

Dependence of Color Hue-shift on Ink and Toner Scattering Power

Chengwu Cui
Lexmark International Inc., Lexington, Kentucky

Abstract

Printed colors are the results of the optical interaction of colorant (ink or toner) and media. Colorant can be modeled as an optical media that possesses spectrally selective optical scattering power and absorption power. With both optical properties estimated, the optical behavior of colorant on media (or the printed colors) can be predicted theoretically. In this paper, a two-constant Kubelka-Munk model is used to characterize printing inks and toners in terms of their optical scattering and absorption power. Printed colors were then predicted by alternating the orders that inks and toners are placed on media. It was found that the order of ink and toner placement could produce significant hue-shifts depending on the corresponding scattering power. The Magnitude and direction of the shift were also verified with printing samples.

Introduction

A printer prints colorants on media and the combined physical structure of colorant and media selectively modifies the incident illumination light spectrum and produces the sensation of color when viewed by the human observer. Most printers are binary printers and use various halftoning techniques to produce continuous color tones. These printers usually place inks or toners on media in fixed orders. It is known that the order of inks or toners placement can produce a significant hue difference, or hue-shift, which can be difficult to correct and compensate. Such hue-shift can be of different causes for laser printers and for inkjet printers. Inks and toners consist of small colorant particles that will produce light scattering when light waves pass through them. The scattering effect of ink or toner can be characterized by their optical scattering power. A colorant with no scattering power is often referred to as optically clear or transparent. When two transparent colorant layers are placed on top of each other, the order will produce no difference. The combined effect of the two layers can be modeled accurately by Beer's law. In the other extreme, if the scattering power of a colorant is significantly strong, it will be referred to as optically opaque. When two optically opaque colorant layers are placed on top of each other, the color of the combined layers will be the color of whichever layer is on the top. Current popular inks and toners are often regarded as transparent. While this may be true for organic inks, it may not be true for toners and pigment inks.

This paper is intended to investigate the potential contribution of the optical scattering power of inks and toners to the aforementioned potential hue-shifts.

Methods

To characterize the optical scattering power of colorants, the two-constant Kubelka-Munk model can be used. In the case of electrophotographic printing, color toners are placed on media in consecutive layers by the corresponding electro-photographic printing system and then fused together. Each layer of toner will remain as a distinctive layer. In this case, the Kubelka-Munk model can be applied layer after layer. In the case of inkjet printing, the situation will depend on the specific technology. Organic inks, in theory, are water-soluble and they do not possess any optical scattering power. For pigment inks, they may possess certain optical scattering power, depending on the physical dimensions of the colorant particles. When pigment inks are printed on media, they will also most likely deposit on media in layers. Because the main concern of this paper is to explore the potential impact of colorant optical scattering power, the two-layer model will be used both for toners and for inks. For soluble inks, the hue-shifts due to the orders that different color inks are printed are likely due to the ways that inks penetrate into the media, and will not be discussed here.

The Two-Constant Kubelka-Munk Theory

The two-constant Kubelka-Munk theory describes light scattering and absorption in a turbid media by the optical scattering coefficient (S) and absorption coefficient (K) of the media.[1] Light reflection to be measured also includes surface reflection that can be compensated by the Saunderson correction. [2]

The optical absorption and scattering coefficients can be obtained by solving the original two constants Kubelka-Munk equations. Because there are two unknowns, it will need two independent equations. In practice, the same colorant layer is applied to two different backings. For this reason, the Leneta™ card is often used (see later). [3]

If the reflectance of the first backing and the colorant layer over the first backing is R_1 and CR_1, respectively; and the second backing and the colorant layer over the second backing is R_2 and CR_2, respectively, K and S can be computed by the following equations: [4]

$$S = \frac{\operatorname{atanh}\left[\dfrac{b(CR_1 - R_1)}{1 - a(CR_1 + R_1) + CR_1 R_1}\right]}{bh}$$

$$K = S(a-1)$$

$$where,$$

$$a = \frac{(1 + CR_1 R_1)(CR_2 - R_2) + (1 + CR_2 R_2)(R_1 - CR_1)}{2(CR_2 R_1 - CR_1 R_2)}$$

$$b = \sqrt{a^2 - 1} \tag{1}$$

Because scattering strength of inks and toners are likely to be very low, surface reflection can be a significant source of noise. Therefore, it is important to separate true optical scattering power of a colorant from potential measurement noise that can be caused by sample surface reflection or the limitation of the measurement instrument. The total amount of sample surface reflection is determined by the refractive index of the sample surface. The amount of surface reflection measurable depends on the surface structural characteristics and the measurement geometry of the measurement instrument. Common spectrophotometers for the printing industry are usually of the 0/45 measurement geometry. For a perfect smooth surface, the surface reflection measured with the 0/45 geometry should be zero. For a perfectly diffuse surface, the value should be 4% for a colorant layer of a refractive index of 1.5. In actual measurements, because the Leneta ™ paper surface finish may be different from that of the colorant layer finish, proper compensation has to be made in order not to mistake surface reflection as colorant scattering.

The Scattering Power of Typical Toners

To characterize the hiding power of a coating film, the Leneta card, which has a black region and a white region, is often used. In this study, we used a printer friendly model of Leneta paper, a regular bond paper with a black stripe printed in the middle to characterize the optical properties of the toners. Fig. 1 shows the reflectance of the black portion of the Leneta paper. A Lexmark™ C710 laser printer was used to print 100% toner patches on the Leneta paper. Because 100% toner was printed per layer, the halftoning algorithm used was considered unimportant. The reflectance of each toner over the black region of the Leneta paper is also shown in Fig. 1. All the measurements were done with a X-Rite™ 938 spectrophotometer. To improve measurement accuracy, each measurement was done randomly across the interested region for ten times and averaged.

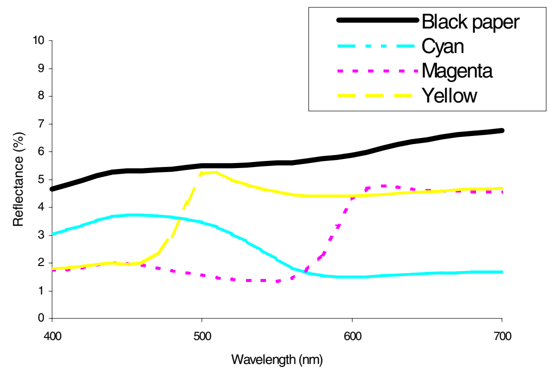

Figure 1. Direct measured spectral reflectance of the black portion of the special Leneta™ paper and the spectral reflectance of the 100% cyan, magenta and yellow toner printed on the black portion of the Leneta paper, respectively.

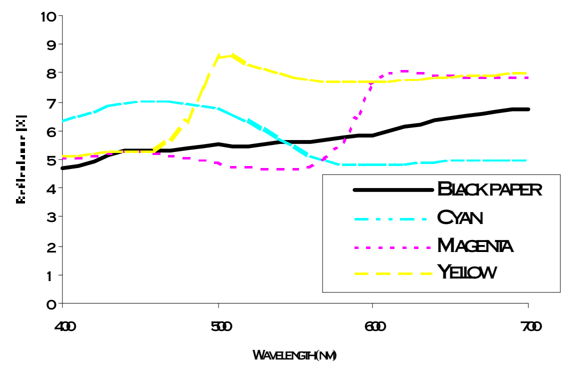

Figure 2. Spectral reflectance of the black paper and the compensated spectral reflectance of the 100% cyan, magenta and yellow toner printed on the black portion of the Leneta™ paper, respectively.

Fig. 1 shows that the actual measured reflectance of all three toners on the black paper. Apparently, the reflectance measured over some spectral regions of all three toners was well below the theoretical 4% reflectance, if the refractive index of the toner was 1.5. It indicated that the printed areas had higher gloss than the Leneta paper. To apply the Kubelka-Munk model, this type of measurement geometry and surface gloss related discrepancy (between the original Leneta paper and the printed areas) had to be considered and compensated. The lowest spectral reflectance of all three printed colors formed a flat curve that was roughly parallel to the black Leneta paper spectral curve. The difference between the two lowest points of the two curves was used as the concerned measurement geometry related measurement discrepancy. After the compensation of the measurement discrepancy, the spectral reflectance is redrawn in Fig. 2. Fig. 2 shows that the spectral reflectance in some regions of the three toners exceeds that of the black portion of the Leneta paper. This phenomenon clearly indicates that each toner has some scattering power that causes the reflectance to be higher than the original black paper. The compensated reflectance was used to compute the K and S values using Equation 1 and the results for all three toners are shown in Fig. 3 and 4. The unit of the coefficients was arbitrarily set for display convenience based on the "per unit thickness" unit.

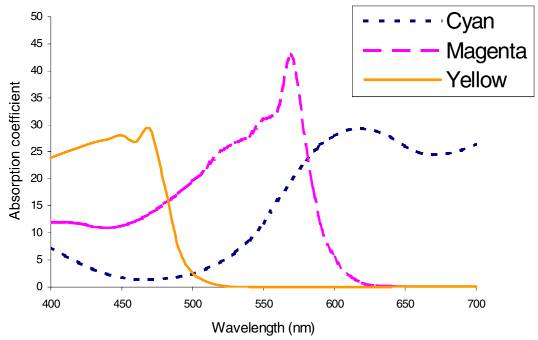

Figure 3. Optical absorption coefficients of the three toners.

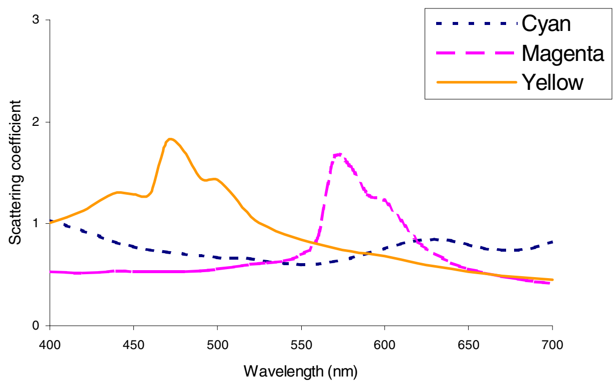

Figure 4. Optical scattering coefficients of the three toners.

Hue Shift Caused By Toner Orders

Once the K and S coefficients are known, the spectral reflectance of two toner layers printed on top of each other can be predicted. The computation is to apply the Kubelka-Munk model twice, first using paper as the backing and then using the paper and first layer toner combination as the backing. Saunderson corrections and measurement difference due to surface gloss difference also need to be taken into consideration. To demonstrate the hue-shift effect due to the scattering power of toners or inks (pigment), a series of assumed scattering power of the toners, based on the actual measured scattering powers, were used. Combination of two of the three toners will produce the three primary colors: red (100% yellow and 100% magenta), green (100% yellow and 100% cyan) and blue (100% cyan and 100% magenta), and the order the toners are printed will produce a color difference. The results are shown on the CIELAB chromaticity diagram in Fig. 5.

The assumed scattering power is *0.1, 0.5, 1, 1.5, 2.0, 2.5, 3.0, 3.5, 4, 4.5, and 5* times of the measured scattering power of the three toners, respectively. Each symbol represents the color printed with a specific order the toners are printed at a specific assumed scattering power. Each trace of symbols represents one color (of similar hue) printed by a specific order of two toners with various degrees of scattering power. Adjacent pairs of symbol traces show the color difference due to the difference in toner order for all assumed scattering power, with each specific pair of symbols of the same assumed scattering power connected by a line segment. The thicker connecting line segments represent the case of the actual toner scattering power of the toners measured.

The computed color differences due to the toner order differences with their individual visual components, using the true (actual) toner scattering power measured, are listed in Table 1.

Table 1. Computed color differences (absolute) due to toner order differences for red, green and blue color, respectively.

	ΔE*	ΔL*	ΔC*	ΔH*
Red	7.11	2.31	4.29	5.19
Green	8.01	1.52	0.37	7.85
Blue	7.61	0.12	1.04	7.54

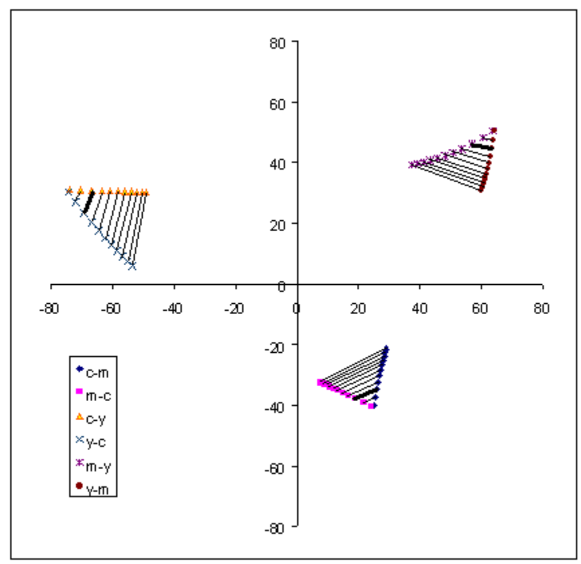

*Figure 5. Hue-shifts due to the difference in toner orders. Each trace represents the a*b* coordinates plot of a specific toner order, assuming 0.1, 0.5, 1, 1.5, 2.0, 2.5, 3.0, 3.5, 4, 4.5, and 5 times of the actual measured toner scattering power, respectively, for demonstration purposes.*

Measurement Verification

The same toners were printed on the white portion of the Leneta paper using different printing orders. They were printed via two passes in order to print toner layers in the desired orders. Six different patches were obtained with two patches of different toner orders for each of the three primary colors: red, green and blue. The color patches were measured in the same way the single toner layer samples were measured. The measured spectral reflectance of the red color patches is shown in Fig. 6, along with the predicted spectral reflectance. The agreements between the measured and predicted spectral reflectance for other two colors were similar to that of the red color.

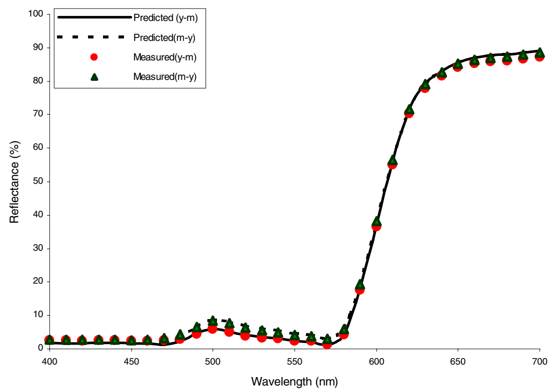

Figure 6. Measured and predicted spectral reflectance of the red color for two different toner orders, respectively. Solid lines represent the predicted spectrums and symbols represent the actual measured spectrums for the two different toner orders, respectively; solid line and dots represent yellow over magenta; broken line and triangles represent the magenta over cyan.

The measured color differences of red, green and blue due to the toner order differences, along with their individual visual components were computed and given in Table 2.

Table 2. Measured color differences (absolute values) due to toner order differences for printed red, green and blue color, respectively.

	ΔE*	ΔL*	ΔC*	ΔH*
Red	5.76	2.35	4.34	2.96
Green	7.56	0.65	4.67	5.90
Blue	8.07	0.09	3.51	8.07

Discussion

Fig. 6 proves that the Kubelka-Munk theory can be effectively used to model the hue-shift produced by the scattering power of toners and inks with small amounts of scattering power. Table 1 and 2 shows that there are some significant differences between predicted color differences and the actual measured differences. The differences could be caused by a number of factors. First, the K-M model assumes all light involved is in the diffuse form. In our case, the instrument was of the 0/45 geometry and the toner layer was translucent, the diffuse condition was violated. The quality of the Leneta paper and the potential non-uniformity of the printing process could also contribute to the prediction error. The measurement instrument was also a low-end spectrophotometer and it might have introduced measurement errors.

Nonetheless, the predicted hue-shifts were reasonably close to the measured hue-shifts. Fig.5 shows the strong dependence of this type of hue shifts on the scattering power of toners and inks (pigment). The magnitudes of the hue-shifts for the printer used were large. Toners or inks of half the scattering power of the toners used in this study can still cause hue-shifts that will be clearly visible. Optical scattering is also harmful to chroma.

Conclusion

This study shows toners and inks may possess a small amount of optical scattering power which will produce colors of large hue differences when printed in different orders. This effect is proportional to the scattering power of toners and inks and can be modeled by the two-constant Kubelka-Munk theory.

Acknowledgements

I would like to thank Mr. Cary Ravitz at Lexmark International for helpful discussion.

References

1. P. Kubelka, J. Opt. Soc. Am., 38, 448-457 (1948).
2. J. L. Saunderson, J. Opt. Soc. Am., 32, 727-736 (1942).
3. http://www.leneta.com
4. Hans, G. Volz, Industrial color testing, translated by Ben Teague, VCH, New York, 1995, p.99.

Biography

Chengwu Cui received his BS degree in optics from Shandong University, MS in color science from Chinese Academy of Science and PhD in vision science from the University of Waterloo. From 1995 to 1999, he worked for GretagMacbeth as a color scientist. He is currently with Lexmark International. His research interests include human vision, ocular optics, image quality, color measurement, daylight simulation, computer color formulation and psychophysics.