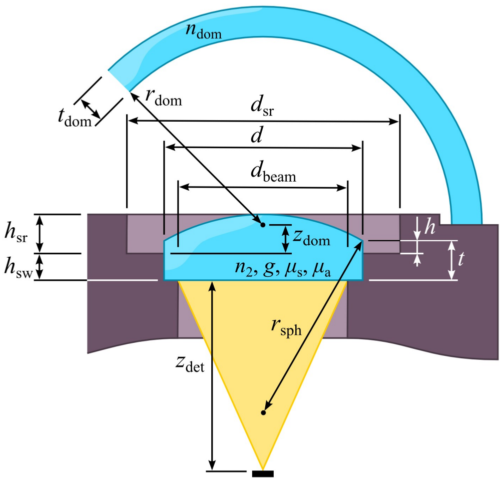
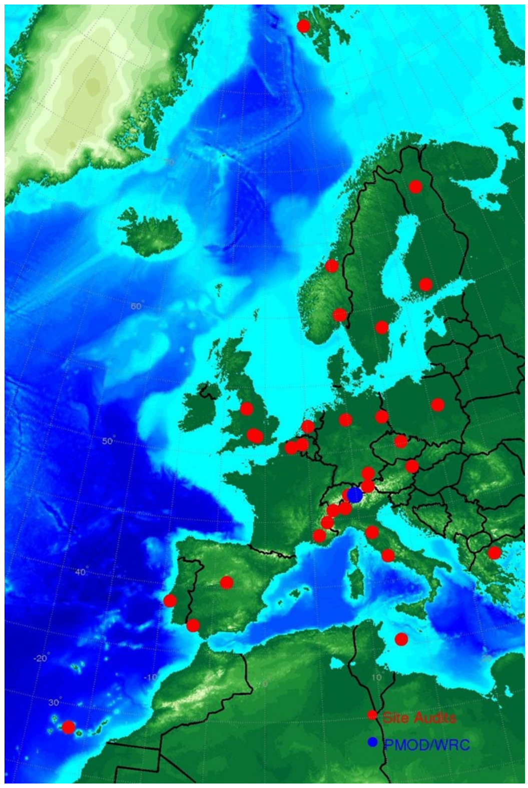
UV NEWS

The official newsletter of the Thematic Network for Ultraviolet Measurements





Issue 9 / January 2013

Aalto University

EMRP
European Metrology Research Programme
Programme of EURAMET

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

Measurement of spectral radiation in UV curing systems

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Abstract

Measurements of spectral irradiance in laboratories are common practice. In industrial environments, broadband radiometers have been in use in UV curing systems for years. Their sensitivity functions differ widely depending on the apparatus used, as a result of which their measurement results cannot be compared. It was only the availability of a compact spectral radiometer that enabled standardized measurements to be made in such systems. This article describes the development of a mobile UV spectral radiometer for industrial use and compares its measuring principle and measurement errors with those of a broadband radiometer.

UV curing

The quality and production speed of modern printing and painting systems have improved rapidly over the last few years. The solvent-based paints and varnishes used in the past have been increasingly replaced by solvent-free coatings. These paints and varnishes are cured with UV radiation in a way that respects the environment and acquire an excellent resistance against organic solvents, chemicals and mechanical environmental factors [1].

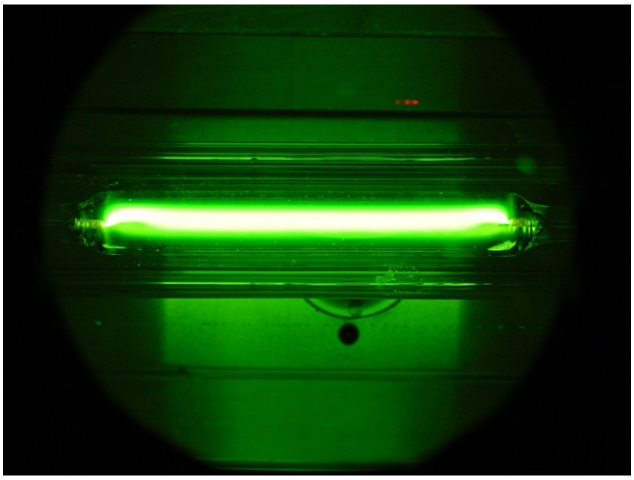

Figure 1. Medium pressure mercury lamp for use in UV curing systems.

However, the problems with this technique concern the cure monitoring of the paints and varnishes. In existing systems, the paint itself is not monitored. Rather, the quality of the curing process is monitored by referring to the measured values of the irradiance and the radiation dose. The UV lamps usually employed in such curing systems have electrical power ratings ranging from a few hundred watts up to approx. 20 kW. Figure 1 shows just such a lamp, which generates irradiances in the region of a few W/cm2 in production plants. If the lamp is doped with indium, gallium or for example iron, this allows the emission spectrum to be adjusted to the absorption of the photoinitiator. The photoinitiator, as a component of a UV paint, initiates the chemical cross-linking of the liquid paint. In addition, UV LED modules with irradiances of up to 16 W/cm^2 are suitable for thermally critical processes.

In most systems, flat articles are cured, e.g. from the furniture industry. Very often their height is only 15 mm. In order to attain high irradiances, the separation between the UV lamp and the item due to be irradiated is kept as small as possible and the articles are moved on conveyor belts at speeds of up to 35 m/min. Due to the small installation height, the measuring device employed is exposed to a high thermal load from lamps operating at temperatures of over 1000ºC.

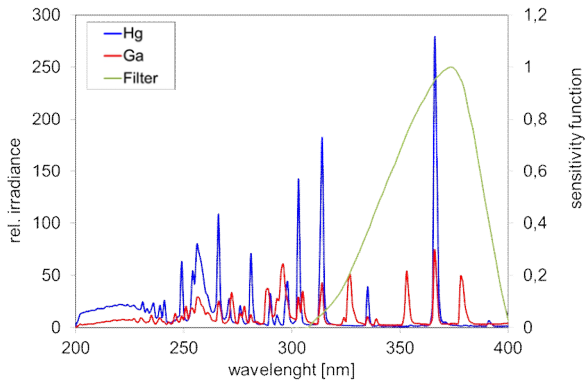

Figure 2. Emission spectra of a mercury (Hg) and a gallium (Ga) medium pressure lamp and a sensitivity function of a broadband radiometer.

Common procedures for monitoring curing systems consist of compact broadband radiometers in a robust housing with an installation height of between 10 and 15 mm. They are supplemented by mobile spectral radiometers, whose advantage lies in the traceability of the measurement of the irradiance back to national standards.

Broadband radiometer

Broadband radiometers consist of a photodiode (Si, SiC, GaP) with an optical filter placed in front. Through the careful selection of the filter, the measuring range can be roughly adjusted to a particular UV spectral range. However, standardized division [2] into UVA, UVB and UVC is not possible.

Following a simple change of lamp, say from a mercury lamp to a gallium lamp, precise measurements of the irradiance and the radiation dose with a broadband radiometer are, to a certain extent, no longer possible. By way of example, the spectra of these two lamps are shown in Figure 2 together with a sensitivity function of a broadband radiometer.

The irradiance shown on the measuring device corresponds to the weighting of the spectral sensitivity S_λ of the receiver diode-filter combination with the emission spectrum E_λ of the UV lamp according to its optoelectronic conversion. In order to achieve this, upon calibration with a known irradiance, a calibration factor k_1 is assigned to a photovoltage U_{photo}

$$E = \int E_\lambda \cdot S_\lambda d\lambda \overset{!}{=} k_1 \cdot U_{Photo} \quad (1)$$

However, broadband radiometers are only calibrated by their manufacturers for one type of lamp and are therefore only able to reproduce correct measurement results for this type of lamp. For example, the deviation with respect to the spectral radiometric target value of the gallium lamp for the spectra shown in figure 2 is -18%.

Thus broadband radiometers are suitable for monitoring moving systems since in such cases it is only necessary to check whether the lamp is dirty or shows signs of ageing. It is also possible to compare systems of identical design. However, as soon as the lamp's spectrum changes or other lamp technologies such as UV LEDs are employed, the measured values for identical devices differ.

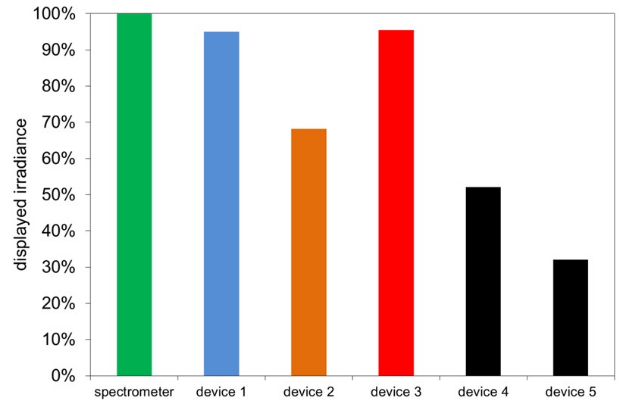

Figure 3. standardized irradiance from a comparison of measuring devices involving five broadband radiometers and a spectral radiometer.

A further problem concerns the arbitrary, manufacturer-specific sensitivity functions of such devices. If broadband radiometers from different manufacturers are compared on the same UV system, then manufacturer-specific deviations emerge that prevent a irradiance reading (as a measured figure). Figure 3 shows the standardized irradiances of five broadband radiometers and a spectral radiometer on a UV curing system with a mercury lamp. What becomes clear is that in some instances, there are deviations of up to 40%. This is why such comparisons between different types of measuring devices are carried out in practice. In order to ensure proper curing, UV systems are usually oversized. In this example, the use of precise measuring technology could reduce the lamp power consumption by 40%. This could lead to reductions in CO2 emissions for a system with a lamp power of 20 kW of around 42 t per year.

The irradiance of printing and painting systems can thus be monitored with broadband radiometers although new systems can only be set up after a comparison of measurement devices. The result is that printing and painting systems are very often oversized, which reduces their cost-effectiveness and worsens their eco-balance.

Spectral radiometer

For scientific purposes, the irradiance is measured using spectral radiometric means. Here, measurement devices consisting of a spectrometer or a monochromator, a cosine-corrected optical probe and, if necessary, an optical fiber. The simulation of a ray path between the optical components of a spectrometer in a Czerny-Turner configuration is shown in Figure 4.

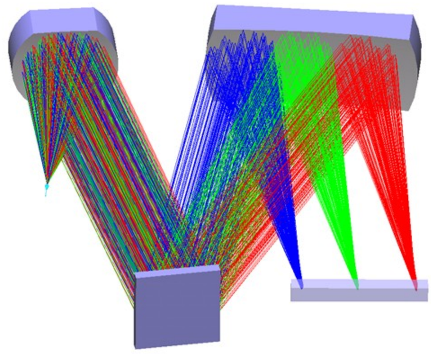

Figure 4. Simulation of a ray path in a Czerny-Turner array spectrometer.

Setup

Its functional principle can be outlined as follows: the input slit is located at the focal point of the collimating mirror on the input side. The mirror parallelizes the impinging ray of light and reflects it onto a diffraction grating, which separates the ray into its spectral components and guides it onto the focusing mirror located on the output side. The mirror then focuses the light onto the detector. The distance between the detector and the mirror on the output side is referred to as the focal length and together with the dispersion grating it defines the spectrometer's basic optical parameters. In the case of compact array spectrometers, whose array detector captures a complete spectrum in parallel, the focal length is usually between 40 and 75 mm. The advantage of the Czerny-Turner configuration is the small degree to which the scattered light is dispersed in the spectrometer, which particularly affects measurement precision in measurements in the UV range or involving highly dynamic spectra. For array spectrometers, suppressions of scattered light of approx. between 10^{-3} and 10^{-4} are attained.

A standardized value for the total irradiance can be obtained through the mathematical integration of the spectral irradiance. In addition, this class of measurement devices can be calibrated in a way that is traceable back to the national meteorological institutes (PTB, NIST).

Wavelength-resolved measurements obtained by weighting the lamp spectrum with the absorption of the photoinitiator allow a production process to optimized and monitored by also referring to the effects [3]. This is useful if doped lamps are used since such lamps increase their emission of a mercury spectrum at the end of their service life.

For mobile measurements in UV systems, a commercial device was set up as an unsymmetrical variant of a Czerny-Turner configuration. Its overall height of 14.4

mm allows it to be used wherever space is at a premium (Fig 5).

Figure 5. Mobile spectral radiometer with an array spectrometer in a Czerny-Turner variant.

Technical requirements

If spectral radiometers are used in UV conveyor systems then the following should be observed:

The item due to be irradiated/measurement device heats up to +40ºC in the space of a few seconds and is exposed to ambient temperatures of up to 70ºC. Due to curing runs measuring in the region of a few meters, the spectral radiometer must either possess long optical fibers that are nevertheless capable of attenuating in the UVC range of the spectrum or must be capable of being deployed on a mobile basis, i.e. without any fiber optic or cable connection. The overall height of common spectrometers means that it is either difficult or impossible to use them in production plants. Even so-called mini-spectrometers with overall heights of between 25 and 40 mm are too large.

The most important requirements and boundary conditions are as follows:

1. Low overall height
2. Ambient temperatures up to 70ºC and resistance to temperature changes
3. Suppression of scattered light
4. Real time evaluation of measurement data
5. The current-carrying capacity of lithium batteries prevents the use of signal processors
6. It must be implemented in a way that ensures that untrained personnel are able to carry out spectral-radiometric measurements.

The low overall height and the suppression of scattered light were achieved through an optimized design. Amongst other things, this includes the coupling of the ray of light through the use of a miniaturized Ulbricht sphere, which combines a cosine correction and 90º deflection of the ray. In addition, the use of highly integrated electronics enabled a spectrometer to be obtained with a focal length of 76 mm.

Spectral-radiometric collection allows measurements to be performed that refer to effects by rear-mounted photoinitiator absorption spectra. This is otherwise only possible in PC-based measurement devices. The resulting repeatability of such a measurement with its standard deviation of 2% is at a high level and is not substantially worse that the results of < 1% obtained with a broadband radiometer.

Calibration

The most important criterion of spectral-radiometric measurements is the validity of the calibration, since these measurement devices can only be used after they have been calibrated. Typical calibration standards are quartz halogen lamps, type FEL 1000 W, in the spectral range 250 – 2500 nm and deuterium lamps in the spectral range 20 – 400 nm. The calibration distance is 50 – 70 cm, which is why spectral irradiances of between 0.5 mW/m²/nm and 10 mW/m²/nm are obtained for calibrations below 400 nm. There are seven orders of magnitude between the use of the measurement device and its calibration. No typical calibration standards can be obtained for the measurement device for measurement device dynamics lying between 10^4 and 10^5. A possibility would be the reduction of the calibration distance which, however, would not allow a sufficient signal-noise ratio to be attained. In order to enable calibration at high irradiances, Hg-, Hg-Xe or Xe short-arc lamps can be used as calibration sources. The spectral irradiance attained by a HBO 1000 W at a distance of 10 cm is shown in Figure 6 together with the spectral irradiance of an Hg-Xe calibration lamp [4].

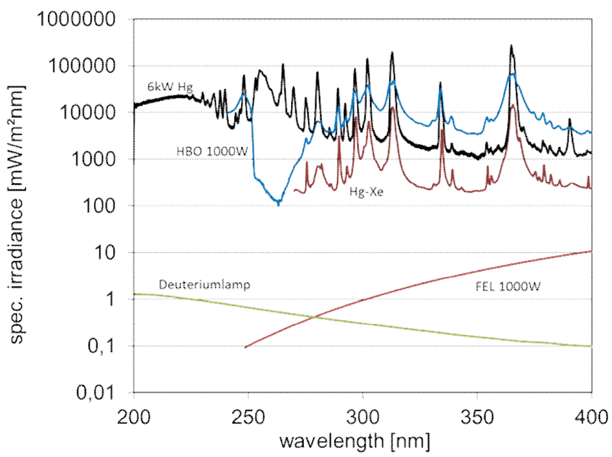

Figure 6. spectral irradiances of calibration lamps (deuterium, FEL 1000 W, Hg-Xe) and production lamps (HBO 1000W, 6 kW Hg).

The challenge for the calibrator is to transfer the partial irradiance of suitable UV lamps to mobile spectral radiometers. The complexity of a spectral calibration at a higher irradiances is, however, justified by the universal applicability of the spectral radiometer.

If validly calibrated, spectral-radiometric measurements of lamps with different doping contents (Hg, Ga, Fe) or UV LEDs are possible, the irradiance of which can be measured in conformity with standards and thus transferred. In this way, laborious comparisons of measurement devices can be dispensed with.

Summary

Spectral radiometers, in the same way as broadband radiometers, enable the measurement of irradinaces in UV curing systems. In addition, they also enable a comparison of radiation measurements since the calibration is also valid for different lamps and standardized irradiance readings can be taken.

Above all, this allows the deliberate oversizing of the systems to be reduced since the irradiances required to cure the paints and varnishes can be individually and precisely measured. This also leads to a reduction in the electrical power consumption of the systems. Moreover, the use of spectral radiometers means that complex comparisons of measurement devices can be dispensed with, something that is unavoidable in the case of broadband radiometers.

Special requirements must be taken into account when developing a spectral radiometer as a mobile device, e.g. a small overall height, the possibility of using it under harsh ambient conditions and its ease of use.

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