Use of a Thermal Dye Diffusion Model to Predict Printing Line-Times

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Abstract

A numerical, finite-difference model has been developed to simulate the dye transfer thermal printing process. This model has been used previously for calculating the amount and depth of the dye diffusion into a receiver. The simulation incorporates the multiple layers of the head/media interface and uses finite-difference techniques to calculate the temperature and mass distributions. Surface boundary conditions have been determined from experimental printhead temperature data. This allows different pulse modulation heating schemes to be used in the analysis. The concentration dependence of the diffusivity is taken into account, and this leads to a nonlinear governing equation.

As one increases the amount of power delivered by the thermal head, larger quantities of dye will be transferred into the receiver. In a similar fashion, any changes to the dimensionality and/or thermal properties of the materials comprising the donor and receiver will affect the temperature distribution. This, in turn, will cause the amount of dye transfer to change. These changes have been investigated, and the predicted amounts have been calculated for dye transfer. Comparing the amount of calculated dye transfer to that calculated from known operating conditions, one is able to predict the amount of time required for an equivalent transfer to occur. The effects of head power, donor thickness, solubility, and dye concentration have been investigated. Predictions of line-time have been made for each of the parametric changes, as well as an overall "best case" scenario.

Introduction

An application of a numerical model developed to simulate the dye transfer thermal printing process will be described. The simulation incorporates the multiple layers of the head/media interface and uses finite-differences to calculate the temperature and mass distributions. Surface-boundary conditions have been determined from experimental printhead temperature data. This enables us to use different pulse modulation heating schemes. The concentration dependence of diffusivity is taken into account, and this leads to a non-linear governing equation. The amount of dye transferred and its distribution in the receiving material can be predicted.

This model has been used as a tool for identifying those factors that are most important in achieving a robust design. In particular, the effects of the donor and receiver glass transition temperatures, dye diffusion partition coefficients, line-printing times, pulse-enabled width schemes, and receiver dimensions were studied. These factors were incorporated into a pseudo design of experiments[1]. Responses included the amount of dye transferred from the donor to the receiver and the distribution profile of the dye in the receiving material. The responses were calculated using the simulation model previously described.

Over the past 20 years, a new printing technology known as "resistive-head thermal printing" has emerged. Thermal printers are used for a variety of printing needs, ranging from inexpensive monotone fax printers to near photographic quality continuous-tone color images. The highest quality output is produced by the dye diffusion thermal printer. The thermal printing operation is driven by a thermal printhead that consists of a number of resistive heating elements closely arranged along the axis of the head. Between 200 and 600 heating elements are aligned per inch. During the dye diffusion printing process, the thermal printhead is brought into contact with a dye-coated donor ribbon (see Figure 1). A chemically coated receiver sheet sits beneath the donor ribbon. The donor/receiver surfaces are compressed between the printhead bead and an elastomeric drum, creating a very small but highly pressured nip contact region. The high pressure creates the close contact between the layers that is necessary for efficient thermal transfer. During printing, each resistive element on the head is pulsed with current in order to create heat. This heat then drives the diffusion process. By manipulating the thermal resistor pulsing scheme, one can control the temperature history and, subsequently, the amount of diffusion taking place beneath each resistor. In the color dye diffusion process, three printing passes are used to overlay yellow, magenta, and cyan dye. The result is a high-quality, continuous-tone color image.

In order to simulate the dye transfer process within this heated and pressured nip contact region, we have created a finite-difference model that simultaneously solves the heat and dye diffusion equations. Figure 2 shows an exaggerated cross section of the printing system. Individual components are identified along with the regions of calculation. This model will allow us to optimize the system parameters that most influence the transfer process. In the past, a number of studies have focused on the heat transfer aspects of the problem. Setani et al[2] created a 3D finite element code to study the thermal effects due to adjacently heated pixels. Connolly[3,4] created a 1D finite element model to study the effects of the thermal characteristics of the material within the printhead itself. In 1991, Kaneko[5,6] created a simulation using finite-differences to model the heat and dye transfer process. In his simulation, he enforced surface temperatures, based on experimental data, in order to determine media interface temperatures. He later used a finite-element technique in which he accounted for "back diffusion", meaning diffusion from the receiving layer to the dye layer on the second or third pass. Still others have done work in thermal and diffusion modeling, and the reader is directed to the published literature for further information.

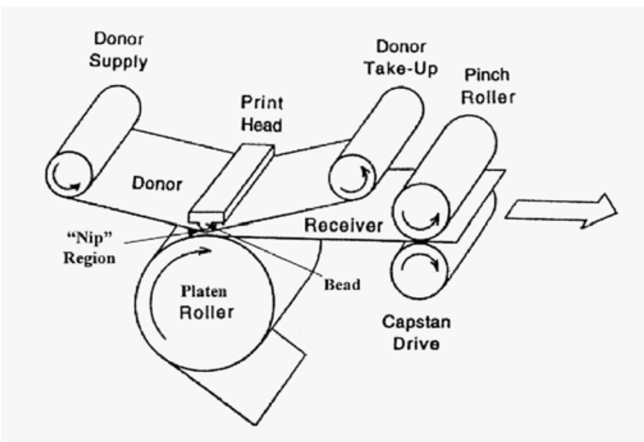

Figure 1. Thermal Printer

One of the keys to our modeling approach was to use a constant-flux boundary condition at the surface of the printhead resistor, rather than a constant temperature. In the present model, it is not our goal to predict the thermal behavior within the head itself but, rather, to determine the temperature and diffusion behavior between the donor and receiver. Therefore, our approach will be to replace the actual thermal resistor with a flux boundary condition and to replace the heat sink of the head with a single heat loss term. Using experimental thermal head temperature data, we will describe a method for finding this boundary condition. In such an approach, we account for the fact that the experimental head temperatures measured in air are higher than the head temperatures we expect to find when the media is brought into contact with the head. In the model, we will also account for the concentration dependence of the diffusivities that leads to a nonlinear diffusion equation. Finally, we will run a number of test cases that illustrate the capabilities of the model

Model Development

The purpose of our heat and dye diffusion model is to simulate the transient thermal behavior within the donor and receiver layers and the subsequent dye transfer between the two surfaces.

The two equations we solve simultaneously are very similar. The simplified one-dimensional heat equation can be written as:

$$\partial T/\partial t = (K/C_p)(\partial^2 T/\partial x^2) \qquad (1)$$

where K = thermal conductivity (W/m-K), C_p = heat capacity (J/m^{3}K), T = Temperature (K), and t = time (sec). A description of the discretization can be found in LaFleche.[7,8]

The diffusion equation shown below cannot be solved as simply because some dyes used in the thermal printer industry have a concentration-dependent diffusivity leading to the non-linear governing equation

$$\partial c/\partial t = \partial/\partial x[D(c(x))\cdot \partial c/\partial x] = D\, \partial^2 c/\partial x^2 + dD/dc[\partial c/\partial x]^2 \qquad (2)$$

where D(c) = diffusivity (m^2/sec), x = position (m), t = time (sec), and c = concentration (non-dimensional). In order to account for the concentration-dependent diffusivity, we have linearized the diffusion equation. Details of this linearization and the finite-difference solution techniques for the heat and dye diffusion can be found in LaFleche.[8]

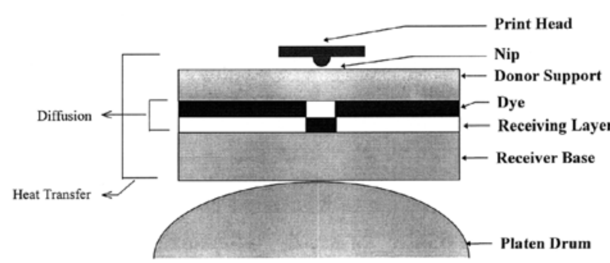

Figure 2. Cross-section of the printing system

Surface Boundary Condition

Experimental temperature profiles on the surface of a thermal printhead were measured using infrared microscopy. These experiments were performed on a 300 dpi TDK thermal printhead, using an EDO Corporation Radiometric infrared microscope with a 36 µm aperture. We use this experimental data to find the surface-boundary condition to be used in our temperature model. The data are fitted to the relationship

$$q\cdot\alpha = -K\,[\partial T/\partial x] + h\cdot (T-T_\infty) \qquad (3)$$

where, q = flux (W/m^2), α = efficiency (0-1), h = loss term (W/m^2K), T = head temperature (K), T_∞ = room temperature (K), and K = thermal conductivity (W/m-K).

Constants for a particular system are chosen by matching experimental data for the temperatures measured at the surface of the head. The constants q, h, α, and T_∞ are adjusted accordingly. During the pulsing algorithm, when the heater is on, the flux term q is included. Otherwise, this term is set equal to zero. Through the use of the loss term h, heat is constantly being removed from the system. Figure 3 shows the measured temperature values compared to those predicted by the model.

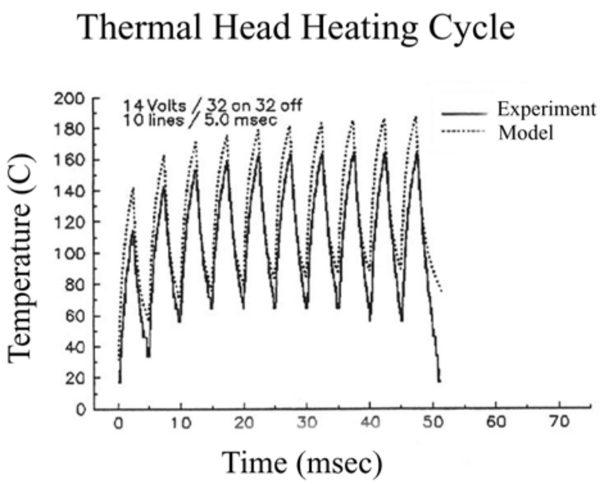

Figure 3. Head Temperature Values

Applications of the Model

The numerical simulation allows us to study the relationship between many different parameters that affect the transfer process. In terms of heat transfer, we can make modifications to heat capacity and thermal conductivity. We can examine the efficiency of the printhead as a function of media type, thickness, number of layers, and the properties of those layers. Modifications to the pulsing algorithm can be made. Adjustment of these parameters leads to changes in temperature history, subsequent diffusivity, and the overall volume and position of the transferred dye. In terms of the diffusion equation, we can examine the effects of dye thickness and dye concentration and make changes to the diffusion laws. These laws account for glass transitions of the coatings and the chemistry of the individual dyes.

The calculations were performed using seven layers for the temperature computations. These layers represent the ceramic bead of the printhead, the layers of the dye donor ribbon, and the receiving layers of the output media. Two layers were used for the diffusion computations--the dye-containing layer of the donor ribbon and the receiving layers of the output media. The mesh structure of the numerical calculation and the type of solution have been defined to optimize the speed of calculation, maintain convergence, and provide consistency and agreement with known closed-form results.[9,10] A sample output plot of the calculated dye profile is shown in Figure 4. The individual curves represent the dye concentration profile in the receiving layer, following each of the yellow, magenta, and cyan printing passes along with the lamination pass #4.

Previous work has shown good agreement between model predictions and actual observations.[11] Using the calculated dye concentration profile for a typical 5 msec line-time printer application as a reference point, calculations are performed for varying amounts of head power, donor dye loading, solubility differences, and component thickness. Equivalent line-times are determined by comparing the amount of dye transferred from the donor to the receiver to the amount calculated for the 5 msec case and adjusting the time value to achieve the same amount of dye transfer.

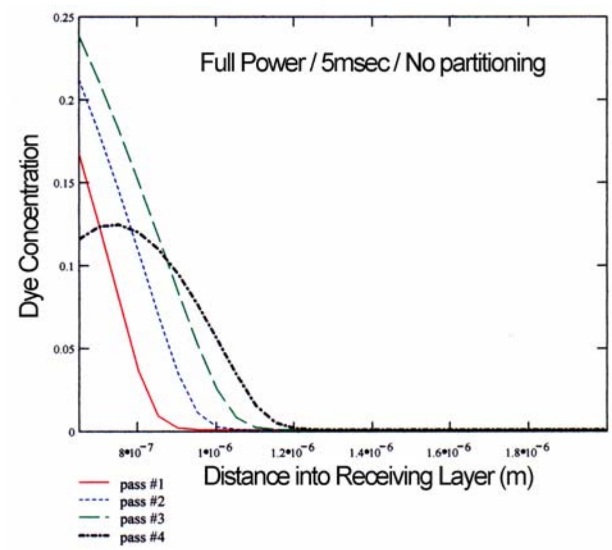

Figure 4. Dye Concentration Profiles

Using a power value that represents the maximum amount of power specified for the thermal printhead, calculations are performed using standard donor and receiver properties. This is shown in Figure 5 as the common 1.7 msec linetime value. Additional calculations were performed by varying one parameter while keeping all others constant. Three components were investigated: the thickness of the donor substrate, the amount of dye loaded into the donor ribbon, and the solubility ratio of the receiving layer to the dye layer. The donor thickness was reduced 25% for the second calculation and 50% for the third run. Similarly, the dye loading was increased by 25% for the second case and 50% for the third calculation. The receiver/donor solubility ratios were 1, 2, and 3, respectively. Figure 5 summarizes the results of these calculations. As one would suspect, the linetimes decrease as the donor becomes thinner (greater heat transfer), the dye loading increases (more dye), and the solubility ratio, commonly referred to as the partition coefficient, increases. Changing the amount of dye loading and the receiver solubility value affects the linetime prediction more than thinning the base of the donor ribbon. Such changes, however, can create additional problems that complicate their use.

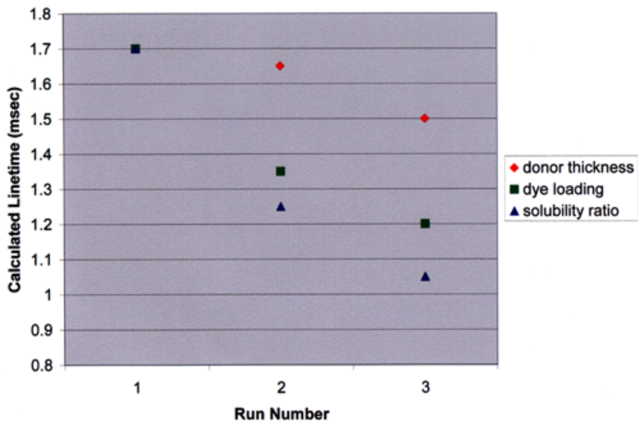

Figure 5. Predicted Linetimes

Assuming that all of these changes can be successfully implemented, one can calculate an "ultimate" linetime value for this system. A predicted linetime of 0.8msec (800 µsec) is obtained. Such sub-one msec time is very attractive for high productivity systems. This would enable fast turn around time at a thermal print station (kiosk) or even the capability of using this printer in a mini-lab environment.

Conclusion

The mathematics of the heat transfer/dye diffusion process has been represented using a finite-difference modeling technique. The approach has successfully described the profile of the dye in the receiving layer. The ability to apply a heat-flux boundary condition to the printhead has provided a better representation for the thermal input. Its ability to do multiple-pass calculations, to incorporate nonlinear diffusivity behavior, and to accommodate differences in solubility by using a partition coefficient has provided the user with a valuable design tool. This model has allowed one to investigate the influence of input power and material properties on print speed. From these calculations, linetime is seen to vary accordingly with an "ultimate" value predicted for the best-case situation.

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Biography

Edward Ozimek is a Research Associate with Eastman Kodak Company. He received a Ph.D. in experimental solid-state physics from Colorado State University in 1977 and joined Kodak in 1984. He is a member of the Electronic Imaging Products Division in the Research & Development Laboratories and has worked in the areas of magnetic recording, CCD image sensor packaging, and digital printing. In addition to being a member of the IS&T, he has been awarded 13 patents.