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LABORATORY RESEARCH ON PHOTOBIOLOGICAL SAFETY OF LED LIGHT SOURCES

Key words: blue light hazard, light emitting diode (LED), photobiological safety, risk group.

Abstract: The article presents a method of evaluating irradiance, spectral irradiance, and spectral radiance, for purposes of determining risk groups of light sources. Measurement methods have been developed on the basis of general requirements and diagrams incorporated in the standard EN 62471: 2008. The paper classifies risk groups of light sources and luminaires in terms of photobiological hazard and exposure limits when the skin is at the hazard of visible and infrared radiation. The construction of the stand for measuring parameters of optical radiation used the system of the Bentham type IDR300-PSL based on double monochromator. That system has been specially designed to assess photobiological safety of light sources. Five LED light sources selected for the examination were characterized and the results of their measurements were presented. On these bases, a risk assessment of photobiological tested sources has been estimated and the appropriate risk group and time of safe exposure has been assigned for each of light source. The article has been finalized with the conclusions on the results of measurements.

Badania laboratoryjne bezpieczeństwa fotobiologicznego źródeł światła LED

Słowa kluczowe: zagrożenie światłem niebieskim, diody emitujące światło (LED), bezpieczeństwo fotobiologiczne, grupy ryzyka.

Streszczenie: W artykule przedstawiono metodę badania natężenia napromienienia, widmowego natężenia napromienienia i widmowej luminancji energetycznej na potrzeby określania grup ryzyka źródeł światła. Metody pomiarowe zostały opracowane na podstawie ogólnych wymagań i schematów zawartych w normie EN 62471:2008. Opisano klasyfikację grup ryzyka źródeł światła ze względu na zagrożenia fotobiologiczne oraz granice ekspozycji przy zagrożeniu skóry promieniowaniem widzialnym i podczerwonym. Opisano budowę stanowiska pomiarowego do pomiarów parametrów promieniowania optycznego z wykorzystaniem systemu spektroradiometrycznego firmy Bentham typ IDR300-PSL wyposażonego w podwójny monochromator. System ten został specjalnie zaprojektowany do wykonywania oceny bezpieczeństwa fotobiologicznego źródeł światła. Scharakteryzowano wytypowanych do badań pięć źródeł światła typu LED oraz zaprezentowano wyniki ich pomiarów. Na tej podstawie dokonano oceny ryzyka fotobiologicznego badanych źródeł poprzez przypisanie im odpowiedniej grupy ryzyka oraz czasu bezpiecznej ekspozycji. Artykuł zakończono wnioskami dotyczącymi wyników pomiarów.

Introduction

The lighting market now provides many types of semiconductor light sources, i.e. light-emitting diodes (commonly referred to as LEDs). Considering their undoubted advantages, such as energy efficiency and durability, LEDs are more and more often used to provide lighting at working stations, and in rooms in homes. As conventional light bulbs over 7 W were withdrawn on 1 September 2016, it is possible to claim that LEDs will become the main replacement. It is an already observable tendency, because the next generation fluorescent lamps and halogen bulbs are at the margins of the lighting market. However, their method of optical radiation (white light) generation is different, compared to other types of light sources.

Where in the case of ultraviolet or infrared emitting illuminators, the users usually are less or more aware of the fact that the emitted radiation can be harmful to them [2]; however, they appear not to have such a concern when it comes to other light sources, especially new generation ones. This is mainly due the lack of the general awareness of the fact that optical radiation emitted by the sources (except possible ocular and skin hazard due to ultraviolet radiation) may also pose a risk to the retina by visible radiation, especially within the range of the "blue light," and to the retina, cornea and lens by infrared radiation.

Usually, the user selects a replacement for the conventional light bulb based on the light emitting technology used, the price, and/or parameters declared by the manufacturer, such as rated power, bulb equivalent output, and light colour.

However, the question arises whether the use of new generation light sources (LEDs) is safe and, in particular, whether the emitted optical radiation poses no health risk. To make an attempt and answer this question, five selected LED light sources were tested to determine risk groups to be assigned to in terms of photobiological safety.

This paper is aimed at the presentation of risk groups, determined on the basis of tests, classified by photobiological safety of new generation GLS light sources and general conclusions resulting for the users.

1. Classification of light sources by photobiological safety

The standard [4] provides criteria of the photobiological safety of lamps that are defined as sources designed for the generation of optical radiation [3]. There are four risk groups [4] according to the following:

1) Exempt group,
2) Risk Group 1 (Low-Risk),
3) Risk Group 2 (Moderate-Risk), and
4) Risk Group 3 (High-Risk).

Exposure limit values for individual risk groups are defined based on existing criteria and maximum permissible exposure values used for the assessment of optical radiation hazard in the working environment. The difference is that separate assumptions on permissible safe exposure times for each of the five photobiological hazards in the same category were made to determine criteria for classification into individual risk groups.

Exposure limit values and safe exposure times assumed for individual risk groups (except Risk Group 3) as regards individual hazards are summarised in standard [4]. According to the applied classification, Risk Group 3 includes light sources that may pose a hazard even for momentary or brief exposure, and light sources whose parameter values (obtained by tests to determine hazards) exceed the limits for Risk Group 2. As a rule, the risk group assigned to the illuminator corresponds to the highest risk group indicated (resulting from all concerned photobiological hazards).

2. Scope of testing for photobiological safety of light sources

For general lighting service sources, the following measurements shall be taken according to the standard [4]:

1) Irradiance in order to determine:
   - Lens near-UV hazard over the wavelength range 315 to 400 nm, E_{UVA},
   - Corneal and lens infrared hazard over the wavelength range 780 to 3 000 nm, E_{IR};
2) Spectral (effective) irradiance in order to determine the ocular and skin hazard due to UV radiation over the wavelength 200 to 400 nm, E_S;
3) Spectral (effective) radiance in order to determine:
   - Retinal blue light hazard over the wavelength range 300 to 700 nm, L_B,
   - Retinal thermal hazard over the wavelength 380 to 1 400 nm, L_R.

3. Method of light source testing to determine photobiological safety

The measurement method relating to the parameters of optical radiation emitted by electric optical radiation sources to be classified into risk groups in terms of photobiological hazards due to optical radiation was developed in accordance with requirements of the standard [4] and Directive [5] regarding artificial optical radiation [1]. The method was based on the IDR300-PSL spectroradiometer system supplied by Bentham. The system was specially designed to evaluate photobiological safety of lamps.

As provided for in the standard [4], general lighting service sources, i.e. sources intended for lighting spaces (e.g., those used for lighting offices, schools, homes, factories, roadways or automobiles) shall be measured at a distance where the illuminance is 500 lx (typical value of general lighting service illuminance used in, for example, offices, schools, etc.).

4. Description of the IDR 300-PSL spectroradiometer system supplied by Bentham

The main element of the entire spectroradiometer system is the IDR 300-PSL double monochromator that features one input aperture and three output apertures (one in the first monochromator and two in the other one) – see Fig. 1.

The input circuits are used to connect the following detectors:

– DH-3 photomultiplier tube (port PMT) – UV-radiation precise measurement within the range 200 to 320 nm,
– DH-SI silicone detector (port DH-Si) – radiation measurement within the range 200 to 1 100 nm,
– DH-InGaAs detector (port) – IR radiation measurement within the range 900 to 1 700 nm, and
– DH-PbS-TE detector (port) – IR radiation measurement within the range 1 000 to 3 000 nm.

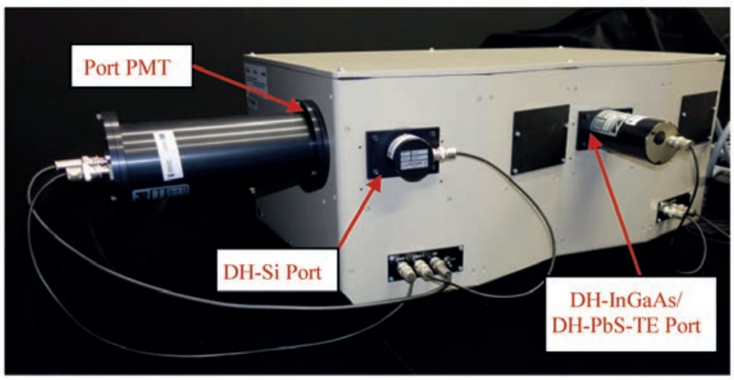


Fig. 1. View of the monochromator with marked input circuits
Source: Author.

The photomultiplier is installed at the port opposite to the aperture, the SI detector is installed at the port near the photomultiplier, and the InGaAs or PbS detectors are interchangeably installed at the output aperture of the first monochromator.

The spectroradiometer system is equipped with two multiple fibre quartz lines that are interchangeably connected to the monochromator input aperture. The first optical fibre line together with the D7 optical component (equipped with a PTFE diffuser ensuring cosine corrections) is used to measure the relative spectral emission of radiation sources and determine absolute irradiance by irradiance measurements. The other optical fibre line connects the monochromator input to the TEL 309 telescope used to measure radiance (Fig. 2).

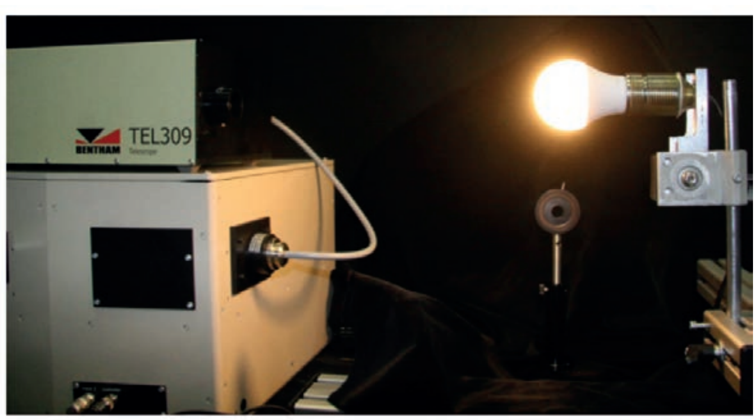


Fig. 2. View of the TEL 309 telescope connected to the monochromator during radiance measurements
Source: Author.

To ensure proper measurements, the spectroradiometer system requires calibration. For this purpose, there are three standard sources installed in a photometric sphere: a CL 7 deuterium type, a CL 6-H quartz-halogen type, and a SRS 12 quartz-halogen type.

- The CL 7 deuterium standard source (Fig. 3) is used to calibrate the spectroradiometer system within the range 200 to 40 nm. It is equipped with the 706-type power supply (Fig. 3).

Fig. 3. View of the CL 7 deuterium standard source and the 706-type power supply
Source: Author.

• The CL 6-H quartz-halogen standard source (Fig. 4) is used to calibrate the spectroradiometer system within the range 300 to 1 100 nm. It is equipped with the 605-type DC power supply (current 6.3 A) – see Fig. 4.

• The SRS 12 (sphere) quartz-halogen standard source (Fig. 5) is used to calibrate the spectroradiometer system within the range 300 to 1 400 nm to measure radiance. It is equipped with the 605 type DC power supply (current 8.3 A).

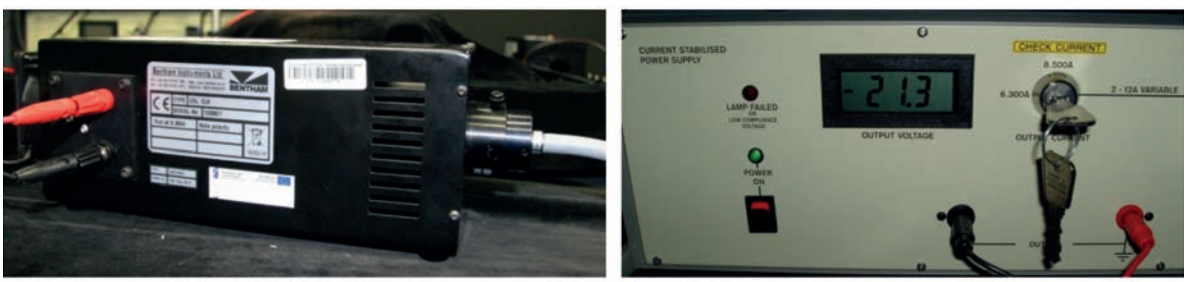


Fig. 4. View of the CL 6 quartz and halogen standard source and the 605-type DC power supply
Source: Author.

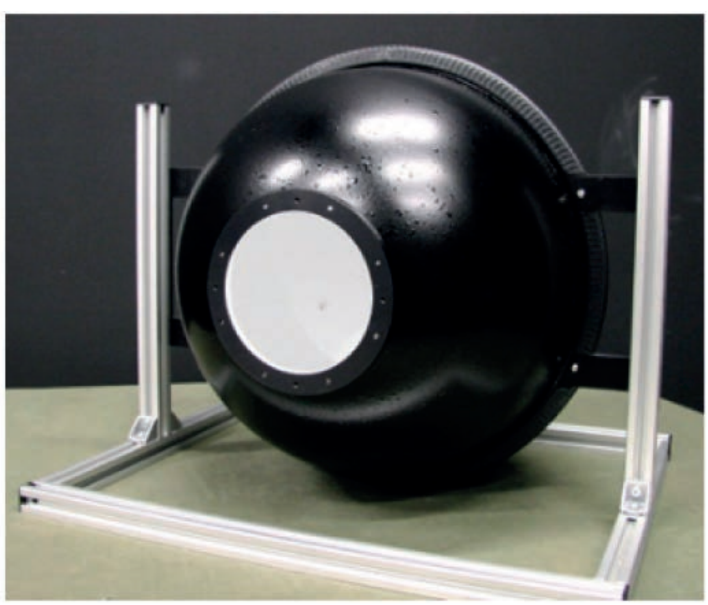


Fig. 5. View of the SRS 12 quartz-halogen standard source (sphere) on the input side
Source: Author.

For infrared radiation hazard measurements, a relay optical component with the 417-type power supply and the PbS_TE detector are used. The relay optical component comprises a set of lenses and a speed selector. The main element in the selector is a blade with five apertures to cover the optical sensor located on the selector base (Fig. 6). The selector base is attached to the relay cylinder of the optical component. Figure 6 shows the complete relay optical component installed at the monochromator input.

Fig. 6. Complete relay optical component installed at the monochromator input and the 417-type power supply
Source: Author.

5. Measurement conditions

5.1. Light source ageing

To maintain stable radiant flux emitted by the light source during the measurement process and provide reproducible results, new light sources shall be seasoned (the so-called ageing or seasoning) for at least 100 hours prior to optical radiation measurements. Prior to measurements, LED sources shall be kept switched on for at least 60 minutes. This time is required to stabilise the luminous flux emitted by the sources.

5.2. Test environment

The measurements were taken in a dark room at the Optical Radiation Laboratory at the Central Institute for Labour Protection at the optical radiation hazard test station. There are no windows in the room and the walls are coated with matt black paint. The photometric darkroom prevents the effect of optical radiation being directly emitted from sources other than the tested ones and the radiation being reflected from elements of the equipment, room walls, and measuring instrumentation. In addition, the room is air-conditioned to obtain a stable ambient temperature, which is essential to maintain stable operation of the light sources being tested and limit the measurement error during measurements of the radiation emitted by such sources.

5.3. Illuminance

Illuminance measurements were taken using the DH400-VL luxmeter head connected to the IDR300-PSL monochromator supplied by Bentham. The head features a relative sensitivity suitable for the relative sensitivity of the human eye V_λ. The measurement was taken on the vertical plane at the location of the measuring detector. By changing the distance of the source being tested, changing indications of the luxmeter display were observed. If the indication was 500 ±1 lx, the distance was assumed as the measuring distance during the measurement of irradiance spectral distribution.

5.4. Software used to aid the procedure of light source testing – Kreator PSL Wizard

Kreator PSL Wizard serves as a guide that starts the test procedure by entering data relating to the source to be tested, through the selection of hazards being assessed, to a report with results of individual test stages.

The optical radiant energy emitted by the source depends on the source visual angle that is associated with the applied field of view. Therefore, the energy should be measured at the properly determined distance. Apart from the determination of distance at which the tested source emits 500 lx, it is also essential to determine properly the dimensions of the source and the distance from its apparent image, because the data is used to find the source visual angle.

If the source has no optical system, the measurement distance to be assumed starts on the surface mapped into the eye. (This applies to sources with diffuse (iridescent) bulbs.) If the source is equipped with an optical system (e.g., a lens), the magnified apparent image is generated behind the system. Moreover, the image of the source with a clear bulb is visible behind the bulb. It is the apparent source for which the measurement distance must be selected, because the source is mapped into the eye.

The visual angle defines the area of the exposed retina. The source being observed is directly mapped onto the retina (Fig. 7) for momentary irradiance and the effective angular subtense (α_{eff}) at the distance h, which is the same as the source visual angle during the assessment performed at the distance H. The information about the retinal image size is necessary to evaluate the retinal hazard. The measurement at the minimum distance of 200 mm corresponds, in practice, to the highest retinal hazard.

The distance from the reference point on the source to the spot with the apparent source must be positioned using the PSL Profiler attachment (Fig. 8).

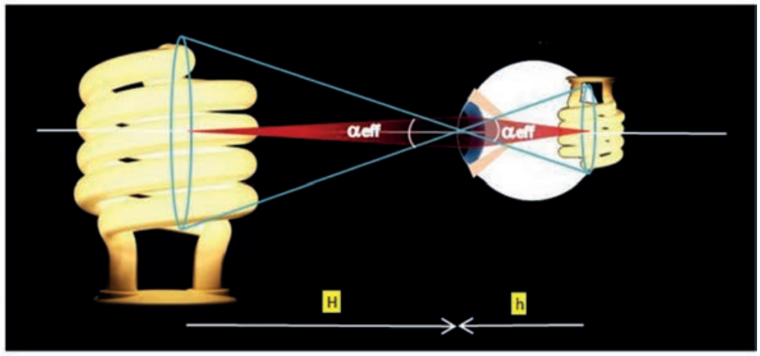


Fig. 7. View angle of the source and the retinal image
Source: Author.

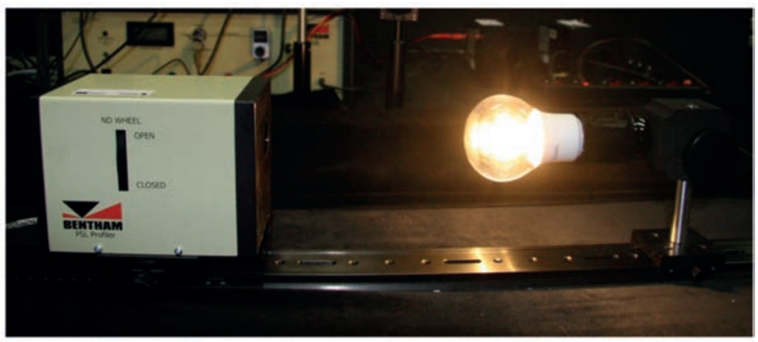


Fig. 8. View of the PSL Profiler attachment during assessment of apparent source positioning
Source: Author.

The maximum field of view for the PSL Profiler is approximately 120 mrad (to maintain sufficient resolution of the CMOS matrix for the smallest sources with the angular subtense of 1.7 mrad). As recommended in the standard [4], the minimum illuminating surface of the source during measurement shall be at least 50% of the total emitting surface of the source.

For sources with diffuse-coating bulbs or sources with diffusers, it is required to check whether the emission area is uniform. As for sources with integrated reflectors, lenses and other optical systems, the emission area may be defined not only by the source, but also jointly with such systems.

For the tested LED sources, four of them featured diffuse bulbs; therefore, there was no problem with proper determination of the measuring distance. However, for the CorePro LED bulb supplied by PHILIPS, it was necessary to use the PSL Profiler attachment. The obtained source image behind the reference point is shown in Fig. 9.

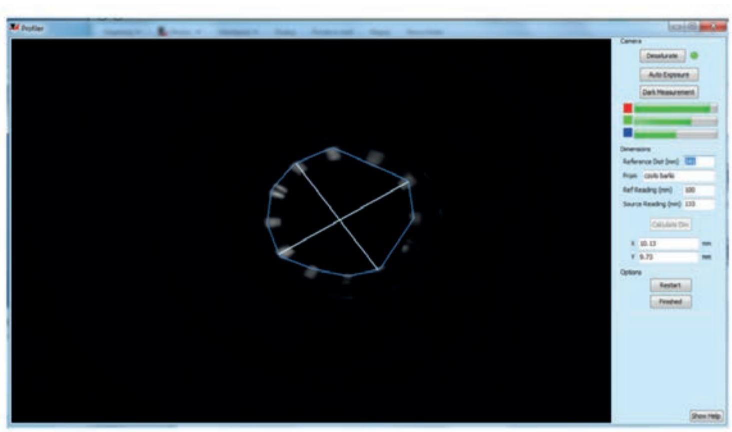


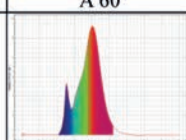
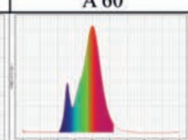
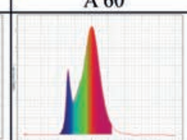
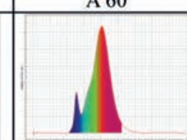
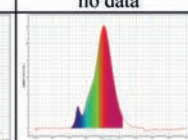
Fig. 9. View of the source image behind the reference point in the PSL Profiler opening
Source: Author.

6. Technical description of tested LED source

All tested LED sources are replacements for traditional A-series light bulbs; therefore, they come with the E 27 screw base. The tests concerned three LED sources supplied by PHILIPS, GTV, and BEMKO. Moreover, two LED sources available in supermarkets were used (Castorama – DIALL and Auchan – HFNE), which are considered generic. Four sources (GTV and BEMKO as well as DIALL and HFNE) are equipped with the A 60 type bulb that is diffused (iridescent). As for the bulb in the LED source supplied by PHILIPS, it is clear and LEDs are eclipsed by a specially designed optical system. As declared by the manufacturers, the sources are interchangeable with bulbs whose output is 40 W (PHILIPS), 60 W (GTV, HFNE and DIALL), and 75 W (BEMKO).

Table 1 summarises basic parameters on light source packaging as provided by the manufacturers. Basic performance parameters of light sources that are interchangeable with conventional bulbs include the following: power, luminous flux, life of a lamp, colour temperature, colour rendering index, and lamp dimensions (length and diameter).

Table 1. Description of the tested LED sources with the E27 screw Base – parameters provided by the manufactures

Source code	LED 1	LED 2	LED 3	LED 4	LED 5
Manufacturer / Distributor	GTV	BEMKO	AUCHAN	DIALL/Castorama	PHILIPS
Product name	LD-PC3A60-10W	E27-A60-120-3K	HFNE A60-P	LED*806 lm	CorePro LEDbulb
Power [W]	10	12	10	9	6.5
Luminous flux [lm]	840	1 055	806	806	470
Colour temperature [K]	3000	3 000	3 000	2 700	2 700
Colour rendering index [-]	≥ 80	≥ 80	bd	no data	no data
Luminous flux beam angle [°]	220	no data	no data	210	no data
Life of a lamp [h]	40 000	30 000	15 000	15 000	15 000
Type of bubble	A 60	A 60	A 60	A 60	no data
Spectrum of a radiation					
Photo of the light source					

7. Test results

According to requirements in the standard [4] concerning the tested general lightning service LED sources, the evaluation of photobiological safety covered the following:

– Ocular and skin actinic ultraviolet hazard (E_{IR}) over the wavelength 200 to 400 nm,
– Ocular near ultraviolet hazard (E_{UVA}) over the wavelength 315 to 400 nm,
– Retinal blue light hazard (L_B) over the wavelength range 300 to 700 nm,
– Retinal thermal hazard (L_R) over the wavelength 380 to 1 400 nm, and
– Ocular infrared radiation thermal (L_R) over the wavelength 780 to 3 000 nm.

Therefore, irradiance and radiance measurements were taken correspondingly to the tested hazards and ranges. The results presenting the listed hazards, assigned risk groups, and times of safe exposure are presented in Table 2.

Conclusion

The presented results of individual hazards of the tested LED sources unambiguously conclude that the sources are safe and pose no photobiological hazard. Therefore, all tested LED sources are classified into the exempt group. Please note that the obtained results relate only to unitary items of LED sources that were selected at random from among a wide and still-changing offer on the market.

For LED sources used for general lightning service, thermal hazards do not occur because the values obtained from measurements range from 0.005% to 0.1% of the exposure limit value. A similar conclusion is also drawn from the ocular near-ultraviolet (UV-A) hazard, because the values obtained by measurements range from 0.0004% to 0.0021% of the exposure limit value for the hazard.

Practically speaking, potential hazard posed by LED sources may be determined by ocular and skin hazard due to actinic ultraviolet radiation and ocular

Table 2. Summarised assessment results for photobiological hazard posed by a LED sources

Type of photobiological hazard	Wave-lengths [nm]	Function of biological efficiency	Symbol	Denomi-nation	Source code	Exempt group		Safe exposure time [s]
						Measurement result	*Emission limits*	
Actinic UV	200–400	$S_{UV}(\lambda)$	E_s	$W \cdot m^{-2}$	LED 1	$17.5\ 10^{-5}$	0.001	> 30 000
					LED 2	$14.3\ 10^{-5}$		
					LED 3	$6.79\ 10^{-5}$		
					LED 4	$7.25\ 10^{-5}$		
					LED 5	$1.13\ 10^{-5}$		
UV-A	315–400	–	E_{UVA}	$W \cdot m^{-2}$	LED 1	0.00021	10	> 10 000
					LED 2	0.00016		
					LED 3	$9\ 10^{-5}$		
					LED 4	$7\ 10^{-5}$		
					LED 5	$5.65\ 10^{-5}$		
Blue light	300–700	$B(\lambda)$	L_B	$W \cdot m^{-2} \cdot sr^{-1}$	LED 1	13.912	100	> 100
					LED 2	17.419		
					LED 3	9.07		
					LED 4	9.569		
					LED 5	12.228		
Retina thermal hazard	380–1 400	–	L_R	$W \cdot m^{-2} \cdot sr^{-1}$	LED 1	272.63	280 000	> 10
					LED 2	297.33		
					LED 3	$6.79\ 10^{-5}$		
					LED 4	258.48		
					LED 5	566.78		
Cornea and lens thermal hazard	780–3 000	$R(\lambda)$	E_{IR}	$W \cdot m^{-2}$	LED 1	0.00456	100	> 1 000
					LED 2	0.00568		
					LED 3	$9\ 10^{-5}$		
					LED 4	0.00412		
					LED 5	0.00648		

blue light hazard. For the former case, the highest value of 17.5% was obtained, relative to the exposure limit value that poses no hazard. However, values of 1% were obtained as well. For the latter case of ocular blue light hazard, similar maximum values were obtained, but the lower limit was higher (9% to 17%). The hazard level depends mostly on the emitted luminous flux, light colour, and the type of the LED source used.

By comparison of the values declared by the manufacturer (colour temperature and the value obtained by measurement), one may conclude that there is practically no difference between the values; whereas, for the LED source manufactured by Philips, a very warm colour temperature of 2500 K was obtained, which is rare on the market, but very sight friendly. For the colour rendering index, all tested sources feature a level of 80.

Based on an analysis of the obtained measurement results, it is to be concluded that the tested LED sources may be successfully used interchangeably with A-series light bulb in homes and offices.

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