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A standardized method to measure the longitudinal UV emittance of low-pressure-lamps in dependence of water temperature

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ABSTRACT

The high level of acceptance of ultraviolet (UV) irradiation for water disinfection in the past decade is due to the development of quality standards, especially for drinking water disinfection in Europe (Austrian Standards Institute, German Standards Institute). The central parts of a UV-disinfection device are the UV lamps. Despite their importance, their characterisation and quality assurance is far from being a matter of course and had not been regulated so far. This holds especially with regard to their temperature behaviour. The UV radiation (UVR) emittance of Mercury-Low-Pressure- and Amalgam-Low-Pressure-lamps (LP-lamps) depends on temperature. Each lamp type has its own optimal temperature where UVR emittance is highest. At lower or higher temperatures, UVR emittance is reduced. Additionally LP-lamps do not emit homogeneously along their length and this emission profile can change with temperature. In this paper, we present a standardized method to measure the UVR emittance of LP-lamps along the length in water in dependence of water temperature. This method has been included in the updated Austrian standard ÖNORM M 5873-1 (2020) and in the new release DIN 19294-1 (2020). With this method, the UVR emittance of LP-lamps can be characterized and different types of lamps can be compared.

Key words: quality control, UV emittance, UV low pressure lamp, UV water disinfection, temperature behaviour

HIGHLIGHTS

- The temperature behavior of UV low pressure lamps has been so far an underestimated factor in UV disinfection of water.
- For the first time a standard test procedure is presented providing objective, independent and reproducible assessment.
- The overall method takes into account the critical properties of the measuring method. With these, measurements become independent from different setups

INTRODUCTION

The irradiation of water with ultraviolet (UV) radiation for disinfection has gained great importance in the last decades in drinking water production, as well as for technical purposes (e.g. process water, water for pharmaceutical plants, and so on) and waste water treatment. The high level of acceptance is due to the development of quality standards, especially for drinking water disinfection in Europe (Austrian Standards Institute, German Standards Institute). The quality control of the UV-disinfection process is based on two main pillars: firstly, on a full-scale biodosimetric test of the UV-disinfection device and secondly on the possibility to check the correct measurement of the device radiometer during practical disinfection operation by an independent reference radiometer traceable to a standard.

In water disinfection by means of UV irradiation, the lamp and its radiant emittance (radiant flux per unit area) in the UV range (further called UVR emittance) is the performance-determining part of the UV-disinfection device. The UVR emittance determines the fluence rate received by the microorganisms in water. UVR emittance can be monitored as irradiance measurement by a radiometer. Despite the importance of lamps, their characterisation and quality assurance is far from being a matter of course and had not been regulated so far. This holds especially with regard to their temperature behaviour. Since the UVR emittance of gas discharge lamps, like mercury (Hg) low pressure (LP) lamps, depends on the temperature, the microbicidal efficacy is temperature-dependent, too. Based on its composition, the surface temperature of a Mercury-LP-lamp is around 40 °C (105°F) and roughly 100 °C (215°F) in the case of amalgam-LP-high-output (ALPHO) lamps. The optimal environmental temperature, at which UVR emittance is highest, is around 20 °C (70°F) for the pure Hg-LP lamps. For ALPHO lamps, the optimal temperature depends on the amalgam composition (He 2012). At lower or higher temperatures, UVR emittance is reduced. Such lamps (together with a protective quartz sleeve) are used for disinfecting water by the use of UV radiation (UVR), whereas the flowing water can easily affect the temperature of the lamp and causes, with that, changes in UVR emittance. Depending on the climate zone and the source of the water used for drinking water production (ground water, surface water) the temperature ranges between 4 °C (39°F) to 30 °C (86°F) during the UV irradiation process for disinfection. For other applications like UV irradiation of process water and hot water systems, temperatures of the water may be up to 60 °C (140°F). Thus, in UV disinfection devices, water temperature changes may occur over time in dependence of the water source and season. This holds also for ground water showing seasonal variability in temperature (e.g. Schmalwieser *et al.* 2015). Resulting changes in UVR emittance are measurable in UV-disinfection devices under practical operation (e.g. Schmalwieser *et al.* 2015). The UV fluence (fluence rate accumulated over time) received by the microorganism in such a device depends, beside flow and UV transmittance of the water, primarily on the UVR emittance of the lamps. If UVR emittance is reduced, the flow must be reduced to ensure sufficient inactivation of pathogens. If UVR emittance decreases below the threshold value for disinfection, the device must display an alarm and the insufficiently irradiated water must no longer be delivered to the consumer (e.g. the water flow has to be stopped). Therefore exact knowledge of the temperature behaviour of the specific type of lamp is essential in order to avoid unexpected reductions of water flow or even shutdowns and to ensure the necessary fluence at all intended water and ambient temperatures and thus to ensure the supply with the necessary amount of microbiologically safe drinking water at all temperatures that occur at the individual place of use.

A recent topic is power control and dimming of lamps. Dimming can be applied to save electric power when the UVR emittance of the lamp is higher than required for the minimum required UV irradiance related to the actual flow of the water to be disinfected. This may occur on the one hand when the UV-254 nm transmittance of the water is higher than expected for the respective application resulting in a higher UV irradiance measured by the device radiometer (W/m^2). On the other, hand the lamp power can be reduced if less water is needed than allowed by the maximum permissible flow corresponding to the given UV irradiance (W/m^2). The influence of water temperature on the UVR emittance of the dimmed lamp differs from that of a lamp driven with full power. Therefore, the UVR emittance profile in dependence of temperature has to be determined, too.

During the past, a few methods have been proposed to characterize the UVR emittance of LP-lamps used for the disinfection of drinking water. The simplest one is to measure the total UVR emittance of the lamp at a certain distance in air (Keitz 1971) as proposed by IUVA Manufacturers' Council (Lawal *et al.* 2008; Bolton & Santelli 2016; Lawal *et al.* 2017). This method delivers a single value only, and was designed to determine the ratio of the electrical input power and the output in the ultraviolet (UV)-C wavelength range (200–320 nm), the so called UV-C efficiency. Recently this method was expanded by putting the lamp inside its corresponding quartz sleeve and immersing it partially or fully in water (Zhang *et al.* 2021). This method delivers as well only a single value.

However, a single measure of irradiance does not characterize an LP-lamp satisfactorily, especially for critical applications like the disinfection of drinking water. A more sophisticated approach was undertaken by Schmalwieser *et al.* (2014) who have measured the UVR emittance of lamps along the length very close to the surface of the bulb. This method delivers a very detailed UVR emittance profile of a lamp. It could be shown that the UVR emittance of the lamp is not homogeneous along its length. Irradiance increases from the electrodes towards the middle of the lamp. The maximum UVR emittance does not necessarily have to be in the middle. Maxima can be found before and a local minimum can be found in the middle of a lamp. The influence of even little artefacts (narrowing of the glass bulb, Amalgam-dots, etc.) may affect the measurement result. Furthermore, it becomes evident, that lamp ageing changes the UVR emittance profile of a lamp compared to that of a new one.

In Austria, the first national standard for UV disinfection devices, ÖNORM M 5873, was released in 1983 (Austrian Standards 1983). Periodical updates ÖNORM 1996, ÖNORM M 5873-1:2001, ÖNORM M 5873-2:2003, ÖNORM 2020 (Austrian Standards 1996, 2001, 2003, 2020a, 2020b) continuously included the latest knowledge and experiences on the different aspects of UV disinfection for drinking water (e.g. Sommer & Cabaj 1993; Cabaj *et al.* 1996; Sommer *et al.* 1996, 1997a, 1997b, 1998, 1999, 2001, 2008; Cabaj & Sommer 2000, Cabaj *et al.* 2002; Cabaj *et al.* 2005). The essential quality improvement in the development was the introduction of the biodosimetric test of commercial UV-disinfection devices and the implementation of the parameter Reduction Equivalent Fluence, REF (J/m^2) (Cabaj *et al.* 1996; Sommer *et al.* 1996). The delivered REF of a UV-disinfection device in full scale is measured at different UV transmittances of the water and water flows, resulting in a permissible operating range (flow vs. irradiance vs. UV transmittance) (Schmalwieser *et al.* 2017). The operation of a UV disinfection device within this range ensures correct disinfection conditions with a REF of 400 J/m^2. The adjustment of the water flow and the UV transmittance of the water over a wide range can be easily accomplished, the latter by adding for example sodium thiosulfate ($Na_2S_2O_3$). However, in the frame of a full-scale test of a UV disinfection device, the adjustment of the temperature of the water would only be feasible with enormous technical effort and is practically impossible. Moreover, although the emission of the lamps inside a UV disinfection device is controlled by at least one UV radiometer measuring the UV irradiance at a defined position in the irradiation chamber, it is not foreseen that the lamps' UVR emittance along their length will be monitored in the irradiation chamber because of practical reasons.

However, the knowledge of a lamp's UVR emittance along its length at different temperatures is necessary because:

(1) A significant decrease of UVR emittance with temperature will restrict the application range of the UV-disinfection device (e.g. temperature range, flow range, etc).
(2) Those parts of the lamp that are closer to the radiometer contribute more strongly to irradiance than more distant parts (e.g. absorption by water). If UVR emittance of distant parts (e.g. lamp's end) decreases more strongly with temperature than other parts, then the radiometer overestimates the UV-disinfection performance. This must be avoided.
(3) The above points have to proven when the lamps are attended to be driven in praxis with reduced power (dimming), because a dimmed lamp reacts differently to temperature.
(4) Additionally, if an existing lamp type has to be replaced by another one (e.g. the original manufacturer has stopped production), than it must be ensured that the replacement mimics the original lamp not only in total irradiance, but also along the length (see 2).

The updated Austrian standard ÖNORM M5873-1:2020 (Austrian Standards 2020) and the identical newly released German standard DIN 19294-1:2020 (German Standards 2020a, 2020b) now address both topics, the differences of UVR emittance along the length of a lamp and the temperature sensitivity of UVR emittance at full power and dimmed, if this use is intended. For this purpose, a test facility had to be developed and standardized together with instructions for measurements and requirements for the quality of the lamps.

Measurements of irradiance are influenced by several factors, as (1) the properties of the used radiometer (e.g. temperature sensitivity, field of view), (2) the used sensor attachment system (SAS) (UV transmittance of the quartz glass window) and (3) the used water to be irradiated (e.g. temperature, UV transmittance). Although the standard regulates properties and requirements for the equipment and the measurements, a certain degree of variability remains. If the setup of the experimental design does not change, this variability cannot be recognized and measurements are repeatable to a high extent. If measurements are carried out with different types of radiometers, different types of SAS or by using water with different UV transmittances, the measured irradiance of the same lamp differs. Corrections are necessary to eliminate the influencing factors on measurements to enable the comparability of the measurements.

In this paper, we derive correction factors, which take into account the critical properties of the measuring method. With the application of these, all influencing parameters are considered, measurements become independent and discrepancies in the results from different setups (e.g. in different laboratories) are avoided. Vice versa, it is possible to quantify differences. Further, we demonstrate the application of the correction factors to measurements and show a few examples for the temperature dependence of LP lamps.

MATERIALS AND METHODS

In this chapter, we describe the test chamber and the temperature control system together with UVR radiometry of the lamp's UVR emittance (measurements of irradiance at 254 nm) according to ÖNORM M 5873. Subsequent to the discovery of the influencing parameters on measured irradiance, we propose a correction procedure for measurements. With that, measurements made under different conditions (e.g. temperature, UV transmittance of the water, type of radiometer) become comparable. In the following, we refer for simplification to ÖNORM/DIN-1 and ÖNORM/DIN-3 only, because ÖNORM M 5873 and DIN 19294 are identical. It should be noted that in the following, UVR refers to a wavelength of 254 nm. The appendix provides a complete list of the abbreviations and nomenclature used.

Test chamber and temperature control

The test chamber (see Figure 1) consists of a steel tube (inner diameter = 168 mm, length = 2,044 mm, for more details see ÖNORM/DIN-1). Every 100 mm, a sensor attachment system (SAS) can be mounted, which denotes up to 18 SASs in total. A SAS – according ÖNORM/DIN-1 – consists of a steel tube and a quartz window (thickness 5 to 10 mm) and enables attachment of a corresponding standard sensor for measurements of irradiance at 254 nm. The test chamber is connected to a water circulating system, which also takes the temperature regulation and control. The heating and cooling system must be able (at least, according ÖNORM/DIN-1) to vary the temperature of the water T_{water} within 5 °C (41°F) and 25 °C (77°F), whereas a wider range is advantageous (e.g. process water). An important requirement for this system is that the T_{water} must be held constant within ± 0.5 °C (± 1°F) independent of the heat input from the lamp and of the heat input from or loss to the surroundings. For control, the T_{water} has to be measured continuously before the inlet and after the outlet with an accuracy of ± 0.5 °C (± 1°F). The water flow must be at least 1.5 m^3/hour (400 gal/hour).

The protective quartz sleeve, which houses the lamp, is mounted and centred by the flange at the end of the chamber and by a special holder inside, at the top of the sleeve. The lamp has to be positioned inside following the manufacturer's recommendation. Connective wires should generally lie at the bottom. The spiral-wound filament must be centred in an SAS to guarantee high reproducibility of measurements. It should be mentioned that the lamp-sleeve combination is a critical issue and is specified by the manufacturer of the lamp. Only parts (e.g. lamp, sleeve, ballast, wires, etc) approved by the manufacturer of the lamp may be used. In the following, we refer generally to a specified lamp-sleeve combination.

Measurements of irradiance

Generally, reference (or device) radiometers according to ÖNORM/DIN-1 and ÖNORM/DIN-3 should be used, because these fulfil specific requirements such as dimensions of the sensor or construction of the entrance optics. The standards define the field of view (160°) and give limits for their properties, e.g. upper and lower limit for the angular response. Such radiometers consist of a sensor that is sensitive to UVR (at 254 nm) and an electronic unit, which converts the electric signal (voltage or current) from the UVR-sensitive photo-element (e.g. SiC-diode) into values of irradiance in units of W/m^2. The electronic unit can be located in a separate housing (together with a display) or inside the sensor housing (with a separate display unit outside). The properties of these radiometers are determined with high accuracy during the ÖNORM certification process and are made available for the user by the certificate. However, it is also possible to use more sophisticated instruments like spectroradiometers with an appropriate input optics, to measure the full emittance spectrum of a lamp instead of just the irradiance at 254 nm like the standard radiometers do.

It is important that final measurements are taken after the lamp-sleeve combination has stabilized (e.g. after ignition, after dimming, or after T_{water} has changed) by reaching its final temperature and UVR emittance. Multiple measurements of irradiance over time can indicate this. A lamp is regarded as stabilized when irradiance changes (non-directional) do not exceed 2% within 10 minutes.

In practice, we measure irradiance with a reference radiometer according to ÖNORM/DIN-3. Such a reference radiometer, although identical in construction, fulfils higher requirements than a device radiometer, for example in deviation from linearity. The reference radiometer used in this study consists of a research grade radiometer type IL1700 equipped with a sensor

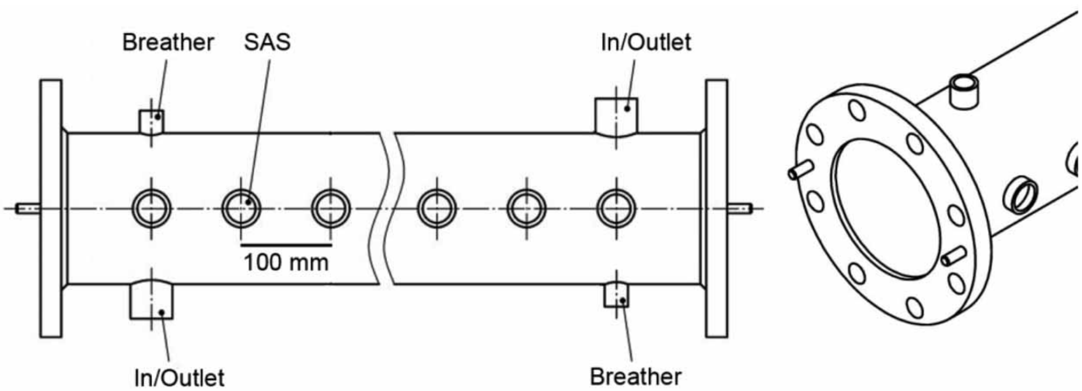

Figure 1 | Schematics of the irradiation chamber according ÖNORM M 5873-1 and DIN 19294-1.

type SED 240 NS254 (International Light Inc., USA) and an adapter that fits into the SAS. The sensor of the reference radiometer is kept outside the SAS (at constant temperature). Only for measurements, the sensor is placed inside the SAS. To avoid condensation at the quartz window of the SAS, the SAS is flooded with dry air before and while the sensor is inserted. If sensors are continuously within the SAS, it has to be ensured that condensation cannot occur (e.g. by sealing). With this approach, measurements of irradiance are repeatable within a variation coefficient of $\pm 1\%$.

Further, the radiometer must be calibrated according to the procedure defined by the standard (e.g. quasi-parallel beam) and has to be traceable to a national metrological institute (in our case Physikalisch-Technische-Bundesanstalt (PTB), Germany).

Data correction

Irradiance measurements of a lamp in water are affected by the properties of the radiometer and the properties of the water. There are intrinsic properties like the angular response of the sensor or the UV transmittance of the water and properties, that change with temperature (e.g. an electric signal from the sensor). Measurements are influenced by these properties to a certain extent, but can be corrected. The most important properties are the UVR transmission coefficient of the SAS, the UV transmittance of the water, the temperature sensitivity of the radiometer and its angular response. Our proposed corrections will refer measured irradiance to high-purity (or ultra-pure) water, gained with a radiometer possessing the highest allowed angular response according ÖNORM/DIN and to a temperature of 20 °C (70°F). Figure 2 depicts schematic drawing of the measuring geometry.

(1) **UV-transmission coefficient of the SAS:** According the Austrian Standard the spectral transmission coefficient at 254 nm of the quartz plate of the SAS (see 'Quartz' in Figure 2) must be at least 0.9 or higher. There could be differences in the transmission coefficient $\sigma_{SAS,n}$ of the different SAS n, because of several reasons (manufacturing process, type, thickness of the quartz plate or manufacturer). However, $\sigma_{SAS,n}$ does not change with temperature ($<< 1\%$ in the temperature range of interest). The transmission coefficient of all SASs has to be measured (e.g. by a spectrophotometer within $\pm 0.1\%$ at 254 nm) and corrected. We propose to eliminate the influence of the SAS. The corresponding correction factor $c_{SAS,n}$ for the SAS at position n is the inverse of the measured spectral transmission coefficient at 254 nm:

$$c_{SAS,n} = \frac{1}{\sigma_{SAS,n}} \tag{1}$$

It should be noted that this is a slight simplification (because related to a perpendicular beam), but is valid as we correct differences between the (standardized) SASs only.

(2) **Deviation of the UV-radiometer from linearity:** In general, deviation from linearity of radiometers is a minor problem. However, this property should be taken into account as well. $c_{LIN,n}$ corrects the deviation of the radiometer (used at position/SAS n) from linearity and depends on the measured irradiance $E_{meas,n}$. The reference point for deviations from linearity is the irradiance $E_{cal,n}$ at which the absolute calibration of the radiometer is done.

With that:

$$c_{Lin,n}(E_{meas,n} = E_{cal,n}) = 1.0 \tag{2a}$$

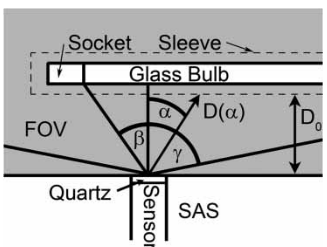

Figure 2 | Schematics of the measuring geometry. Parts of no importance are omitted to hold the schematics simple.

In practice, calibration is done at an irradiance value in the range from 1 W/m^2 to 10 W/m^2, because a quasi-parallel beam is necessary. Deviation from linearity must be known for each gain range of the radiometer. In respect to the gain range, three different radiometers are available. Radiometers with only one gain range, radiometers with manual selection of the gain range (e.g. 0–2 W/m^2, 2–20 W/m^2) and radiometers with automatic gain range selection.

If the deviation from linearity is constant over the entire working range, the correction factor for deviations from linearity is:

$$c_{Lin,n} = \frac{1}{1 + (E_{meas,n} - E_{cal,n}) \cdot s_{Lin,n}} \tag{2b}$$

where as $s_{LIN,n}$ denotes the relative deviation per W/m^2.

In certain cases, more complex functions for each gain range are necessary. A reference radiometer according to ÖNORM M5873–3 must not deviate more than 5% from linearity within the range of 0.1 W/m^2 to the upper limit of its working range (which must range up to at least 250 W/m^2).

(3) **Temperature sensitivity of the UV radiometer:** The radiometer(s) may be sensitive to temperature. Therefore, the relative temperature response of the radiometer used at position n has to be known and corrected. If the sensor is inside the SAS for more than a few seconds, for examples when measurements are done continuously, then the sensor takes the temperature T_{Sens} of the water T_{water}. The electronic unit may have the temperature $T_{Elect,n}$ of the surrounding T_{air}. The sensitivity of each component $s_{T\text{-}Sens,n}(T)$ and $s_{T\text{-}Elect,n}(T)$ has to be determined in respect to a reference temperature *T-ref of* 20 °C ($s_{T\text{-}Sens,n}$(20 °C) = $s_{T\text{-}Elect,n}$(20 °C) = 1.0) in advance and taken into account:

$$c_{Temp,n} = \frac{1}{s_{T-Sens,n}(T_{Sens}) \cdot s_{T-Elect,n}(T_{Elect})} \tag{3a}$$

If a so-called digital sensor is used (electronic unit is inside the sensor housing and provides a digital value), then only one temperature sensitivity value $s_{digital,n}(T_{digital})$ exists, where this is either T_{air} (when sporadically inside the SAS) or T_{water} (when continuously inside the SAS):

$$c_{Temp,n} = \frac{1}{s_{digital,n}(T_{digital})} \tag{3b}$$

(4) **Internal UV transmittance of the water, field of view of the sensor and angular response:** Although the distance between the entrance optics of the sensor (SAS) and the lamp (sleeve) is in the order of several centimetres, UV-transmission through the water has a noticeable influence on measured irradiance. ÖNORM/DIN-1 recommends to measure internal UV transmittance of the water with a path length of 100 mm ($\tau_{100\,mm}$) in relation to high-purity water. This distance comes close to the distances between sensors and lamps (in UV-disinfection devices too) and enables highly accurate measurements in drinking water. As $\tau_{100\,mm}$ of common tap water can vary over a wide range (e.g. Schmalwieser *et al.* 2015), the Austrian Standard demands the $\tau_{100\,mm}$ of the used water to be at least 0.8 to reduce the influence of τ on a first order. This denotes generally filtering tap water with an activated charcoal filter. The usage of deionized water is not recommended because of its high chemical reactivity (possibly with parts of the setup).

The angular response of the sensor is specified in ÖNORM/DIN by not only a field of view of 160°, but also within an upper and a lower limit, which restricts differences in measurements in any case to 7% (Schmalwieser 2017). The ruled angular response is somewhat lower than the perfect cosine response, because of the ruled design of the entrance optics.

As irradiance decreases exponentially with increasing path length in water, the angular distance between the SAS and the sleeve as well as $\tau(\alpha)$ of the water, the angular response of the sensor $a_n(\alpha)$ and the angular UVR emittance of the lamp $\varepsilon(\alpha)$ have to be taken into account. The problem can be restricted to the longitudinal component of the radiation field, because perpendicular to its axis, the lamp captures only a narrow angle in the field of view of the sensor ($< \pm$ 10°). In this range, the angular response is close to 1.0. Further, it is assumed that the overall radiation field depends on the UVR emittance

$\varepsilon(\alpha)$ of the lamp. The received (relative) irradiance from all directions $R_{a,\tau,n}$ can be described as:

$$R_{a,\tau,n} = \int_{\alpha=\beta_n}^{\gamma_n} R_{a,\tau,n}(\alpha) \cdot d\alpha = \int_{\alpha=\beta_n}^{\gamma_n} \tau_n(\alpha) \cdot a_n(\alpha) \cdot \varepsilon(\alpha) \cdot d\alpha \tag{4}$$

α is the viewing angle, which is within β_n and γ_n.

β_n and γ_n are either the angular length of the lamp on the right and left side (in respect to the perpendicular) of the sensor or the limiting angles of the field of view (see Figure 2). For example: if the lamp fills the field of view of the sensor, then $\beta = -80°$ and $\gamma = +80°$. If the lamp ends on the right side within the field of view, then $\gamma < 80°$. Both angles β_n and γ_n change with the position n of the SAS in respect to the lamp.

$\tau_n(\alpha)$ is the internal UV transmittance of the water column $D_n(\alpha)$ between the SAS and the sleeve in the direction of α.

$a_n(\alpha)$ is the angular response of the radiometer respectively sensor at position n.

$\varepsilon(\alpha)$ is the angular UVR emittance of the lamp.

We suppose to relate the correction for the angular response to the upper limit (*a-up*) of the angular response (=most sensitive sensor). So the correction factor $c_{AR,n}$ is:

$$c_{AR,n} = R_{a-up,\tau,n}/R_{a-sens,\tau,n} \tag{5}$$

whereas, $R_{a\text{-}sens,\tau,n}$ denotes the irradiance (application of Equation (4)) received by the sensor (used for measurements), which possesses the angular response $a_n(\alpha) = a\text{-}sens$. $R_{a\text{-}up,\tau}$ denotes the irradiance (application of Equation (4)) that would be received by a sensor with the highest allowed angular response $a_n(\alpha) = a\text{-}up$.

The factor $c_{\tau,n}$ for correcting the influence of τ can be calculated by:

$$c_{\tau,n} = R_{a-up,\tau=1,n}/R_{a-up,\tau,n} \tag{6}$$

whereas, $R_{a\text{-}up,\tau=1,n}$ denotes the received irradiance (application of Equation (4)) by a sensor with the highest allowed angular response *a-up*, but in high-purity water ($\tau = 1.0$).

The integral (Equation (4)) can be solved numerically for each SAS position n as follows:

$$R_{a,\tau,n} = \frac{1}{Z_n + 1} \cdot \sum_{i=0}^{Z_n} R(\alpha_i) = \frac{1}{Z_n + 1} \cdot \sum_{i=0}^{Z_n} a(\alpha_i) \cdot \tau(\alpha_i) \cdot \varepsilon(\alpha_i) \tag{7}$$

whereas:

$$\alpha_i = \beta_n + i \cdot d\alpha(\beta_n \leq \alpha_i \leq \gamma_n) \tag{8}$$

$d\alpha$ is 5° (or 10°), because the angular response $s(\alpha_i)$ of the sensors is available (from the ÖNORM certificate) with this stepwidth and $d\alpha$ determines with that the number of Z_n.

$$Z_n = |\beta_n| + |\gamma_n|/d\alpha \tag{9}$$

The limiting angles β_n and γ_n are calculated trigonometrically from the position of the SAS in respect to the length of the lamp (see below).

$a_n(\alpha_i)$ is the angular response of the sensor used ($a\text{-}sens(\alpha_i)$) or is the upper limit of the angular response ($a\text{-}up(\alpha_i)$).

The internal transmittance of the water depends exponentially on the path length dc. The internal transmittance of the water τ_{dc} is measured by a spectrophotometer (at 254 nm against high-purity water) with a certain path length d_C (length of cuvette, in our case 100 mm). For each angle α_i, the internal transmittance of the water column $\tau(\alpha_i)$ between the SAS and the sleeve, can be calculated from τ_{dc} (measured with a cuvette of length d_C) in respect to the distance $D(\alpha_i)$:

$$\tau(\alpha_i) = \tau_{dc}^{\frac{D(\alpha_i)}{d_c}} \tag{10a}$$

In our case $d_c = 100$ mm. With that:

$$\tau(\alpha_i) = \tau_{100mm}\frac{D(\alpha_i)}{100mm} \tag{10b}$$

$\tau_{100\,mm}$ is the internal transmittance for a path length d_c of 100 mm.

$D(\alpha_i)$ is the path length between the SAS and the surface of the sleeve for the viewing angle α.

This angular distance $D(\alpha_i)$ can be calculated as follows:

$$D(\alpha_i) = \frac{D_0}{cos(\alpha_i)} \tag{11}$$

D_0 is the perpendicular distance between the SAS and the surface of the sleeve and is the same at all positions n.

$\varepsilon(\alpha_i)$ is the angular emission of the lamp. It is not a critical quantity, because its nature does not differ significantly in LP lamps. Assuming a Lambertian source with

$$\varepsilon(\alpha_i) = \cos\alpha_i \tag{12}$$

fulfils our needs, especially as the correction factors $c_{AR,n}$ and $c_{\tau,n}$ are gained by dividing two terms ($R_{a,\tau,n}$), which both include the emission ε.

(5) **Correction of measured irradiance:** Using the correction factors from above, the measured irradiance $E_{meas,n}(T,\tau,Rad,SAS,E)$ at position n, at a certain water temperature T_{water} (gained with a certain radiometer *Rad*, using a certain SAS, when water had a certain τ) can be corrected as follows to get the irradiance $E_n(T_{water})$ in high-purity water by the highest allowed angular response:

$$E_n(T_{water}) = E_{meas,n}(T_{water}, \tau, rad, SAS) \cdot c_{Lin,n} \cdot c_{SAS,n} \cdot c_{Temo,n} \cdot c_{AR,n} \cdot c_{\tau,n} \tag{13}$$

With this correction, measured irradiances – caused by the emission lamps at a certain temperature and position n along the length of the lamp – can be compared with high accuracy, because the corrected irradiance becomes independent of equipment and conditions.

This correction allows also determination of the temperature dependence of a lamp's emission (with high accuracy), because the influence of temperature on the radiometer is eliminated.

(6) **Normalisation of irradiance:** absolute irradiance values gained and corrected as described above can be used to compare different lamps at different temperatures and/or different longitudinal positions. However, to describe the behaviour of the lamps within the temperature range, it is appropriate to use normalized values of irradiance η. We propose to normalize the measurements $E_n(T_{water})$ to the maximum irradiance $E_{max}(T_{water} = 20\,°C)$ found along the length of the lamp at a water temperature T_{water} of 20 °C (70°F):

$$\eta_n(T_{water}) = \frac{E_n(T_{water})}{E_{max}(T_{water} = 20\,^\circ C)} \tag{14}$$

The normalized values allow a quick estimate of the changes in irradiance of a lamp (within a UV-disinfection device) and with that on the delivered fluence and the possible water flow of a UV-disinfection device in dependence of T_{water}.

RESULTS AND DISCUSSION

Practical calculation of correction factors and application

In the following, we provide a practical calculation of the correction factors and their application for measurements of irradiance. The calculation and application can be done with two tables (realized e.g. by a spreadsheet calculation) and another one that contains the necessary input quantities.

In this example, irradiance measurements of a lamp are done under the following conditions (Table 1) using components for the setup according to ÖNORM/DIN-1:

- As mentioned above, we relate our corrections: to high-purity-water ($\tau\text{-}ref_{100\,mm} = 1.0$, and τ_{dc} is measured with a path length d_c of 100 mm) (first two lines of Table 1); to a reference temperature *T-ref* of 20 °C (line 3); and to the highest limit of the angular response *a-up(α)* according to ÖNORM M5873 (line 4; numbers have to be input in column 7 of Table 2).
- Measurements were done at a room temperature of $T_{air} = 20$ °C (line 5), while the temperature of the water was $T_{water} = 4$ °C (line 6) and $\tau_{100\,mm} = 0.8$ (=80%) (line 7).
- The distance *B* (see Figure 3) between the wound-spiral filaments is 1,150 mm and the length of the uncovered glass bulb L is 1,200 mm (line 8). As the filament is centred in the middle of the first SAS (SAS 1), the length of the lamp to the left of SAS 1, $l_{end} = (L\text{-}B)\ /2$, is 25 mm (line 9). The lamp covers 11 SASs (line 10) and the distance between the SASs and the quartz sleeve (D_0) was measured to be 60 mm (line 11).
- The SASs possess a σ of 0.925, but deviating (randomly) within ± 0.025 (line 12; the measured σ_n of each SAS is input in line 7 of Table 3).
- Measurements are done with one type of radiometer, which was calibrated at 1 W/m^2 (line 13). The radiometer shows a deviation from linearity of a 4% decrease in the range from 1 W/m^2 (irradiance of calibration) to 250 W/m^2 ($= -1.60 \cdot 10^{-4}$ (W/m^2)$^{-1}$, line 14). The radiometer consists of a sensor and an electronic unit. The sensor stays inside the SAS

Table 1 | Values for reference points and for conditions under which the measurements were performed

No.		Parameter	Value
1	Reference	$\tau\text{-}ref\ [1] =$	1.00
2		$d_c\text{-}ref\ [mm] =$	100.0
3		$T\text{-}ref\ [°C] =$	20.0
4		$a\text{-}ref(\alpha) =$	Upper limit according to ÖNORM M5873 (see Table 2)
5	Conditions	$T_{air}\ [°C] =$	20.0
6		$T_{Water}\ [°C] =$	5.0
7		$\tau_{100\,mm}\ [1] =$	0.8
8		$L\ [mm] =$	1,200.0
9		$l_{end}\ [mm] =$	25.0
10		$N\ [1] =$	11
11		$D_0\ [mm] =$	60.0
12		$\sigma_{Sas,n}\ [1] =$	0.925 ± 0.025 (see Table 3)
13		$E_{cal}\ [W/m^2] =$	1.00
14		$s_{lin,n}\ [\mathrm{W/m^2}]^{-1} =$	- 1.60 · 10^{-4}
15		$s_{T\text{-}sens}(T_{Water})_{n=1\text{-}11}\ [1] =$	0.96
16		$s_{T\text{-}elec}(T_{air})\ _{n=1\text{-}11}\ [1] =$	1.00
17		$s_{Temp}(T_{Water}, T_{air})\ _{n=1\text{-}11}\ [1] =$	0.96
18		$a\text{-}sens(\alpha)\ _{n=1\text{-}11}\ [1] =$	see Table 2
19		$\varepsilon(\alpha)\ [1] =$	Lambertian
20		$E_{meas,n}\ [W/m^2] =$	see Table 3

Table 2 | Angular (α) distribution of the radiation field described by the angular distance between SAS and sleeve $D(\alpha,D_0)$, $\tau(D)$ over this distance, angular UVR emittance $\varepsilon(\alpha)$ and angular response of the used radiometer *a-sens*(α) as well as the upper angular response *a-up*(α) according to ÖNORM. The last three columns contain the angular contribution of received irradiance for the used radiometer $R_{a\text{-}sens,\tau}(\alpha)$, a radiometer with the highest allowed angular response $R_{a\text{-}up,\tau}(\alpha)$ and when high-purity water (τ-*ref*) would have been used $R_{a\text{-}up,\tau\text{-}ref}(\alpha)$

1 α [°]	2 $D(\alpha,D_0)$ Equation (11) [mm]	3 $\tau(D)$ Equation (10b) [1]	4 τ-ref *Input* [1]	5 $\varepsilon(\alpha)$ Equation (12) [1]	6 a-sens(α) *Input* [1]	7 a-up(α) max *M5873* [1]	8 $R_{a\text{-}sens,\tau}(\alpha)$ $=\tau(D)\cdot\varepsilon(\alpha)\cdot$ a-sens(α) [1]	9 $R_{a\text{-}up,\tau}(\alpha)$ $=\tau(D)\cdot\varepsilon(\alpha)\cdot$ a-up(α) [1]	10 $R_{a\text{-}up,\tau\text{-}ref}(\alpha)$ $=\tau\text{-}ref\cdot\varepsilon(\alpha)\cdot$ a-up(α) [1]
−80	345,5	0,463	1,00	0,174	0,044	0,104	0,004	0,008	0,018
−75	231,8	0,596	1,00	0,259	0,124	0,187	0,019	0,029	0,048
−70	175,4	0,676	1,00	0,342	0,205	0,274	0,047	0,063	0,094
−65	142,0	0,728	1,00	0,423	0,287	0,361	0,088	0,111	0,153
−60	120,0	0,765	1,00	0,500	0,369	0,445	0,141	0,170	0,223
−55	104,6	0,792	1,00	0,574	0,451	0,525	0,205	0,238	0,301
−50	93,3	0,812	1,00	0,643	0,531	0,601	0,277	0,314	0,386
−45	84,9	0,828	1,00	0,707	0,608	0,671	0,356	0,393	0,474
−40	78,3	0,840	1,00	0,766	0,681	0,735	0,438	0,473	0,563
−35	73,2	0,849	1,00	0,819	0,750	0,794	0,522	0,552	0,650
−30	69,3	0,857	1,00	0,866	0,812	0,846	0,602	0,628	0,733
−25	66,2	0,863	1,00	0,906	0,868	0,891	0,679	0,697	0,808
−20	63,9	0,867	1,00	0,940	0,915	0,930	0,746	0,758	0,874
−15	62,1	0,871	1,00	0,966	0,953	0,963	0,801	0,810	0,930
−10	60,9	0,873	1,00	0,985	0,981	1,000	0,843	0,860	0,985
−5	60,2	0,874	1,00	0,996	0,990	1,000	0,862	0,871	0,996
0	60,0	0,875	1,00	1,000	1,000	1,000	0,875	0,875	1,000
5	60,2	0,874	1,00	0,996	0,990	1,000	0,862	0,871	0,996
10	60,9	0,873	1,00	0,985	0,981	1,000	0,843	0,860	0,985
15	62,1	0,871	1,00	0,966	0,953	0,963	0,801	0,810	0,930
20	63,9	0,867	1,00	0,940	0,915	0,930	0,746	0,758	0,874
25	66,2	0,863	1,00	0,906	0,868	0,891	0,679	0,697	0,808
30	69,3	0,857	1,00	0,866	0,812	0,846	0,602	0,628	0,733
35	73,2	0,849	1,00	0,819	0,750	0,794	0,522	0,552	0,650
40	78,3	0,840	1,00	0,766	0,681	0,735	0,438	0,473	0,563
45	84,9	0,828	1,00	0,707	0,608	0,671	0,356	0,393	0,474
50	93,3	0,812	1,00	0,643	0,531	0,601	0,277	0,314	0,386
55	104,6	0,792	1,00	0,574	0,451	0,525	0,205	0,238	0,301
60	120,0	0,765	1,00	0,500	0,369	0,445	0,141	0,170	0,223
65	142,0	0,728	1,00	0,423	0,287	0,361	0,088	0,111	0,153
70	175,4	0,676	1,00	0,342	0,205	0,274	0,047	0,063	0,094
75	231,8	0,596	1,00	0,259	0,124	0,187	0,019	0,029	0,048
80	345,5	0,463	1,00	0,174	0,044	0,104	0,004	0,008	0,018

and takes the temperature of the water. The sensitivity of the sensor at 5 °C is 4% lower than at 20 °C ($s_{T\text{-}sens} = 0.96$, line 14). The electronic is kept at a room temperature of 20 °C and needs no correction ($s_{T\text{-}Elec} = 1.0$, line 15). In total $s_{Temp} = 0.96$. The angular response of the sensor is at the lower limit of ÖNORM/DIN (line 18; numbers are inserted in column 6 of

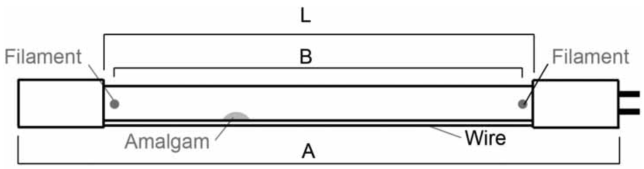

Figure 3 | Schematics of an amalgam-LP-high-output lamp, whereas A denotes the total length of the lamp, L the length of the uncovered glass bulb and B the distance between the spiral-wound filaments. In some lamps, the ends of the glass bulb and in some lamps also the filaments are hidden by the socket. In the last case: B > L.

Table 2). The UVR emittance of the lamp is assumed to be Lambertian (line 19; numbers are calculated according Equation (5) in column 5 of Table 2).

- Finally, the measured irradiance $E_{meas,n}$ at each SAS n is input in Table 3 (line 4).

Now one can start in Table 2 with preparing the calculation of the correction factors for the angular response $c_{AR,n}$ (Equation (5)) and for τ of the water $c_{\tau,n}$ (Equation (6)) by solving the integral (Equation (4)) numerically (according to Equation (7)). For this, we use an angular resolution $d\alpha$ of 5°. According to the field of view (160°) of the ÖNORM sensors, α can range from −80° to +80° (Table 2, column 1). With this, together with the distance $D_0 = 60$ mm (line 9, Table 1), one can calculate $D(\alpha_i)$ using Equation (11) (column 2). For these distances (path lengths), $\tau(\alpha_i)$ is calculated using Equation (10b) (column 3). The next column (column 4) contains $\tau(\alpha_i)$ along $D(\alpha_i)$, when the reference $\tau\text{-}ref = 1.0$ is used (this column is not mandatory and could be incorporated directly into the calculations of column 10 instead).

The fifth column describes the UVR emittance of the lamp $\varepsilon(\alpha_i)$. We assume a simple Lambertian emission (according to Equation (11)). It should be noted that this description of the angular emission has little influence on the correction factors $c_{AR,n}$ and $c_{\tau,n}$, because it is incorporated in the numerator as well as the denominator of the fraction in Equations (5) and (6).

The angular response $a\text{-}sens(\alpha_i)$ of the used radiometer is given in column 6 and the upper limit of the angular response $a\text{-}up(\alpha_i)$ according ÖNORM in column 7.

Column 8, 9 and 10 contain the basic calculations for irradiance factors $R(\alpha)$:

$$\text{Column 8:}\quad R_{a-sens,\tau}(\alpha) = \tau(D)\cdot\varepsilon(\alpha)\cdot a - sens(\alpha)\quad \text{(from column 3, 5 and 6)} \tag{15}$$

$$\text{Column 9:}\quad R_{a-up,\tau}(\alpha) = \tau(D)\cdot\varepsilon(\alpha)\cdot a - up(\alpha)\quad \text{(from column 3, 5 and 7)} \tag{16}$$

$$\text{Column 10:}\quad R_{a-up,\tau-ref}(\alpha) = \tau - ref(D)\cdot\varepsilon(\alpha)\cdot a - up(\alpha)\quad \text{(from column 4, 5 and 7)} \tag{17}$$

(The values of each column will be summed up (sigma sign of Equation (7)) from β_n to γ_n (at each position n) to get the values of $R_{a,\tau,n}$, $R_{a\text{-}up,\tau,n}$ and $R_{a\text{-}up,\tau\text{-}ref,n}$. These are used to calculate the correction factors $c_{AR,n}$ and $c_{\tau,n}$ in the next section (Table 3)).

Now we can continue in Table 3 to calculate the correction factors for the measurements of irradiance at each SAS position n (Table 3, line 1). In this example, measurements have been made at 11 SAS, because the length of the glass bulb L was 1,200 mm and the SASs are 100 mm distant from each other; the last one 164 mm from the end of the chamber. Line 2 and 3 contain the positions of the SAS (l_n and l'_n) in respect to the length of the lamp in units of mm. The filament of the lamp is centred in SAS 1. The positions l_1 and l'_1 are therefore 25 mm (=(L – B)/2, see Figure 3), when regarded as start of the lamp (line2) respectively 1,175 mm (=L – (L – B)/2, see Figure 3) (line 3) when regarded as the end of the lamp. The values l_n and l_n' are used below, for calculating the angular lengths β_n and γ_n of the lamp within the field of view of the sensor (line 11 and 12). As the wound-spiral filament is centred in an SAS (and not the end of the lamp), the distance l_{end}, between the end of the lamp and the centre of the SAS (filament) have to be taken into account. As the lamp overtops the SAS, l_{end} is positive (otherwise it would be negative).

$$l_n = l_{end} + (n-1)\cdot 100\text{ mm} \tag{18a}$$

$$l'_n = L - l_{end} - (n-1)\cdot 100\,\text{mm} \tag{18b}$$

Table 3 | Stepwise calculation and application of correction factors to measured irradiance (see text for details)

	Parameter	Position											Calculation
1	SAS n	1	2	3	4	5	6	7	8	9	10	11	INPUT
2	l_n [mm]	25	125	225	325	425	525	625	725	825	925	1,025	$=l_{end} + (n-1) \cdot 100$
3	l_n' [mm]	1,175	1,075	975	875	775	675	575	475	375	275	175	$=L - l_{end} - (n-1) \cdot 100$
4	$E_{Meas,n}$ [W/m^2]	40,0	85,0	90,0	94,0	89,0	92,0	91,0	88,0	94,0	92,0	87,0	INPUT
5	$\sigma_{SAS,n}$ [1]	0,900	0,910	0,920	0,950	0,910	0,940	0,930	0,900	0,950	0,940	0,920	INPUT
6	$c_{SAS,n}$ [1]	1,111	1,099	1,087	1,053	1,099	1,064	1,075	1,111	1,053	1,064	1,087	$=1/\sigma_{SAS,n}$
7	$s_{Lin,n}$	$-1.6\cdot10^{-4}$	$-1.6\cdot10^{-4}$	$-1.6\cdot10^{-4}$	$-1.6\cdot10^{-4}$	$-1.6\cdot10^{-4}$	$-1.6\cdot10^{-4}$	$-1.6\cdot10^{-4}$	$-1.6\cdot10^{-4}$	$-1.6\cdot10^{-4}$	$-1.6\cdot10^{-4}$	$-1.6\cdot10^{-4}$	(from Tab.1)
8	$c_{Lin,n}(E_n)$ [1]	1,0031	1,0068	1,0072	1,0075	1,0071	1,0073	1,0073	1,0070	1,0075	1,0073	1,0069	$=1.0 + (E_{meas,n} - E_{cal,n}) \cdot s_{Lin,n}$
9	$s_{Temp,n}$ [1]	0,96	0,96	0,96	0,96	0,96	0,96	0,96	0,96	0,96	0,96	0,96	(from Tab.1)
10	$c_{Temp,n}$ [1]	1,042	1,042	1,042	1,042	1,042	1,042	1,042	1,042	1,042	1,042	1,042	$=1/s_{Temp,n}(T)$
11	β_n [°]	−22,6	−64,4	−75,1	−79,5	−80,0	−80,0	−80,0	−80,0	−80,0	−80,0	−80,0	=-min (arctan(l_n/D_0); 80°)
12	γ_n [°]	80,0	80,0	80,0	80,0	80,0	80,0	80,0	80,0	80,0	77,7	71,1	=min (arctan(l'_n/D_0); 80°)
13	$R_{a,\tau,n}$ [1]	0,512	0,469	0,442	0,428	0,428	0,428	0,428	0,428	0,428	0,442	0,455	=avg ($R_{a,\tau,n}$ (β_n) … $R_{a,\tau}$ (γ_n)) (from Tab.2)
14	$R_{a\text{-}up,\tau,n}$ [1]	0,531	0,491	0,463	0,449	0,449	0,449	0,449	0,449	0,449	0,463	0,477	=avg ($R_{a\text{-}up,\tau,n}(\beta_n)$ … $R_{a\text{-}up,\ \tau,n}$ (γ_n)) (from Tab.2)
15	$c_{AR,n}$ [1]	1,036	1,047	1,048	1,049	1,049	1,049	1,049	1,049	1,049	1,048	1,048	$=R_{a,\tau,n}/R_{a\text{-}up,\tau,n}$
16	$R_{a\text{-}up,\tau=1,n}$ [1]	0,620	0,577	0,545	0,577	0,577	0,577	0,577	0,577	0,577	0,545	0,561	=avg ($R_{a\text{-}up,\tau=1,n}(\beta_n)$ … $R_{a\text{-}up,\tau=1,n}(\gamma_n)$) (from Tab.2)
17	$c_{\tau,\ n}$ [1]	1,168	1,176	1,178	1,285	1,285	1,285	1,285	1,285	1,285	1,178	1,177	$=R_{a\text{-}up,\tau,n}/R_{a\text{-}up,\tau=1,n}$
18	E_n [W/m^2]	50,7	110,5	117,5	133,9	126,7	131,0	129,6	125,2	133,9	120,1	113,3	$=E_{Meas,n} \cdot c_{SAS,n} \cdot c_{Lin,n} \cdot c_{Temp,n} \cdot c_{AR,n} \cdot c_{\tau,n}$

Line 4 contains the measured irradiance $E_{meas,n}$. Line 5 contains the measured σ_{SAS} and line 6 the inverses – the correction factors.

As a next step, deviation from linearity (line 7) is taken. As only one type of radiometer is used (in this example), the deviation factor from linearity $s_{Lin,n}$ is all the same. However, the correction factors $c_{Lin,n}$ differ, because they depend on irradiance.

Line 9 contains the temperature sensitivity and line 10 the correction factors $c_{Temp,n}$ (according Equation (3a)) for the sensor (these are all the same, because the same type of radiometer is used at all SAS).

The calculation of the last two correction factors $c_{AR,n}$ and $c_{\tau,n}$, needs somewhat more effort. First, we have to calculate the angular length of the lamp at each SAS. At position 1, the lamp ends within the field of view ($\beta_1 = -22{,}6°$), but on the other side of the SAS the lamp fills the remaining field of view ($\gamma_1 = 80°$). The values of β_n and γ_n can be calculated as for each SAS:

$$\beta_i = -\text{Minimum}\,(\arctan\,(l_n/D_0);\,80^\circ)\,\text{which denotes}\,0 \leq \arctan\,(-l_n/D_0) \leq -80^\circ \tag{19a}$$

$$\gamma_i = \text{Minimum}(\arctan\,(l'_n/D_0);\;80^\circ)\,\text{which denotes}\,0 \leq \arctan\,(l'_n/D_0) \leq 80^\circ \tag{19b}$$

l_n and l_n' are given in line 2 and 3. D_0 is taken from Table 1.

For each $c_{AR,n}$ at position n, we first calculate (line 13) the average of $R_{a,\tau,n}(\alpha_i)$ (given in column 8 from Table 2) from β_n to γ_n and afterwards (line 14) the average of $R_{a\text{-}up,\tau,n}(\alpha_i)$ (given in column 9 from Table 2) from β_n to γ_n. The correction factor $c_{AR,n}$ is gained by dividing $R_{a\text{-}up,\tau,n}$ by $R_{a,\tau,n}$ (line 15).

In line 16, $R_{a\text{-}up,\tau\text{-}ref,n}$ is calculated in the same manner (averaging $R_{a\text{-}up,\tau\text{-}ref,n}(\alpha_i)$ from β_n to γ_n). Dividing $R_{a\text{-}up,\tau\text{-}ref,n}$ by $R_{a\text{-}up,\tau,n}$ provides the correction factor $c_{\tau,n}$ (line 17).

The correction factors are applied in line 18, which contains with that the final corrected irradiance values E_n.

Figure 4 depicts the correction factors at each position. In this example, we took values and properties that deliver almost the highest possible correction factors. The correction factors for linearity are lowest (<1.02). Correction factors for temperature and angular response are in the order of 1.04. The transmittance of the SAS is most variable and within 1.05 and 1.12. The highest correction factors occur for the internal transmittance of the water (1.16 to 1.18), which may be between 0.8 and 1.0. In total, the final correction of measurements in our example is between 1.376 and 1.451. It can also be seen from the Figure, that correction factors are a little bit lower for measurements at the lamp's ends.

Dependence of emission on temperature

In the following, we present exemplary measurements of two different lamps at full power as well as with an input power of 70% (dimmed). Temperature is varied between 5 and 25 °C with a step-width of 5 °C. The wires of the lamp were situated

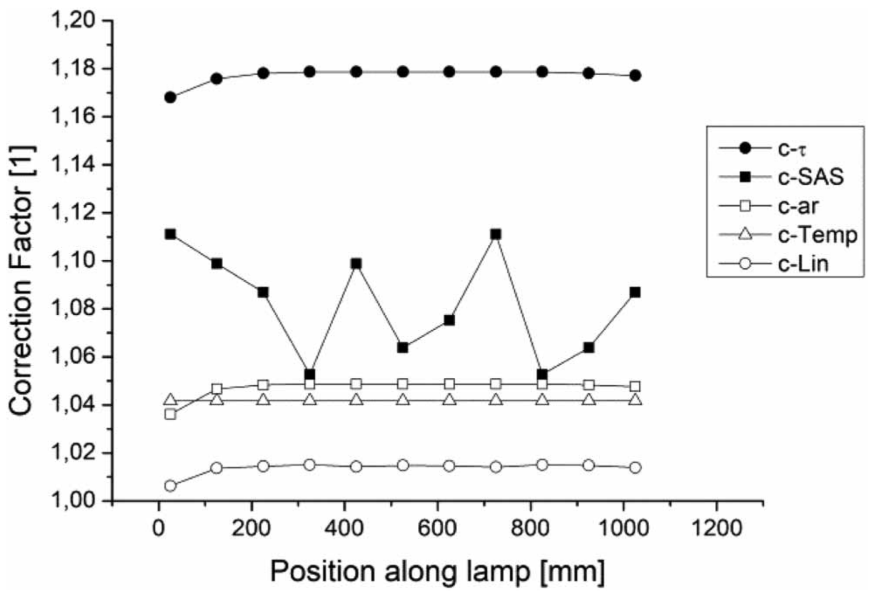

Figure 4 | Depiction of correction factors.

below the bulb. Measurements of irradiance were taken with a single reference radiometer (research grade IL1700, SED240, NS245, ÖNORM-Adapter). In the range of measured irradiance, this instrument shows no deviations from linearity ($c_{LIN,n} = 1.0$). The sensor is brought in the SAS only for measurements. For the electronic and the sensor, room temperature is applicable (19 ± 1 °C). Therefore, also temperature sensitivity is negligible ($c_{Temp,n} = 1.0$). Calibration was done according ÖNORM/DIN-3 and is traceable to the German metrological Institute (PTB, Germany). The angular response was measured, is approximately half way between the lower and the upper limit according ÖNORM/DIN-3, and is used for correction. σ_{SAS} of all SASs was measured prior to irradiance measurements with a spectral photometer at 253.7 nm and was within 0.902 and 0.915.

The first lamp is an ALPHO lamp with a nominal power of 220 W and a length L of 1,200 mm. The distance between the SAS and the sleeve D_0 was 62.5 mm, and $\tau_{100\ mm} = 0.885$. For dimming (70% ballast power), these values were the same. The lamp was ignited and the water was cooled down from 14 °C to 5 °C. Measurements were started after stabilization of the lamp and temperature balance of the setup. Due to the temperature of the dew point (13 °C), the SAS had to be flooded with dry air for measurements up to a temperature of 15 °C to eliminate condensed water from the quartz window of the SAS. Our correction scheme from above was applied. The corrected and normalized irradiances ($E_{max}(T_{water}, n)) = 1.0$) are depicted in Figure 5(a). For this Figure, the length is given in relative units of L ($1.0 \cdot L = 1{,}200$ mm). It can be seen that the longitudinal emission shows a steep increase at the end of the lamp, a slight local maximum around 0.2·L and a slight local minimum at $0.5 \cdot L$. However, the standard deviation along the lamp (without position 1) is less than 0.012 at each temperature. The temperature sensitivity of this lamp is minor between 5 °C and 25°. The standard deviation at each position (0.002–0.010) is lower than the standard deviation along the length (0.010–0.012). Afterwards, the lamp was dimmed to 70% and the procedure was repeated. The corrected values are depicted in Figure 5(b) in the same way. Due to the power reduction, the lamp becomes temperature sensitive with the highest emission at 25 °C and the lowest at 5°. The standard deviation along the lamp becomes between 0.012 and 0.018.

The second lamp is an ALPHO lamp with a nominal power of 350 W and a length of 1,700 mm. The distance between the SAS and the sleeve D_0 was 60.0 mm, and $\tau_{100\ mm}$ was 0.80. Measurements have been corrected correspondingly. As above, dimming (70% ballast power) was applied. The resulting normalized irradiance is depicted in Figure 6. This lamp shows a longitudinal imbalance in emission with higher values on the plug-site ($L = 1$). Local maxima and minima can be recognized. This lamp is sensitive to water temperature. Emission is highest between 5 and 15 °C and decreases with increasing temperature. For confirmation, we increased the water temperature to 30 °C and found a further decrease. Under dimming, the UVR emittance of the lamp is sensitive to temperature as well. UVR emittance increased noticeably from 5 °C to 20° but was only minor at 25 °C.

Stability and uncertainties of measured irradiance

For accurate measurements, it is important that the lamp has stabilized (e.g. in operation temperature). This needs a certain time. The duration varies by lamp type, but is – as a rule of thumb – in the order of 15 minutes for LP lamps. After that, LP lamps are quite stable in emission, resulting in variations of UVR emittance less than $\pm 1\%$. Figure 7 demonstrates exemplarily (and representative for our experiences) the stability of emission and uncertainty of measured irradiance during one hour after ignition. In this example, water temperature was held between 9.9 °C and 10.1 °C. Measurements were taken

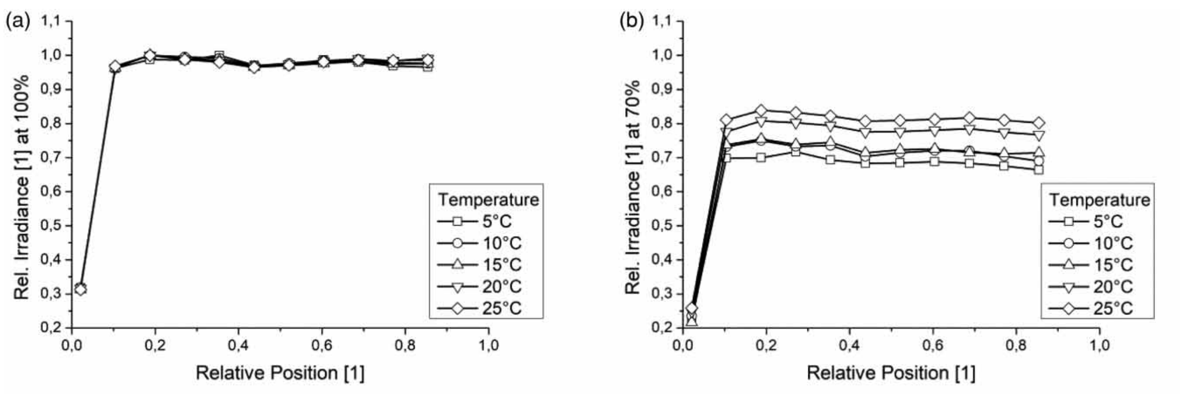

Figure 5 | Relative irradiance along an ALPHO lamp (length $L = 1{,}200$ mm) with a nominal power of 220 W in water at temperatures between 5 and 25 °C at full (a) and at 70% (b) ballast power.

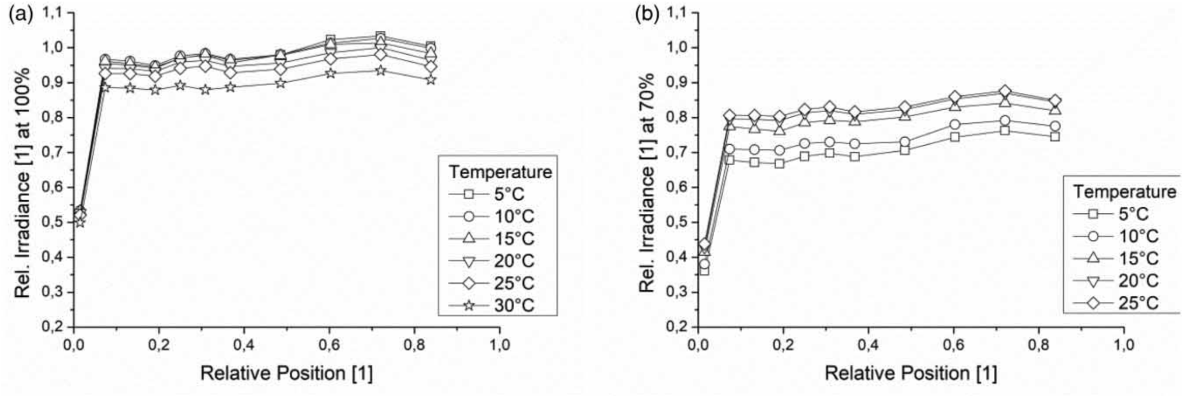

Figure 6 | Relative irradiance along an ALPHO lamp (length = 1,700 mm) with a nominal power of 350 W in water at temperatures between 5 and 25 °C at full (a) and at 70% (b) ballast power.

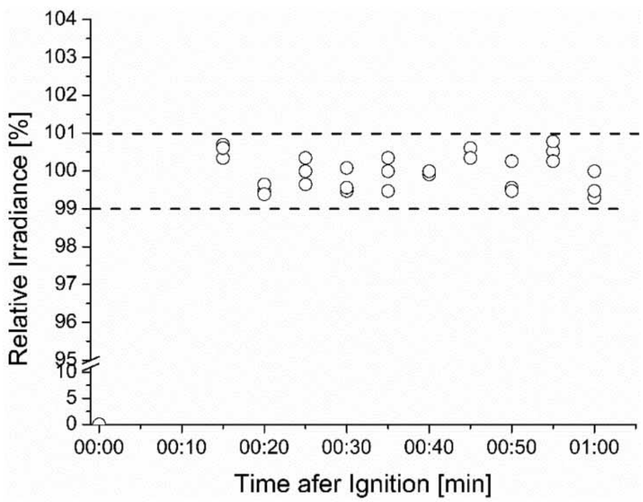

Figure 7 | Relative irradiance of an LP-lamp measured during 1 hour after ignition at a water temperature of 10.0 °C ±0.1 °C at approximately 1/3 of the lamp's length from its end.

approximately at 1/3 of the lamp's length from the end. The SAS had been jetted with dry air before a measurement was taken. Absolute irradiance was 114.6 W/m^2 on average, whereas the measuring resolution of the radiometer was 0.1 W/m^2. The relative irradiance is depicted in Figure 7. Every 5 minutes, three measurements of irradiance were taken. These trios varied between 0.09% (at 0:40) and 0.87% (at 0:35) from each other. All together, these 30 measurements (mean = 100%) were within 99.30% and 100.78% (1.48%), with a total standard deviation of ±0.45%.

It should be noted that LP lamps have to be operated for at least 100 hours before any meaningful measurements of irradiance can be taken (as required by ÖNORM/DIN-1). Within this period, obvious changes in UVR emittance can be observed. After this period, the normal aging (very slow decrease of UVR emittance with time) of the lamps can be assumed.

Reproducibility of measurements

To give an impression of the reproducibility of irradiance measurements, we have measured irradiance along the length of a lamp three times during a day of testing (at a water temperature of 20 °C ±0.1 °C, 100% power, nominal lamp power 150 W). In between, water temperature was varied (5° to 25°) as well as the power level (70 and 100%). Figure 8 depicts these measurements. The columns indicate the irradiance (mean value of several measurements) at each position (SAS 1 to 7) for each of the three measuring runs (MR) (Figure 8, MR1: up hatched columns, MR2: empty columns, MR3: down hatched columns). The error bars indicate the standard deviation. It can be seen that error bars cover almost the differences in irradiance between the three MRs.

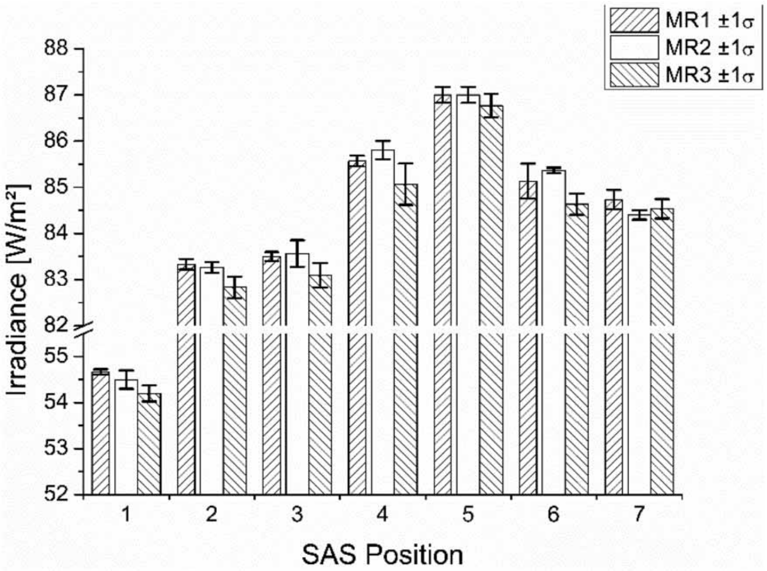

Figure 8 | Three different measurement runs (MR1, MR2, MR3) of irradiance along the length of a lamp made at SAS positions 1 to 7 during a day (at 20 °C $\pm$0.1 °C). Error bars indicate the standard deviation of measurements.

CONCLUSIONS

In this paper, we introduce the procedure for a standardized characterisation and measurement of UV lamps, which have been implemented in the recently released identical updated standard ÖNORM M 5873-1:2020 and the newly established DIN 19294-1:2020. This test bench was developed to measure UVR emittance and the temperature dependence along the length of lamps. The standards rule properties (within certain limits) for the components of the total setup. If the setup does not change, measurements of irradiance are of high accuracy and repeatable to a high extent. However, setups using equipment on the opposite limits of all admissible ranges may result in differences in measured irradiance of up 40%. Therefore we developed correction factors to become independent of all influencing factors.

The test bench (together with the application of the correction factors) allows important applications:

- The UVR emittance along the length of a lamp can be measured independent of the measuring equipment and the water.
- The influence of water temperature along the lamp can be measured.
- With that it is possible to control quality of lamp production or to compare lamps from different origins.
- It allows investigation of the effect of ageing along the lamp by comparing new and aged lamps.

It allows investigation of the influence of dimming (reduction of electrical input power).

- With that it becomes possible to find the most robust position for monitoring radiometers.
- The test chamber can be oriented horizontally as well as vertically, which are the most popular orientations of UV-disinfection devices. However, any other orientation is possible. So all the above investigations can be done for different orientations.

First results show that the UVR emittance along the lamp can be almost uniform, non-uniform but symmetrically, and also longitudinally unbalanced. Some types of lamps are almost insensitive to variations in water temperature, while others are sensitive. Dimming enhances sensitivity to temperature. The results also show that there is no general behavior and every type of lamp has to be investigated for its own.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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