# Model-Based Calibration System for Direct Thermal Printing

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**Abstract:** This document describes a method for maintaining the long-term calibration of a full-color direct thermal printer. An essential component of the system is a thermal model that allows fitting of color data recorded at different temperatures and exposure times to model results for the same conditions. The fitted results reveal the depth and thickness of color dye layers embedded in the medium, and the Arrhenius parameters characterizing their thermal response. These quantities can then be used as control parameters for maintaining long term consistency in the media manufacturing.

**Keywords:** direct thermal printing, calibration, color printing, thermal media.

## 1. Introduction

The manufacture of color thermal printers is complicated by the issue of calibration. The printers have several sources of variability (most notably the variability in the properties of individual thermal print heads) so that printers must be calibrated at manufacture to produce correct color when printing on a standard media. However, the manufactured media used to calibrate them is itself subject to variability from one production run to another. Media characterization has required the used of printers, which are subject to slow aging and wear, so it has been difficult to establish a mutual printer/media calibration that will be immune to long-term drift. There needs to be a primary reference device that fixes the calibration to something more fundamental, and we refer to such a device generically as a "golden printer".

Fig. 1 illustrates an experimental reference device of this kind. The fundamental idea is to have the thermal medium pass, at a measured speed, over a defined length of polished metal surface that is held at an accurately measured temperature. The contact force between the media and metal heater bar is monitored and maintained constant. This constitutes a standard exposure to heat. Prior to contact with the heated surface, the medium passes over an aluminum plate, also held at a measured temperature, to establish a well-defined initial media temperature.

With this exposure we measure the media response, both in optical density and color. In order to obtain a full map of the response, the media speed is varied through a range of values, and the measurements are performed at a variety of temperatures. Time-histories of temperature and speed are recorded along with the optical data.

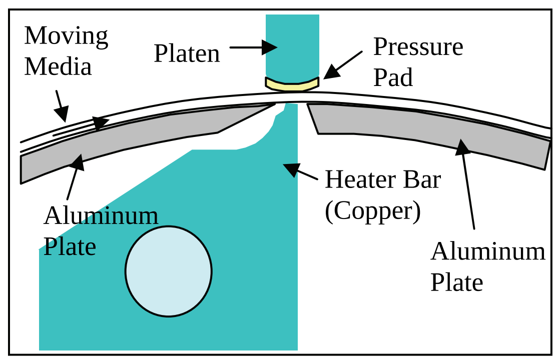


**Figure 1.** Schematic of the "Golden Printer"

## 2. Use of COMSOL Multiphysics

The data are analyzed with reference to a COMSOL model. The model represents the media structure shown in Fig. 2, which is composed of three thermally activated dye layers buried at different depths below the heated surface.[1] The dye layers and separating layers (which include UV and chemical barrier layers) are coated on a somewhat insulating base layer. The thermal properties of the materials have largely been drawn from on-line databases, though some were also measured independently in our laboratory.

The COMSOL model represents the passage of the media over the heater bar, as shown in Fig. 3. The motion of the media is modeled as a convective term in the thermal model, and is given a sinusoidal variation as was used in the experiment. The experiment records the temperature of the heater bar near the surface contacting the sample, and this recorded value is used as a temperature boundary condition in the model.

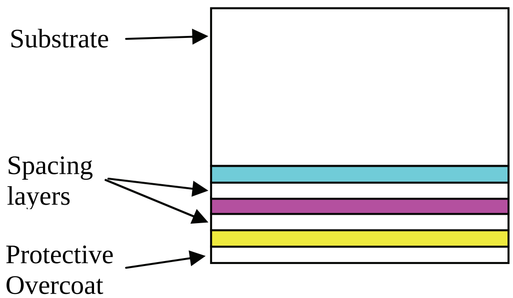


**Figure 2.** Media structure, containing three thermally activated dye layers.

Because the materials used in the coated layers all have similar thermal diffusion constants, the coating is modeled as a uniform material without the layer structure indicated in Fig. 2. The layer positions and thicknesses are added only in the post-processing operation. This allows optimization of the layer parameters without repeating the thermal model at each step.

Post-processing is carried out with MATLAB. Insofar as the optical densities measured in the media are those of points fixed with respect to the media, while the simulation is carried out in a coordinate system that is fixed with respect to the heater bar, the first processing step is to construct a temperature-vs.-time history of each point in the medium, compensating for the convective motion. Once this time-history is known for a point, one can compute the optical density that would be produced if one of the dyes were placed at that point.

The optical response of each dye layer to the applied heat has been shown in separate experiments to be accurately represented by an Arrhenius model of the form:

$$\frac{dN}{dt} = -R(t) * N, \text{ with } R(t) = \exp\left( A - \frac{Q}{T(t)} \right)$$

N is the number of uncolorized dye molecules, A is an adjustable scaling factor, Q is the activation energy (expressed in deg. K) and T(t) is the absolute temperature.

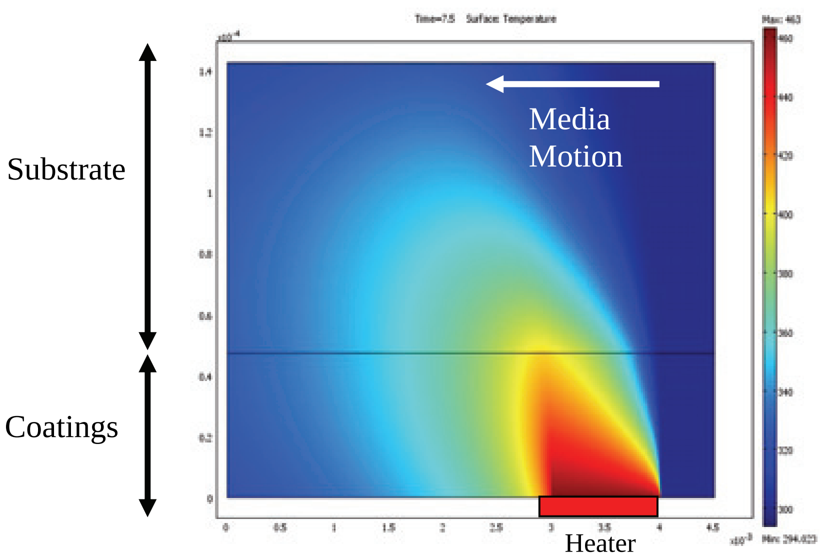


**Figure 3.** COMSOL simulation of the temperature field inside media structure with a heater temperature of 463K and media velocity of 35 mm/sec. The substrate is on top (above the horizontal line at $0.5 \times 10^{-4}$), and the dye layers are at the bottom, contacted by a heater bar on the bottom surface for a length of 1 mm.

The optical density D of each dye layer in the thermally exposed media is:

$$D = D_{\min} + \left(D_{\max} - D_{\min}\right)\left(1 - \exp\left(-\int R(t)dt\right)\right)$$

where $D_{min}$ and $D_{max}$ are, respectively, the optical density of the original unheated media, and the optical density reached after prolonged exposure to temperatures above the threshold of the dye.

Using this computation of the optical density for each color, the dye layer thicknesses and depths and the dye layer Arrhenius parameters are adjusted for best agreement with the experimentally observed color and density over a range of media speed and heater bar temperatures. The fitted quantities are the layer depth, layer thickness and Arrhenius parameters A and Q for each of the dye layers.

As mentioned earlier, a full map of the media response is made by varying both the heater temperature and the speed of the medium. This is accomplished in a single experiment by making a repetitive sinusoidal scan of the media drive velocity while the temperature is slowly scanned through a predetermined temperature range.

In making these scans, we need to ensure that the scanning rates are sufficiently slow that they do not bias the results. In particular, we have found some hysteresis in the sinusoidal velocity scan if the scanning frequency becomes too high. The data analysis is significantly simplified if we avoid the conditions that produce hysteresis, since the results at each velocity are then essentially the same as the model results that would be obtained for a constant-velocity and constant-temperature exposure. In this case, we can pre-compute the results for a range of constant velocities and temperatures, and interpolate them to get the particular results for any recorded velocity and temperature history.

The alternative is to take the recorded velocity and temperature of each experiment, and to use them as boundary conditions for the model. This procedure would be quite time-consuming and is worth avoiding. Nevertheless, it is preferable to make the scanning frequencies as high as possible so that we achieve several cycles of scanning in each experiment.

To investigate the conditions under which hysteresis occurs, we have used the COMSOL model with a variety of simulated sinusoidal scans. An example is shown in Fig. 4, which shows the cyan optical density during a sinusoidal velocity sweep, performed at two different sweep rates at a fixed temperature. The results demonstrate substantial hysteresis for a sweep with a period of 500 ms, but very little hysteresis at a period of 2500 ms.

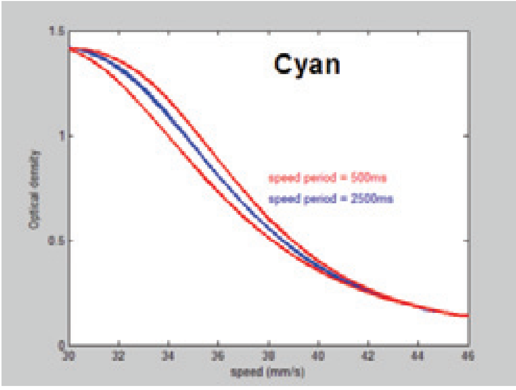


**Figure 4.** Model results for cyan optical density with a sinusoidal sweep in velocity of amplitude 13 mm/s, and with two different scanning frequencies. The heater temperature is 180 C.

This result is consistent with the idea that the hysteresis arises because of the time it takes heat to diffuse from the heater bar contacting the surface to the cyan layer that is buried beneath it. The diffusion time is of the order δt=10, so that under the conditions show in Fig. 4 we can estimate the density error δD between a constant-velocity sweep and a sinusoidal-velocity sweep of period T to be approximately:

$$\delta D = \left(\frac{\partial D}{\partial v}\right)\left(\frac{\partial v}{\partial t}\right)\delta t$$

$$\approx \left(\frac{0.5}{4\text{ mm/s}}\right)\left(8\text{ mm/s} * \frac{2\pi}{T}\right)\delta t = 2\pi\frac{\delta t}{T}$$

Similarly, we checked for bias in the temperature scan by modeling the optical density at a variety of scan rates, using a constant media speed of 25 mm/s. Fig. 5 is a typical result, showing no bias over nearly a decade of thermal scan rate.

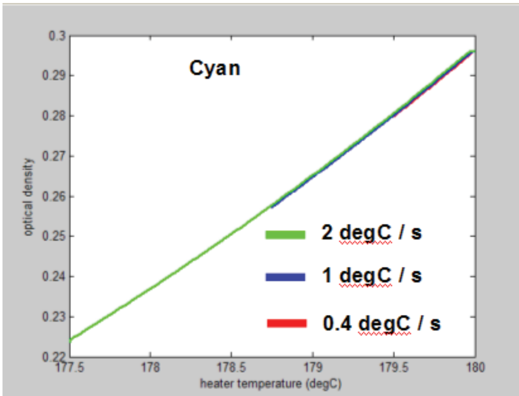


**Figure 5**. Model results for cyan density using a constant media velocity and a variety of thermal scanning rates.

## 3. Results

Fig. 6 is a short data sample from an experiment in which the heater temperature and media speed were adjusted to activate only the cyan layer of the structure. As the media passes over the heater bar, the speed is varied sinusoidally. In places at which the speed is lower, heat from the bar diffuses more deeply into the medium, and is able to reach and colorize the cyan layer. At positions of higher speed, no color is produced. The temperature of the bar is below the activation threshold temperatures of the magenta and yellow dye layers in this particular sample, so these colors do not appear at any speed.

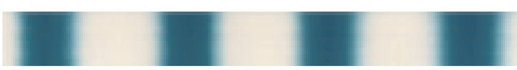

**Figure 6.** Sample data record with temperature and sample speed adjusted for cyan-only recording

Fig. 7 contains a comparison between measured cyan densities and the densities produced by the COMSOL model for a set of fitted cyan model parameters. The COMSOL model computes the mapping based on the depth, thickness and Arrhenius parameters of the cyan layer. These quantities are adjusted for best agreement with the measured data using the MATLAB Optimization Toolbox. For the comparison in Fig. 7, the fit indicated that the mean layer depth was 41 microns, the layer width was 3 microns, and the cyan Arrhenius parameters were A=161, Q=59065 K. The layer depth and width correspond well to the coating targets of 41.2 microns and 2.5 microns, respectively, and the ratio Q/A is close to the known melting temperature of the dye composition as it should be.

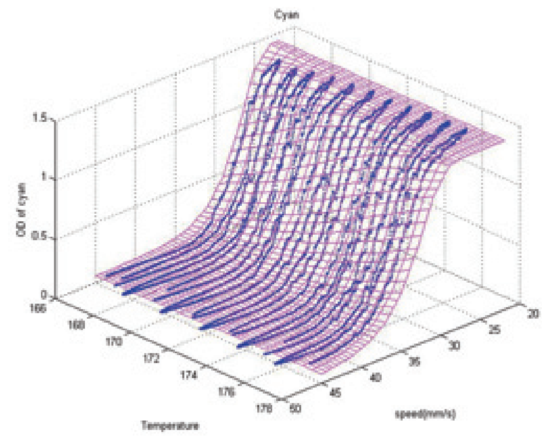


**Figure 7.** Cyan optical density (OD) data as a function of media speed and heater bar temperature. The gridded surface represents the COMSOL model. The blue line shows measured results with a periodic media velocity and a slow temperature scan.

In order to better disply the quality of the fit to the experimental data, Fig. 8 shows a constant-temperature slice from the data and fit in Fig. 7.

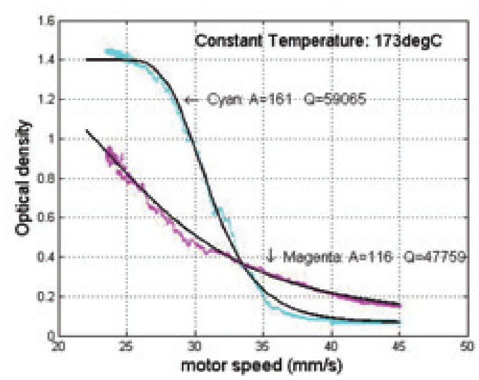


**Figure 8.** A constant-temperature slice from Fig. 7, showing the quality of the parametric fit. Data are also shown for a similar experiment in which the magenta layer was thermally activated.

To test that the cyan Arrhenius parameters have been correctly identified by this calibration system, we have used them in conjunction with a previously published model of direct thermal printing[2] to estimate the response curves that would be expected from a thermal printer writing on this medium. (see Fig. 9)

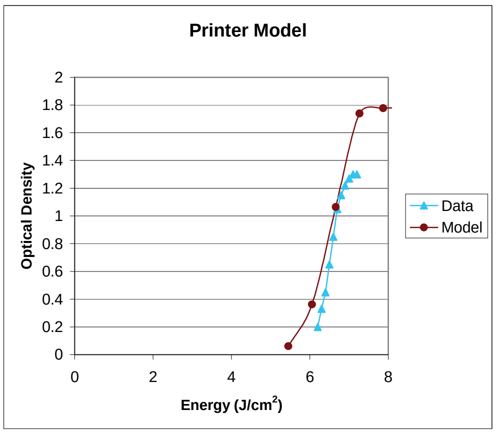


**Figure 9.** Simulation of a thermal printer printing various densities of cyan color, using parameters determined using the calibration system. (Note: Experimental data was recorded only up to densities of about 1.3, at which color cross-talk limited the accuracy of the measurement.)

It should be noted that although both the calibration system and the printer are creating cyan color by applying heat to the media, the models and the hardware are quite different. In the case of the calibration system, the heater bar holds a constant temperature on the surface, and the medium travels at the relatively high velocity of several cm/sec. In the printer, the medium travels an order of magnitude more slowly, while that temperature is applied as very short pulses. In this respect, it is gratifying that the results from the calibrator can be carried so accurately to the printer model.

## 4. Conclusion

A device has been built to evaluate long term variability in manufactured thermal media, as a means of maintaining a calibrated response to thermal exposure. In combination with a COMSOL model of the device, we are able to trace variability in calibration to the media parameter(s) that caused it. The ability of the device to estimate layer depths and thermal properties provides concrete guidance for control of the manufacturing process, and also provides detailed data for our model of direct thermal printing[2,3]. In the future the combination of the two may allow us to infer the full color calibration tables for the media.

## 5. References

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2. William T. Vetterling et al., "A Model of Direct Thermal Printing", *Proc. of the COMSOL Conf. 2007, Boston* (2007).
3. William T. Vetterling et al., "A Model of Direct Thermal Printing", *COMSOL News 2008*, pp. 18f. (2008).