**Zbigniew Stempień,
Magdalena Tokarska,
Krzysztof Gniotek**

**Department for the Automation of Textile Processes,
Technical University of Lodz**
ul. Zeromskiego 116, 90-924 Lodz, Poland
Email: stemp@p.lodz.pl,
emagda@p.lodz.pl,
kgniotek@p.lodz.pl

UV Radiation Measurement System for the UV Curing of Fluids Disposed on Textiles

Abstract

Processes of the latticing of polymer overprints functionalising textiles in the presence of photoinitiators require using high-energy UV radiation sources. However, the values of radiation intensities and UV doses used should be controlled so that they are no greater than those required by the proper course of the latticing process, on account of the high degrading impact of UV radiation on the fibre structure. In this article a mathematical model of intensity and UV dose radiation measurement constructed on the basis of the analysis of the phenomenon and catalogue information given by the producers of the radiation source, the UV filter and the sensor. The model of UV intensity measurement was analysed with regard to inaccuracy on the basis of the uncertainty theory; the relative uncertainty of the measurement obtained was of an order of 3%.

Key words: *disposed fluids, textiles, UV curing, UV dose radiation, UV dose sensor, measurement uncertainty.*

Introduction

The process of polymer overprint latticing by means of a UV source requires supplying an optimal radiation dose. As a rule, the radiation dose during the latticing process ranges from 0.5 to 15.0 J/cm^2. The need for measuring the intensity and dose of UV radiation results from the necessity to optimise the latticing process so that, on the one hand, appropriate durability of the overprints for use and washing is obtained, while on the other, the degrading effect of UV radiation on the fibre structure is limited.

Measurements of UV radiation intensity and doses for the purpose of polymer overprint latticing, over a wavelength range of 200 ÷ 400 nm, are most frequently carried out with optoelectronic processing systems. Typical photosensitive substrates generating an electric signal due to UV radiation are made on the basis of silicon carbide, SiC, titanium dioxide TiO_2, gallium and aluminium nitrides, (Al)GaN [1 - 4]. However, they require appropriate calibration owing to sources of errors related to the nonlinear characteristics of the elements in the optical signal processing circuit and the nonlinear characteristics of the sensor sensitivity in the electric signal processing circuit [5].

There are also solutions in which measurements of the radiation dose are conducted without the processing of this quantity into an electric signal. Yet, they are not suitable for use in control systems, and as a result they are of limited use in latticing processes. As a rule, their use is limited to dose indicators (dosimeters) for people standing within range of UV radiation. The principle of operation of such measuring systems consists in the evaluation of the degradation of the biological material disposed onto the substrate during UV radiation [6 - 9] or in the transformation of chemical compounds due to their excitation by the absorption of waves of the UV radiation range [10].

To programme the intensity and dose of UV radiation, a system was developed for measuring these two quantities on the basis of a semiconductor diode with non-zero sensitivity over a range of wavelengths of 200 ÷ 400 nm. The photosensitive substrate of this diode is made on a base of silicon carbide, SiC. Since no semiconductor sensors for large UV radiation intensities, of an order of 10 - 15 W/cm^2, are produced nowadays, it was suggested that a UV filter reducing the intensity to the levels processed by the sensor be incorporated into the optical signal processing circuit.

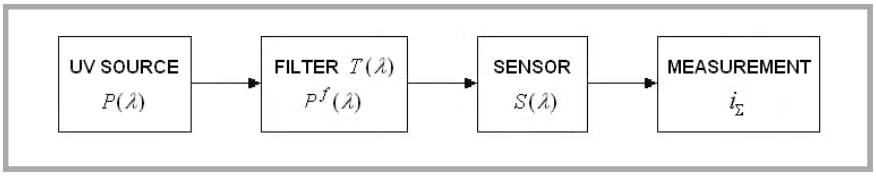

Figure 1. *Conception of the measurement of the intensity and dose of UV radiation.*

Idea and model of the measurement of the intensity and dose of UV radiation

A general conception of a system for measuring the intensity and dose of UV radiation is shown in ***Figure 1***.

Characteristics of the UV radiation source are given in the form of a spectral distribution ***P(λ)*** expressing radiation power. The main element of the system for measuring UV radiation intensity is a measuring head, presented schematically in ***Figure 2***.

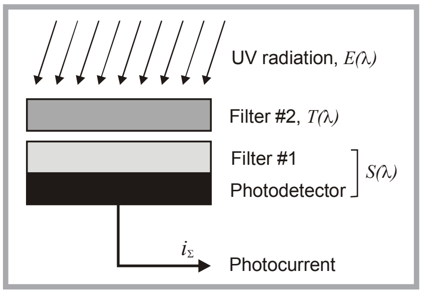

Figure 2. *Layer schematic of the measuring head.*

The sensor processing this intensity into an electric signal is the photodetector of a set sensitivity ***S(λ)***. In addition, in the optical signal processing circuit, two filters are used. The task of filter #1 is to limit the spectrum of radiation falling onto the photosensitive surface of the photodetector to a wavelength range of 200 ÷ 400 nm. The role of filter #2 of the transmission ***T(λ)*** is to limit the intensity ***E(λ)*** of UV radiation to the level proc-

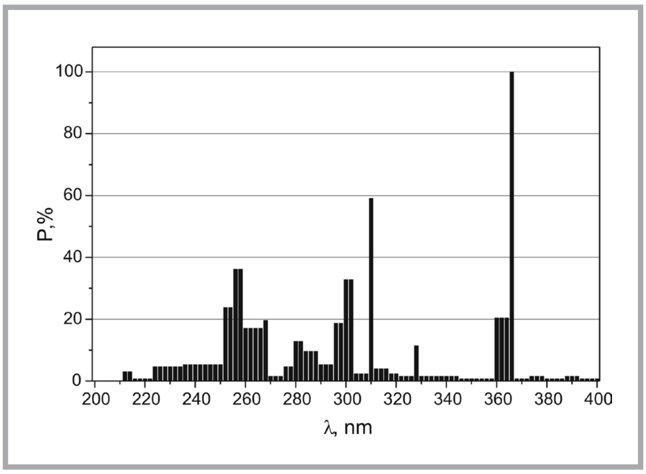

Figure 3. Spectral distribution of the radiation source – a high pressure lamp of the HOK 20/100 type manufactured by Philips [13].

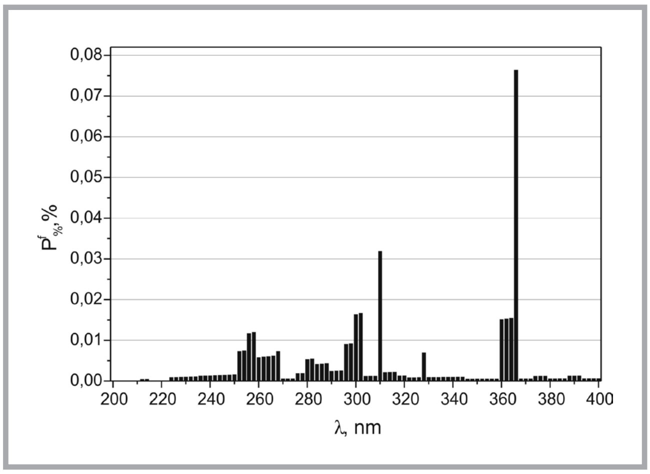

Figure 5. Spectral distribution of the radiation source with the use of a UV filter.

essed by the photodetector. Thus, radiation of spectral distribution ***$Pf(\lambda)$*** reaches the photodetector**.**

Taking into account the parameters of the particular layers of the measuring head, the processing equation can be written in the form:

$$i_\Sigma = \int_\lambda E(\lambda)\cdot T(\lambda)\cdot S(\lambda)\cdot d\lambda\,, \qquad (1)$$

where ***i_Σ*** is the total photoelectric current generated by the photodetector, measured on the stand.

A model for measuring the UV radiation intensity and dose during the exposition of antibacterial and antistatic overprints was constructed on the basis of an analysis of the phenomenon, catalogue information given by producers in the form of characteristics of the source, UV filter and sensor as well as the measurement of the total photoelectric current.

For the wavelength λ_i the UV radiation power, expressed as a percentage, is ***$P(\lambda_i) = P_{\lambda i}$*** (***Figure 3***), where 100% means a maximum of the UV radiation power in the spectral distribution. Taking into consideration the transmission ***$T(\lambda)$*** of filter #2 (***Figure 4***), the value of the power is expressed by the relationship:

$$P^f_{\lambda i} = P'_{\lambda i}\frac{T_{\lambda i}}{100}, \qquad (2)$$

where: ***$T_{\lambda i}$*** – the transmission of the filter for wavelength λ_i; ***$P'_{\lambda i}$*** – the source radiation power in Watts for wavelength λ_i.

On the basis of numerical data of filter transmission in the wavelength domain (***Figure 4***), the characteristic was approximated by linear function ***$T(\lambda)$*** = 0.0004λ - 0.07 to the wavelength range of 200 ÷ 400 nm.

On the basis of equation (2), replacing ***$P'_{\lambda i}$*** by ***$P_{\lambda i}$***,expressed as a percentage, the spectral distribution of the UV radiation source with the use of a filter is shown in ***Figure 5***.

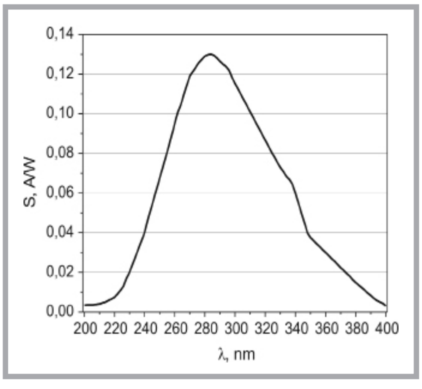

Figure 4. *Transmission of a UV filter of the NDQ-250-0.5 type manufactured by CVI Melles Griot BV [14].*

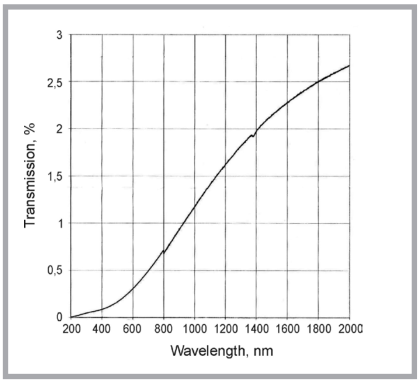

Figure 6. *Spectral sensitivity of a sensor of SG01S-HT type manufactured by sglux [15].*

The total current ***i_Σ*** generated by the UV photodiode is converted into voltage ***U_Σ*** using the current-to-voltage system, which contains two operational amplifiers ***W1*** and ***W2***. A schematic of the electric system is shown in ***Figure 7***.

Hence, with the voltage ***U_Σ*** and resistances ***R_1***, ***R_2***, ***R_f***, the current is expressed by the relationship:

$$i_\Sigma = \frac{R_1 U_\Sigma}{(R_1 + R_2)R_f}\,. \qquad (3)$$

Considering the sensor sensitivity ***$S_{\lambda i}$*** (***Figure 6***) for the wavelength λ_i, the current ***i_Σ*** is expressed by the equation:

$$i_\Sigma = \sum_{i=1}^{k} P^f_{\lambda i} S_{\lambda i}\,. \qquad (4)$$

Assuming the spectral line height in a given wavelength λ_i to be equal to ***$Kf_{\lambda i}$***, the following conjunction is true:

$$i_{\lambda i} = P^f_{\lambda i} S_{\lambda i} \wedge i_{\lambda i} = \frac{K^f_{\lambda i}}{K^f} i_\Sigma \wedge K^f = \sum_{i=1}^{k} K^f_{\lambda i} \qquad (5)$$

where: ***$Kf_{\lambda i}$*** is the area of the spectral line of height ***$Pf_{\lambda i}$***, which expresses the radiation power after the use of a filter as a percentage (***Figure 5***), and width $\Delta\lambda_i = 1 = \lambda_I$; ***k*** is the total number of spectral lines.

From equations (2) and (5), and taking into account the entire range of wavelength λ, the UV radiation distribution is defined by the equation:

$$P'(\lambda) = \frac{100 K^f_\lambda i_\Sigma}{K^f S(\lambda) T(\lambda)}\,. \qquad (6)$$

The studies carried out demonstrate that the radiation distribution (6) differs from the real spectral distribution ***$P(\lambda)$*** determined for the source. For this reason, a

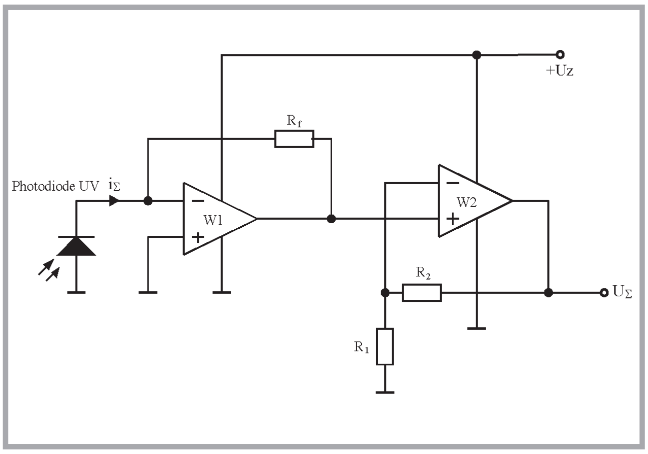

***Figure 7.** Schematic of the electric system.*

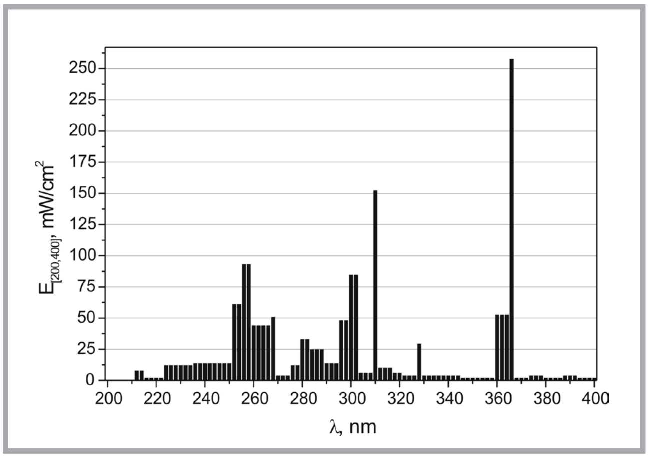

***Figure 8.** Distribution of UV radiation intensity*

correcting dimenssionless function ***g(λ)*** of the following form was introduced into equation (6):

$$g(\lambda)=\frac{P(\lambda)P'_\Sigma}{P_\Sigma P'(\lambda)}, \quad (7)$$

where:

$$P_\Sigma=\sum_{i=1}^{k}P_{\lambda_i}, \quad (8)$$

$$P'_\Sigma=\sum_{i=1}^{k}P'_{\lambda_i}. \quad (9)$$

Then, by including relationships (3) and (7) in equation (6) and going over to the boundary due to the infinite number of divisions of the interval, which is the range of wavelength λ**,** a model of the intensity of UV radiation during the exposition of antibacterial and antistatic overprints was finally obtained:

$$E=\frac{1}{\lambda_{\max}-\lambda_{\min}}\int_{\lambda_{\min}}^{\lambda_{\max}}\frac{100K_\lambda^f U_\Sigma R_1}{K^f A(R_1+R_2)R_f}\frac{g(\lambda)}{S(\lambda)T(\lambda)}d\lambda \quad (10)$$

where: ***A*** – the photosensitive surface area of the diode.

In particular, for wavelength ranges corresponding to UVC, UVB and UVA radiation, we have (equations 11, 12, and 13):

Figure 8 shows the distribution of UV radiation intensity during the exposition of antibacterial and antistatic overprints for wavelength λ in the range 200 ÷ 400 nm, assuming $\boldsymbol{U_\Sigma}$ = 5V.

The UV radiation dose, determined in a time interval from $\boldsymbol{t_1}$ to $\boldsymbol{t_2}$, is expressed by the relationship:

$$Q_\lambda=\int_{t_1}^{t_2}E(t)dt\ . \quad (14)$$

Assessment of the Inaccuracy of the Determination of UV radiation intensity

Analysis of the inaccuracy of determination of the intensity ***E*** of UV radiation for a specified wavelength λ was made on the basis of the uncertainty theory [11-12]. The inaccuracy of intensity measurement, characterising the scatter of the values attributed to the quantity being measured, is described by a complex uncertainty:

$$U(E)=ku_C(E), \quad (15)$$

where: ***k*** – the coverage factor (***k***=2 for confidence level 0.95); $\boldsymbol{u_C(E)}$ – the combined standard uncertainty of estimate ***E***. The equation from which the estimate ***E*** of the true value of UV radiation intensity is calculated results from equation (10). After the characteristics of the radiation source, UV filter and sensor are taken into consideration, and assuming that $\lambda_{max}-\lambda_{min}$ = 1, the measurement model has the following form:

$$E=\frac{P_\lambda U_\Sigma R_1}{K^f A(R_1+R_2)R_f}\frac{g_\lambda}{(0{,}54429-0{,}00143\lambda)} \quad (16)$$

where ***A*** = 0.00054 cm²; $\boldsymbol{R_1}$ = 1000 Ω; $\boldsymbol{R_2}$ = 470,000 Ω; $\boldsymbol{R_f}$ = 220,000 Ω; $\boldsymbol{U_\Sigma}$ = 5 V; for assumed wavelength λ = 310 nm we have $\boldsymbol{g_\lambda}$ = 2.31, hence ***E*** = 152 mW/cm².

Making use of the uncertainty propagation law [11] and assuming that there is a correlation of estimates of quantities $\boldsymbol{P_\lambda}$ and ***Kf***, using equation (16), we obtain a relationship of the combined uncertainty $\boldsymbol{u_C(E)}$ of estimate ***E*** as well as the standard uncertainties of components $\boldsymbol{P_\lambda}$, ***Kf***, λ, $\boldsymbol{R_1}$, $\boldsymbol{R_2}$, $\boldsymbol{R_f}$, $\boldsymbol{U_\Sigma}$. This relationship is of the form equation (17) where: $\boldsymbol{r(P_\lambda,Kf)}$ – the coefficient of correlation of the estimates of the quantities of $\boldsymbol{P_\lambda}$ and ***Kf***.

$$E_{UVC}=\frac{1}{\lambda_{UVC\max}-\lambda_{UVC\min}}\int_{\lambda_{UVC\min}}^{\lambda_{UVC\max}}\frac{100K_\lambda^f U_\Sigma R_1}{K^f A(R_1+R_2)R_f}\frac{g(\lambda)}{S(\lambda)T(\lambda)}d\lambda\,, \quad (11)$$

$$E_{UVB}=\frac{1}{\lambda_{UVB\max}-\lambda_{UVB\min}}\int_{\lambda_{UVB\min}}^{\lambda_{UVB\max}}\frac{100K_\lambda^f U_\Sigma R_1}{K^f A(R_1+R_2)R_f}\frac{g(\lambda)}{S(\lambda)T(\lambda)}d\lambda\,, \quad (12)$$

$$E_{UVA}=\frac{1}{\lambda_{UVA\max}-\lambda_{UVA\min}}\int_{\lambda_{UVA\min}}^{\lambda_{UVA\max}}\frac{100K_\lambda^f U_\Sigma R_1}{K^f A(R_1+R_2)R_f}\frac{g(\lambda)}{S(\lambda)T(\lambda)}d\lambda\,. \quad (13)$$

$$\begin{aligned}u_C^2(E)&=(\frac{\partial E}{\partial P_\lambda})^2u^2(P_\lambda)+(\frac{\partial E}{\partial K^f})^2u^2(K^f)+2(\frac{\partial E}{\partial P_\lambda})(\frac{\partial E}{\partial K^f})u(P_\lambda)u(K^f)r(P_\lambda,K^f)+\\&+(\frac{\partial E}{\partial \lambda})^2u^2(\lambda)+(\frac{\partial E}{\partial R_1})^2u^2(R_1)+(\frac{\partial E}{\partial R_2})^2u^2(R_2)+(\frac{\partial E}{\partial R_f})^2u^2(R_f)+(\frac{\partial E}{\partial U_\Sigma})^2u^2(U_\Sigma)\end{aligned} \quad (17)$$

Equations: 11, 12, 13, and 17.

***Table 1.** Uncertainty budget for uncorrelated quantities.*

Symbol of input quantity	Estimate of input quantity value	Standard uncertainty of Type A	Standard uncertainty of Type B	Combined uncertainty square of input quantity	Sensitivity coefficient square	Component of combined variance of output quantity, $(mW/cm^2)^2$
P_λ	59.15 %W	0.03050 %W	0.00361 %W	0.00094 $(\%W)^2$	6.65×10^{-6} $(W/(\%Wcm^2))^2$	0.00627
λ	310 nm	0.06885 nm	0.00931 nm	0.00483 nm^2	4.66×10^{-6} $(W/(nmcm^2))^2$	0.02251
K^f	0.7928 %W	0 %W	0 %W	0.00001 $(\%W)^2$	3.70×10^{-2} $(W/(\%Wcm^2))^2$	0.23644
R_1	1000 Ω	0 Ω	5.77350 Ω	33.3333 Ω^2	2.32×10^{-8} $(W/(\Omega cm^2))^2$	0.77188
R_2	470000	0	2713.55 Ω	7363333	1.05×10^{-13}	0.77188
R_f	220000	0	1270.17 Ω	1613333	4.80×10^{-13}	0.77516
U_Σ	5 V	0.01049 V	0.00577 V V	0.00014 V^2	9.30×10^{-4} $(W/(Vcm^2))^2$	0.13333

In the case of the remaining estimates of the input quantities, it was found that there are no grounds for rejecting the hypothesis that these variables are not pair correlated at a 0.05 significance level.

Table 1 presents an uncertainty budget of the determination of radiation intensity ***E*** for a wavelength $\lambda = 310$ nm. Calculations of standard uncertainties by the B type method were performed, assuming the existence of a uniform distribution of possible values within the interval.

For estimates of correlated quantities P_λ and Kf, a correlation coefficient was obtained - $r(P_\lambda,Kf) = 0.95$. The covariance for these quantities is $u(P_\lambda,Kf) = 73.8715$ $(\%W)^2$, while the product of sensitivity coefficients corresponding to the estimates of the correlated quantities is equal to $-4.96 \cdot 10^{-4}$ $W^2/((\%W)^2cm^4)$. Thus, the value of the component of the combined variance of the output quantity (the intensity ***E*** of UV radiation) is -0.07327 $(mW/cm^2)^2$.

Finally, the result of the measurement of the UV radiation intensity at a 0.95 confidence level can be written as $E = (152 \pm 4)$ mW/cm^2. Hence, the relative uncertainty of the measurement is 3%.

Conclusions

In the UV curing of fluids disposed on flat textiles and moved under long-arc medium-pressure from a high power mercury lamp, determination of the total dose of UV radiation is possible using the UV radiation measurement system presented. The UV sensor is mounted on the textile area and moves with the textiles through the UV radiation zone.

The solution presented enables to optimise the process of the latticing of overprints functionalising textiles in conditions of extreme UV radiation, from both the point of view of their resistance to washing and fibre degradation. Adjustment of the range of UV radiation intensities processed to the range of intensities processed by the semiconductor sensor is made possible by use of a filter of specific transmission. The mathematical model of the measurement system allows to predict the UV radiation intensity and dose at a given filter transmission.

The relative uncertainty of the UV radiation intensity measurement calculated is 3%. The greatest percentage in the combined variance, 28% each, are shown by the estimates of resistance variances R_1, R_2 and R_f. To improve the metrological quality of the model, resistors of smaller inaccuracy should be used. In the case under consideration, one percent resistors were used.

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For more information please contact:

Anna Ujhelyiova
Department of Fibres and Textile Chemistry, IPM Faculty of Chemical and Food Technology, STU in Bratislava
Radlinského 9, 812 37 Bratislava, Slovak Republic
Tel./Fax: 00421 2 529 68 598, E-mail: anna.ujhelyiova@stuba.sk, marcela.hricova@stuba.sk