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Measuring non-coherent optical radiation at work places

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Abstract
This paper presents the requirements for the method and extent of testing of non coherent optical radiation at work places, as well as the meters used for tests. The requirements are based on the current standards in the field of optical radiation. The scope of the exposure measurements are presented in conjunction with the current values of MDE. There is a description of the method of determining the angular dimension of radiation source α and how to calculate the effective source radiance from the measured effective irradiance. At the end, the paper presents the recommended frequency of testing and suggestions concerning the content of the study.

Introduction

Optical radiation is a natural component of the solar radiation, but it is also manufactured artificially for application in various technological processes, medicine, cosmetics or research and development. Such radiation can be also a by-product of human professional activities, e.g., it is produced during welding or hot technological process in metal works. It can represent potential threat to eyes and skin of employees, when excessive quantity of such radiation reaches exposed tissues. This fact is accounted for in the Directive 2006/25/WE [1] and its execution orders [2, 3, 4], mandating the requirement to assess potential exposure of employees to excessive optical radiation levels. In order to properly assess the optical radiation exposure threat for such employees, it is necessary to conduct appropriate measurements, the general guidelines for which are covered in the respective standards PN-T-06589: 2002 [5] and PN-T-05687: 2002 [6]. Detailed information about measurement methods and exposure assessment process for employees exposed to optical radiation is included in the respective standards PN-EN 14255-1: 2010 [7] and PN-EN 14255-2: 2010 [8].

Requirements for measurement and exposure assessment to incoherent optical radiation

Standards [7, 8] present a general outline of a procedure for assessing exposure to optical radiation, including methods for determining individual parameters of examined optical radiation. These standards do not prescribe the maximum admissible exposure (MDE) for UV, VIS and IR optical radiation. They do specify wavelengths for ultraviolet (180 ÷ 400 nm), visible and infrared radiation (380 ÷ 3000 nm), as well as blue light exposure threat (300 ÷ 700 nm).

General procedure [7, 8]

In order to carry out measurements to assess the optical radiation exposure at the given work station and compare it with the maximum admissible exposure (MDE), included in the Directive [3], the following steps must be undertaken:

– initial assessment, which is intended to confirm whether the associated measurements are to be conducted, or not. Using available information about the optical radiation sources and potential exposure of individual employees to optical

radiation, it is necessary to decide whether the exposure measurement is necessary and whether it is possible to confirm that the maximum admissible exposure (MDE) levels were exceeded, or not, without undertaking any measurements. This assessment process may take advantage of any available information on machine classification (emission category), as determined using respective standards [9] or [10], or information on hazard category for lamps and lamp systems, as determined using the respective standard [11].
- the work station assessment, featuring assessment of:
  - the number, type and location of individual optical radiation sources;
  - potential occurrence of radiation reflections or scattering on walls, materials, machines, equipment etc.;
  - optical radiation spectra – using information provided by the manufacturer (it is worth remembering that it might be modified due to scattering, reflection or absorption);
  - distance between the employee and the optical radiation source;
  - exposure times (one-time and total);
  - potential health hazards;
  - the maximum admissible exposure limits;
  - application of group / personal means of protection.
- measuring the exposure itself – it is expected to be compared with the determined MDE value.

Method for measuring ultraviolet radiation exposure at the work station

In this case, two values are subject to measurement: total (non-selective) and effective irradiation levels. They are assessed in order to determine:

a) photochemical hazards to a human eye, and especially cornea, conjunctiva and lens, as well as skin, when exposed to ultraviolet radiation (180 ÷ 400 nm). For this end, the following steps are taken:
   - measure the effective irradiation E_S [W/m^2] corrected to the spectral efficiency curve $S(\lambda)$;
   - determine the one-time exposure time;
   - determine the total exposure time;
   - determine the effective irradiance H_S [J/m^2];
b) photochemical hazards for a human eye (lens) from ultraviolet radiation in the UV-A (315 ÷ 400 nm), wavelength range. For this end, the following steps are taken:
   - measure the effective irradiance E_C [W/m^2];
   - determine the one-time exposure time;
   - determine the total exposure time;
   - determine the effective irradiance H_{UVA} [J/m^2].

Next, for both aforementioned cases, it is necessary to determine the hazard level and the admissible exposure time. The hazard level is the total for the eye and skin exposure values during a single work shift and the non-selective eye irradiation. The admissible total irradiation time is the product of the MDE value for human eyes in the range of 315 ÷ 400 nm and the measured irradiance intensity and the product of the MDE value for human eyes and skin in the range of 180 ÷ 400 nm and the measured value of the effective irradiance.

Measurement of the maximum irradiation for target body elements is conducted in the target work station of the given employee. To determine the skin hazard level, it is necessary to measure E_S, while to determine the eye hazard level – it is necessary to measure both, E_S and E_C. It is also necessary to determine the total exposure time. When the group means of protection are available on the given work station, such measurements should be conducted with the said means employed. However, when the given employee is equipped with the personal means of protection, such measurements are to be conducted without such means of protection being employed, and then determine their attenuation factor, i.e. determine the ratio for irradiation levels with and without employed means of personal protection.

Method for measuring visible and infrared radiation exposure at the work station

The following parameters are subject to measurement: total (non-selective) and effective irradiation, as well as effective energy luminance (radiance). These parameters are measured in order to determine the following:

a) photochemical hazards for a human eye cornea caused by blue light (300 ÷ 700 nm). For this end, the following parameters are measured:
   - effective energy luminance (radiance) L_B [W/(m^{2}sr)] corrected to the spectral efficiency curve $B(\lambda)$; or
   - effective irradiation E_B [W/m^2] corrected to the spectral efficiency curve $B(\lambda)$.

   Selection of the measured value – effective energy luminance or effective irradiation – depends on the radiation source viewing angle α, which is determined for both cases. Moreover, in both cases it is also necessary to measure a single-time exposure time t_i and the total exposure time t_c.

b) thermal hazards for a human eye cornea caused by visible and infrared radiation. For this end, the following parameters are measured:
   – effective energy luminance (radiance) L_R corrected to the spectral efficiency curve $R(\lambda)$;
   – one-time exposure time t_i;
   – radiation source viewing angle α;
c) thermal hazards for a human eye cornea caused by infrared radiation in the IR-A range (780 ÷ 1400 nm). For this end, the following parameters are measured:
   – effective energy luminance (radiance) L_R corrected to the spectral efficiency curve $R(\lambda)$;
   – one-time exposure time t_i;
   – radiation source viewing angle α;
d) thermal hazards for a human eye cornea caused by infrared radiation. For this end, the following parameters are measured:
   – irradiation E [W/m^2];
   – one-time exposure time t_i;
e) thermal hazards for a human eye cornea caused by visible and infrared radiation (380 ÷ 3000 nm). For this end, the following parameters are measured:
   – irradiation E [W/m^2];
   – one-time exposure time t_i [s];

   and then the value of H_{skin} irradiation is determined using the following formula:

$$H_{skin} = E \cdot t_i \text{ [J/m}^2\text{]} \quad (1)$$

where:

E – irradiation [W/m^2];

t_i – one-time exposure time [s].

The spectral efficiency curve $S(\lambda)$ is shown in table 1 published in the standard [5], while spectral efficiency curves $B(\lambda)$ and $R(\lambda)$ are shown in table 1 published in the standard [6].

The irradiation measurement needs to be conducted at the target work station of the given employee, at the height of eyes or exposed skin. The energy luminance needs to be measured only at the height of the eyes and at the target work station of the given employee. During the measurement process, it is necessary to direct the active surface of the probe towards the radiation source, along the l axis (see Fig. 1). In case of elongated radiation sources, it is necessary to find such a location for the probe where the read value is the highest. At each measurement position, at least three independent measurements need to be taken.

It is also necessary to establish the one-time exposure and total exposure durations by carrying out a dedicated measurement or using data associated with the given technological process executed on the given work station. When the group means of

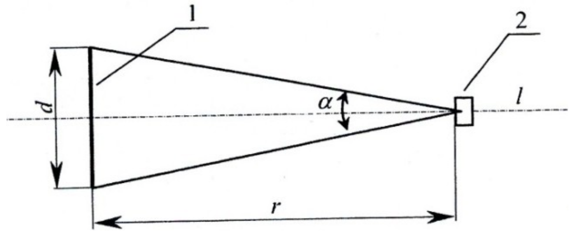

Fig. 1. Measurement setup [6]: 1 – radiation source, 2 – measurement probe, l – axis passing through the middle of the measurement probe and perpendicular to its surface, r – distance between the measurement probe and the radiation source, d – circle diameter

protection are available on the given work station, such measurements should be conducted with the said means employed. However, when the given employee is equipped with the personal means of protection, such measurements are to be conducted without such means of protection employed, and then determine their attenuation factor, i.e. based on conducted measurements determine the ratio for irradiation levels with and without employed means of personal protection.

If no probe designed for measurement of effective energy luminance (radiance) L_S for the light source is available, this value can be derived from the measured effective irradiance intensity E_S. For this purpose, it is necessary to measure the surface of the radiation source, or obtain its value from the appropriate technical documentation (S_{RS}), and compare this value with the circle surface (S_{CIRCLE}), determining the effective circle diameter (d) from the following formula:

$$S_{RS} = S_{CIRCLE} = \frac{\pi d^2}{4} \quad \text{[m}^2\text{]} \quad (2)$$

where:

d – effective circle diameter [m].

Next, it is necessary to measure the distance between the employee's eye and the radiation source – r. The target value of the energy luminance for the radiation source L_S can be then calculated as:

$$L_S = \frac{E_S}{A} \quad [\text{W}\cdot\text{m}^{-2}\cdot\text{sr}^{-1}] \quad (3)$$

where:

E_S – irradiation [W/m^2].

A represents a spatial angle calculated as:

$$A = \frac{\alpha^2 \cdot \pi}{4} \quad \text{[sr]} \quad (4)$$

where α represents the angular size of the radiation source expressed with the following formula:

$$\alpha = \frac{d}{r} \quad \text{[rad]} \quad (5)$$

where:

d – circle diameter [m] from formula (2);

r – distance between the measurement probe and the radiation source [m].

Additional notes on measurement methods

The relative extended measurement uncertainty for $k = 2$ should not exceed 30% at the confidence level 95% for measurements the results of which were compared with the maximum admissible exposure levels. For measurements of irradiance intensity and irradiance, the angular response for viewing angles within ±60° should correspond to the cosine function with ±5% tolerance. When carrying out any measurements, local environmental conditions need to be accounted for, since they may influence the obtained results, including temperature, humidity, dust content, electromagnetic fields etc. Any measurement equipment should be certified. Any measurement geometry should be established by placing the measurement probe close to the exposed body parts at their typical locations and directing the said probe towards the direction of maximum radiation. When measuring the energy luminance (radiance), or the irradiance intensity for blue light, it is necessary to determine the real diameter of the radiation source (D), corresponding to a circle diameter when the given radiation source is circular, or the arithmetic average between the largest and smallest dimension for elongated radiation sources; distance between the radiation source and the exposed employee's body part r and the viewing angle φ, defined as the angle between the line of sight and a line perpendicular to the radiation source. In cases when the radiation source is not located directly in front of e.g. an employee's face, then the observable radiation source diameter must be established using the following formula:

$$D_L = D\cos\varphi \tag{6}$$

where:

D – real diameter of the radiation source;

φ – viewing angle.

Moreover, the effective viewing angle α must be calculated using the following formula:

$$\alpha = \frac{D_L}{r} \tag{7}$$

where:

D_L – diameter of the radiation source observed;

r – distance between the radiation source and the exposed employee's body part.

Another critical aspect is the appropriate measurement time. When constant radiation is observed, the measurement time is undefined. When periodic, regular variations in radiation intensity are observed, the measurement time is defined at 10 variation periods (cycles). When irregular variations in radiation intensity are observed, a sufficiently long measurement time should be used, equal to e.g. a single work shift.

Moreover, when carrying out measurements, people carrying out such measurements must be guaranteed safety, by providing the appropriate personal means of protection, if needed.

Preparing the measurement report

A report drawn up after each exposure measurement and assessment should contain at least:

- date when the measurement was concluded;
- description of the measurement objects;
- analysis of the measurement goal;
- photos or diagrams of the work station and location of the measurement points;
- description of the utilized measurement equipment (type, identification number);
- description of the employed measurement method;
- reference values for the maximum admissible exposure (MDE);
- presentation of the measurement results:
  - in MDE units and magnitudes;
  - separately for each body part under test;
  - if employees change their location or actions during a single work shift, the total irradiation during a work shift should be calculated as the total of all irradiation intensities for all locations and activities undertaken by the employee under test;
- exposure assessment – by comparing the measurement results with the appropriate value of the maximum admissible exposure and identification whether it was met, or not;
- uncertainty value;
- any proposals for improving the exposure conditions and work safety – if needed; when the value of maximum admissible exposure is exceeded, the utilization of appropriate means of protection should be recommended;
- information on the date of next measurement and assessment session. Measurements and the assessment may need to be repeated if:
  - the radiation source or its operating conditions were modified;
  - the work type was modified;
  - the exposure duration was modified;
  - the use of means of protection was started, terminated, or modified;

- the deadline for repeated measurements and the assessment, defined according to the Regulation [4], and resulting from the predetermined measurement frequency expired;

If the MDE multiplier resulting from the concluded measurements has the value of 0.7 or more, the subsequent measurements must be concluded within at least one year since the least measurement. If the MDE multiplier resulting from the concluded measurements ranges between 0.4 and 0.7, the subsequent measurements must be concluded within at least two years since the last measurement. If the MDE multiplier resulting from the concluded measurements is below 0.4, the subsequent measurements must be concluded at two years since the last measurement. If the subsequent measurements indicate the exposure level not exceeding 0.4 MDE value, the given work station may be excluded from further measurements and assessment under the condition that no changes in the technical equipment, or conditions of the employee's work on this work station take place [4].

Practical aspects of measuring optical radiation at work stations

Using the analysis of standards related with measurement of ultraviolet, visible and infrared radiation, as outlined in sections 2.2 and 2.3, it can be concluded in order to complete measurements for all parameters of optical radiation defined in the respective standards, a wideband radiometer equipped with a set of measurement probes will be needed, selected appropriately to the range of examined radiation and the examined exposure vectors:

a) corrected to the relative spectral efficacy $S(\lambda)$ – for the measurement of the effective irradiation intensity (E_S) for the wavelength range 180 ÷ 400 nm;
b) non-selective – for the measurement of the total irradiation intensity (E_C) for the wavelength range 315 ÷ 400 nm (UV-A);
c) corrected to the relative spectral efficacy for causing photochemical damage $B(\lambda)$ – for the measurement of the effective energy luminance (radiance) (L_B) for the wavelength range 300 ÷ 700 nm;
d) corrected to the relative spectral efficacy for causing photochemical damage $B(\lambda)$ – for the measurement of the effective irradiance intensity (E_B) for the wavelength range 300 – 700 nm;
e) corrected to the relative spectral efficacy for causing thermal damage $R(\lambda)$ – for the measurement of the effective energy luminance (radiance) (L_R) for the wavelength range 380 ÷ 1400 nm VIS I IR-A);
f) corrected to the relative spectral efficacy for causing thermal damage $R(\lambda)$ – for the measurement of the effective energy luminance (radiance) (L_R) for the wavelength range 780 ÷ 1400 nm (IR-A);
g) non-selective – for the measurement of the irradiation intensity (E) for the wavelength range 780 ÷ 3000 nm;
h) non-selective – for the measurement of the irradiation intensity (E) for the wavelength range 380 ÷ 3000 nm;

An example of such a wideband meter is the radiometer ILT 1700 manufactured by International Light, USA, as shown in figure 2, which has been available for some time on our market.

Fig. 2. Photograph of the ILT 1700 meter with the exemplary measurement probes [12]

One of the advantages of this meter is the possibility of equipping it with a large number of measurement probes offered by the manufacturer. Among all the available probes, it is possible to select ones enabling almost all measurements of optical radiation discussed before. Figure 3 shows the measurement ranges for individual probes designated for the ILT 1700 radiometer, meeting requirements stipulated in the Directive [3].

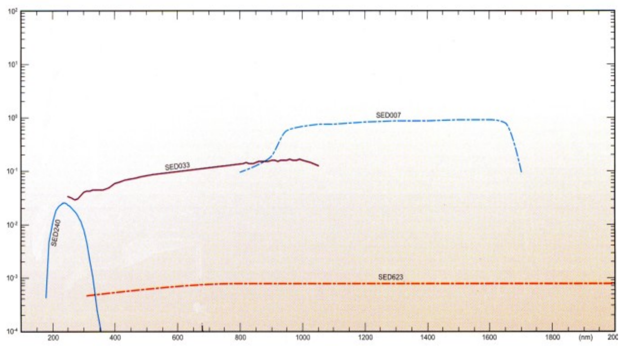

Fig. 3. Measurement ranges for probes designated for the ILT 1700 radiometer [12]

Given the number and type of exposure threats discussed above, it is clear that eight different probes are needed to complete measurement for these threats. However, the International Light company offers only 6 probes, which based on their parameters are considered by the manufacturer to be optimum for the measurement of all appropriate threats. Unfortunately, the offer of the International Light company does not include a probe for measurement of two of the following parameters:

– effective energy luminance (radiance) with correction to $R(\lambda)$ for the wavelength range of 380 ÷ 1400 nm (VIS + IR-A) in order to determine the thermal threat to eye cornea;
– effective energy luminance (radiance) with correction to $R(\lambda)$ in order to determine the thermal threat to eye cornea caused by infrared light for the wavelength range of 780 ÷ 1 400 nm (IR-A).

In the first case, the energy luminance can be determined based on the statement included in the standard PN-EN 14255-2: 2010 [8], paragraph 7.4.3: „in order to cover the whole measurement range, more than one measurement device may be used”. The statement included in the standard PN-T-05687: 2002 [6], paragraph 2.5.5 related with the determination of the effective energy luminance for the radiation source based on the measured effective irradiation intensity is applicable in both cases.

Taking the above statements into consideration, the effective energy luminance for the wavelength range of 380 ÷ 1400 nm can be determined based on the total of all measurement results for two probes used to measure:

- the effective irradiation intensity of visible optical radiation (blue light wavelength range) – having multiplied obtained results by 10 to factor in correction from $B(\lambda)$ to $R(\lambda)$ curve;
- the effective irradiation intensity of infrared (IR-A) optical radiation.

In both cases, the results obtained from the respective measurement probes need to be converted into the energy luminance following formulas 3, 4 and 5.

Conclusions

When examining the threat of potential photochemical damage to an employee’s eye cornea, conjunctiva and lens, as well as skin, caused by ultraviolet radiation, regulations towards the measurement equipment and the measurement procedure included in the standard PN-EN 14255-1: 2010 [7] should be applied. When the radiation source covers the wavelength range of 180 ÷ 400 nm, then following the stipulations included in the standard [7], appropriate measurement probes, corrected to the relative biological efficacy of the ultraviolet radiation $S(\lambda)$, need to be used.

When examining the threat of potential photochemical damage to an employee’s eye cornea and thermal damage to an employee’s eye cornea, conjunctiva and lens, as well as skin, caused by visible and infrared radiation, regulations towards the measurement equipment and the measurement procedure included in the standard PN-EN 14255-2: 2010 [8] should be applied. Following the stipulations included in the standard [8], covering the assessment of threat to employees caused by blue light (photochemical effects to eye cornea), appropriate measurement probes, corrected to the relative spectral efficacy of causing photochemical damage $S(\lambda)$, need to be used. On the other hand, probes designed for the assessment of thermal damage to eye cornea must be corrected to the spectral efficacy of causing thermal damage $R(\lambda)$.

When no measurement probes suitable for measurement of the effective energy luminance of the radiation source L_S are available, in order to assess the thermal damage to eye cornea caused by infrared radiation, the standard PN-T-05687: 2002 [6] provides a very useful methodology for calculating this value based on the measured effective irradiation intensity E_S for this radiation.

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