Scientific Journals
Maritime University of Szczecin

Zeszyty Naukowe
Akademia Morska w Szczecinie

2013, 35(107) pp. 118–124
ISSN 1733-8670

2013, 35(107) s. 118–124

Assessing visible radiation threat at soldering work stations

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Key words: blue light hazard, electrical welding, gas welding, occupational risk

Abstract
The article discusses criteria for the assessment of exposure to visible radiation (blue light), methods of measurement of radiation exposure and hazards during welding. Then, the author presents the results of measurements of exposure to visible radiation in the electrical and gas welding. Based on the results of these measurements the occupational risk for the studied positions has been determined.

Introduction

The group of maximum admissible exposure (MDE) values included in the Decree of the Minister of Labour and Social Policy, covering the maximum admissible concentrations and intensities of agents harmful to human health in work places [1], includes also requirements related to the visible radiation in the range of blue light (300÷700 nm). The established MDE values determine potential threat to human eyes caused by visible radiation, with the special focus on the blue light range (425÷450 nm), so called blue light hazard. This particular threat is examined in the context of its direct emission by sources generating such strong radiation directly towards human eyes. However, the potential occurrence of this particular threat is not associated with visible radiation generated by lighting luminaries used for general lighting purposes, and hence does not indicate that such lighting represents a health hazard.

Effects of the exposure to the visible radiation in the range of blue light are especially visible in people exposed to this radiation due to their occupation. This observation applies also to employees working in open spaces (solar radiation), as well as people participating in selected technical processes – especially during welding. This type of radiation is also generated by electric light sources or radiation sources used for, e.g., visual inspection or exposing light-sensitive layers.

Evaluation criteria for exposure to visible radiation (blue light)

The current evaluation criteria for assessing the effects of exposure to incoherent optical radiation in Poland have been adapted to the requirements of European Union and the USA, which allows for application of uniform assessment of visible light exposure threats for employees. The applicable MDE values for incoherent optical radiation are included in the decree [1], and mandate the assessment of visible optical radiation threats at work places, resulting in the need to conduct measurements in compliance with the methods described in the respective standards [2, 3].

According to [1], the blue light radiation hazard is related to visible radiation with the wavelength ranging from 300 to 700 nm, covering partially the UV-B band, completely the UV-A band, and a large share of the visible light. However, in practical applications, the blue light radiation hazard covers only the wavelength range of 400 to 490 nm in the visible light band, which produces the blue colour. Optical radiation in this wavelength range is especially harmful to eyes exposed to high intensity optical radiation. Such light can cause thermal or photochemical damage of the exposed eyes, resulting in various ailments.

In the case of radiation sources with a large angular size, greater than 11 mrad, the image of the light source in the eye is also very large. In such a case, the hazard assessment is based on measurements of the effective luminance (L_s). On the other hand, in the case of radiation sources with a small angular size, i.e., smaller than 11 mrad, the hazard assessment is based on measurement of the effective irradiance (E_s).

The established values of L_s or E_s are then compared with the appropriate MDE values included in the decree [1], established depending on the total exposure time (t) – the total time of exposure relative to the daily work time, irrespective of its actual duration.

When the total exposure time does not exceed 10,000 seconds, then the formulas for MDE for L_B and E_B (see Table 1) account for the total exposure time. When the total exposure time exceeds 10,000 seconds, then the MDE values for L_B and E_B are given constant values as indicated in table 1.

Table 1. Maximum admissible exposure (MDE) values for eye retina for photochemical hazard (based on [1, 4])

Wave-length [nm]	Value maximum admissible exposure (MDE)	Unit	Total time of exposure needed to determine MDE t [s]	Angular size of the optical radiation source α [mrad]
300÷700	$L_B = 10^6/t$	W m^{-2} sr^{-1}	$t \leq$ 10,000 s	$\alpha \geq 11$
	$L_B = 100$	W m^{-2} sr^{-1}	$t >$10,000	
	$E_B = 100/t$	W m^{-2}	$t \leq$ 10,000 s	$\alpha < 11$
	$E_B = 0.01$	W m^{-2}	$t >$10,000	

Values used as criteria for assessing photochemical damage to eye retina are determined based on spectral efficiency of photochemical eye retina damage – represented by the $B(\lambda)$ curve in figure 1. The thermal damage is assessed based on the $R(\lambda)$ curve, which is also presented in figure 1. Both curves have their maxima in the range of 435 to 440 nm, which additionally emphasizes the wright of the blue light hazard.

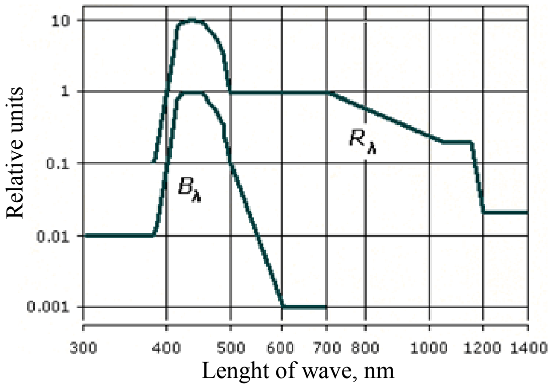

Fig. 1. Spectral efficiency for thermal $R(\lambda)$ and photochemical $B(\lambda)$ damage to eye retina [2, 4]

Characteristics of visible radiation hazards (blue light) occurring during the welding process

The welding process results in the occurrence of many factors causing potential health hazards for welders and their immediate surroundings. The most dangerous and harmful factors include dust, other chemical substances (gases), as well as optical radiation released during the welding process. The profession of a welder is one of the most hazardous and harmful from all industrial professions. These particular chemical factors combined with harsh working conditions favour development of a series of ailments and professional illnesses. Electrical arc used for welding is one of the most common sources of blue light. Moreover, at such high temperatures, plasma within the welding arc reaches the temperature of approx., 3000 K, emitting high intensity ultraviolet radiation (UV-B and UV-C bands), as well as infrared radiation (IR-A and IR-B bands). When using gas welding, the flame temperature does not exceed 2000 K, hence the resulting optical radiation does not contain ultraviolet radiation and blue light. Figures 2 and 3 represent examples of electric arc and gas welding work posts.

Visible and infrared radiation is examined in conjunction during the health hazard analysis, since some of adverse effects of this radiation are caused by both of these radiation types. Visible radiation reaches the eye retina entirely, hence can cause

Fig. 2. Example of electric arc welding

Fig. 3. Example of gas welding

damage primarily to the eye retina. Optical radiation with the wavelength longer than 700 nm (photo energy between 1.6 eV and 3.4 eV) may additionally initiate photochemical reaction in exposed tissue, while any optical radiation with the wavelength longer than 380 nm may additionally initiate thermal reactions in the same exposed tissue. Therefore, both the thermal, as well as photochemical hazard to the eye retina is accounted for in the analysis. It is further assumed that for the exposure times shorter than 10 seconds, thermal damage is dominant, while for the exposure times exceeding 10 seconds, photochemical damage is dominant.

In the case of skin exposure, optical radiation enters relatively deep into the human skin (especially any optical radiation with the wavelength longer than 500 nm), reaching sub-skin tissue. In such cases, thermal skin hazards must be also assessed accordingly.

Due to superimposition of various effects of all-day exposure to optical radiation, the eye retina is typically damaged due to previously described photochemical effects. Thermal damage to the eye retina caused by industrial radiation sources is typically very rare, due to the natural eye reflex, protecting it against optical radiation sources with very high intensity.

Measurement method for exposure to optical radiation (blue light) in work places

In order to assess photochemical hazards caused by blue light, according to the regulations included in standards PN-T-05687: 2002 [2] and PN-EN 14255-2: 2010 [3], the selection of the measured parameter depends on the viewing angle of the optical radiation source (α). For the viewing angle $\alpha \geq 11$ mrad, it is necessary to measure the effective luminance L_s, while for the viewing angle $\alpha < 11$ mrad – it is necessary to measure the effective irradiance E_s. In both cases, measurements cover the wavelength range of 300 to 700 nm, and the measurement heads must be calibrated to the relative spectral efficiency of the photochemical damage caused by the measured optical radiation ($B(\lambda)$ curve). In both cases, it is additionally necessary to measure the duration of the one-time exposure and determine the aforementioned viewing angle for the radiation source (α).

In practice, to carry out the aforementioned measurements of optical radiation at the work posts, it is most convenient to use a wideband radiometer. The ILT 1700 radiometer, manufactured by international Light (USA, see Fig. 4) is a good example of such a wideband radiometer, which can be used to carry out the aforementioned measurements. It needs to be equipped with the appropriate measurement heads.

Fig. 4. Radiometer ILT 1700 with example measurement head

When measuring the effective luminance for optical radiation (with the special focus on blue light), it is necessary to employ the SED 033/TBLU/SCS395/R sensor, manufactured by International Light (USA). According to the data sheet, the said sensor has the following characteristics:

- measurement range: $5.56e^{-9}$ to $5.56e^{+0}$ W/(cm^2/sr);
- spectral range: 305÷700 nm;
- $B(\lambda)$ curve correction;
- cosine fitting;
- viewing angle for the measurement head equal to 1.5°.

When measuring the effective irradiance for visible radiation (with the special focus on blue light), it is necessary to employ the SED 033/TBLU/SCS395/TD sensor, also manufactured by International Light (USA). According to the data sheet, the said sensor has the following characteristics:

- measurement range: 7.41e^{-10} to 7.41e^{-1} W/cm^2;
- spectral range: 305÷700 nm;
- $B(\lambda)$ curve correction;
- cosine fitting.

The radiometer together with the measurement sensors must be calibrated.

Any measurements to determine photochemical hazard to the eye retina caused by blue light must be carried out at the target work post, at the height of eyes. During the measurement process, the active surface of the appropriate sensor must be directed towards the radiation source, aligned with the axis *l* (see Fig. 5). In case of elongated radiation sources, care must be taken to find such a position of the measurement sensor in which the read-out value is the highest. In this case, the measurement value is equal to the arithmetic mean of the irradiance or luminance. When determining exposure levels for people changing their location at the work post, it is necessary to conduct measurements in all individual locations where they execute their functions.

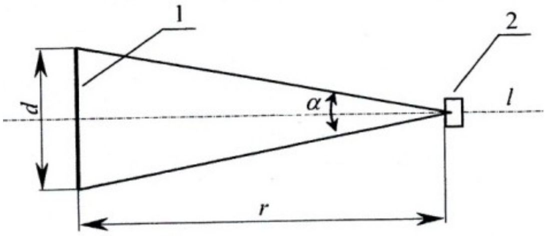

Fig. 5. Measurement system [2]; 1 – radiation source, 2 – measurement sensor, *l* – axis passing through the center of the measurement sensor and perpendicular to its surface, *r* – distance between the measurement sensor and the radiation source, *d* – diameter

Figures 6, 7 and 8 represent examples of electric arc and gas welding work posts and associated measurements of parameters for optical radiation in order to determine eye hazard levels.

When the measuring sensor appropriate for the measurement of the effective luminance of the optical radiation source L_s is missing, this value can be determined based on the measured effective radiance E_s. For this end, it is necessary to establish the surface of the optical radiation source and then compare it with the area of the circle, and finally establish the diameter *d* of the said circle using the following formula:

$$S_{\text{SOURCE}} = S_{\text{CIRCLE}} = \frac{\pi d^2}{4} \qquad (1)$$

Fig. 6. Measurement of eye hazard levels during electric arc welding

Fig. 7. Measurement of hand hazard levels during electric arc welding

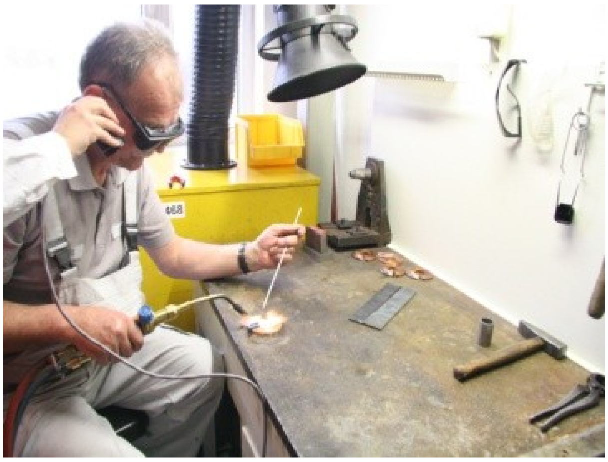

Fig. 8. Measurement of eye hazard levels during gas welding

Next, it is necessary to measure the distance between the eyes of the employee and the optical radiation source – designated as *r*. The target luminance value for the optical radiation source L_s is determined then using the following formula:

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

where *A* represents a spatial angle calculated as follows:

$$A = \frac{\alpha^2 \pi}{4} \quad [\mathrm{sr}] \tag{3}$$

where α represents the angular dimension of the optical radiation source, calculated as follows:

$$\alpha = \frac{d}{r} \tag{4}$$

During the process of measurement, it is necessary to account for specific environmental conditions, which might potentially affect the measurement results, including temperature, humidity, dust content, electromagnetic fields, etc. The measurement geometry must be fixed by placing the measurement sensor in the proximity of the exposed body parts in their typical locations / placement, and exposing them towards the maximum intensity of the optical radiation.

When carrying out the measurement of the effective radiance of the irradiation intensity for blue light, it is necessary to establish the actual diameter for the optical radiation source D (it is defined as the diameter for circular optical radiation sources, or the arithmetic average of the longest and the shortest dimension for elongated optical radiation sources), distance between the optical radiation source and the exposed body part r, as well as the viewing angle Φ (defined as the angle between the normal to the optical radiation source and the line of sight). In a case when the optical radiation

Table 2. Measurement results for exposure levels for optical radiation generated during the process of electric welding

Distance beetwen the head and the welding arc [m]	Angular size of the optical radiation source α [mrad]	Total time of exposure t_c [s]	Average effective irradiance E_B [W/m^2]	Maximum admissible exposure (MDE) values for photochemical hazard [W/m^2]	Increase in the MDE	The maximum work time without the use of means of personal protection t_{dop} [s]
TIG welding of stainless steel materials with an argon shield using a fusible steel wire, Φ = 2 mm, I = 83 A						
0.34	8.8	16 200	21.9	0.01	2 190	–
Electric welding (MMA) of steel materials using a fusible steel electrode with a cladding, Φ = 2 mm, I = 160 A						
0.45	6.67	3 600	29.4	0.028	1 054	3
MIG welding of stainless steel materials with an argon shield using a fusible steel wire, Φ = 1 mm, I = 115 A						
0.46	10.86	3 600	2.95	0.028	105.4	34
Electric welding (MMA) of steel materials using a fusible steel electrode with a cladding, Φ = 3.25 mm, I = 110 A						
0.60	5.0	1 800	18.5	0.056	330	5
TIG welding of stainless steel materials with an argon shield using a fusible steel electrode with a cladding, Φ = 3.25 mm, I = 98 A						
0.58	5.2	1 800	12.6	0.056	225	8
Electric welding (MMA) of steel materials using a fusible steel electrode with a cladding, Φ = 4 mm, I = 120 A						
0.60	8.3	120	4.78	0.01	478	–
Electric welding (MMA) of steel materials using a fusible steel electrode with a cladding, Φ = 3.25 mm, I = 90 A						
0.56	8.0	18 000	5.09	0.01	509	–
Electric welding (MMA) of steel materials using a fusible steel electrode with a cladding, Φ = 3.25 mm, I = 100 A						
0.46	10.86	10 800	6.07	0.01	607	–
Electric welding (MMA) of steel materials using a fusible steel electrode with a cladding, Φ = 3.25 mm, I = 130 A						
0.60	9.99	18 000	9.16	0.01	916	–
Electric welding (MMA) of steel materials using a fusible steel electrode with a cladding, Φ = 3.25 mm, I = 180 A						
0.50	6.7	2 064	10.2	0.05	203	10
Electric welding (MMA) of steel materials using a fusible steel electrode with a cladding, Φ = 3.2 mm, I = 120 A						
0.46	10.86	1 884	4.46	0.053	84	22.4
Electric welding of steel materials using a fusible steel electrode, Φ = 6.0 mm, I = 180 A						
0.54	9.2	18 000	22.3	0.01	2 230	–
Electric welding of steel materials using a fusible steel electrode Φ = 6.0 mm, I = 210 A						
0.36	10.91	1 800	45.7	0.056	816	2
Electric welding (MMA) of aluminum materials using a fusible aluminum wire, Φ = 2 mm, I = 160 A						
0.46	10.86	16 200	66.8	0.01	6 680	–
TIG welding of aluminum materials with an argon shield using a fusible aluminum wire, Φ = 4 mm, I = 200 A						
0.46	10.86	21 600	24	0.01	2 400	–

MMA (manual metal arc welding) – a method of electric welding employing a fusible metal electrode, covered with a flux cladding; Φ – diameter of the electrodes [mm]; I – welding current [A] source is not located directly in front of the person (e.g., in front of their face), it is necessary to establish the actual visible diameter of the optical radiation source $D_L = D\cos\varphi$. Moreover, it is necessary to calculate the viewing angle for the optical radiation source (α) using the following formula:

$$\alpha = \frac{D_L}{r} \tag{5}$$

Measurement results for photochemical hazards caused by blue light, established for selected work places

Tables 2 and 3 contain example results for measurements of the effective luminance of electric welding arcs, carried out by the author of this paper, and accounting for the $B(\lambda)$ efficiency curve. In all cases of the examined welding process, using either electric or gas arc techniques, the angular size of the optical radiation source (α) was established to be smaller than 11 mrad. Depending on the total exposure time, the appropriate MDE value was then established (according to Table 1). The last column shows the admissible exposure time for an employee not using any means of personal protection, determined when $t \leq 10{,}000$ seconds, according to the formula included in the decree [1]

$$E_B = \frac{100}{t} \ [\mathrm{Wm^{-2}}] \tag{6}$$

Conclusions

The values of effective irradiance (E_B), as presented in tables 2 and 3, depend on the employed welding method, the angular size of the optical radiation source, as well as the distance between the head and the welding arc.

In the case of electric welding, the distance ranges between 0.34 and 0.6 meters, and was associated with the actual welding conditions. The values of E_B for electric welding of steel materials range between 2.95 W/m^2 and 29.4 W/m^2. The largest values were obtained for electric arc welding using a fusible metal electrode with a cladding, as well as TIG welding with an argon shield. Even larger values of E_B were obtained when welding steel (45.7 W/m^2). The highest values were observed for electric arc welding of aluminum (66.7 W/m^2). The total time of exposure to electric welding arc during a complete work turn was obtained based on information collected from employees, ranging from 120 to 21,600 seconds. This information was indispensable for determining the maximum admissible exposure (MDE) values. Based on the conducted measurements of E_B for the wavelength range of 300÷700 nm for actual electric welding work posts, the target MDE values were exceeded anywhere between 84 and 6680 times. This means, in turns, that such work places feature very high professional hazards associated with the excessive amount of blue light. When possible, the maximum work time without the use of means of

Table 3. Measurement results for exposure levels for optical radiation generated during the process of gas welding

Distance beetwen the head and the welding arc [m]	Angular size of the optical radiation source α [mrad]	Total time of exposure t_c [s]	Average effective irradiance E_B [W/m^2]	Maximum admissible exposure (MDE) values for photochemical hazard [W/m^2]	Increase in the MDE	The maximum work time without the use of means of personal protection t_{dop} [s]
Gas welding of copper materials using a fusible silver wire						
0.53	9.43	360	0.88	0.28	3.1	115
0.53	9.43	21 600	0.88	0.01	86.7	–
Gas welding of steel materials using a fusible steel wire, $\Phi = 3.25$ mm						
0.53	9.43	360	2.18	0.28	7.8	46
Gas welding of steel materials using a fusible copper plated steel wire, $\Phi = 3.25$ mm						
0.62	5.7	1 800	0.19	0.056	3.5	510
Gas welding of steel materials using a fusible the steel wire, $\Phi = 2$ mm						
0.48	10.42	1 800	0.14	0.056	2.5	714
Acetylene-powered cutting of steel materials						
0.50	9.99	1 700	0.0785	0.059	1.33	1 274
Acetylene-powered cutting of steel materials						
0.62	8.1	2 900	0.028	0.035	0.8	3 571
Acetylene-powered cutting of steel materials						
0.75	10.67	18 000	0.295	0.01	29.5	339

Φ – diameter of the electrodes [mm] personal protection was established to be equal to anywhere between 2 and 34 seconds.

When using gas welding, the distance between the employee's head and the welding arc was slightly larger and ranged between 0.48 and 0.75 meters. The values of E_B were substantially smaller, and ranged between 0.028 W/m^2 and 2.18 W/m^2. The smaller of E_B values were observed for acetylene-powered cutting. The total time of exposure to gas welding arc during a complete work turn was established anywhere between 360 and 21,600 seconds. Using the obtained values of E_B, only in one case the average professional risk was established to be below the limit (equal to 0.8 MDE). In all other cases, high professional hazard was established, with the MDE values exceeded anywhere between 1.3 and 29 times. When possible, the maximum work time without the use of means of personal protection was established to be equal to anywhere between 46 and 7143 seconds. For example, the increase in the total exposure time from 360 seconds to 21,600 seconds (welding a copper wire), caused the increase in the MDE excess from 3.1 to 86.7 times.

When observing the effective radiance for visible optical radiation generated during the process of electric or gas welding, it is possible to conclude that electric arc welding causes substantially higher professional hazards when compared with gas arc welding. This is further confirmed by comparing the values of E_B and the admissible exposure times when working without any personal means of eye protection.

In summary, optical radiation generated by the process of electric arc welding represents substantial health hazard to welders, as well as any other people working in the proximity of such work places, primarily because of the excessive MDE values. For this reason, it is necessary to undertake specific actions to limit the exposure of employees on these work places. If this end cannot be achieved through technical (e.g.: changing the type of optical radiation source, or shielding it) or organizational means (increasing the distance between the employee and the optical radiation source), it is then necessary to employ appropriate means of personal protection for exposed skin and eyes. Even though the exposure times for unshielded eyes were established, under no circumstances it is recommended to undertake welding, and especially starting the process of welding, without the use of means of personal protection. Precise determination of the existing hazards is possible only through the measurement of appropriate parameters of optical radiation. It is indispensable to establish the levels of professional hazards, required by the decree [5] for each work place.

Acknowledgements

This paper has been prepared on the basis of the results of a research task carried out within the scope of the second stage of the National Programme "Improvement of safety and working conditions" supported in 2011-2013 – within the scope of state services and statutory activity – by the Ministry of Labour and Social Policy. The Central Institute for Labour Protection – National Research Institute is the Programme's main co-ordinator.

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