample:

Solid content	0-60%
Viscosity	0.6-10000cp
Mobility	10^{-5}-10^{-12}m^2/V/s
Conductivity	0.01 - 1000pS/cm
Q/M	1-1000µC/g

HFTC Device:

Minimal sampling rate	5µs
Signal amplitude	-400 - +400V
Signal frequency	0 -100kHz
Electric field	10^4-10^8V/m
Measurement time:	~10min per toner sample

Capabilities of HFTC

The main fields of application for the HFTC method could be summarized by the following two categories: a) analytical tool for quantitative measurements of electrical properties of liquid toners, and b) quality control tool, i.e. test device that makes it possible to replicate real conditions established during electrophotographic printing processes and to assess toner behavior off-line. The HFTC apparatus is also believed to be suitable for:

- Investigations of electrophoresis under high electric fields (~10^7V/m);
- Measurements of toner mobility, conductivity, Q/M and permittivity;
- Measurements of both toner adhesion and electrical fatigue; Assessment of toner dispersion stability versus electric field (electrophoretic compaction);
- Assessment of optical reflection density during toner particle deposition;
- Investigations of charge exchange at interfaces;

Measuring Techniques

To date we have established a number of different procedures to convert current plate-out curves into toner conductivity, mobility and Q/M values. We have also carried out a series of tests using two optical channels and assessed the validity of algorithms and procedures that allow us to unequivocally determine electrophoretic mobility of toner particles from optical transient curves.

It has to be noted, however, that a single value received from the measurements for every toner characteristic, such as σ, µ and Q/M represents an average figure for an ensemble of charge species. The other comment that is worth mentioning is the high level of so-called space charge developed during electrophoresis of highly concentrated toners. Electric fields typical for the HFTC are very high (>10^6V/m), and in most techniques known to the authors, the effect of space charge would be negligible. However, this is not the case for highly concentrated toners. Simple estimates using a typical example of a toner with 20% solid content having σ = 10pS/cm, µ = 10^{-10}m^{2}V^{-1}s^{-1}, cell gap L = 50µm, toner permittivity ε = 2 and substituting these in the following well-known expression, gives

$$E_\sigma \approx \frac{\sigma L}{\mu \varepsilon_0 \varepsilon} \approx 3 \times 10^7\ V/m \tag{1}$$

As one can see from expression (1), the conditions for space charge are far from being negligible.

AC Signal

As previously explained, a low voltage and low frequency sinusoidal signal is used for measuring conductivity of conventional liquid toners. We have designed a new method where the sinusoidal waveform is replaced with a triangular signal (Figure 3). The HFTC has the ability to vary the amplitude of this signal to extend the measuring conductivity range. The test conditions, including the selection of voltages and frequencies, are chosen to provide relatively small oscillations of toner particles. This makes the method non-destructive to the toner sample.

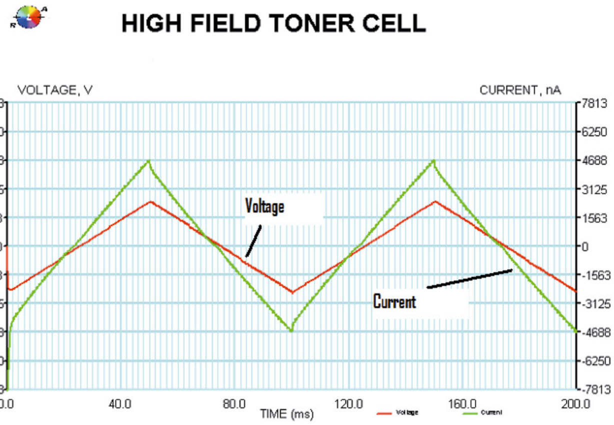

Figure 3. HFTC response to AC triangular voltage

The equation for the current flowing across the cell gap, when voltage signal changes linearly with time, such as, for example, in a triangular waveform, is represented by (2):

$$I(t) = \alpha C_T + \frac{\alpha t + U(t=0)}{R_T}, \qquad (2)$$

where

$$\alpha = \frac{dU}{dt} = \text{constant and } U(t) = \alpha t + U(t=0).$$

In practice, equation (2) enables one to determine both capacitance (3) and resistivity (4) of a toner sample from tangents to the current and voltage transient curves in the linear regions:

$$C_T = \frac{I\big|_{U=0}}{\frac{dU}{dt}} \qquad (3)$$

$$\rho_T = \frac{A}{L} \times \frac{\frac{dU}{dt}}{\frac{dI}{dt}} \qquad (4)$$

where, ρ_T – toner resistivity, A – electrode area and L – gap between electrodes.

Optical Transient

The optical transient enables the derivation of electrophoretic mobility by sensing the arrival time of charged toner particles to one of the electrodes. The presence of identical an optical emitter-detector pair focused on the surface of both top and bottom electrodes of the cell allows one to determine mobility and when calibrated, the ratio between the optical densities associated with positive and negative toner particles for bipolar toner systems. The arrival time is determined at the moment when the reflection density sensed by the emitter-detector pair occurring as the result of particle compaction due to electrophoresis reaches saturation or when the first differential equates zero. Compaction process is believed to be responsible for changing the light scattering mechanism and hence, affecting the reflected light intensity registered by the optical detectors. The ratio of sensor transient amplitude to sensor initial amplitude, i.e. dynamic range of the optical device can be optimised by the proper sensor alignment and focusing procedure and by increasing signal to noise ratio of the optical detection circuitry.

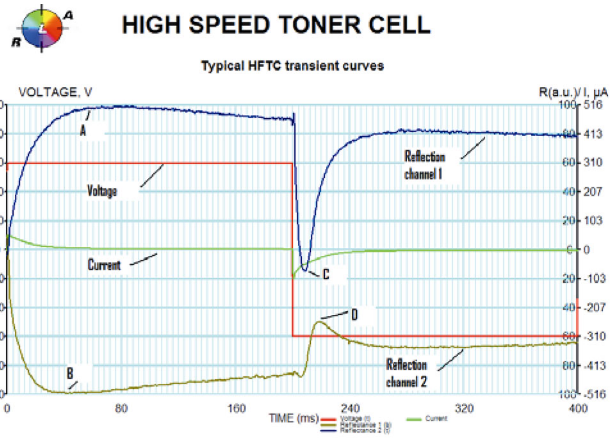

Figure 4. Optical response of a typical HVT to DC step signal

Figure 4 presents a typical response by current and optical channels to a step voltage signal. This figure gives a good illustration to the main trends and characteristic points associated with the drift of toner particles subjected to a high electric field. If one looks at the first half of the voltage signal (positive polarity), the extremes A and B on the reflectance curves from the first and second channels (differential of optical reflectance is plotted) correspond to almost the same transient time. In this region, when toner particles start their motion from the state of uniform distribution in the gap between the cell electrodes, the particle transient time registered by both optical detectors is envisaged to be similar, but different in sign. Small difference between the extremes A and B could be due to the variations between the electronics of the two optical channels. When the voltage polarity is changed to negative, toner particles that were residing adjacent to one of the electrodes start drifting towards the opposite electrode. These changes are, first of all, associated with the changes in the type of extreme for the selected reflectance channel (from maximum to minimum for channel 1 and from minimum to maximum for channel 2), and secondly, yields the time difference between those extremes (points C and D). This time difference (τ_D- τ_C) is believed to be a measure of the particle transient time across the cell gap.

Mobility values derived from optical transient curves by using the approach presented above correlate well with other well-known methods. For example, a typical high concentration toner sample being a dispersion of magenta pigment and binding resin in a mineral oil carrier was measured using the PALS technique (diluted further in carrier) yielded the value of 1.6 x $10^{-11}m^2V^{-1}s^{-1}$. The same sample, but undiluted measured using HFTC resulted in electrophoretic mobility value of 2.0 x $10^{-11}m^2V^{-1}s^{-1}$.

Toner Electrical Stability

It is well known that toner electrical properties can degrade with the toner being subjected to high electric fields exerted during operation of a typical electrophotographic printer. These changes in electrical properties occurring in the toner are sometimes referred to as toner electrical fatigue. The HFTC allows the investigation of toner electrical stability by an application of a series of positive and negative pulses forcing the toner to be displaced from one electrode to another in cyclic fashion. Due to the fact that the current response is digitally recorded at every cycle, it is possible to monitor the changes in toner conductivity as a function of the number of cycles. Stability of toner conductivity, particle electrophoretic mobility and charge can then become a criterion for assessing the toner's electrical stability.

Conclusion

The HFTC has shown a great deal of usefulness and uniqueness when applied to not only measuring electrical properties of highly concentrated liquid toners, but also to understanding the physical mechanisms governing liquid toner electrophotographic processes. Several years of research and development into the HFTC method have demonstrated excellent correlation between the cell results, image quality and system performance in proprietary liquid electrophotographic technologies being developed by Research Laboratories of Australia. Understanding the potential capabilities of the HFTC method and the multitude of its possible applications, the authors will endeavor to continue the R&D activities in this area with the ultimate goal being the delivery of a commercial version of the HFTC.

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Biographies

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Charlie Mao joined Research Laboratories of Australia as a research physicist in 1996. Since then, he has been working in the field of advanced and novel imaging technologies on developing mathematical modeling techniques and through his participation in client project activities. His main interests are in the areas of theoretical research and experimental development, and modelling and implementation of color image reproduction evaluation. He worked as a university lecturer in the area of mining and a research scientist in soil science before 1996. He received his B.Eng and M.Eng from PRC in China in early 1980s and his PhD in Applied Science from the University of South Australia, Australia in 1995.