CALCULATION OF THE CIRCADIAN ILLUMINANCE DISTRIBUTION WITH RADIANCE

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ABSTRACT

New circadian photoreceptors are be able to regulate natural body clock. Using spectral circadian efficiency function it is possible to define circadian quantities. Calculation of circadian illuminance distribution using interreflections can be done using spectral values of reflectance and spectral distribution of radiation.

Keywords: circadian cycle, illuminance distribution calculation

1. INTRODUCTION

The configuration of the photometric values connected with the vision process bases upon the spectral luminous efficiency function V(λ) (Fig. 1). There are known other impacts of the optical radiation on a human organism related with the photo-biological processes that cause various effects (conjunctivitis, skin irritation and bacteria destruction). The configurations connected with these processes base upon known spectral luminous efficiency of radiation functions S(λ).

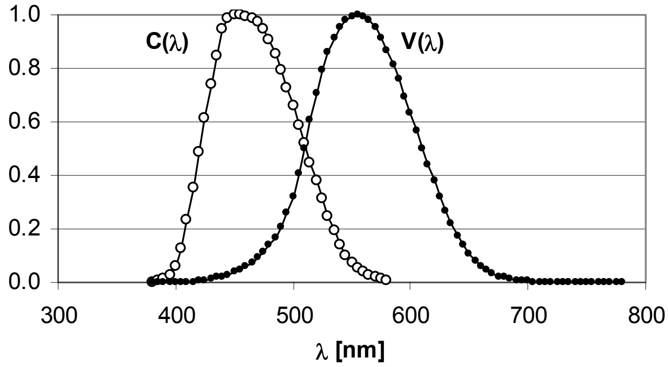

Fig. 1. The relative spectral luminous efficiency functions V(λ) and relative spectral circadian efficiency functions C(λ).

In 2001, there has been published the data describing the newly discovered receptors located on the eye retina [2, 3]. Stimulation of these receptors influences attenuation of the melatonin production. The melatonin hormone level changes during the day and the mentioned changes are connected with so-called day-around cycle. The day-around cycle denominated the circadian cycle (originated from Latin circa-around and dies-day), is one of the oldest inborn rhythms and has created many persisting physiological mechanisms (as for example sleepiness when people got sleepy in the evening). The circadian cycle is influenced mainly by the light that operates as the synchroniser of the day-and-night cycle as well as synchroniser of the activity and rest phases (wakefulness – sleep). When the light quantity is reduced as happens during the winter, there can occur the circadian cycle disorder (increase of melatonin level), as well as the mood depression denominated season depression. However, in case we have recognized the properties of the receptor responsible indirectly for the circadian cycle then we can influence the cycle. On the basis of the published spectral circadian responsivity of the human eye [2, 3], there has been recognized the relative spectral circadian efficiency function C(λ) [1] (Fig. 1). At present, there is conducted a research that tends towards establishing the required radiation doses assumed in accordance with the circadian efficiency criteria that shall cause the desired results as far as the circadian cycle formation is concerned.

2. CIRCADIAN RADIOMETRIC QUANTITIES

The circadian flux Φ_C can be defined with use of the equation (1) containing the value K_m that represents the maximum spectral luminous efficiency value equal to 683 [lm W^{-1}], and $\Phi_{e\lambda}$ [W m^{-1}]. represents the spectral distribution of radiant flux.

$$\Phi_c = K_m \int_\lambda \Phi_{e\lambda}\, C(\lambda)\, d(\lambda) \quad [lm_c] \tag{1}$$

In general, when defining the effective flux of a given radiation there is applied the constant K equal to 1. Then, the flux value is expressed in the effective Watts [W_{ef}] [4]. The herein described method of circadian flux definition (1) has been presented in a number of papers [1] and the unit of such a quantity is the circadian luminous flux [lm_C]. The constant K_m and adjective luminous have been connected until now with the photometric values configuration. The introduction of these concepts to the circadian quantities description can be explained and justified by the need of seizing their relative changes in respect of the photometric (luminous) values. When accepting this course of reasoning, it is possible to introduce successive quantities such as the circadian illuminance E_C and the circadian luminance L_C (2, 3).

$$E_c = K_m \int_\lambda E_{e\lambda}\, C(\lambda)\, d(\lambda) \quad [lx_c] \tag{2}$$

$$L_c = K_m \int_\lambda L_{e\lambda}\, C(\lambda)\, d(\lambda) \quad [cd_c\ m^{-2}] \tag{3}$$

where: $E_{e\lambda}$ - spectral distribution of irradiance, $L_{e\lambda}$ - spectral distribution of radiance

When applying the analogy to the luminous flux reflectance definition ρ there can be introduced the dependence describing the circadian flux reflectance factor ρ_c (4).

$$\rho_c = \frac{\Phi_{c\rho}}{\Phi_c} = \frac{K_m \int_\lambda \Phi_{e\lambda}\ \rho_\lambda\ C(\lambda)\, d(\lambda)}{K_m \int_\lambda \Phi_{e\lambda}\ C(\lambda)\, d(\lambda)} \tag{4}$$

where: $\Phi_{c\rho}$ - reflected circadian flux

The circadian efficiency factor a_{cv} [1] (5) describes the relation between circadian quantities (in this case photometric circadian quantities) and photometric quantities (in the equation denominator Φ signifies luminous flux).

$$a_{cv} = \frac{\Phi_c}{\Phi} = \frac{K_m \int_\lambda \Phi_{e\lambda}\ C(\lambda)\, d(\lambda)}{K_m \int_\lambda \Phi_{e\lambda}\ V(\lambda)\, d(\lambda)} \tag{5}$$

Between circadian radiometric quantities X_{ec} (circadian flux shall be then expressed in the effective Watts [W_{ef}]) and photometric circadian quantities X_c there proceeds the relation (6).

$$X_{ec} = \frac{X_c}{K_m} \tag{6}$$

3. CALCULATION OF THE CIRCADIAN ILLUMINANCE DISTRIBUTION USING RADIANCE

Calculating the circadian illuminance distribution inside interiors is connected with the necessity to consider the flux interreflections between surfaces composing the interior. In case there shall be applied selective materials with photometric properties being the wavelength function, it is necessary to make calculations including the spectral quantities within the visible range of the electromagnetic radiation, i.e. the spectral distribution of lamp radiant flux and spectral reflectance coefficients.

There have been made the exemplary calculations with use of the backward ray tracing method [5], using the *rtrace* programme, from Radiance system [5] that performs the tracing process by indicating rays crossing points with surfaces in the space. The visible range of the electromagnetic radiation has been divided into nine sections $\Delta\lambda$. For these sections, there have been calculated quantities of the relative spectral luminous efficiency $V(\Delta\lambda)$ and relative spectral circadian efficiency $C(\Delta\lambda)$ (Table 1).

Table 1. The nine sections within the visible electromagnetic radiation range that have been considered for the purpose of making calculations.

Lp	$\Delta\lambda$ [nm]	Section	$V(\Delta\lambda)$	$C(\Delta\lambda)$
1	380– 415	B3	0.000441	0.076750
2	415– 455	B2	0.019150	0.793000
3	455– 495	B1	0.124505	0.916500
4	495– 535	G3	0.599500	0.450500
5	535– 575	G2	0.973988	0.068000
6	575– 625	G1	0.628400	0.001400
7	625– 675	R3	0.128000	0.000000
8	675– 725	R2	0.006490	0.000000
9	725– 780	R1	0.000166	0.000000

There have been calculated the spectral irradiation intensity distributions $E_{e\lambda}$, and on their basis (by replacing integration with summation) there have been calculated the illuminance distribution E and circadian illuminance distribution E_C (2). Calculations have been made for the rectangular room configuration having the following dimensions: length 6m, width 4 m and height 3.2 m (Fig. 2).

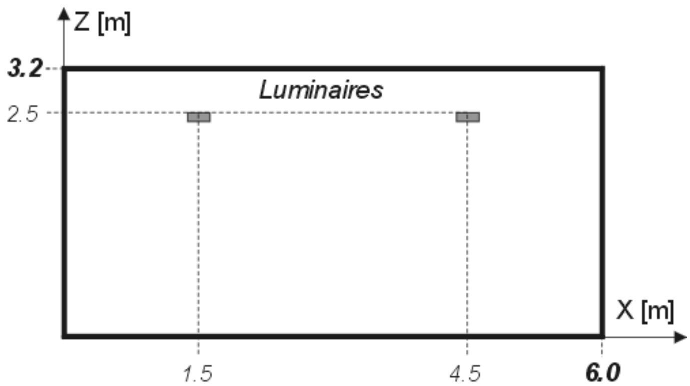

Fig. 2. The room model for which calculations have been made.

At the height h=2.5 m there have been distributed two luminaires with fluorescent lamps Lumilux 58W/21-840, 5200 lm and for the next example Lumilux Skywhite 58W 4900 lm (when making calculation, there have been taken into consideration the fluorescent lamps spectral distribution, Fig. 3). The circadian efficiency factor a_{cv} for Lumilux 58W/21-840 has got the value equal to 0.55 and for Lumilux Skywhite 58W value equal to 0.99.

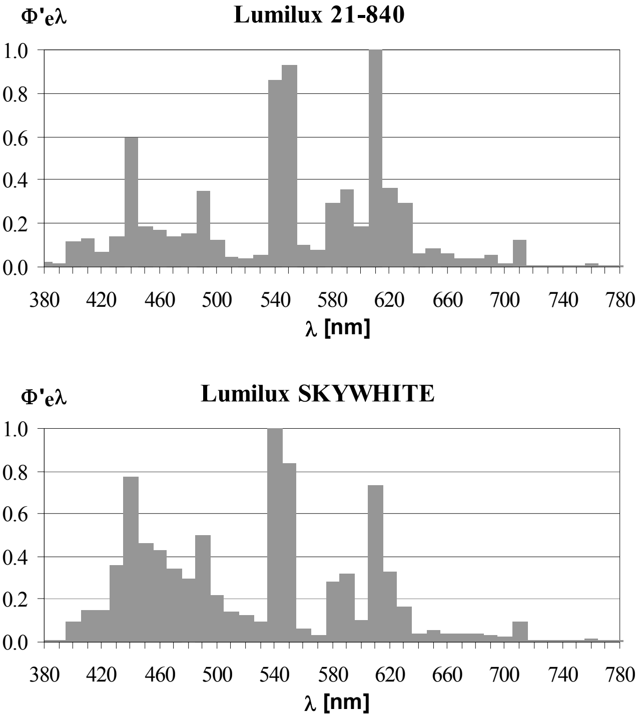

Fig. 3. Spectral distribution of the fluorescent lamp Lumilux 21-840 and Lumilux Skywhite.

There have been considered two variants where once the luminaires produce light towards up (indirect lighting) and secondly towards down (direct lighting). Calculations have been made for four selective materials covering all internal surfaces (Fig. 4). There have been considered that materials are characterized by the isotropic diffuse reflection.

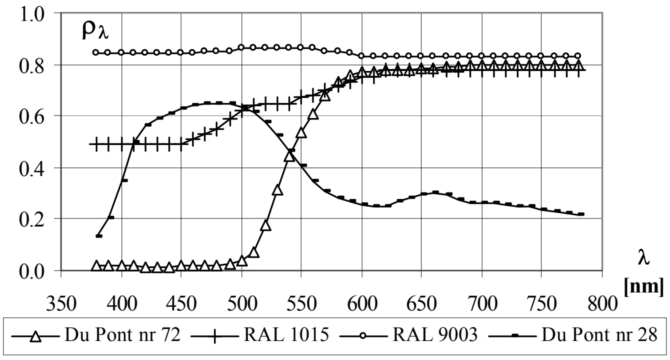

Fig. 4. Spectral reflectance factors of paints samples from Du Pont catalogue and coloured samples from RAL colours catalogue.

3.1 Radiance techniques (9X method)

Making calculations required preparing data for calculations and starting calculations in a special way.

Preparing data for calculations:

a) First step is dividing the visible range of the electromagnetic radiation into sections $\Delta\lambda$. For these sections, values of the relative spectral luminous efficiency $V(\Delta\lambda)$ and relative spectral circadian efficiency $C(\Delta\lambda)$ are calculated as average values. For the first example the visible range of the electromagnetic radiation has been divided into nine sections (see Table 1),

b) Spectral reflectance factors of materials should be calculated for all spectral sections from spectral data (Fig. 4) as average values, then reflectance factor values should be written as arguments of e.g. `plastic` materials for three channels:

```
void plastic material-R
0
0
5     0.233167    0.263080    0.286560    0     0

void plastic material-G
0
0
5     0.261800    0.381725    0.584300    0     0

void plastic material-B
0
0
5     0.643700    0.597100    0.294725    0     0
```

Radiance uses three channels in one calculation process. To introduce data for nine channels it is necessary to make calculations three times. Each single process is made for different section group R, G and B (see table 1). For each single process there is introduced different file with material description and each material contains three channels:
- file with `material-R` : channels R1, R2 and R3
- file with `material-G` : channels G1, G2 and G3
- file with `material-B` : channels B1, B2 and B3

c) Spectral distribution of luminaires should be calculated from spectral data of the lamps for all spectral sections. There are calculated spectral radiance of luminaires $L_{e\lambda}$ [W m^{-2} sr^{-1}] from relative spectral distribution of radiant flux $\Phi'_{e\lambda}$ of lamps (Fig. 3). To calculate spectral radiance, first is presented following equation (7):

$$I_{C,\gamma} = S'_{C,\gamma}\, K_m \sum_{\lambda=380nm}^{\lambda=780nm} k\, \Phi'_{e\lambda}\, V(\lambda)\, \Delta\lambda \quad [lm\ sr^{-1}] \tag{7}$$

where:
$I_{C,\gamma}$ - luminous intensity of the luminaire in a given direction C,γ (the value which is known),
S' - projected area of luminous solid of the luminaire in direction C,γ,
K_m - maximum spectral luminous efficiency value equal to 683 [lm W^{-1}],

$$L_{e\lambda} = k\, \Phi'_{e\lambda} \tag{8}$$

where:
k - coefficient that should be calculated.

Products of *k* and $\Phi'_{e\lambda}$ (for λ from 380 nm to 780 nm with step $\Delta\lambda$ = 2nm, 5nm or 10nm) should give such a value of $L_{e\lambda}$ that right part of equation (7) will be equal to known value of luminous intensity of the luminaire in a given direction $I_{C,\gamma}$. The best way is made it for direction C=0, γ=0. It is possible to find *k* in some different ways. For example there could be used approximation method. Values of spectral radiance should be calculated for nine sections as sum of all spectral radiance $L_{e\lambda}$ within given section (9).

$$L_e^{R1} = \sum_{\lambda=725nm}^{\lambda=780nm} L_{e\lambda}\, \Delta\lambda \qquad L_e^{R2} = \sum_{\lambda=675nm}^{\lambda=725nm} L_{e\lambda}\, \Delta\lambda \qquad L_e^{R3} = \sum_{\lambda=625nm}^{\lambda=675nm} L_{e\lambda}\, \Delta\lambda \qquad \text{etc...} \tag{9}$$

Then it is possible to prepare three files where properties of luminaire are described. There is presented one of these files `luminaire-R.rad`:

```
#luminaire for two SKYWHITE 58W Fi=4900lm, section group R
#luminaire distribution in luminaire.dat

void brightdata luminaire.dist
5 flatcorr luminaire.dat source.cal src_theta src_phi2
0
1 0.005135838

#"0.005135838" is 1/I(C=0,gamma=0),
#here I=194.7102[cd/1000lm], see luminaire.dat

luminaire.dist light lampa_100
0
0
3 0.094570  0.332746    0.577927
#upper are three values of spectral radiance
#here for sections R1, R2 and R3

#shape of luminaire No 1
lampa_100 polygon lampa1
0
0
12
      1.35  1.25  2.39
      1.35  2.75  2.39
      1.65  2.75  2.39
      1.65  1.25  2.39

#shape of luminaire No 2
lampa_100 polygon lampa2
0
0
12
      4.35  1.25  2.39
      4.35  2.75  2.39
      4.65  2.75  2.39
      4.65  1.25  2.39

# luminaire body generation
xform -n 1 -t 1.35 1.25 2.399
genbox mat_body ob 0.3 1.5 0.1
```

File `luminaire.dat` is as follows:

```
# luminaire 2x58W Skywhite,
# Fi(lamps)=2x4900lm, 1.5mx0.3m, opal diffusor
# Fi(luminaire)=5994.66 lm, L(luminaire)=4240.35 cd/m2
# Here are presented values of luminous intensity distribution
# I [cd/1000lm]
1
0     180   19
194.7102
191.7506
182.9692
168.6190
149.1480
125.1597
97.3551
66.5909
33.8017
0.0000
0.0000
0.0000
0.0000
0.0000
0.0000
0.0000
0.0000
0.0000
0.0000
```

Starting calculations:

a) For one scene it is need to run three `rtrace` processes for calculation of illuminance distribution. Each process can make calculations for one section group (R, G or B).

```
oconv material-R.rad luminaire-R.rad room.rad > R.oct
oconv material-G.rad luminaire-G.rad room.rad > G.oct
oconv material-B.rad luminaire-B.rad room.rad > B.oct
rtrace @par.opt -h -I R.oct <points.txt> outR.txt
rtrace @par.opt -h -I G.oct <points.txt> outG.txt
rtrace @par.opt -h -I B.oct <points.txt> outB.txt
```

b) The next step is to join three output files using `lam` program:

```
lam outR.txt outG.txt outB.txt > out-RGB.txt
```

c) All previous data (prepared for calculations and obtained as results of calculation processes) are spectral data, so now we can decide what values we want to receive: photometric (luminous) or circadian. Photometric illuminance is calculated with the following process:

```
rcalc -e
'$1=0.000166*$1+0.006490*$2+0.128000*$3+0.628400*$4+0.973988*$5
+0.599500*$6+0.124505*$7+0.019150*$8+0.000441*$9' out-RGB.txt >
out-V.txt
```

circadian illuminance is calculated with the process:

```
rcalc -e
'$1=0.000000*$1+0.000000*$2+0.000000*$3+0.001400*$4+0.068000*$5
+0.450500*$6+0.916500*$7+0.793000*$8+0.076750*$9' out-RGB.txt >
out-C.txt
```

Please see that there are used for `rcalc` process relative spectral luminous efficiency $V(\Delta\lambda)$ and relative spectral circadian efficiency $C(\Delta\lambda)$ values (see table 1).

d) The last step is multiply calculated values by 683 (the maximum spectral luminous efficiency K_m [lm W^{-1}])

```
rcalc -e '$1=683*$1' out-V.txt > out-EV.txt
rcalc -e '$1=683*$1' out-C.txt > out-EC.txt
```

3.2 Results

The total reflectance of luminous flux ρ and circadian flux ρ_C values that have been calculated for the spectral distribution of the Lumilux 58W/21-840 and Lumilux Skywhite 58W fluorescent lamp have been presented in the Table 2. There have been calculated values of the illuminance distribution E and circadian illuminance E_C on the floor level and on their basis there have been calculated average values E_{AV} and $E_{C\text{-}AV}$. There have also been calculated the illuminance E_V and circadian illuminance $E_{C\text{-}V}$ values on the vertical plane for the observer located in the room centre and for the observation direction along the room (Table 2).

Table 2. Calculated reflectance, illuminance and circadian illuminance values.

first value for Lumilux 21-840 / second value for Lumilux Skywhite		Du Pont 72	RAL 1015	RAL 9003	Du Pont 28
ρ		0.57 / 0.51	0.69 / 0.68	0.85 / 0.85	0.38 / 0.41
ρ_C		0.07 / 0.05	0.54 / 0.53	0.84 / 0.85	0.60 / 0.61
Indirect lighting	E_{AV} [lx]	214 / 178	259 / 234	490 / 464	75 / 81
	$E_{C\text{-}AV}$ [lx_C]	8 / 9	71 / 119	239 / 406	88 / 154
	E_V [lx]	200 / 166	243 / 219	475 / 451	64 / 70
	$E_{C\text{-}V}$ [lx_C]	7 / 8	64 / 107	232 / 394	81 / 141
Direct lighting	E_{AV} [lx]	469 / 419	514 / 475	780 / 741	326 / 317
	$E_{C\text{-}AV}$ [lx_C]	139 / 233	194 / 328	384 / 651	212 / 364
	E_V [lx]	485 / 432	535 / 494	809 / 769	329 / 322
	$E_{C\text{-}V}$ [lx_C]	133 / 221	201 / 339	398 / 675	220 / 378

Significant differences between illuminance $E_{AV(V)}$ and circadian illuminance $E_{C\text{-}AV(V)}$ values concern indirect lighting case when it is influenced by the applied materials characteristics (in particular for Du Pont 72 and Du Pont 28 materials), with a given lamp spectral distribution results in significant differences within reflectance factor values. The differences obtained for the direct lighting result mainly from differences between the fluorescent lamp luminous and circadian luminous fluxes.

To verify accuracy of proposed method the following calculations are made:

a) Radiance method. Standard Radiance calculations for aselective (grey) materials and lamps with equal energy spectrum,

b) 3X method. The visible range of the electromagnetic radiation divided into three sections $\Delta\lambda$. New values of the relative spectral luminous efficiency $V(\Delta\lambda)$ and relative spectral circadian efficiency $C(\Delta\lambda)$ were calculated. Materials have their spectral selective characteristics. Skywhite fluorescent lamp have non-equal energy spectrum (Fig. 3).

c) 9X method. The visible range of the electromagnetic radiation divided into nine sections $\Delta\lambda$ (as described above). Materials have their spectral selective characteristics. Skywhite fluorescent lamp have non-equal energy spectrum (Fig. 3).

Results are presented in table 3.

Table 3. Calculated illuminance values for three methods.
Estimated error between 3X and 9X method.

		Du Pont 72				RAL 1015			
Lumilux Skywhite		Radiance	3X method	9X method	error δ [%]	Radiance	3X method	9X method	error δ [%]
Indirect lighting	E_{AV} [lx]	118	107	178	-40	218	208	234	-11
	$E_{C\text{-}AV}$ [lx$_C$]		25	9	178		114	119	-4
	E_V [lx]	105	95	166	-43	204	195	219	-11
	$E_{C\text{-}V}$ [lx$_C$]		22	8	175		104	107	-3
Direct lighting	E_{AV} [lx]	346	321	419	-23	452	427	475	-10
	$E_{C\text{-}AV}$ [lx$_C$]		216	233	-7		297	328	-9
	E_V [lx]	357	331	432	-23	471	445	494	-10
	$E_{C\text{-}V}$ [lx$_C$]		209	221	-5		307	339	-9

		RAL 9003				Du Pont 28			
Lumilux Skywhite		Radiance	3X method	9X method	error δ [%]	Radiance	3X method	9X method	error δ [%]
Indirect lighting	E_{AV} [lx]	454	423	464	-9	82	75	81	-7
	$E_{C\text{-}AV}$ [lx$_C$]		350	406	-14		86	154	-44
	E_V [lx]	442	411	451	-9	71	64	70	-9
	$E_{C\text{-}V}$ [lx$_C$]		340	394	-14		76	141	-46
Direct lighting	E_{AV} [lx]	725	675	741	-9	312	290	317	-9
	$E_{C\text{-}AV}$ [lx$_C$]		563	651	-14		267	364	-27
	E_V [lx]	752	700	769	-9	318	295	322	-8
	$E_{C\text{-}V}$ [lx$_C$]		584	675	-13		275	378	-27

There may occur high error when it is used 3X method (three sections) to calculate illuminance for spectral data, especially when spectral characteristics of materials and lamps strongly depend on wavelength.

4. CONCLUSIONS

Within the room lighting there must be expected significant differences between illuminance and circadian illuminance values because of differences that may concern fluxes and reflectance factors (both photometric and circadian ones). In the presented here examples, generally there have been observed the value decrease of the circadian quantities in relation to photometric ones. Calculations made with use of interreflections for the selective materials must be performed with use of spectral and not integral values [6].

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