Quantitative Characterization of the Effects of Ink Penetration in Ink Jet Printing

Li Yang*

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Abstract: Ink penetration has been known as one of the most critical factors that affect quality of color reproduction in ink-jet printing, when ordinary paper (say office copy-paper) is used as substrate. The effects of ink penetration can be sorted into two groups, color shift and reduction of color saturation. In this report we propose a method characterizing the effects of ink penetration, including depth of ink penetration and the optical properties of ink-paper mixture resulting from ink penetration. The method provides us with a framework for simulating ink-paper mixture from properties of corresponding components: inks and paper. With help of simulations, comparative studies of prints with and without ink penetration have been made.

Introduction

Ink penetration into substrates is a complex process, which depends on rheologic properties of liquid inks, surface characteristics of substrates, and bilateral interaction between inks and substrates. To understand the effects and, more favorably, to be able to characterize the effects of ink penetration are of essential importance in accomplishment of faithful color reproduction. For this purpose, a model reflecting the fundamental aspects of ink penetration is needed.

From Graphic Arts point of view, the fundamentals of ink penetration may include the following issues:

1. Optical properties of inks, and printed ink volumes.
2. Optical properties of substrates.
3. Optical properties of ink-paper mixtures, or how the optical properties of the inks are modified upon ink penetration.
4. Depth of ink penetration.
5. Effects of ink penetration on color performance of printed colors.

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*Campus Norrköping (ITN), University of Linköping, S-60174 Norrköping, Sweden.

The first issue concerns characterization of ink-jet inks and ink application controlled by an ink-jet engine. In TAGA conference of year 2002, we reported our work on this issue (Yang, 2002). In that work, we determined the scattering and absorption powers of inks ($s_q z_q$ and $k_q z_q$) of primary and secondary colors, and the ink volumes, z_q, (or ink layer thicknesses) controlled by printer, where the subscripts, $q=c,m,y$,r,g,b, denote primary and second colors. The second issue concerns the absorption and scattering properties of substrates. Knowledge of the optical properties of inks and substrates forms a ground for understanding and modelling ink penetration.

In this report we present our work concerning the rest three issues, i.e., the absorption and scattering properties of ink-paper mixtures, the depth of ink penetration, and the chromatic effects of ink penetration.

Model and Assumptions

Our model is based on the Kubelka-Munk theory, which provides us with an unified framework for determination of scattering and absorption powers of a midium layer: an ink-layer, sheet of plain paper, and an ink-paper mixture in the case of ink penetration. In this section, the model and related assumptions are described.

A. Model

For a medium layer whose scattering and absorption powers are *sz* and *kz*, where *s* and *k* are scattering and absorption coefficients of the medium, and *z* the medium thickness, the reflectance of the medium layer can be computed from

$$R = r_0 + \frac{(1-r_0)(1-r_1)\left[sz(Az - szR_g)e^{-\left[\frac{(sz)^2-(Az)^2}{Az}\right]} - Az(sz - AzR_g)\right]}{(Az - szr_1)(Az - szR_g)e^{-\left[\frac{(sz)^2-(Az)^2}{Az}\right]} - (sz - Azr_1)(sz - AzR_g)} \quad (1)$$

where

$$Az = sz + kz - \sqrt{(kz)^2 + 2kzsz} \quad (2)$$

r_0 and r_1 in Eq. (1) are the external and internal (from within the medium layer) boundary reflection values at the air/medium interface, and quantity, R_g, the spectral reflectance of a substrate lying under the medium layer. By fitting to two sets of measurement data, one obtains the scattering and absorption powers, *sz* and *kz*, of the medium.

If the scattering and absorption powers of primary inks are $s_q z_q$ and $k_q z_q$ ($q=c,m,y$), scattering and absorption powers of secondary colors that are mixtures of primary inks, can be expressed as superpositions of those of their primary components. Color red, for example, is composed of ink magenta and yellow. Its scattering and absorption powers can thus be expressed as

$$
\begin{aligned}
s_r z_r &= \beta_m{}^r s_m z_m + \beta_y{}^r s_y z_y \\
k_r z_r &= \beta_m{}^r k_m z_m + \beta_y{}^r k_y z_y
\end{aligned}
\tag{3}
$$

where β_q^t (q=m,y and t=r) are the amounts of primary colors. β_q^t can be determined by fitting to measured spectral reflectance values of secondary colors, and have been known from our previous studies (Yang, 2002 and 2003a).

Ink penetration results in an ink-paper mixture. If the scattering and absorption powers of a single sheet of paper are $s_p D$ and $k_p D$, the scattering and absorption powers of ink-paper mixture may be expressed as

$$
\begin{aligned}
s_{qp} D d_{qp} &= s_q z_q + s_p D d_{qp} \\
k_{qp} D d_{qp} &= \mu k_q z_q + k_p D d_{qp}
\end{aligned}
\tag{4}
$$

where D is the thickness of the paper sheet, and d_{qp} the depth of ink penetration (in percentage of D). Quantity μ in Eq. (4), is a factor depending on light distribution within the ink-paper mixture. In the case of diffuse light distribution, $\mu = 2$. Detailed discussions about this issue can be found in Ref. (Yang, 2003b).

Substituting s and k in Eqs. (1, 2) by s_{qp} and k_{qp}, one can then predict the spectral reflectance values of the ink-paper mixture, provided s_{qp} and k_{qp} are known.

Because quantities, $s_q z_q$, $k_q z_q$, β_q^t ($q=c,m,y$ and $t=r,g,b$), and $s_p D$, $k_p D$, have been known from our previous studies (Yang, 2002), the only unknown quantity in Eq. (4) is d_{qp}, i.e., the depth of ink penetration. Therefore, by fitting to experimental spectral reflectance values of prints on plain paper, one can actually determine, d_{qp}, the depth (in percentage of the paper thickness, D) of ink penetration for each color.

B. Assumptions

1. Paper making materials, fibres, fillers, etc., are uniformly distributed in the paper.

2. Ink concentration within the paper is uniform and independent of the depth of ink penetration.

3. No ink is left on the surface of the paper and consequently, the depth of ink penetration is proportional to amounts of the printed inks.

4. Light becomes completely diffused once it enters the paper and ink-paper mixture.

5. The scattering and absorption powers of ink-paper mixture fulfill the additivity assumption (expressed in Eq. (4)).

Introduction of the first two assumptions is for simplicity of studies as being a first attempt to simulate ink penetration. With the help of the mathematical framework developed for non-uniform ink penetration (Yang, 2000, Yang, 2003b), this model can readily be extended to non-uniform cases, when needed. Additionally, the second assumption may be a reasonable approximation for a combination consisting of dye-based liquid inks and plain paper. Because sizes of the cellulose pores in the paper are generally much larger than that of the dye micro-cell (100 Å), ink can easily penetrate into the substrate, which results in little gradient of ink concentration. On the other hand, the inks are completely absorbed by the substrate which forms the fundamental aspect for the third assumption.

Physical considerations behind assumption No. 4 are that the paper materials have a very strong scattering power. The strong scattering power of the paper materials leads to a very strong scattering power of the ink-paper mixture. Therefore, light becomes diffused in the ink-paper mixture. Such a consideration is of fundamental importance in the current study, for an approporiate application of the additivity assumption (assumption No. 5).

Quantity k is a phenomenological description of light absorption in the medium, which depends not only on the physical properties of the medium but also on light distribution within the medium. Considering the fact that the ink is of little scattering power, light propagates essentially through a straight path within the ink layer. Correspondingly, the absorption power, $k_q z_q$, is responsible for the light extinction along that path. However, in the ink-paper mixture, the light is scattered and consequently propagates in a zigzag fashion. The light propagates a longer path and has, therefore, a greater possibility of being absorbed, if it passes the same vertical depth within the ink-paper mixture as that within the ink layer. Thus, the averaged absorption power of the ink in the ink-paper mixture becomes $2k_q z_q$, if the light is completely diffuse in the layer. It was experimentally observed that the absorption power of the colored paper is approximately twice that of the cellophane compared at a given amount of dye (Borch and Scallan, 1976).

The additivity assumption given by assumption No. 5 has been confirmed valid in the case of color mixing, i.e., the secondary colors are composed of primary inks (Yang, 2002, 2003a). As one will see later, that it holds even for the ink-paper mixtures, if a factor of 2 is introduced into the absorption coefficient of the inks, because of the diffuse light distribution in the ink-paper mixtures (see Eq. (4)).

Characteristics of inks and paper

For convenience of the discussion, the characteristics of the inks and the paper are briefly presented in this section.

A. Optical properties of the inks

Determination of the scattering and absorption powers of the inks, $s_q z_q$ and $k_q z_q$ (q=c,m,y), need two sets of measured spectral reflectance values, R_I and R_{II}. These two sets of data are obtained from measurements of full tone samples printed with two different ink thicknesses. The samples are once (R_I) and twice (R_{II}) printed, respectively, with the same ink amount. Assuming the thickness of the twice printed ink layer is twice that of the once, one can drive the following relation,

$$\frac{sz - AzR_{II}}{Az - szR_{II}} = \frac{(sz - AzR_I)^2 (Az - szR_g)}{(sz - AzR_g)(Az - szR_I)^2} \tag{5}$$

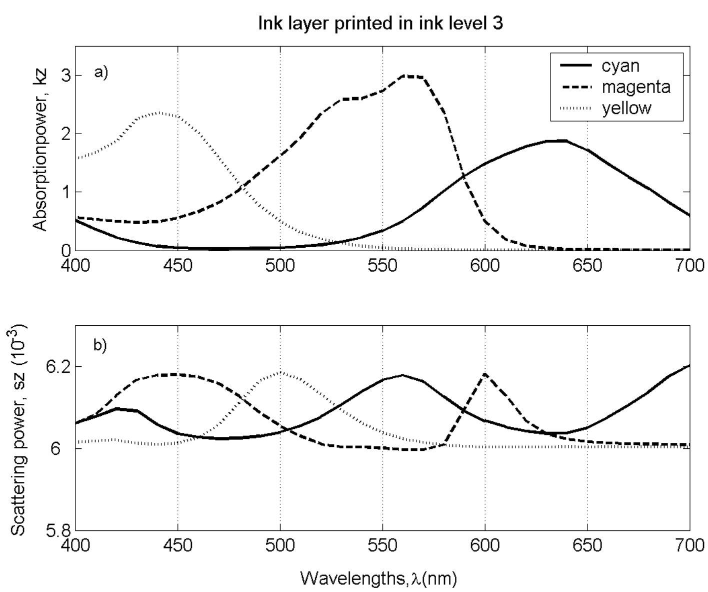

Figure 1, Scattering and absorption powers of primary inks.

Additionally, when the boundary reflection is negligible, or, $r_0=r_1=0$, one has (from Eq. (1))

$$R=\frac{sz(Az-szR_g)e^{-\left[\frac{(sz)^2-(Az)^2}{Az}\right]}-Az(sz-AzR_g)}{Az(Az-szR_g)e^{-\left[\frac{(sz)^2-(Az)^2}{Az}\right]}-sz(sz-AzR_g)} \quad (6)$$

Combining Eqs. (5) with (6), one can fully determine the scattering and absorption powers of inks, s_qz_q, A_qz_q, and in turn, k_qz_q, through Eq. (2).

The scattering and absorption powers of primary colors (ink level 3) are shown in Fig. 1. As been expected, inks cyan, magenta, and yellow show strong absorption in the long-, middle-, and short-wavelength bands, respectively. In other words, cyan has a transparent window in the short to middle wavelengths, yellow has a window in the middle to long wavelengths, and magenta has two widows in short and long wavelengths, respectively. Nevertheless, the scattering power of the inks is rather weak and has values of about 0.006. It means that the scattering power of the dye based ink layer is practically negligible, which is favorable for creating color of high saturation.

B. Optical properties of the office copy-paper

Similar to inks, the scattering and absorption powers of the office copy-paper, s_pD and k_pD, are determined by applying two sets of spectral reflectance values, R_w and R_k which correspond to the reflectance values of a single sheet of paper of two types of backings, black (R_k) and white (R_w), respectively.

Let R= R_w and R=R_k in Eq. (1), one has two equations about the scattering and absorpttion powers of the paper, s_pD and k_pD. Solving these equations numerically, one gets s_pD and k_pD. The simulations of the clean paper and the ink-paper mixture reveal existence of boundary reflectation at the air/paper interface. According to simulations, the experimental spectra are best fitted, when the refractive index, n=1.2. Additionally, a UV filter was employed in measurements in order to minimize effects of fluorescence.

The scattering and absorption powers of a single sheet of office copy-paper is shown in Fig. 2. The paper shows little absorption to green and red light, but it absorbs somewhat blue light. Nevertheless, the absorption is still much weaker than that of the inks as shown in Fig. 1. On the contrary, the paper has much stronger scattering power than that of the inks. The scattering power of the paper is nearly constant in green to red light regions, but gradually increases from green to blue light wavelength regions, and reaches its maximum at about λ=430nm. After that it decreases sharply toward even shorter wavelength region. This observation generally coincides with the fluorescence distribution observed by bi-spectral measurements (Mourad, 2002) and may indicate existence of residual fluorescence which survives from the UV filtering. Combination of the increasing absorption with decreasing scattering at the short blue region makes the paper less reflective in this wavelength region, if there are no brightening materials added.

The possible failure in completely removing the fluorescence from the measurements will cause errors in determination of the scattering and absorption powers of the paper. Consequently, these errors will result in errors in the simulations of the ink-paper mixture. Indeed, there exists remarkable discrepancy between the simulations and the measurements of cyan and blue, as one will see it later on.

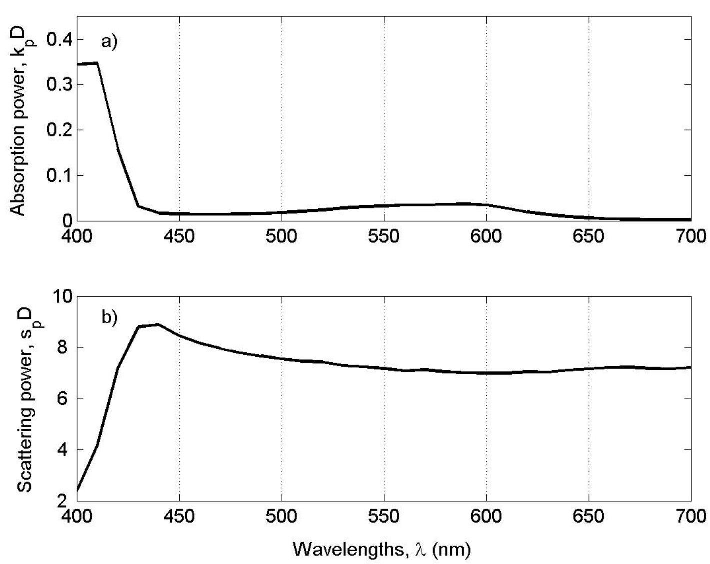

Figure 2. Scattering and absorption powers of a sheet of office copy- paper.

Simulation of prints on office copy-paper

Full tone samples (solid patches) of primary and secondary colors were printed on the office copy-paper, where the secondary colors are mixtures of two of the three primary colors. By varying ink-level specifications in the printer driving software (commonly available from the printer manufacturer), one can obtain samples printed with up to 5 ink levels (ink-volume increases from ink-level 1 to 5). Measurements were carried out by applying a spectrometer, which covers a spectral range of 380 to 730 nm at a interval of 10 nm. A UV filter was employed in order to minimize the impact from fluorescence.

A. The primary colors

According to assumption No. 4, light distribution in the ink-paper mixture is completely diffuse. The scattering and absorption powers of the ink-paper mixture can therefore be written as

$$\begin{aligned} s_{qp} Dd_{qp} &= s_q z_q + s_p Dd_{qp} \\ k_{qp} Dd_{qp} &= 2k_q z_q + k_p Dd_{qp} \end{aligned} \tag{7}$$

where q=c,m,y represent for primary colors, and d_{qp} the depths of ink penetration.

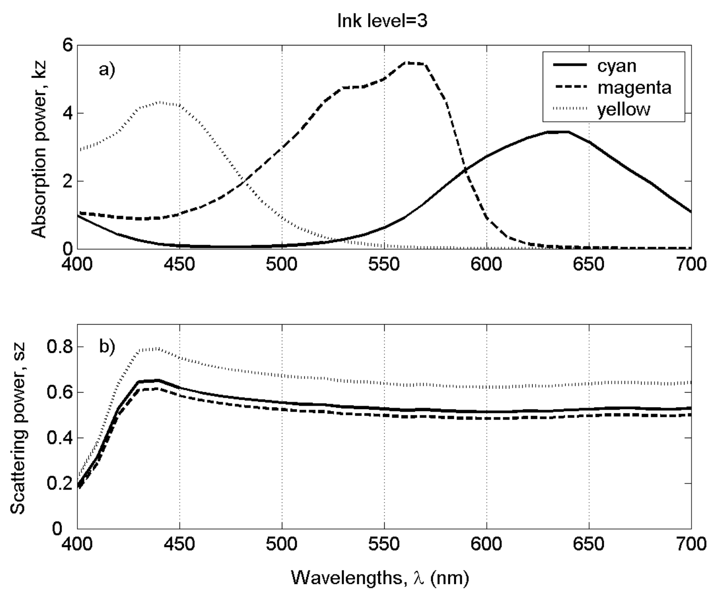

Figure 3. Scattering and absorption powers of the ink-paper mixture (ink level 3).

Because of existence of discontinuity of refractive index at the air/paper interface, boundary reflection between the air and the paper (or ink penetrated paper) has to be considered. Simulations showed that a relative refractive index, *n=1.2*, provided the best fit to the measured spectral reflectance values of both printed and non-printed paper. Correspondingly, the external and internal boundary reflection values in the case of diffuse light distribution are, $r_0=0.0443$ and $r_1=0.3363$.

The scattering and absorption powers of the ink-paper mixture of print (ink level 3) have been depicted in Fig. 3. Evidently, the scattering power of the ink penetrated paper bears a general similarity to that of the bare paper. On the other hand, the absorption power is of similar shape to that of the inks. These observations reflect the facts that the scattering characteristics of the ink-paper mixture are predominated by the paper and the absorption characteristics by the inks.

A comparison between the simulated and the measured spectral reflectance values of the primary inks of ink level 3 is shown in Fig. 4. Generally speaking, agreement between the experiments and the simulations are fairly good, for all the colors and over the entire visible spectra. Color differences between the measurements and the simulations are just about visible, and $\Delta E=3.28$, 4.14, and 5.15, for cyan, magenta, and yellow, respectively. The remarkable discrepancy occurs, for ink cyan at around λ=460 nm, may be a consequence of the residual fluorescence resulting from the brightening substances of the paper as being observed from the bare paper.

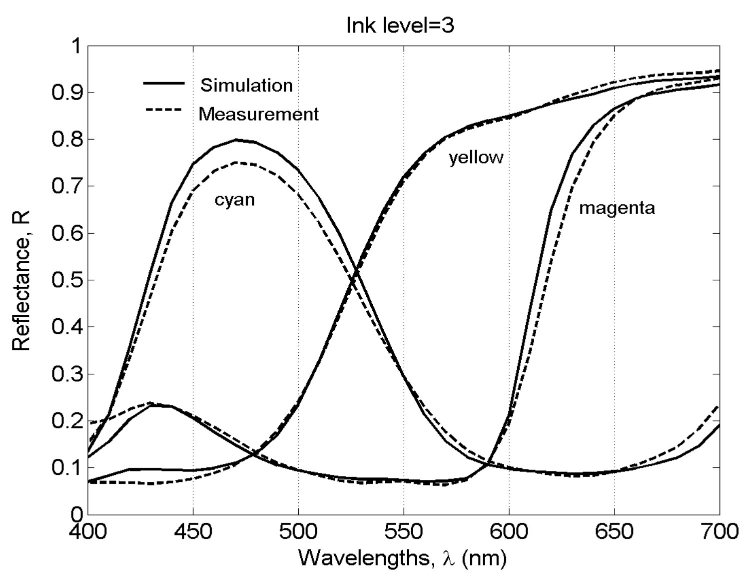

Figure 4. Spectral reflectance values of the primary colors printed on the office copy paper (ink level 3).

Bispectral fluorescence measurements made by Mourad (Mourad, 2002) revealed that, for a brightened paper, the fluorescence has its peak at about λ=450 nm and the fluorescence had remarkable contribution even to the spectra of the printed cyan and blue in λ=400-480 nm region. Therefore, there is a need of independent studies on the efficiency of the UV filter employed in the present measurements. Such studies may provide clues to a better understanding of the discrepancies.

Closer observation of the spectra of all the primary colors reveals that the minima of the reflectance values are far from zero and are generally independent of the color. This is in remarkable contrast to those observed from the ink layers (Yang, 2002 and 2003a), where the minima were actually zero.

The possible explanation to the observation is the boundary reflection occurring at the boundary between the air and the ink penetrated paper. Another possible origin lies at the strong scattering power of the ink-paper mixture that contributes to the light reflection.

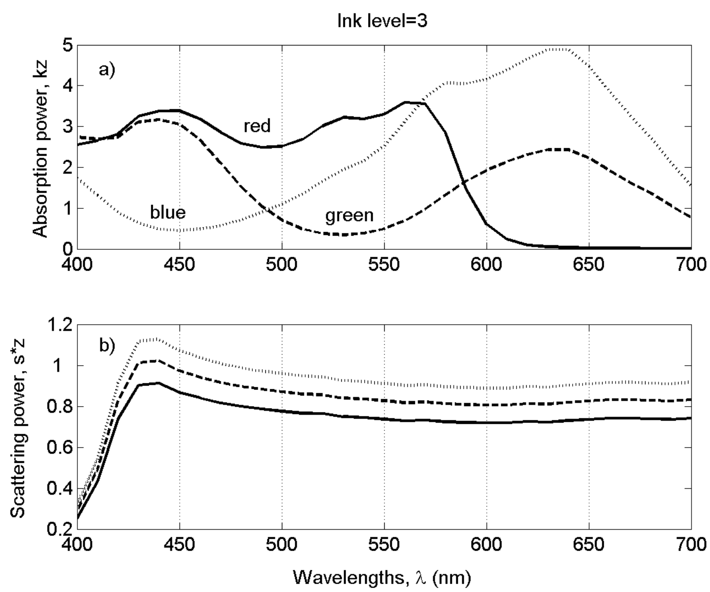

Figure 5. Scattering and absorption powers of the ink-paper mixture of secondary colors (ink level 3).

B. The secondary colors

Reliability of the quantities, d_{qp}, obtained from the primary colors (on the paper) subject direct tests when they are applied to predict spectral reflectance values of secondary colors. For secondary colors, according to assumption No. 5, the scattering and absorption powers of the ink-paper mixture may be expressed as (color red, r, for example),

$$
\begin{aligned}
s_{rp} D d_{rp} &= \beta_m{}^r s_{mp} d_{mp} + \beta_y{}^r s_{yp} d_{yp} \\
k_{rp} D d_{rp} &= \beta_m{}^r k_{mp} d_{mp} + \beta_y{}^r k_{yp} d_{yp}
\end{aligned} \tag{8}
$$

The scattering and absorption powers of the ink-paper mixture of the secondary colors (ink level 3) is shown in Fig. 5. Similarly to those of the primary colors, the scattering is predominated by the paper and the absorption by the inks.

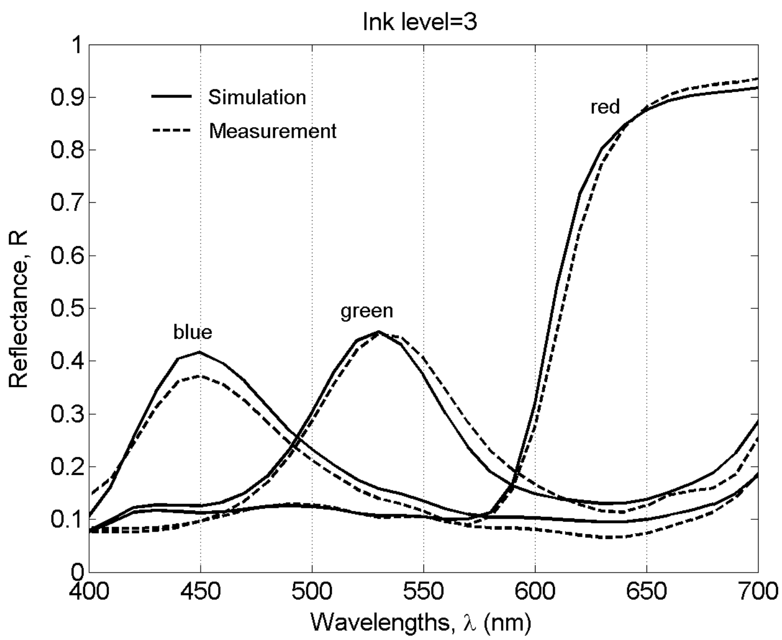

Figure 6. The spectral reflectance values of secondary colors printed on the office copy-paper (ink level 3).

All the quantities, in Eq. (8), have been known, namely, β_q^r and D from the previous studies (Yang, 2002, and 2003a,b) while, $s_{qp}d_{qp}$ and $k_{qp}d_{qp}$, from the previous subsection. Therefore, by applying $s_{rp}d_{rp}$ and $k_{rp}d_{rp}$ to Eq. (1), one can predict the spectral reflectance values of the secondary colors. Because there is no data fitting involved in predicting the spectra of the secondary colors, a comparison between the predicted and the measured spectral values provides us with a test to the availability of the model and the reliability of the parameters obtained. The predicted spectra of the secondary colors (ink level 3) are depicted in Fig. 6, together with the correspondent experimental values. As seen, the prediction is in fairly good agreement with the experiments of all the secondary colors and over the entire visible wavelength region.

It is convenient to measure the depth of ink penetration in terms of the percentage of the thickness of a single sheet of paper. The depths of ink penetration, of both primary and secondary colors and all 5 ink levels, are demonstrated in Fig. 7. Observe that only the depths of the primary colors were obtained by fitting to the measured spectral reflectance data, all the rest were actually computed according to Eq. (8).

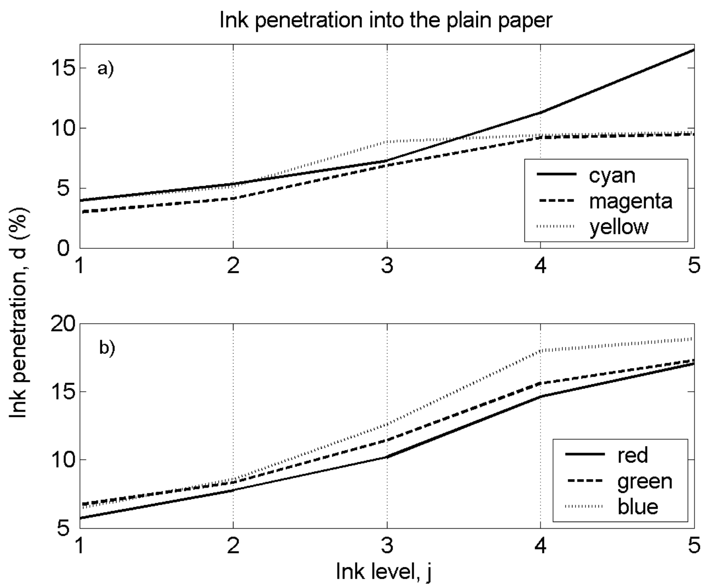

Figure 7. Depthes of ink penetration of the primary and secondary colors.

Optical effect of ink penetration

In order to evaluate consequences of ink penetration, it is desirable to directly compare prints with and without ink penetration by using the same type of substrate. Unfortunately, there exists no substrate which allows for ink penetration to be *switch on* or *off* at will. In practice, to avoid ink penetration, a paper surface is modified by coatings. In other words, a high grade paper other than the original is used. Such a modification to the paper surface can indeed reduce or even eliminate ink penetration into the cellulose structures. Nevertheless, this changes the (optical, fluid dynamic, etc.) properties of the paper which essentially implies another type of substrate.

Although there is no direct experimentally possible comparison, it can be achieved with help of simulations. The comparison is made for print of ink level 3 (the default ink level of the printer). Because the scattering and absorption powers of the inks ($s_q z_q$, $k_q z_q$), and the ink-paper mixture ($k_{qp}Dd_{qp}$, $s_{qp}Dd_{qp}$) are known from our studies, the spectral reflectance values of *prints on the office copy-paper* with and without ink penetration can be simulated according to Eq. (1). In the case of no ink penetration, boundary reflection between the air/ink interface is ignored ($r_0=r_1=0$), while $r_0=0.0443$ and $r_1=0.3363$ in the case of ink penetration.

The simulation results for the primary and secondary colors have been depicted in Fig. 8. From the figure one can clearly see the significant effect of ink penetration. Interestingly enough, the effect shows a strong wavelength dependence. For convenience of discussion, we refer to the band containing the local maximum as the *transparent* band and that containing the local minimum as the *absorption* band. In the transparent band, the print for the case of no ink penetration has greater reflection compared to that with ink penetration. In contrast, in the case of the absorption band, the print with ink penetration shows stronger reflection than that without. These observations reflect the collective contribution to light reflection from the substrate, the ink-layer, and ink-paper mixture. In the case of no ink penetration, the print consists of an ink-layer and a substrate backing (plain paper), while in the case of ink penetration it consists of an ink-paper mixture layer and the substrate backing. As is known the ink-layer (no ink penetration) has little scattering power, the reflection in the transparent band is essentially due to reflection from the substrate. Comparatively, the layer of the ink-paper mixture has much stronger scattering power which blocks the light from reaching the substrate backing to some extent. On the other hand, the absorption power of the ink-paper mixture (there exists absorption even in the transparent band of the ink) is twice that of the pure ink-layer. These factors work together and result in weaker reflection for the print with ink penetration. In the absorption band, on the other hand, the light is dramatically attenuated by absorption when it passes through the ink-layer (in order to be reflected by the substrate). Nevertheless, the light may return to the air before it passes through the ink-paper mixture due to scattering of the paper materials, which makes the ink-paper mixture more reflective.

Table 1. Color differences ΔE induced by ink penetration.

color	cyan	magenta	yellow	red	green	blue
ΔE	13.13	31.98	30.61	29.20	36.97	25.40

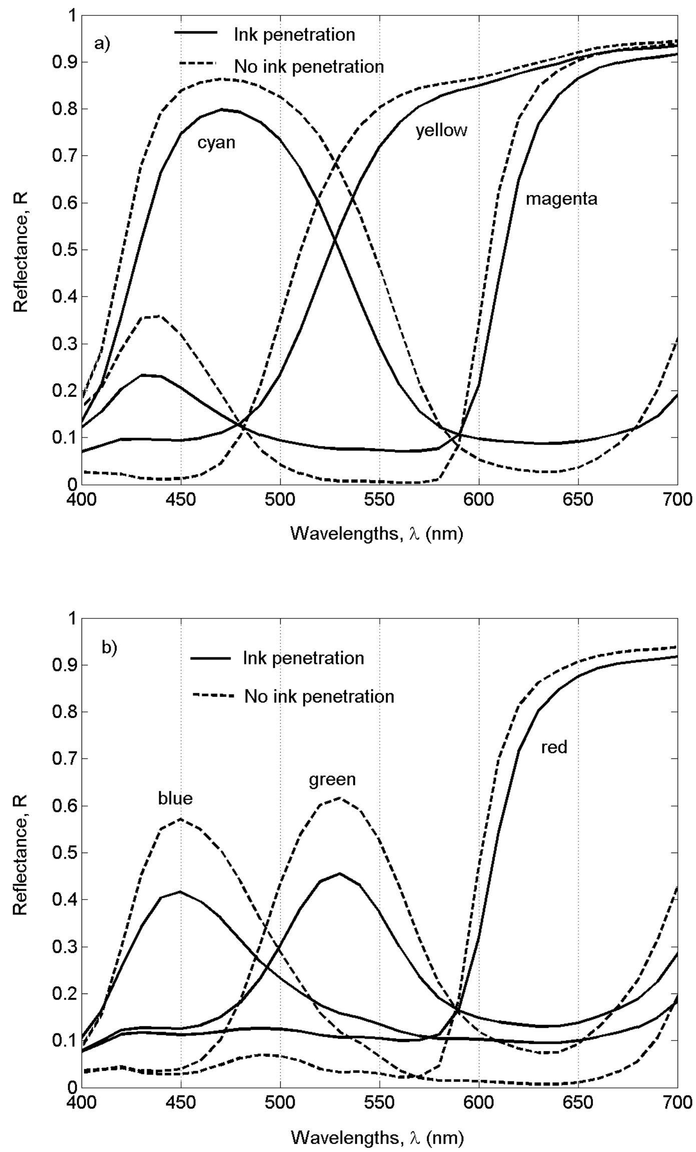

Figure 8. Comparison of colors printed on the office copy-paper, in the case of with and without ink penetration.

Ink penetration also has significant effects on the color appearance of the print. Because color saturation depends on the contrast between the peaks of the transparent bands to the bottoms of the absorption bands, the comparison suggests that ink penetration significantly reduces the saturation of the printed color. At the same time, it causes even color shift (hue variation) because of nonlinear modifications to the spectral reflectance values by ink penetration. A quantitative measurement of the color difference induced by ink penetration is given in Tab. 1. Clearly, ink penetration has a significant impact on the color reproduction. Detailed discussions about the impact of ink penetration on the color rendition and, correspondingly, their graphical representations may be found elsewhere (Yang, 2003b).

Summary

In this presentation, a model accounting for optical effects of ink penetration in printing systems consisting of dye based liquid ink and plain paper is presented. The model uses optical properties (scattering and absorption powers) of inks and paper as inputs to simulate ink-paper mixtures, resulting from ink penetration. A method used for determination of fundamental quantities, like depth of ink penetration, by combining spectral reflectance measurements with simulations has been proposed and tested. A parallel comparison between prints with and without ink penetration has been made and, it has been shown that ink penetration causes significant reduction of color saturation and hue shifting.

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