Safety and risk assessment for UV curing systems

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Abstract

Due to European Directive 2006/25/EC employers must perform a risk assessment for every kind of UV and other artificial radiation. This risk assessment must be done on every workplace determining the total dose during an eight hour working day.

In practice nearly every UV source is harmful and risks as erythema or skin cancer must be considered. Simplifying assumptions or manufacture notes are useful, but in most cases measurements must be performed taking into account photobiological risks. This is usually done by actinic and spectroradiometers. Unfortunately measuring ranges of common belt radiometers are too high to detect effective irradiances of 0.01 mW/cm² for eight hour working days.

This paper presents the exposure limits and measurement principles, gives practical advice and simplifying assumptions for UV curing systems. Measurement uncertainties will be compared to requirements of DIN EN 14255-1.

Introduction

UV sources are used for all kind of applications like gluing, curing and fluorescence detection. On some systems the employee is not completely protected against UV radiation. In this case the workspace must be evaluated by the employer. One way is to use sources rated class 0 according DIN EN 62471:2009. These sources are risk-free. Unfortunately for most systems this rating is not available or reachable.
This means that a risk assessment must be done to determine the total dose during eight hour working day. Methods, measurements and requirements are described in DIN EN 14255-1:2005 while the exposure limits are regulated in 2006/25/EG:

In the risk assessment account shall be taken to:

- exposure conditions in normal operation, maintenance and repair work
- duration of exposure to artificial optical radiation
- the wavelength range
- exposure limit values
- impacts on the health and safety of workers, especially for vulnerable groups and photosensitizing chemical substances

Note, that this list is not a complete excerpt from 2006/25/EG. While 2006/25/EG lists 15 different exposure limit values this paper will concentrate on only tree values (table 1):

table 1: Exposure limits (excerpt from 2006/25/EG)

symbol	meaning	Exposure limit
E_λ	spectral irradiance	
E_{eff}	effective irradiance weighted with S_λ	
E_{UVA}	the irradiance in wavelength range 315 - 400 nm	
E_B	the effective irradiance weighted with B_λ	0,01 W/m² for t > 10.000 s 1/t W/m² for t ≥ 10.000s
H_{UVA}	radiant exposure (315 - 400 nm)	10^4 J/m²
H_{eff}	effective radiant exposure	30 J/m²

Measurement devices are necessary that are sufficient sensitive to the UV radiation while being not sensitive to other spectral ranges. In most cases the measurement device should be mobile and cost effective too, while being traceable calibrated.

Therefore three groups of measurement devices can be differed. Passive dosimeter based on polysulfone [CIE 98, 1992] or other films, active broadband radiometers and spectroradiometers.

The effective irradiances using the spectral weighting functions S_λ and B_λ, given in 2006/25/EG and depicted in figure 1, can be calculated according equation (1) to (3) for spectroradiometric measurements.

(1) $E_{eff} = \int_{180}^{400} E_\lambda \, S_\lambda \, d\lambda$ (2) $E_{UVA} = \int_{315}^{400} E_\lambda \, d\lambda$ (3) $E_B = \int_{300}^{700} E_\lambda \, B_\lambda \, d\lambda$

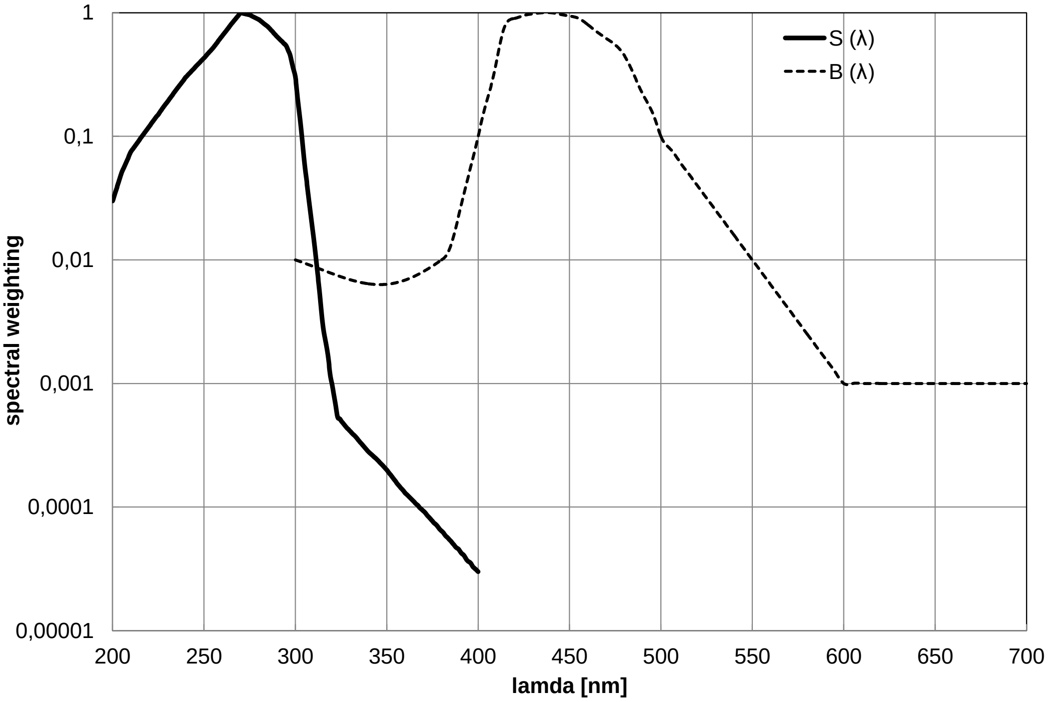

figure 1: the spectral weighting functions S_λ and B_λ vs. wavelength

Note that DIN EN 5031:10-2013 lists 28 different actinic spectra. All spectra are tabulated and the effective irradiance can be calculated. One problem is the internal stray light in combination with actinic functions, because those functions can change in magnitudes over only a few nanometers. Then stray light produces and significant measurement error if it is not corrected or known. The second problem is the sensitivity range of the spectroradiometers. Assuming a UVA-Dose of 10^4 J/m² per eight hour working day the measurement device must be sensitive enough to measure 0.035 mW/cm² in the UVA spectral range. A measurement device for E_s must be sensitive enough to measure 0.01 mW/cm².

To reach this sensitivity filtered broadband radiometers may be used if the filter and calibration is adapted to the requirements of 2006/25/EG and DIN EN 14255-1:2005. In addition the mandatory uncertainty must be less that 30%.

Usually broadband radiometers consist of a photodiode (Si, SiC, GaP) with optical filters placed in front. Through the careful selection of the filters, the measuring range can be adjusted. However, differences between S_λ and B_λ and the sensor sensitivity in the range of >80 % or partly non-sensitivity may occur for some wavelength ranges.

In addition to effective sensors standardized versions for UVA, UVB and UVC may be used for a first measurement or to assist spectroradiometric measurements. These standardized sensors are calibrated by their manufacturers for one type of lamp and are therefore only able to reproduce correct measurement results for this type of lamp.

As soon as the lamp's spectrum changes or other lamps or UV LEDs are used, the measured values differ. This is called spectral mismatch. While characteristics and classification for actinic / effective radiometers are given in DIN EN 5031-11:2011 sensitivity functions may be manufacturer-specific for standardized versions.

Experimental Setup

In this paper we are presenting measurements of exposure to incoherent, artificial UV sources using a high quality scanning double-monochromator, a laboratory UV spectrometer, a handheld spectrometer and broadband radiometers. As reference a scanning double monochromator IDR300 from Bentham is used. The double-monochromator consists of a UV diffusor, light guide and motorized slits as entrance optic. The focus length is 320 mm; two holographic gratings (2400 l/mm) are used. As detector a sensitive photomultiplier tube is used. The recommendations for stray light suppression, wavelength accuracy and spectral bandwidth of DIN EN 62471:2009 are fulfilled. The spectral bandwidth was set to 1 nm.
The laboratory spectrometer, USB-Spectometer by Opsytec Dr. Gröbel, consists of a high-throughput polychromator with diffusor, light-guide and Si-photodiode array. The spectral resolution of 1.2 nm is reach by a focus length of 140 mm and a UV-enhanced grating with 300 l/mm.
As mobile spectrometer the UVpad by Opsytec Dr. Gröbel is used. The device is designed to measure the spectral irradiance of UV belt systems. The spectral resolution is 2 nm. This is realized by a focus length of 70 mm in combination with a 600 l/mm grating. The spectral range is 200 – 440 nm.
Common for all UV monochromators and spectrometers is that the sensitivity is not as high as for broadband radiometers. But the main advantage is that the reading value is correct even when the lamp spectrum mismatches the calibration spectra. In comparison to these devices UV sensors are used with sensitivities in the UVA, UVB and UVC spectral region as well as one sensor with sensitivity from 400 to 490 nm.
All systems are calibrated traceable to PTB using an absolute calibrated FEL lamp and a calibrated deuterium lamp.
Three different lamps have been investigated. First a mercury (Hg) medium pressure lamp operated at 2.7 kW. As second lamp a UV spot system with a 120 W Hg high pressure lamp and light guide was used. The third system consists of a high power UV-LED with peak emission at 365 nm and optical power of 550 mW. The overall irradiance for all measurement devices and lamps is several mW/cm². The measurements have been done in the boundary area of the UV systems to detect direct radiation from the sources. Due do different entrance optics and position errors the measurement values may not be absolutely the same, but in the same range. Due to spectral mismatch of the investigated light source compared to calibration light source there are additional errors for the UV sensors that can be corrected by using the same light source for calibration. The measured irradiance for all lamps and measurement devices is given in table 2.

table 2: irradiance E (200 - 400 nm) for all lamps and measurement devices

E	Hg medium pressure	Hg high pressure	UVLED 365 nm
double monochromator	3.91 mW/cm²	8.79 mW/cm²	0.87 mW/cm²
laboratory spectrometer	3.87 mW/cm²	7.87 mW/cm²	1.13 mW/cm²
mobile spectrometer	3.70 mW/cm²	7.71 mW/cm²	1.01 mW/cm²
UV Sensors	5.35 mW/cm²	6.28 mW/cm²	0.81 mW/cm²

Figure 2 depicts the lamp spectra measured with the double monochromator. The measurements show typical emission spectra in the wavelength range 200 – 600 nm. The spectral irradiance is depicted using a logarithmic scale to show the stray light in the range of 10^{-4} to 10^{-6} mW/cm²/nm. Figure 3 depicts the same lamp spectra, but measured with the laboratory spectrometer. The stray light is obvious and in the range of 10^{-3} to 10^{-4} mW/cm²/nm.

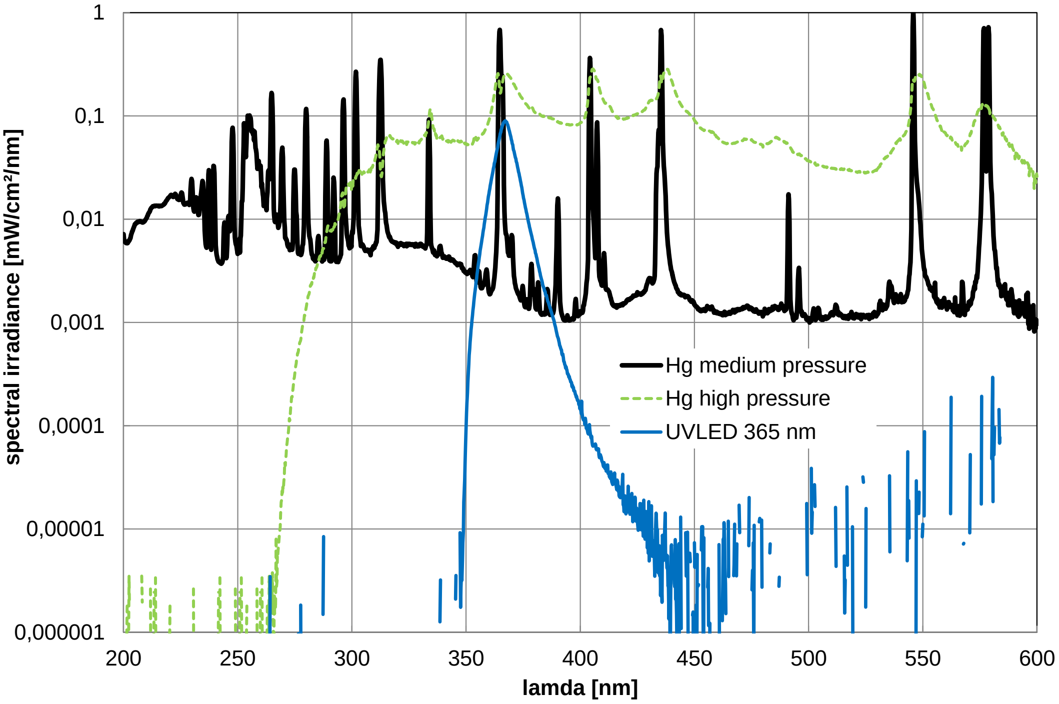

figure 2: emission spectra measured with double monochromator

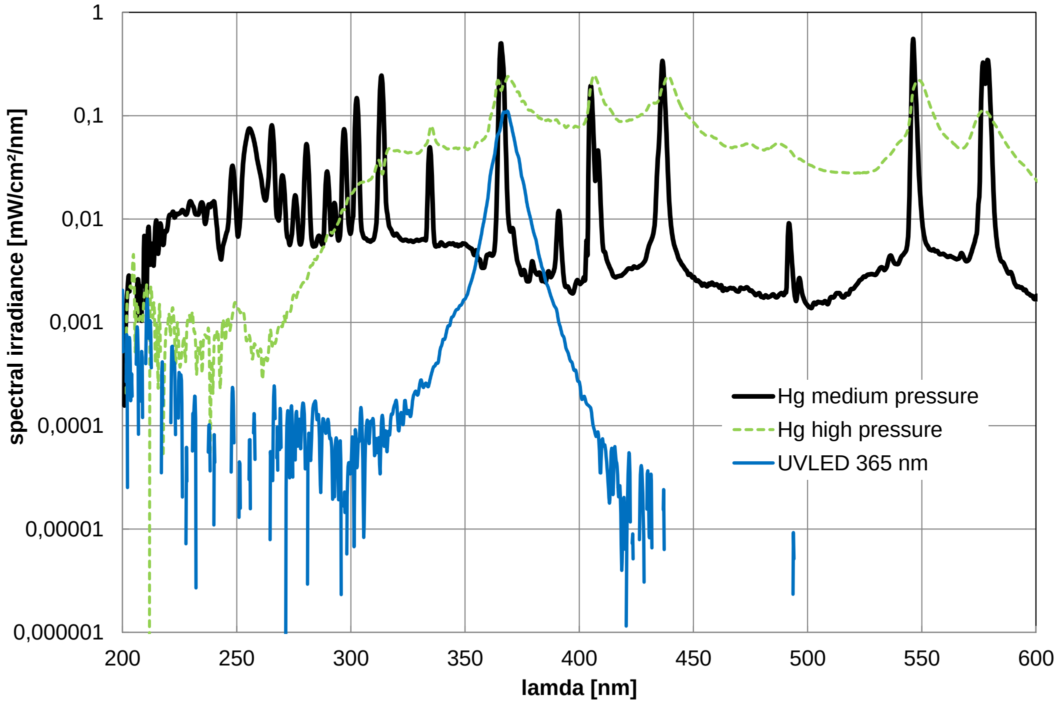

figure 3: emission spectra measured with laboratory spectrometer

Effective irradiances

Especially for the Hg high pressure lamp a significant stray light level is measured below 260 nm using the laboratory spectrometer. This stray light level is produced due the strong lamp emission in the VIS and NIR spectral range.

Using the measurements shown above the effective irradiances have been calculated by equations (1) to (3) for the three spectroradiometers. For the UV sensors a simplifying assumption was made by using the average value for the spectral weighting functions in the sensor specific wavelength ranges UVA, UVB, UVC and 400 – 490 nm according to equation (4) and (5). E_{UVA} is the reading value of the UVA sensor.

$$(4) \qquad E_{eff} = \frac{E_{UVA}}{n} \int_{315}^{400} S_\lambda \, d\lambda + \frac{E_{UVB}}{n} \int_{280}^{315} S_\lambda \, d\lambda + \frac{E_{UVC}}{n} \int_{200}^{280} S_\lambda \, d\lambda \qquad (5) \qquad E_B = \frac{E}{n} \int_{400}^{490} B_\lambda \, d\lambda$$

Note that these assumptions have to be proven for each application / light source and may not be valid in general. The results are given in table 3, normalized to the total irradiance E.

table 3: Effective irradiances normalized to E (table 2)

	E_{eff} / E			E_B / E			E_{UVA} / E		
	Hg med	**Hg high**	**UVLED**	**Hg med**	**Hg high**	**UVLED**	**Hg med**	**Hg high**	**UVLED**
double monochromator	26.5%	1.51%	0.01%	0.42%	1.23%	0.79%	31.4%	92.3%	100.0%
laboratory spectrometer	24.5%	1.81%	0.06%	0.50%	1.26%	0.81%	38.8%	92.4%	100.2%
mobile spectrometer	26.4%	0.46%	0.04%	-	-	-	35.9%	98.6%	100.0%
UV Sensors	30.1%	3.88%	0.13%	0.53%	1.27%	1.37%	23.6%	90.2%	99.8%

For the Hg medium pressure lamp (Hg med) the effective irradiance E_{eff} is nearly identical for all spectroradiometers and within allowed uncertainty range according DIN EN 14255. For the Hg high pressure lamp the stray light in laboratory spectrometer courses a higher value, but would be within tolerance while measurements with the mobile spectrometer are out of tolerance.

The E_{eff} values for the UVLED is up to 6-times higher for the laboratory and mobile spectrometers compared to the double monochromator. The large uncertainty can be reduced with a UVC and UVB sensor measurement. The sensor reading here is zero, and the stray light signal can be reduced without doubt. Note that the UV sensors here cannot be used without special calibration.

E_B estimations for the mobile spectrometer are not possible because of the limited spectral range. The two other spectroradiometers are close together. The E_B values for sensor measurements are within tolerance for Hg medium and high pressure lamps, while for the UV-LED the value is only a rough estimation.

E_{UVA} isn't weighted and not sensitive to stray light. All spectroradiometric measurements would be acceptable and show good agreement. Only the sensor estimation is a little bit out of tolerance for Hg medium pressure lamp.

To summarize the comparison:

- The measurements with the laboratory spectrometer show a good agreement with the double monochromator reference. Especially if the lamp emits in the total measurement range so that stray light is superimposed by real signal the results are very accurate.
- Stray light can be compensated using UVB and/or UVC sensors to ensure that there is no irradiation in that wavelength range.
- Assuming average weighting factors for UV sensors the accuracy strongly depends on known calibration spectra, lamp spectra and sensor sensitivity.

Sensitivity remains a problem. While measurements have been done in the low mW/cm² range the exposure limit would be reached within 0.4 to 143 s. For example the laboratory spectrometer could measure irradiances that are two decades lower with the same accuracy.

But this may not be low enough. To do this we combine sensor measurements with spectrometer measurements to obtain reliable measurement results even at lowest irradiance. Therefore only a few steps are necessary:

1. Measure the spectra at normal irradiance level (for example in boundary area or laboratory)
2. Check for stray light especially in UVB and UVC spectra range
3. Calculate effective irradiances
4. Measure the irradiance with a UV sensor matching lamps main emission
5. Calculate calibration factors for UV sensor using effective values
6. Measure the irradiance with the UV sensor at workplace (very low intensity)
7. Determine total dose or maximum exposure time for every workplace

Naturally this procedure isn't time nor cost effective but strongly reliable by ensuring lowest spectral mismatch for the sensors and highest sensitivities. Using this procedure assumes that equal or less UVC and UVB radiation may be reflected and reaches workplace. Note that this is common if no cold mirrors are used outside the lamp or system housing.

Another method is to use a sensor with known and calibrated spectral sensitivity in combination with high quality lamp spectrum. For example this spectrum can be obtained from manufactures notes or provided by a laboratory. The sensor can be calculated to effective values and the spectral mismatch can be eliminated. Using this method, maybe combined with a software tool, standardized sensors can be used to measure the absolute and effective irradiance level.

For this method a spectrometer (calibrated by known irradiance standard), a calibrated photodiode and a calibrated precision voltmeter will be used. Assuming random, not systematic and independent error of measurement the total uncertainty would be like this:

table 4: Uncertainty estimation

	uncertainty
Spectrometer calibration	7 %
Transfer uncertainty to obtain lamp spectra	4 %
Spectral sensitivity of reference detector	6 %
Transfer uncertainty for spectral UV sensor sensitivity	3 %
Absolute sensor calibration [mW => V]	7 %
Voltage calibration	2 %
total uncertainty	**12.8%**

With a total measurement uncertainty of 12.8 % the method is precise enough, but may overestimate effective exposure values by given assumption.

Summary

Exposure limits and measurement principles have been discussed for safety and risk assessment on UV curing systems. A comparison between high-grade double monochromator, laboratory and mobile spectrometers as well as UV sensors was presented. The effective irradiances for photo-biological risks have been shown for two typical UV systems with HG medium / high pressure lamp and a UVLED system.

According to DIN EN 14255-1:2011 a measurement uncertainty of 30% is necessary. A good agreement was found for a laboratory spectrometer. The necessary sensitivity can be obtained by combination with UV sensors. Therefor two methods have been presented to reduce the sensors spectral mismatch and calibrate for effective irradiances. The measurement uncertainty was estimated to 12.8 %.