OPTICAL PROPERTIES OF PRINTED TRANSPARENT SUBSTRATES

BATES, I.; KLANJAC, M.; KNEZEVIC, N. & MODRIC, D.

Abstract: *This paper provides an analysis conducted by means of expanded Murray-Davies model on a transparent substrate which was printed with solvent-based ink and UV ink. The research is based on empirical methods developed using the model (extended Murray-Davies equation derived from the Yule-Nielson model) to define the printed pattern on a substrate in order to improve the quality of reproduction in halftone imaging. Applicability of these equations, developed for research of media such as paper, was examined on a transparent substrate. Model contains two empirically derived parameters "w" and "v", whose determination are based on data from microscopic images. Spectroscopic results were obtained by quantitative spectrometer built with a digital camera.*

Key words: *Murray-Davies, substrate, inks, spectrometer*

Authors´ data: Dipl.-Ing. Ass. **Bates**, I[rena]; **Klanjac**, M[arina]; **Knezevic** N[eda]*; PhD.Ass.Prof. **Modric**, D[amir], Faculty of Graphic Arts, Getaldiceva 2, 10000, Zagreb, Croatia, irena.bates@grf.hr, marina.klanjac@grf.hr, neda.knezevic@grf.hr, damir.modric@grf.hr

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1. Introduction

The influence of various parameters on the color reproduction has been continuously studied. In this work was performed study of optical properties of complex made from solvent based and UV curable inks when they are printed on a transparent substrate i.e. foil. The expanded Murray-Davies model has been used to determine the optical properties of ink. The first optical model used to calculate the real reproduction of colors on print is the Murray-Davies equation (Murray, 1936; Yule & Nielsen, 1951).

$$R(F_i) = F_i R_i + (1 - F_i) R_p \tag{1}$$

The Murray-Davies equation shows how one can control a printing device to produce any desired gray level by controlling the dot area fraction, F_i. The Murray-Davies equation is a very simple description of halftone imaging, and not surprisingly it is a good description only for ideal halftones. Failure of the Murray-Davies equation, regardless of cause, is often called dot gain (Yule , J. A.C., 1967).Deviation from the stated linearity was regularly evidenced and remodeled with the modified Murray-Davies equation called Yule-Nielsen equation.

$$R(F_i) = \left[F_i R_i^{\frac{1}{n}} + (1 - F_i) R_p^{\frac{1}{n}} \right]^n \tag{2}$$

The Yule-Nielsen equation describes quite well the tone and color reproduction in many halftone systems (Ruckdeschel & Hauser, 1978).The values R_i and R_p are reflectance values of the ink and the substrate, and the factor “*n*” is the empiric constant that has been selected in order to enable the best match between values of R and F_i. The value of “*n*” is usually within range $1 \leq n \leq 2$. It appears that the Yule-Nielsen equation may reflect some fundamental theoretical behavior of the ink and substrate. Although Murray-Davies method implies the conservation of photon energy, the photon flux adds linearly, the reflectance predicted by Murray-Davies equation is generally higher than the measured reflectance, the actual printed image is almost always darker than predicted. Yule and Nielsen corrected the Murray-Davies equation by introducing a photon flux with power factor of $1/n$ describing in that way the lateral scattering. The developed model describes preservation of reflectance additivity in the Murray-Davies model with additional factors to calculate nonlinearity between R and F_i. This has been done by recognizing that R_i and R_p as a functions of F_i, $R_i(F_i)$ and $R_p(F_i)$, respectively. It describes the scattering of photons as overall reflectance of printed dots and substrate between dots. The reflectance from dots, $R_i(F_i)$ and reflectance from the substrate between dots, $R_p(F_i)$ are read off from the microscopic image histogram defined as the frequency distribution of reflectance values (Arney J. S. et al., 1995).

The fundamental cause of optical dot gain is the lateral scattering of light within substrate(Calabria, 2000). The light that enters the substrate between the halftone dots can scatter laterally within substrate before returning to the surface as a part of reflected light. This lateral scattering in a substrate increases the probability that the light will encounter a halftone dot and be absorbed. Thus the effective absorption of the halftone dot is larger than the physical size of the dot(Rogers, 1998).This term is still in use even though the underlying causes are more involved than a simple increase in the physical size of the printed dot.

The following equations are used for defining $R_i(F_i)$ and $R_p(F_i)$ when factor "w" is in the range 0 < 1. The factor "w" describes the optical spread function of substrate relative to the spatial frequency of halftone dots.

$$R_i(F_i) = R_g T_i \left[1-(1-T_i)F_i^{w}\right] \tag{3}$$

$$R_p(F_i) = R_g \left[1-(1-T_i)(1-F_i^{w})\right] \tag{4}$$

In these two equations above, R_g is actually R_p. The transparency of the ink, T_i, has been obtained by using digital camera as a laboratory spectrometer.

2. Experimental

This model was developed for patterns printed on paper and the aim of this research was to demonstrate the usability of this model on foil. Patterns were printed with solvent based ink or UV curable cyan color ink on polypropylene foil (Bates et al., 2009).The samples were printed with fulltone and halftone pattern (50%) in cyan color on polypropylene foil. Polypropylene substrate has the thickness of 0,03 mm. The same printing plate was used during both printing processes as well as printing procedures for achieving satisfactory reproductions.

The color reproduction of patterns printed with flexographic technique on foil, i.e. transparent substrate has been rarely analyzed (Andreas et al., 2000; Barros, 2006) therefore, this paper presents the analysis of the usability of equations which were applied on patterns printed on paper. The expanded Murray-Davies equations were used for analyzing efficiency of such an approach in the implementation on foil (Dzimbeg et al., 2006).In order to determine the value of mean reflectance $R_i(F_i)$ in equation 3, and $R_p(F_i)$ in equation 4, the reflectance of surface (R_p) has been obtained with a SpectroEye spectrophotometer.

For the determination of the ink transparency (T_i), we constructed quantitative laboratory spectrometer from the several laboratory components(Bates et al., 2009).The transmission spectra of ink T_i were investigated by means of image analysis program Image-J and OriginLab (OriginPro8). It was necessary to perform some procedures in order to make the spectrometer (in our case, camera and optical grating) useful and applicable laboratory tool: the imaging of spectra of different light sources to calibrate spectrometer defined by optical grating (Born & Wolf, 1986), the determination of background effect and location of each pixel, embedding pixels to particular wavelengths (calibration of spectrometer), the linearization of spectrum with MathCad (RGB separation) and the calculation of spectra. Digital camera for the imaging of spectra (Canon EOS 5D, resolution 13 Mpx, t=10 s, f=22), optical grating, box with a slit, printing materials, Wolfram light source (Philips 75W 230V A55 E27 ES, 2800K) were the components used. The recording of transmission spectra with designed laboratory instrument is based on a digital camera image acquisition. In addition to the total intensity of a source, the spectral characteristics must be considered. The light source needs to include emission at every wavelength within the visible range which is the primary reason for the application of different light sources (high pressure Hg, Nd, halogen elements; D65) to calibrate the realized instrument for further color testing. Most of the used sources have a strong emission in infrared region which generates additional problems for data acquisition with photo camera due to the fact that auto focusing mechanism works in the same spectral region which leads to inaccurate focusing and blurred image (Arvo, 1995).We had to perform linearization of spectrometer in order to become quantitative measurement equipment. Spectra captured with camera were determined in pixels, so it was necessary to embed particular wave length to each pixel. Gained data was digital, thus the associating was carried out with the corresponding image. Resulting spectra were standardized to the standard light source – D65 by means of applying mathematical program MathCad (Klanjac M. et al, 2008).

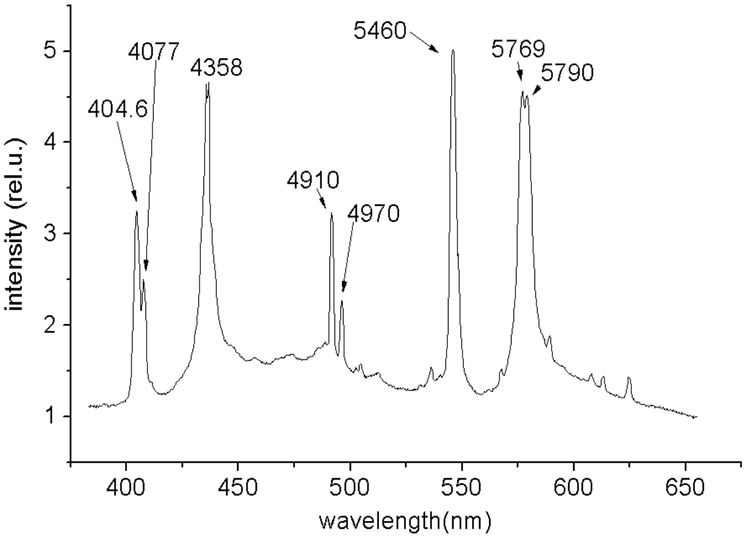

Fig. 1. Identification of particular wavelength for high pressure mercury lamp

Spectra of aforementioned different light sources were used for the calibration of spectrum by applaing a linear interpolation function to generate linear dispersion spectra (the specific change of pixels corresponds to a specific change of wave length):

$$\Delta\lambda = \Delta px \tag{5}$$

Dispersion graph (Fig. 2.) shows the linearity of spectrum in interval of 400-600 nm gained by the spectrum of mercury lamp.

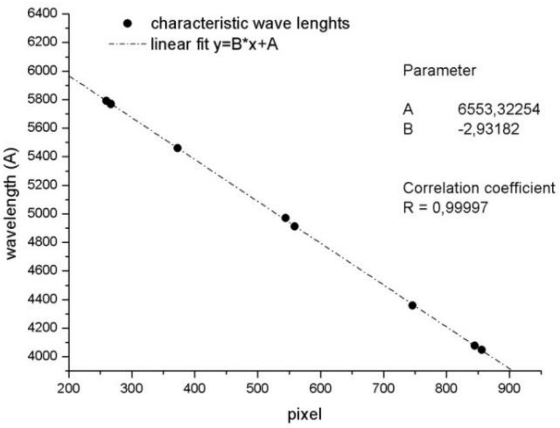

Fig. 2. Spectrometer dispersion graph

In order to measure the spectral sensitivity of the camera, the spectrum of a light source must be known. Most cameras offer a certain level of built-in white balance capacity. The primary purpose is to rule out any “coloration” being added by the light source which will affect resultant spectra. Once the white balance is performed, the color differences can be predicted for any final lighting condition(Nicodemus , 1976).

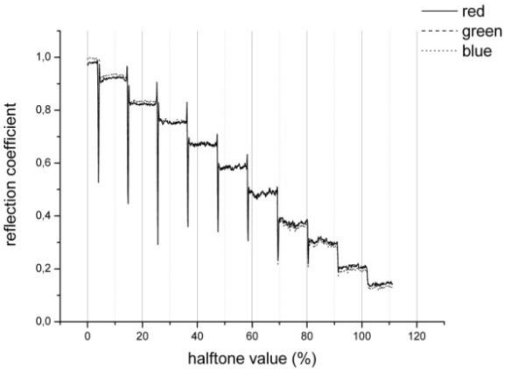

Fig. 3. Dependency of coefficient of reflection and halftone value for all separations (RGB)

The linearization of camera's spectral sensitivity was also one of the prerequisites (RGB separation) because it was necessary to check if the camera's CCD is sensitive to all colors equally. That was carried out with test fields (strip) constant 0,1 (the difference between halftone pattern value of each field starting from 0 to 1). Strip is a printed field of 5 x 6 mm average dimensions, used for quality control and placed on a part of a printed sheet (or web) which will be trimmed. RGB separation was made on test fields’ digital image with a program ImageJ. The dependency of reflection coefficient and halftone value for all separations is presented with a graph (Fig. 3.) which confirms that there are no significant deviations of spectral sensitivity for any color separation. These phases provided for the use of the quantitative spectrometer as a suitable apparatus for further research. To obtain and standardize expected spectro photometric transmission spectra for gained T_i we used Wolfram light source which was standardized to the regular source D65 (Wyszecki & Stiles, 1982.) with a temperature of 2800 K.

The transmission spectra was formed and captured as the light radiation passes through analyzed prints printed with cyan printing inks on polypropylene foil(Bohren & Huffman, 1983;Kubelka, 1948). Measured spectral transmission and reflectance histogram of investigated prints on polypropylene foil printed with UV inks and solvent based inks have been shown in Fig.4. and Fig. 5., respectively. UV inks display better coverage than inks on the solvent-basis (Kipphan H., 2004). However, the experimental values on the graphs show opposite behavior than previously mentioned, with increased transmittance (reduced reflectance) of UV inks. Polypropylene foil is white pigmented and partially transparent which could affect its transmittance. It can be seen that the behavior of the value of cyan reflectance of prints on polypropylene foil is less strong in the wavelength region 300-550 nm, which causes that the intensity of color and its perception is weakened due to stronger absorption in blue-green spectrum region. It should be noted that the influence of substrate polarization was not analyzed in this paper. In any case, the study of these effects will be a part of our further efforts in understanding the scattering of light in transparent foil.

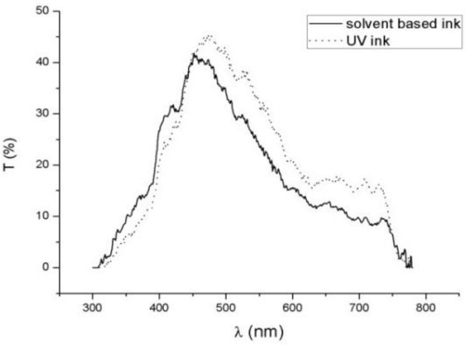

Fig. 4. Transmission of fulltone prints with solvent based ink and UV ink

3. Results

The picture of halftone patterns was taken with a microscope Leica microscope EC 4D and processed in ImageJ program It is possible to read off the value of $R_i(F_i)$ and $R_p(F_i)$ (Arney et al., 1995)on the histograms, where dots and the substrate between dots are shown. The intention of this research was to determine $R_i(F_i)$ and $R_p(F_i)$ when factor *"w"* is fitted from0 to 1 for our transparent media. The value $R_i(F_i)$ read off the histogram was used for comparison between factor *"w"* and the calculated $R_i(F_i)$. The calculated values of $R_i(F_i)$ according to equation (3) are shown in Fig. 6.and Fig. 7. with the downscaled graph, whereby certain parts have a visible reflection larger than 1, which means that in our system we have some optically active substances (Rushmeier & Torrance, 1990).In our first approximation we assume that there are no such components in inks or substrate so this part of spectra was omitted in our analysis. The part, where the values of $R_i(F_i)$ are the closest to the values of $R_i(F_i)$that were read off the histogram, has been enlarged. The value of $R_i(F_i)$ from the histogram is marked by the dashed line. The enlarged graph also shows a part of the curve which has been marked with a square in the downscaled graph. Formula has been calculated for values F_i= 50%, F_i = 30% and F_i =70%.

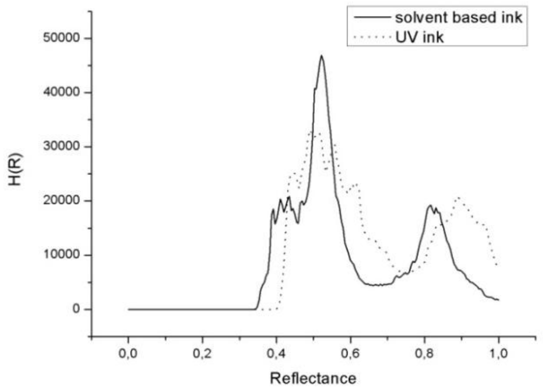

Fig. 5. Reflectance histograms values of halftone pattern with solvent based ink and UV ink

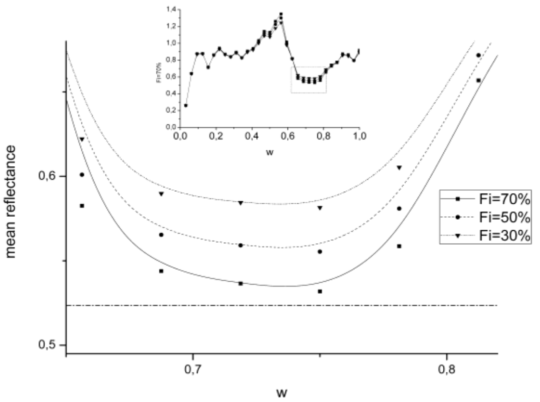

Fig. 6. Calculated mean reflectance $R_i(F_i)$ of prints with solvent based ink as a function of the factor "*w*"for different fractional area, F_i

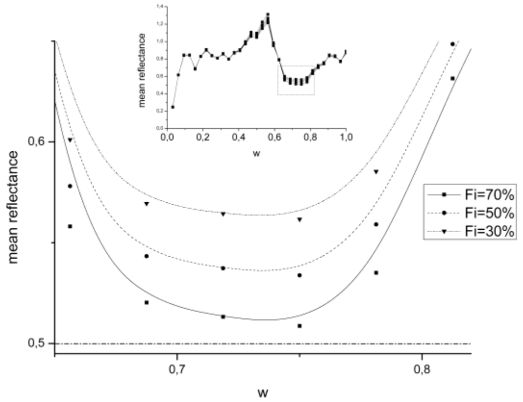

Fig. 7. Calculated mean reflectance $R_i(F_i)$ of prints with UV ink as a function of the factor *"w"* for different fractional area, F_i

We obtained similar results for both patterns. With this model it is possible to determine that the value of factor *"w"* would range between 0.7 and 0.8 when F_i would be slightly higher than 70%. For the calculation of the value of reflectance of the substrate between dots, $R_P(F_i)$ values Fi = 50% have also been used, which is the theoretical value of halftone pattern, while the value F_i= 70% has been used if a positive dot gain occurred and F_i= 30% if a negative dot gain occurred(Rogers, 1997). The value of $R_P(F_i)$ from the histogram was marked by a dashed line.

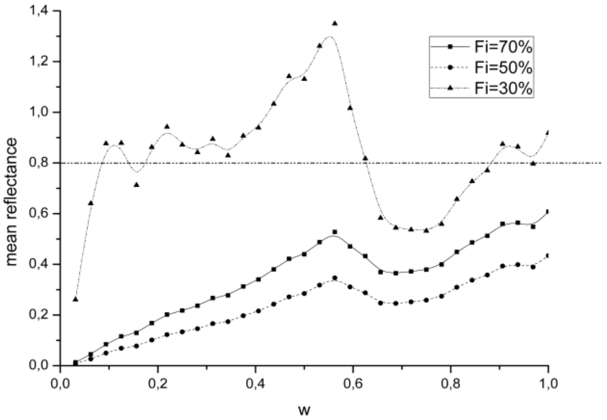

Fig. 8. Calculated mean reflectance *$R_P(F_i)$* of print with solvent based ink as a function of the factor *"w"* for different fractional area, *F_i*

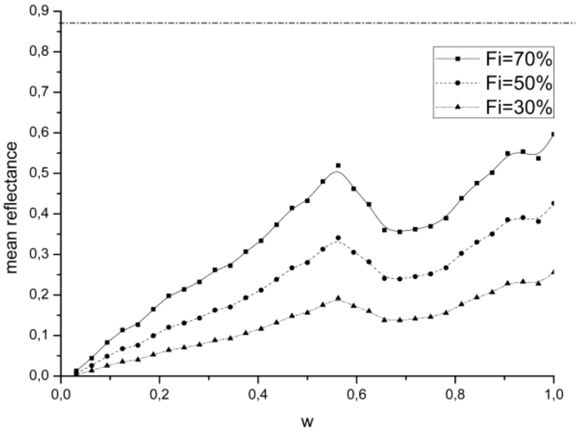

Fig. 9. Calculated mean reflectance *$R_P(F_i)$* of print with UV ink as a function of the factor *"w"* for different fractional area, *F_i*

The reflectance values of the substrate between dots do not match completely. In case of samples printed with solvent based ink and calculated with F_i= 30%, the shape of reflection curve differs from other curves. In case of these graphs, the value of *$R_P(F_i)$* from the histogram and the calculated values of *$R_P(F_i)$* cannot be compared.

4. Conclusion

The optical properties of inks, the printing substrate and their interactions play an important role in graphic reproduction. The structure and homogeneity of the polypropylene substrate on which were examined the prints generated with flexographic printing technique, indicate the possibility of applying expanded Murray-Davies approach. It was assumed that lateral dispersion in this material is minimal. On the opposite, lateral light dispersion is noticeable for polypropylene foil with immersed white pigment. Based on the obtained results, it can be concluded that further testing of optical properties of foil is necessary as well as a certain modification of the used formula. Our research indicates that expanded Murray-Davies model needs further modifications for more realistic description of transparent media. The model was mainly defined for paper while transparent foil has the different structure and therefore different optical and mechanical properties. In the absence of needed laboratory equipment, it was necessary to generate a spectrometer that can obtain transmission spectra. Conducted research showed that such a spectrometer can provide results that can be used for further modeling. The future studies will cover the topic of defining optical properties of ink and transparent substrate. This paper shows that the lateral scattering and optical dot gain are affected with medium characteristic absorption and transmission spectra, which depend on the composition of the substrate, which in turn, depends on the proposed application of graphic products.

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