Characterization of Ink Properties in Ink Jet Printing

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Abstract: The ink-jet printing quality is primarily determined by the paper substrate, the printer and its inks. The printer controls the process of ink application and the scheme of ink mixing for the generation of secondary and tertiary colours. The inks selectively absorb different wavelengths from the illumination and produce the visible colour output. Therefore characterizations of the output print in terms of ink distribution and volume, the scheme of ink-mixing, light absorption and light scattering are of essential importance in controlling and understanding the quality of the colour reproduction. In this paper, we present a method to characterize the ink volume and the properties of the ink by means of spectral reflectance measurements together with theoretical simulations. The scheme of colour composition for generating the secondary colours were also obtained. Measurements confirm the model for rendition of colour prints.

Introduction

Ink-jet is a non-impact dot-matrix printing technology in which droplets of inks are jetted from a small aperture directly to a specified position on a substrate to create an image (Le98). An ink jet printing system may be divided into three critical components, the printer, the inks and the substrate (Bahr et al 2001). Briefly speaking, the printer acts as a distributor for the ink droplets and the substrate acts as a receiver. It is the ink droplets that provides the colors by selectively reflecting (or more precisely, selectively absorbing and scattering) the illuminating light. Therefore these three components together control quality of the printed image. Substrate related issues including optical dot gain (or Yule-Nielsen effect) and ink-paper interaction, say ink penetration, have been reported elsewhere (Arney 1997, Rogers 1998, Yang *et al* 2001a,b,c).

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The printer- and the ink-related issues include, among others, where the ink is placed and by how much, how the primary inks (cyan, magenta and yellow) are mixed in order to obtain the secondary colors (red, green and blue), and of course, the optical properties of the inks (scattering and absorption coefficients). In this report we present our work in characterizing the printer- and ink-related issues.

In the next section, we describe briefly our methods for experimental measurements and for theoretical modelling and simulation. It is followed up with presentations of he experimental and simulated results with explanations and discussions. In the final section we summarize the work and conclusions.

Experiment, data analysis and simulation

This section consists of a brief description for the experimental measurements and theoretical backgrounds for the data analysis and simulation.

A. Samples and measurements

The full tone samples were printed with primary- (cyan (c), magenta (m), and yellow (y)) and secondary-colors (red (r), green (g) and blue (b)). In order to prevent the inks from penetrating into the substrate, ink-jet films were used as the substrates. Therefore the sample consists of an ink layer and the plastic substrate. By varying ink-level specification in the printer driving software, one can obtain samples printed with up to 5 ink levels with the ink-volume increasing from the ink-level 1 to 5 (the number of the ink level specification depends on the printer and its driving software).

The measurements were carried out by applying a spectrometer, which covers the a range of wavelength from *380* to *730 nm* with an interval of *10 nm*. To achieve high reflection from the samples, a white and opaque background (a bunch of white paper) has been put under the samples. The spectral reflectance values of the colored area were measured.

B. Data analysis and simulation

According to the Radiative Transfer Theory (Chandrasekhar 1944), the spectral reflectance value of an ink layer is a function of its scattering- and absorption-lengths, $s_q(\lambda)z_q$ and $k_q(\lambda)z_q$, i.e.

$$R_q(\lambda, z_q) = f(s_q(\lambda)z_q, k_q(\lambda)z_q) \tag{1}$$

where $s_q(\lambda)$ and $k_q(\lambda)$ are the scattering- and absorption-coefficients and z_q is the thickness of the ink layer. The subscript, q, is an index of the inks, and $q=c,m,y$ means cyan, magenta and yellow, respectively. When the interface reflection is negligible, the function in Eq. (1), according to Kubelka-Munk (K-M) theory (Kubelka and Munk 1931), may be written as (Pauler 1987)

$$f(sz, kz) = \frac{(R_\infty - R_g)\exp\left(-\left(\frac{1}{R_\infty} - R_\infty\right)sz\right) - R_\infty(1 - R_g R_\infty)}{R_\infty(R_\infty - R_g)\exp\left(-\left(\frac{1}{R_\infty} - R_\infty\right)sz\right) - (1 - R_g R_\infty)} \tag{2}$$

where $R_g(\lambda)$ is the spectral reflectance of the bare substrate, while

$$R_\infty(\lambda) = 1 + \frac{k}{s} - \sqrt{\frac{k^2}{s^2} + 2\frac{k}{s}} \tag{3}$$

stands for that of an infinitely thick ink layer. Therefore by fitting to two sets of the measured spectral reflectance values, one can sufficiently determine the scattering- and absorption-lengths of the ink layer.

In data analysis, the scattering- and absorption-lengths of the primary inks ($s_q(\lambda)z_q$, $k_q(\lambda)z_q$) were first obtained by fitting to two sets of the spectral reflectance values of the samples printed with a certain ink level, say ink level 3. Then these scattering- and absorption-lengths were applied to compute the spectral reflectance values of the samples printed with other ink levels (ink level 1,2,4 and 5). By such applications, one can test the quality of the obtained scattering and absorption data. The thickness of the ink layer printed with different ink levels was estimated by fitting the computed spectral reflectance value

$$R_q(\lambda, \alpha_q z_q) = f(\alpha_q s_q(\lambda) z_q, \alpha_q k_q(\lambda) z_q) \tag{4}$$

to the experimental one. The quantities α_c, α_m, and α_y have therefore meanings of relative (to z_c, z_m, and z_y) ink thicknesses for cyan, magenta and yellow, respectively.

After obtaining the scattering- and absorption-lengths of the primary inks, one can compute the scattering- and absorption-lengths of the secondary colors ($s_q(\lambda)z_q$, $k_q(\lambda)z_q$, $q=r,g,b$) by applying the assumption of additivity (Pauler 1987). For color blue, $s_b(\lambda)z_b$ and $k_b(\lambda)z_b$ may be expressed as

$$s_b z_b = \beta_c s_c z_c + \beta_m s_m y_m \tag{5}$$
$$k_b z_b = \beta_c k_c z_c + \beta_m k_m y_m$$

where $s_q(\lambda)z_q$, $k_q(\lambda)z_q$ $(q=c,m)$ are the scattering- and absorption-lengths of the ink cyan and ink magenta, as defined in Eq.(4). Therefore by substituting

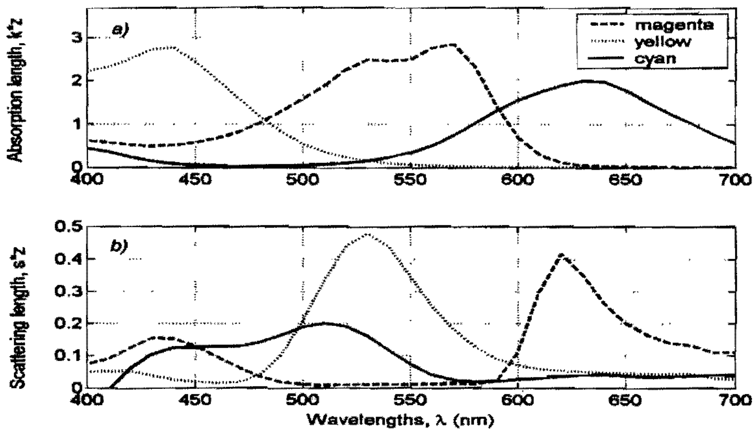

Figure 1: Scattering- and absorption-lengths of the primary inks obtained by fitting into the measured spectral reflectance values of samples printed on ink-jet films with (printer driving) program specified ink level 3.

$s_b z_b$ and $k_b z_b$ into Eqs.(1-3), one can compute the spectral reflectance values of blue, R_b. Inversely the contribution from the primary inks β_c, β_m can be determined by fitting to the measured spectral reflectance values of the secondary color (blue). Observe that the quantities, β_c and β_m, are defined exactly the same way as α_c and α_m in Eq. (4). Therefore they are the primary ink amounts relative to z_c and z_m that are needed to obtain the blue color.

Results and discussions

In this section we present the experimental measurements together with our theoretical analysis and simulations. The spectral absorption- and scattering-lengths (kz and sz) of the primary inks were obtained by fitting to the experimental spectral reflectance values of samples printed with ink level 3 that is specified by the printer driving software. In order to sufficiently determine the sz and kz values, another set of experimental data (spectral reflectance values) is needed. It was achieved by measuring a sample that was twice printed with ink level 3 (the sample was printed and dried 24 hours before the secondary printing).

A. Spectral characteristics of the primary inks

The scattering- and absorption-lengths of the primary colors are shown in Fig. 1.

As being expected inks cyan, magenta, and yellow show strong absorption-lengths in long-, middle- and short-wavelength regions (noted as absorption regions hereafter), respectively. In the other words, they have transparent windows in the short-, middle- and long-wavelength regions (noted as window regions hereafter), respectively.

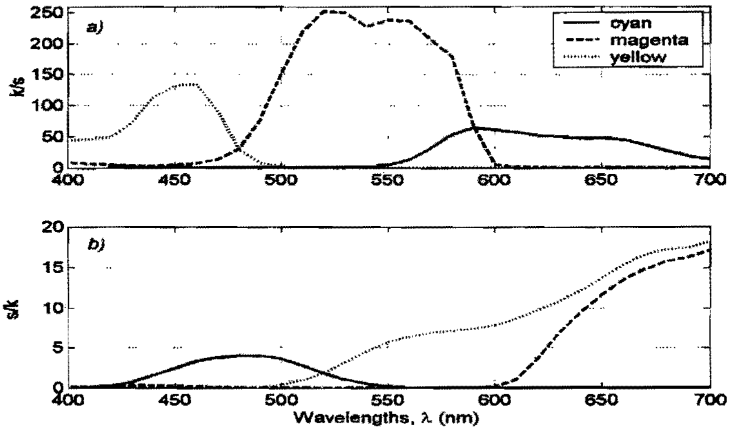

Figure 2: Spectral variation for the relative strength of the absorption and the scattering.

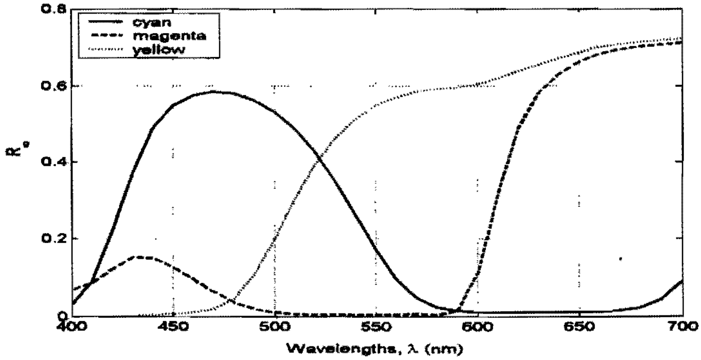

Figure 3: spectral reflectance values of primary inks with infinitely thick ink layer.

Interestingly enough, the inks show remarkable scattering strengths in their window-regions (compare to the absorption in the same regions), even though, their peak values are 8 to 10 times smaller than those of their absorption-lengths. Observe that the spectral reflectance values depend not only on the absolute values of their scattering- and absorption-lengths, but more importantly on their relative strength (it can be clearly seen from the expression of R_{oo}). In the absorption regions (see Fig. 2), the absorption is the dominant factor ($k/s >> 1$) and the spectral reflectance of the thick ink layer (R_{oo}, see Fig. 3) becomes eventually zero. On the contrary, in the window regions of each color, the scattering process plays a dominant role ($s/k >> 1$). Consequently it makes the color visible even for a thick ink layer where reflection from the substrate background becomes negligible (see Fig. 3).

It has usually been said that inks are of strong absorption but of little scattering. This kind of statement is conditionally correct only, i.e. in the ink's absorption regions. In the window regions, the scattering can nevertheless play a dominant roll as we have seen from Fig. 2. This theoretical prediction can be verified experimentally and will be reported elsewhere (Yang 2002).

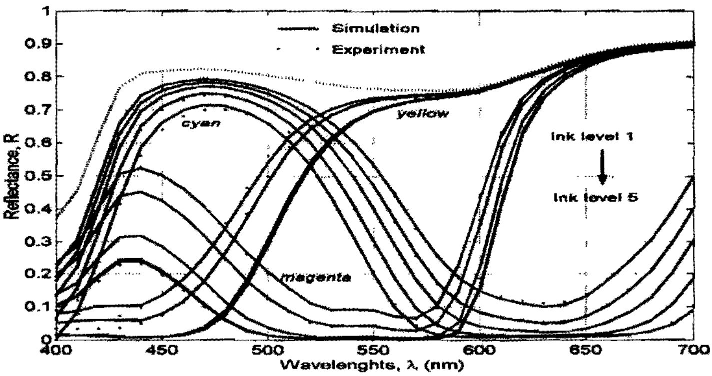

Figure 4: Simulated and measured spectral reflectance values for samples printed with different (printer driving) program specified ink levels. The dot line (on top) is the spectral reflectance values of the bare film.

B. Spectral reflectance values and relative ink thickness of primary inks

The scattering- and absorption-strengths, $s_q(\lambda)z_q$ and $k_q(\lambda)z_q$, were obtained by fitting the computed spectral reflectance values of samples printed in ink level 3 (correspondingly ink thicknesses are z_q, $q=c,m,y$) to the corresponding experimental values. It is worthwhile to test their reliability quantitatively. The test was made by applying the scattering- and absorption-strengths to compute spectral reflectance values of samples printed with other 4 ink levels (ink level 1,2,4 and 5) and to compare to the measured values. Because the different printing ink volume (ink level) results in differently thick ink layer on the substrate, the scattering- and absorption-lengths of one sample may be expressed as $\alpha_q s_q(\lambda) z_q$ and $\alpha_q k_q(\lambda) z_q$ where the quantity, α_q, stands for the relative ink thickness.

The simulated spectral reflectance values together with the measured ones, for the samples printed with 5 ink levels, are shown in Fig. 4. The excellent agreement between the computed and the measured spectral reflectance values over the whole range of visible light (there are 31 wavelength-sampling points over this range in the measurements) may be considered as a confirmation to the method validity and to the reliability of the $s_q(\lambda)\ z_q$, $k_q(\lambda)\ z_q$ values. It is worth to notice that the 5-ink volume specification in the printer driving program does not always mean 5 different printing ink levels. For cyan there are 5 different ink levels, but there are practical 3 and 4 different ink levels for yellow and magenta, respectively. The variation of the actual ink volumes with respect to the program specified ink levels is shown in Fig. 4. As shown the practical ink volumes vary non-linearly with respect to the program specified ones.

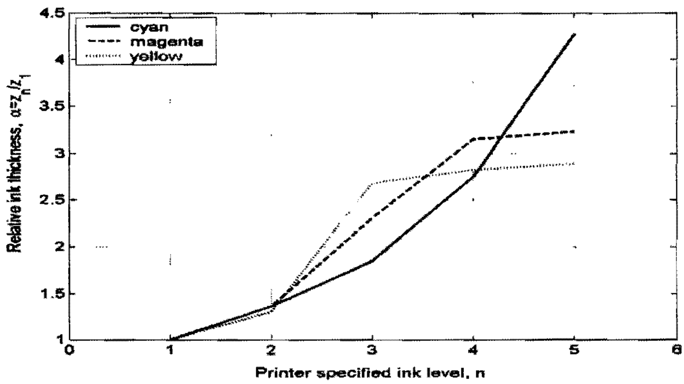

Figure 5: .Relative ink volume vs. printer specified ink volumes. The ink volume for the program specified ink volume 1 has been set as unit for each color.

C. Spectral reflectance values and relative ink thicknesses for the secondary colours

Because the samples of secondary colors were obtained by mixing 2 of the 3 primary colors in printing processes, they may serve as excellent examples to test the additivity assumption as expressed in Eq. (5).

The relative ink volume of the primary inks mixed to obtain the secondary colours given by $\beta_q(q=c,m,y)$, have been collected into Tab. 1. Similar to the case for the primary inks, the actual ink volume varies nonlinearly with respect to the printer specified ink level. For color red, the relative contribution from magenta and yellow, β_y/β_m, varies little with respect to different ink levels. However it changes remarkably for colours green and blue. This seems to count our intuition but might be understood from the fact that our colour vision responses nonlinearly to the ink thickness.

Table 1 Ink composition of secondary colours from their primary components

Secondary colour	Printer Ink level	Relative ink thickness* β_c	β_m	β_y
Red	1		0.81	2.18
	2		1.12	3.01
	3		1.52	4.09
	4		1.80	4.82
	5		2.34	6.28
Green	1	0.82		0.91
	2	0.96		1.24
	3	1.30		1.98
	4	1.65		3.17
	5	2.05		3.41
blue	1	1.25	0.54	
	2	1.72	0.64	
	3	2.82	0.80	
	4	3.98	0.98	
	5	4.12	1.21	

* The relative ink thickness, β_q $(q=c,m,y)$, is defined similarly to α_q in Fig. 5.

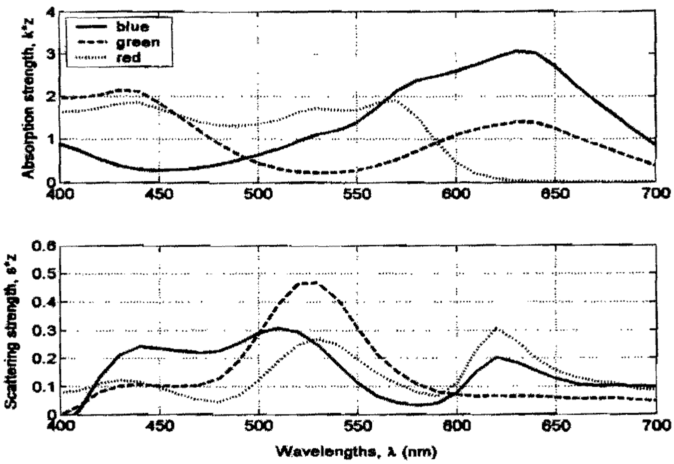

Figure 6: Scattering- and absorption-lengths of secondary colors obtained by applying the assumption of additivity (for ink level 3).

The scattering- and absorption-lengths, for samples printed with the (printer driving) program specified ink level 3, were shown in Fig. 6. They were obtained by applying the additive principles expressed in Eqs. 5. The weighting factors (β_q, $q=c,m,y$) representing the contributions from the primary colors, were determined by fitting the simulations to the experimental spectral reflectance data. Plots in Fig. 6 show clearly the existence of absorption/window structures that match well with intuitiveness. Consulting to the absorption/scattering characteristics of the primary colors (Fig. 1), one can easily see the correlation between the secondary colours and their primary components. For color green, for example, the strong absorbing bands come clearly from yellow (*400-480 nm*) and cyan (*580-680 nm*). Similar argument holds for the scattering-strengthe.

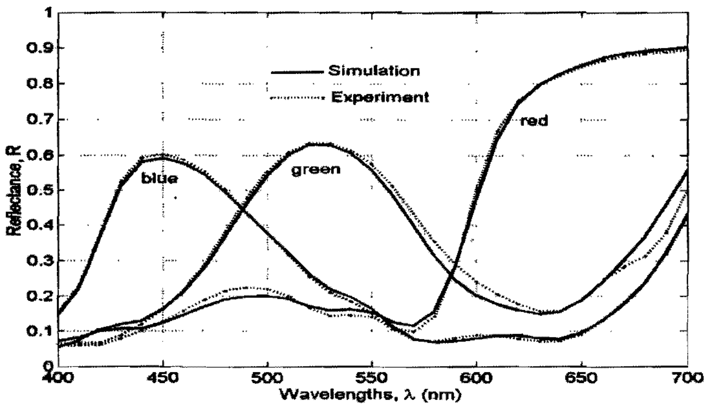

Figure 7: Simulated and measured spectral reflectance values of samples in secondary colors. The samples were printed with program specified ink level 1.

The simulated spectral reflectance values together with the corresponding experiment values (for samples printed with ink level 1) are shown in Fig. 7. As one can see that the simulations agree fairly well with the experimental data. It may imply that the additive assumption for the absorption and scattering lengths holds.

It has long been discussions around the validity for applying the K-M theory to a system having strong absorption, like printed inks. One of the most important argument from the opposite side is that the K-M theory requires a diffused light distribution in the media. This requirement (assumption) can not be fulfilled when there exists significant light absorption, even though the original illumination is diffused. However the present study shows that the simulations based on the K-M theory has been in fairly good agreement with the experimental measurements. The reasons behind the successes may lie on two factors. First the portion of light that stimulates human colour vision has wavelength well off the absorption regions of the inks. This portion is properly described by the K-M theory, because of the relatively strong scattering in these regions. Second the portion of illumination whose wavelength lies in the absorption region will mostly be filtered out by the ink absorption even though the light may not be accurately treated in the K-M theory. Detailed analysis concerning the validity of the K-M theory has been made and will be reported elsewhere (Yang 2002).

Conclusion and Summary

We developed a method to characterize the printed ink volume and the properties of the inks by means of spectral reflectance measurements. The measured data were analyzed with the help of theoretical simulations. The printed ink volume (equivalently thickness of the printed ink layer) for the primary colors and their absorption and scattering characteristics were determined. Spectrally the inks show clear opaque- and window-band structure with respect to the wavelengths of illumination. The scheme of color composition for the secondary colors (from the primary inks) was obtained. In addition, additivity assumption for obtaining the scattering and absorption lengths of the secondary colors from their primary components have been tested. Simulations for the spectral reflectance values have been carried out for both primary- and secondary colors. The simulations have been in fairly good agreement with the measurements.

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Literature Cited

Arney J.
1997 "A probability description of the Yule-Nielsen effect", J. Imaging Sci. Technol. vol. 41, pp. 633-636.

Bahr M., Kizling J., Zhmud B., and Tiberg F.
2001 "Spreading and penetration of aqueous solutions and waterborne inks in contact with paper and model substrates", in Advances in Printing Science and Technology-Advances in Paper and Board Performance}, vol. 27, pp. 87--102.

Chandrasekhar S.
1944 Astrophys. J., vol. 100 p.76

Le H.P.
1998 "Progress and trends in ink-jet printing technology", J. Imaging. Sci. Technol., vol. 42, pp49--62

Kubelka P. and Munk F.
1931 "Ein Beitrag zur Optik der Farbanstriche", Z. Tech. Phys. vol. 11, pp.593-601.

Pauler N.
1987 "A model for the interaction between ink and paper", in Advance in Printing Science and Technology, Proceeding of the 19th International Conference of Printing Research Institute (Pentech. Press), pp116-136.

Rogers G.
1998 "Optical dot gain in a halftone print", J. Imaging Sci. Technol. vol. 41, pp.643-656

Yang L. and Kruse B.
2000 "Ink penetration and its effect on printing", in Proceedings of SPIE, Color Imaging: Device-independent Color, Color Hardcopy, and Graphic Arts V (SPIE-The International Society for Optical Engineering), vol. 3963, pp.365-375.

Yang L. and Kruse B.
2001a "Chromatic variation and color gamut reduction due to ink penetration", in Proceeding of TAGA, pp.399-407

Yang L., Lenz R., and Kruse B.
2001b "Light scattering and ink penetration effects on tone reproduction", J. Opt. Soc. Am. B vol. 18, pp. 360-366.

Yang L. and Kruse B.
2001c "Modelling ink penetration for ink-jet printing", in Proceeding of IS&T's NIP-17: International Conference on Digital Printing Technologies, pp. 731--734

Yang L. and Kruse B.
2002 "Modelling ink-jet printing-Does the Kubelka-Munk theory apply ?", to be published