

# Dielectric Constant of Ink Layer on HP-Indigo Developer Roller

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## Abstract

*The binary ink developer (BID) in the HP-Indigo press converts low viscosity ElectroInk® into a paste that is presented to the photoreceptor to form the image. The developed mass density depends on the voltage applied as well as the dielectric thickness of the photoreceptor and the paste. For a given ink thickness, less is deposited if its dielectric constant  $\epsilon$  is lower. In this work we describe a technique to determine the ink impedance over a wide frequency range. From this it is possible to extract  $\epsilon$  at concentrations near that of the paste in the development nip. For an Indigo-compatible magenta ink, we find that  $\epsilon \approx 2$ , quite close to that of the carrier fluid. The impedance spectra of the ink layer also show features not present in the dilute state, shedding more light on the ink constituents.*

## Introduction

The HP Indigo presses use a liquid electrophotographic (LEP) process to produce excellent print quality (PQ) [1,2]. One key element is the binary ink developer (BID) unit [3,4] which converts the low viscosity ElectroInk® [5,6] entering the BID to a much more usable paste-like material on the developer roller. This densified ink is then pressed against the photoreceptor (PR) and sticks instantaneously to the latent image, allowing the process speed to reach 2.15 m/s in the Series III presses that debuted at DRUPA08 with the HP Indigo 7000. The developer roller and the PR ground serve as the two electrodes between which the ink paste chooses allegiance depending on the local E-field [7].

The PR charge and developer voltages needed to ensure clean background and sufficient image density reflects the system efficiency, which depends on factors such as the ink characteristics in the development zone. The relevant ink parameters include its charge and dielectric thickness. The former can be tuned widely and thus have a large effect on efficiency. But the latter, the product of the dielectric constant and the ink thickness, also has an influence. The thickness can be obtained using the layer-shaving technique [4] we had introduced to determine the solids density profile within the ink layer. The ink dielectric constant is influenced by the ink solids and carrier fluids and thus likely spans a comparatively small range for different ink compositions.

On the other hand, just knowing that dielectric constant is desirable to correctly understand the development process. In addition, the ink becomes a more important component of efficiency if the PR thickness is significantly decreased. In this paper we describe an impedance technique to obtain the dielectric constant of the ink layer on the developer roller using two different cells. While the measurements were indirect, they likely come close to the equivalent value in the development zone based on similar results from the ink paste prepared under different conditions. The data also provides other information on the ink layer, which may be related to its internal constituents.

## Dielectric Constant from Capacitance

The relative dielectric constant  $\epsilon$  of a material filling the space between two parallel electrodes, can be obtained from the measured capacitance  $C$  by

$$C = \epsilon \epsilon_0 A / d \quad (1)$$

where  $\epsilon_0$  is the permittivity of free space,  $A$  the area and  $d$  the gap between the electrodes. The formula applies to infinite electrodes and remains fairly accurate if the lateral dimensions are much larger than the spacing. A dielectric typically behaves as leaky capacitor with impedance  $Z$  given by

$$1/Z = 1/R + i\omega C \quad (2)$$

where  $R$  is the resistance and  $\omega$  is  $2\pi$  times the frequency  $f$ . Then  $\epsilon$  follows from Eq.1 if  $C$  can be determined from the measured  $Z$ .

## Experimental Technique

The impedance measurements were done using the Solartron 1280B Electrochemical Test Unit that had been used previously to obtain results on Indigo-style blankets [8]. This instrument returns  $Z$  as  $(|Z|, \theta)$ , as well as components  $(Z', Z'')$ . If  $\theta \approx -90^\circ$  at high  $f$ , then  $\omega C \gg 1/R$  and  $C$  can be obtained simply from Eq. (2). The unit can operate from 1 mHz to 20 kHz, a frequency range that includes the portion useful for LEP-related studies. For the Series II-type blankets tested, the results were obtained between 1 Hz and 10 kHz, which covered the critical frequencies and beyond. For ink we focus on the development nip, which has a corresponding frequency of up to several hundred Hz depending on the process speed. But as with the blanket, it is desirable to look at the impedance spectrum over a wider span so that trends in the data can be seen. With a similar range we cover the relevant frequency and more while keeping the measurement time reasonably contained. For some situations the lower limits was moved down to 10 mHz. This change increased the expended time to several hours and was only used when more details there were needed.

Previously we had tried to get the impedance spectrum of the ink on the BID roller by direct measurement. This involved using an appropriately-shaped electrode against the ink layer on the roller stopped in the midst of operation. But translating the results to a meaningful  $\epsilon$  seemed difficult at best. We were not confident that the surface tolerance on the electrode was sufficient to provide contact without distorting the layer. Even more challenging is the confounding factor introduced by dielectric behavior of the modestly conducting polymeric roller. For this work we choose instead a path where the dimensions are well defined and the electrode highly conductive.

We start with our standard cell shown in Fig. 1. This consists of a fluoropolymer housing with an imbedded polished 10 cm<sup>2</sup> Al disk about 10 mm thick. An ITO-coated glass slide acts as the second electrode. The housing has a fence and a pin against which the slide can rest. Since the glass can be accurately located, its ITO can be patterned to reflect the Al to form parallel electrodes. For contact to the slide, copper tape was added on the end away from the housing. This means the circular pattern must actually have a narrow handle to provide a connection and hence does not absolutely duplicate the Al surface. Nevertheless, the two are quite similar over most of the circumference. The pocket depth can be varied by inserting Al electrodes of different thicknesses.



**Figure 1.** Standard cell with ITO-coated glass (left). Filled cell (right).

The slide increases the reliability of the results compared to an opaque electrode such as Al. For calibration as well as testing with inks, being able to see beneath the electrode is quite helpful. Trapping large bubbles inside the cell turns out to be the rule rather than the exception, and the apparent capacitance would be decreased accordingly. Our cell was designed for suppressing bubbles using channels that act as inlet and outlet. These appear as extensions to the circular pocket of the filled cell in Fig. 1 (right). To start, the slide is first moved slightly to expose the legs, and the fluid is injected from the left one. By slightly tilting the cell so that the right opening is up, the air pocket can be forced out. After that the slide is move back to its intended position. With an opaque electrode and no channels, some technique can probably still be devised to eliminate bubbles, but one just cannot be quite certain they are absent.

The standard cell is normally used to obtain the  $\epsilon$  of ink and other fluids. When desired, it can also be converted to move ink solids to the slide by applying a high (-) voltage to the imbedded Al electrode with the ITO at ground. For this we typically use -10 kV from a Trek 610E power supply with a 4 mm deep pocket. Not all the colorant is pulled to the glass. But a much higher electric field cannot be used since sparking occurs with a 3 mm gap at the same voltage. On the other hand we found that a thicker, perhaps less densely packed layer can be deposited with a 5 mm pocket at 10 kV, albeit with a darker residue. These observations suggest that the tinge may be associated with lower charged particles.

The ink on the ITO should be similar to that on the developer roller deposited in the electrode region of the BID unit [3]. The roller then proceeds to the squeegee where the ink is further compacted before proceeding to the PR. Hence the layer on the ITO is less compacted than that in the development nip. The coated slide is placed on the special cell shown in Fig. 2 (right). Here the Al electrode actually protrudes from the body by about 0.12 mm. This allows the ink layer to dry and thin over time without the potential havoc that can be caused by shrinkage with

the standard cell. Clearly the special cell is only used for the paste form since a low viscosity material would just run off. An ink disk can be made in other ways to fit the special cell. But the standard cell is well suited to produce a roller-like layer with its reasonably uniform, round deposit aligned to the Al. The cell without any ink is shown in Fig. 2 (left). The dial indicator used to track the ink layer thickness is set to zero with the glass electrode in contact.



**Figure 2.** Special cell with ITO-coated glass in place (left). Cell with ink paste between electrodes (right).

## Cell Calibration

The dielectric constant of isolated parallel electrodes should be very close to 1. For our measurement cells, the Al disk is surrounded by materials with higher dielectric constants. Hence E-field lines can be pulled beyond where they would otherwise sit, which would result in a larger apparent  $\epsilon$ . For our standard configuration with a 1 mm pocket and the patterned ITO, we translated the measured Z to  $\epsilon = 1.95$  using Eq. 1 with the 10 cm<sup>2</sup> area assumed for the electrodes. To verify proper instrument operation, standard component capacitors were measure and found to be very close to labeled values. Thus the significant deviation seen with the empty cell is likely due to extra capacitance associated the housing.

To test this hypothesis, we simulated a simplified version of our standard cell geometry using COMSOL Multiphysics. We found  $\epsilon$  to be as high as 1.56 with the assumed electrode area if enough prominent features were added, even leaving out some parts that would add to the value. The model also confirmed that the housing attracted field lines away from the electrode edges, thus enlarging its effective area. In addition the thickness of the embedded Al electrode was shown to contribute to this increase. Thus we felt confident that the higher  $\epsilon$  is associated with the housing and not an artifact of the measurement.

The simulation also showed that filling the cell with a dielectric material with constant  $\epsilon$  would increase the measured value by  $\epsilon - 1$ . So to find  $\epsilon$ , we can use

$$\epsilon = \epsilon_{\text{meas}} - \epsilon_{\text{cell}} + 1 \quad (3)$$

where  $\epsilon_{\text{meas}}$  is the value with the cell filled and  $\epsilon_{\text{cell}}$  is that with the same empty. For each pocket depth, the appropriate calibration must be used. The 5 mm pocket had  $\epsilon_{\text{cell}} \approx 3.94$ , indicative of much more field lines directed into the housing with the deeper electrode. For the special cell  $\epsilon_{\text{cell}}$  varies with the spacing between the glass and the Al. We obtained its dependence using 3 mm plastic spacers of different thicknesses.

## Results and Discussion

Table 1 summarizes  $\epsilon$  results from the standard cell on Indigo-compatible magenta ink. Isopropyl alcohol and Isopar L were done because they can be compared to the literature and the latter is the dominant ink carrier fluid. Impedance spectra show the alcohol to be quite conductive with the transition from capacitive to resistive prominence varying from run to run. Asymptotic resistivity changed as well. These results suggest perhaps different moisture pickup depending of conditions. The average  $\epsilon$  at each depth is fairly consistent although somewhat higher than the known value, especially for 5 mm. This may well be due to high- $\epsilon$  alcohol-filled channels that pull in extra field lines from the buried electrode. We believe the other material tested, with their relatively low  $\epsilon$ , would attract much less and hence not distort  $\epsilon_{\text{meas}}$  anywhere near what is seen with isopropyl alcohol.

**Table 1**

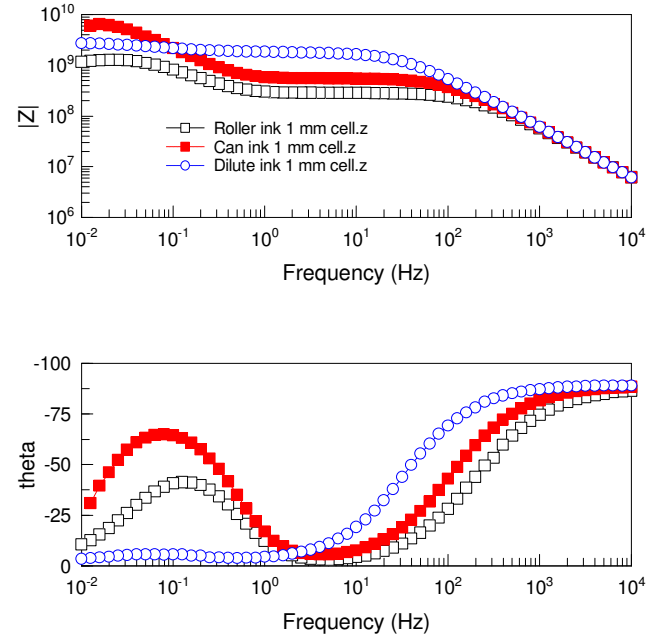
	1 mm	5 mm	Literature
Isopar L	2.05	2.10	$\approx 2.0$
IPA	18.75	19.3	18.3
Dilute ink	2.05	2.10	
Can ink	2.08	2.12	
Roller ink	2.10		

Published data could not be found explicitly for Isopar L, but those available for Isopar G and oils of similar molecular weight have  $\epsilon$  close to 2.0. The dilute magenta ink from the Indigo press ink tank has  $\approx 2$  wt% concentration of solids and the ink from the supply can somewhat over 20 wt%. The roller ink was scraped from a BID unit had been determined earlier in Ref. 4 to be around 25 wt%. The table shows a slight skew toward higher  $\epsilon$  as the solids content increases, but the change is quite small. Perhaps the solids  $\epsilon$  of this Indigo-compatible magenta ink is not that much larger than that of the carrier fluid.

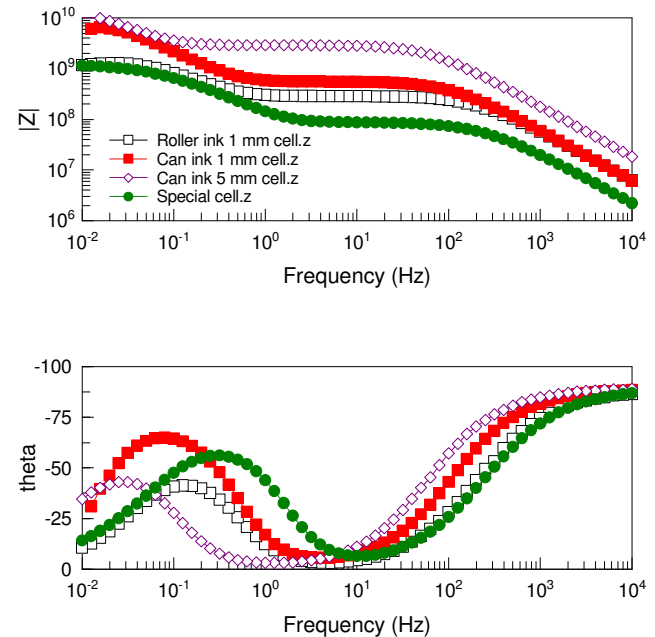
Figure 3 shows the impedance spectra of magenta ink in three forms taken from the 1 mm standard cell.  $\epsilon$  can be extracted where  $\theta$  close to  $-90^\circ$  at the highest  $f$  at 10 kHz. These are very close as indicated in Table 1 and not separable in the figure. The Isopar L  $|Z|$  (not shown) falls on top of the others in this region but continues along the same slope as  $f$  goes down to 1 Hz and beyond, in contrast to the others that having leakage currents that dominate  $Z$  below  $\sim 100$  Hz. Within the development nip where the applicable frequency is several hundred Hz, the roller ink behaves mainly as a capacitor with small current flow. Hence the layer should split more or less as envisioned in a typical development model [7].

In the flat  $|Z|$  region between around 1 and 100 Hz, the roller ink is least resistive and the dilute ink the most. This is consistent with the expected concentration of free charge directors in the

layers. The roller ink undergoes the highest electric fields in a two-step process where charged particles are concentrated against the roller surface. Although the ink is scraped off and mixed as it is deposited into the pocket, apparently sufficient charge remains to distinguish it from the can ink.



**Figure 3.** Magenta ink Impedance spectra for paste from the supply can and developer roller as well as dilute ink from the Indigo press ink tank.



**Figure 4.** Magenta ink impedance spectra of ink paste from the supply can and developer roller from Fig. 3 compared to that from the special cell. Can ink result from the thicker 5 mm standard cell is also shown.

In the  $|Z|$  plot, each paste has a second sloped region below  $f \approx 1$  before flattening again. For blanket impedance we also saw a second plateau. This behavior was attributed to the two individual layers above the blanket ground [8]. The slope at high  $f$  was linked to the composite capacitance from which total dielectric thickness can be obtained. With decreasing  $f$ , the curve levels out for a small segment before turning up again. The flattening is simply the behavior of any leaky capacitor where the resistive part dominates  $Z$  at lower  $f$ . The additional rise was indicative of current getting stopped at a second, more resistive dielectric. We associated this with the thinner outer layer of the blanket and deduced its dielectric thickness from the observed slope.

An analogous explanation is desired for the results of Fig. 3. As with the blanket, the slope at high  $f$  was assumed to be due to the capacitive behavior of the material between electrodes, here the ink. We seek the equivalent of the second layer. Consider the can ink. The two sloped regions are separated by a factor of 200. With the cell at 1 mm, the second dimension is  $\approx 5 \mu\text{m}$  assuming the same  $\epsilon$ . This must be related to the solids since the dilute ink has only the slightest hint of similar features in  $|Z|$  and  $\theta$ .

On the other hand  $5 \mu\text{m}$  is nowhere near the solids dielectric thickness between the electrodes. That would be roughly the cube root of the solids content,  $\sim 58\%$  or  $\sim 580 \mu\text{m}$  since  $\epsilon$  of the carrier fluid and solids are close according to Table 1. Nevertheless, some link to individual particles is likely because its value is dependent on the sample source. This is evident by comparing the can with the roller which has 2.5x lower capacitance, making the second dimension about  $2 \mu\text{m}$ . The difference is consistent with the E-field squashing the particles in the BID unit.

Fig. 4 shows the impedance spectra of magenta paste from the can in a 5 mm cell and from the special cell ( $\approx 0.27 \text{ mm}$ ), which accompany the can and roller results from Fig. 3. Note that the sloped regions of the  $|Z|$  curves cannot be directly compared at different layer thickness due to varying  $\epsilon_{\text{cell}}$  shifts. The data plotted here by the instrument also does not allow for manual correction. Nevertheless, one can estimate how the capacitive regions would move without the distortion using the ratio of  $\epsilon$  to  $\epsilon_{\text{meas}}$ .

The special cell capacitive regions should be shifted down to 0.77x the original. This moves the second dimension derived from the capacitance to just over half of that of the roller ink,  $\approx 1 \mu\text{m}$ . It seems very unlikely that the roller would have squeezed the ink less than the electrodes since the former uses much higher E-fields aided by mechanical forces. But the apparent contradiction can readily be dismissed. Both scraping the roller with a blade and smearing the content into the cell would mix the ink. Thus the particle orientation is probably rather random, and the capacitance only benefits a bit from the particle flattening.

While the discussion thus far has suggested a link between the second dimension and individual particles, the situations is more complicated. This is evident from the 5 mm can data. Here the capacitive regions should be moved up by 1.6x compared to the 1 mm, based on the ratio. This makes the second dimension  $\approx 13 \mu\text{m}$ , which is not proportional to the cell thickness and hence not directly related to some particle feature summed over the stack. But it is also not likely to be associated with the single layer(s) on the electrode surface(s), which would have made the result the same for both pocket depths. Thus the second feature still eludes an encompassing explanation.

## Conclusions

In this work we showed that the dielectric constant of an Indigo-compatible magenta ink on the developer roller can be accurately measured. Calibrating the cells used was necessary. After that the experiments were quite straightforward. We found that the constant is basically the same for all ink samples tested irrespective of solids content from the dilute form up to that on the roller and beyond. These results suggest that the dielectric constants of the solids in this particular ink are likely not very different from that of the carrier fluid.

The impedance spectra obtained in the course of the study provided other interesting information. For example, the particle size appears linked to a second implicit dimension if the ink is in paste form, although the exact nature of the connection could not be definitively determined. In addition in the regions where resistivity dominates, the impedance magnitude seems to be associated with the free charge director content.

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