Use of Thermal Dye Diffusion Model to Predict the Effects of Increased Thermal Printhead Efficiency

Edward J. Ozimek
Eastman Kodak Company
Rochester, New York, USA

Abstract

A numerical, finite-difference model has been developed to simulate the dye-transfer thermal printing process. This model was used previously for calculating the amount and depth of the dye diffusion going into a receiver and for estimating the printing line times required for the dye transfer processes. The simulation incorporates the multiple layers of the head/media interface and uses finite-difference techniques to calculate temperature and mass distributions. Surface-boundary conditions have been determined from experimental printhead temperature data. 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 from known operating conditions, one is able to predict the amount of time required for an equivalent transfer to occur. The efficiency of heat transfer for a typical thermal resistive head is low (~15%). Producing a more efficient printhead will enable equivalent quantities of heat to be transferred at lower applied voltage levels. At the same voltage levels, larger amounts of heat transfer will result in faster printing speeds. Situations are analyzed for current thermal printer materials, and predictions are made for reduced printing time requirements.

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 into 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-enable 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 dye-diffusion thermal printer produces the highest quality output. 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 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 allows 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 3-D finite element code to study the thermal effects created by adjacently heated pixels. Connolly[3,4] created a 1-D 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. Others have done work in thermal and diffusion modeling, and the reader is directed to the published literature for further information.

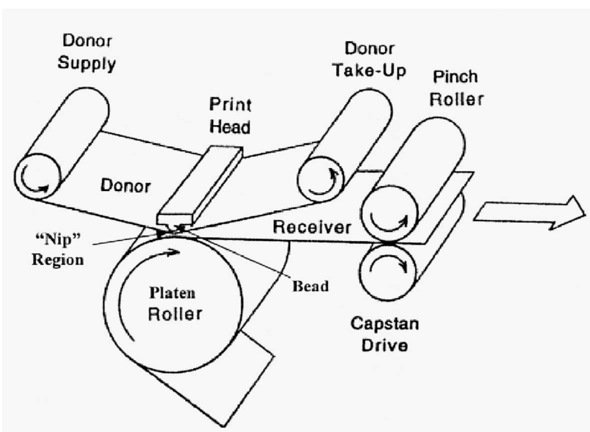

Figure 1. Thermal printer

One of the keys to our modeling approach is 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 is 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 describe a method for finding this boundary condition. With this 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 also account for the concentration dependence of the diffusivities that leads to a nonlinear diffusion equation. Finally, we 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 1-D heat equation can be written as:

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

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

The diffusion equation shown below cannot be solved as simply as Eq. (1) because some dyes used in the thermal printer industry have a concentration-dependent diffusivity leading to the non linear governing equation

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

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]

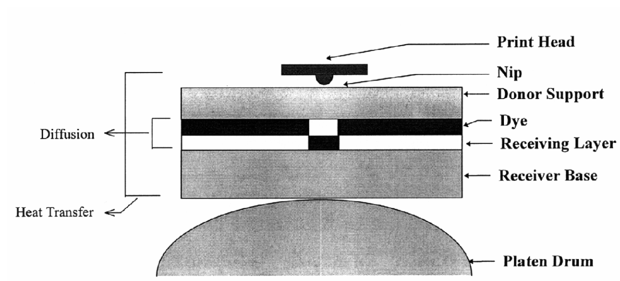

Figure 2. Cross-section of the printing system

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 fit 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^{2}K), 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.

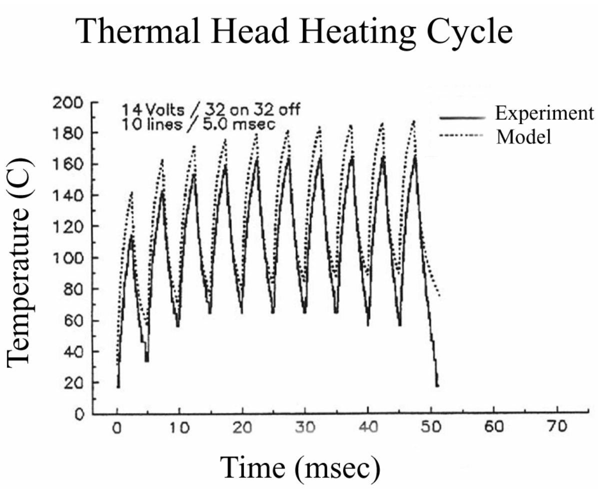

Figure 3. Head temperature values

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 were 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 ms line-time printer application as a reference point, calculations have been performed for varying amounts of head power, donor dye loading, solubility differences, and component thickness. Equivalent line times were determined by comparing the amount of dye transferred from the donor to the receiver to the amount calculated for the 5 ms case and adjusting the time value to achieve the same amount of dye transfer.[12]

The amount of heat transferred to the donor/receiver is a small portion of the energy going to the printhead. Using the values that were experimentally derived, and setting the term representing heat loss (h) to zero, one finds that an efficiency (α) value of 0.15 results in a similar temperature profile created when heat loss is considered.

Calculations were performed for head efficiencies ranging from 1X to over 4X the native value. A more efficient head will produce a larger thermal profile that will result in more dye being transferred. A faster line time will result in an equivalent amount of dye being transferred. Figure 5 shows the results of these calculations. The upper curve shows the amount of dye transferred, and it is quite uniform. Its corresponding line time is shown in the lower curve. The time has dropped from a starting point of 5ms to a value of 1.65ms at the opposite end. Thus, a 4.3X increase in efficiency resulted in a 3X improvement for line time.

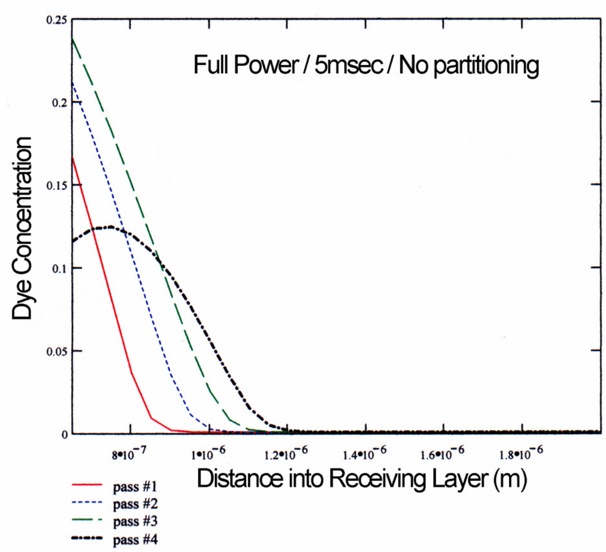

Figure 4. Dye concentration profiles

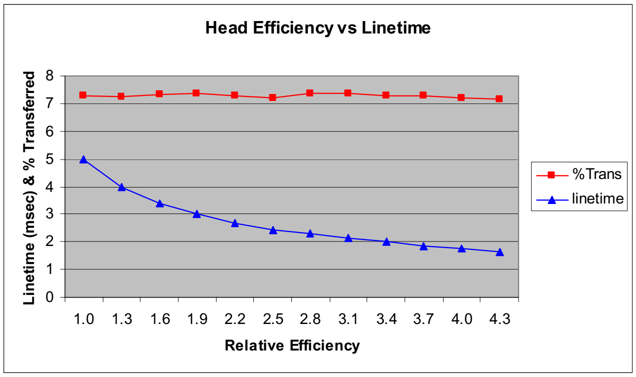

Figure 5. Predicted line times

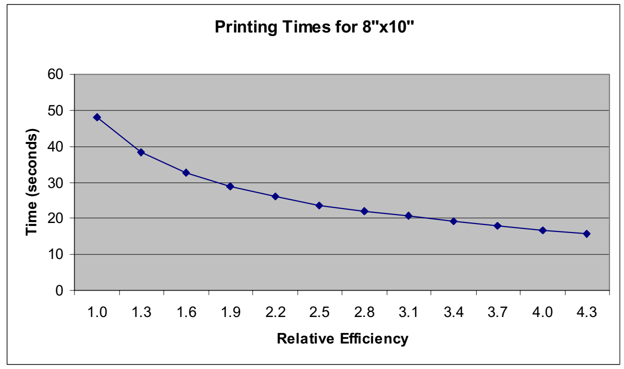

Figure 6. Printing times for 8 x 10 image

A faster line time will lower the printing speed of the system. Assuming we are printing an 8 x 10 image at 300dpi, and using three color passes and one lamination pass, we find that the print time varies from 48 s initially to under 15 s at the most efficient point. Refer to Figure 6.

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, in addition to accommodating differences in solubility by using a partition coefficient, has provided the user with a valuable design tool. This model has allowed investigation into the influence of the thermal printhead efficiency upon the printing speed of the system. A more efficient head will produce better heat transfer that will result in more dye being transferred. This will create shorter line times, which will result in faster printing speeds.

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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 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 and has 20 published papers.