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Research of parameters of light emitting diode lamps and their suitability for lighting of working areas

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Abstract. The current paper describes the results obtained during several experiments in Tallinn University and Tallinn University of Technology considering the parameters of light emitting diode (LED) lamps. Four different LED lamps were investigated, all of them defined (by vendors and/or manufacturers) fitting to replace a 60 W incandescent lamp. The lamps investigated were the only ones fitting the definition and possible to purchase from vendors in Tallinn, Estonia in the beginning of year 2012, when the experiments were carried out. Several methods were used to determine parameters such as: working temperature of luminaires, illuminance, working power, the spectrum of created light, the flicker produced. According to the results of flickering, frequency and the modulation index of the flickering were calculated. The purpose of the research was to draw conclusions concerning the hypothesis, that by replacing a 60 W incandescent lamp (IL) with a fitting LED lamp, the lamp that uses less electrical power is equivalent to the previously popular IL by the spectral properties as well as the produced illuminance. Conclusions were also drawn considering the influence of such light on people exposed to it.

Key words: LED lamps, working temperature of luminaires, illuminance, working power of luminaires, spectrum of light, flickering of light, occupational health, colour rendering index.

INTRODUCTION

Usage of incandescent lamps (IL) has been limited, alternatives have been sought. One of the alternatives is light emitting diode (LED) lamps that might prove to be a better alternative than compact fluorescent lamp (CFL).

LEDs are electronic devices that transform electricity to visible light. The general principle allowing such transformation is usage of semiconductor crystals that have been excited by the influence of electric current. Because of the recombination of the excited charge carriers in the crystal, the light is emitted. During the creation of light, some heat is also created. To avoid the decrease of the emitted luminous flux it is most important to lead the created heat away from the recombination area where the pn-junction takes place.

To create white light with LEDs two different approaches have been developed: a) use of multiple primary-colour LEDs (red, green and blue, the RGB); b) use of blue or ultraviolet LEDs in combination with wavelength down-converting phosphor (Mirhosseini et al., 2009).

The world of LED lamps is developing rapidly. The experiments described in this article were carried out in the beginning of year 2012, therefore only a few different types of LED lamps were investigated – the ones that were possible to purchase from vendors in Tallinn, Estonia. The importance of the research emerges from the need to find a substitute luminaire to both IL and CFL. The former needs too much electrical power to create suitable lighting conditions and the latter has a spectrum that really is not suitable for excellent colour rendering (because of consisting of only some wavelengths instead of representing the full spectrum). Also a widely known problem considering FLs is the need to use mercury in them, which is a considerable chemical hazard, from an environmental viewpoint (Aman et al., 2013). The possible human health risks from mercury exposure from broken CFL has been investigated (Nance et al., 2011) – the results show that exposure to a broken CFL, even if the broken lamp is not cleaned up immediately and the room is poorly ventilated, then a health risk is unlikely; although the lamp's inner surface's vapour release rate is greater than the release rate in case of a single drop of liquid mercury (Johnson et al., 2008) due to the large area of surface where the mercury is adsorbed onto.

Bellia et al. published an introduction to discoveries considering photobiology in 2011. Although the centroid of the article was on the circadian rhythms of the light-dark cycle (especially the circadian action factors and efficiency of some certain luminaires) some attention was drawn to several problems, which cannot be dismissed related to this article's topic:

- The modern lighting design practice is devoted to the effects of lighting on the (indoor) workplace and environment itself, rather than the visual effects and health impact on human beings. The current European standard EN 12464-1 (referring exclusively to electric lighting systems used for indoor working places) does not take the spectrum of light under consideration. This leads to a need for new spectral weighting functions.
- In the future, the standards, recommendations and lighting design practices should be aimed at the light's influence on health (physiology) and mood (psychology).
- To improve the perception of lighting conditions, the spectral properties of the materials in the environment should accord to the colour temperature of luminaire and *vice versa*.

The main problems considering CFLs are the spectral properties – since they have line spectrum unlike sunlight or IL. LED lamps have better spectral properties, but the spectral power distribution could be a problem.

The spectral power distribution defines the colour rendering performance (or colour rendering index, CRI), which is a critical characteristic, whilst describing luminaires in general lighting applications. High CRI values (100) require a broad spectrum, covering the whole visible region of electromagnetic field spectra (Mirhosseini et al., 2009).

In addition to previous parameters, the frequency and the modulation index (MI) of the emitted light, must be considered. The variation frequency of the visible light can be one of the parameters which can lead to disturbances of human visual perception. The main cause of flickering is the voltage variation of lamps that induces changes in luminous flux and/or in illuminance. Flickering as a physical phenomenon can be registered during the working cycle of all AC powered luminaires due to the working frequency of the power grid (50 Hz in Estonia). The flickering can be altered, producing frequencies in ranges up to several kHz. The flicker with 100 Hz frequency is usually imperceptible for a human being but frequencies of 40 Hz and less inflict discomfort and health risks (Drápela & Šlezingr, 2010).

It has been observed, that in the case of a flickering luminaire, the perception of light is not in accordance with the shape of the pulsation, rather with the MI (or the percent flicker) of the luminaire. In case of sinusoidal oscillations it can be defined as correlation between the modulation amplitude and the average illuminance (or the average luminance) (Martin, 1986).

One way to determine the modulation index E_{MI} of flickering is to calculate it from the results obtained from experiments, using the formula (1):

$$E_{MI} = \frac{E_{P\max} - E_{P\min}}{E_{P\max} + E_{P\min}}, \quad (1)$$

where $E_{P\max}$ – represents the maximum illuminance of a luminaire (100%) and $E_{P\min}$ – represents the minimal illuminance; $E_{P\min}$ – can be calculated using formula (2):

$$E_{P\min} = \frac{P_{\min} \cdot 100\%}{P_{\max}}, \quad (2)$$

where $P_{\min}$ and $P_{\max}$ are the minimal and maximal power values from the oscilloscope.

The aims of the study were: 1) to investigate parameters of LED lamps; 2) to compare results obtained during the experiments with results of previous similar experiments (considering CFLs); 3) to draw conclusions concerning the hypothesis, that by replacing a 60 W IL with a LED lamp (that has been estimated to be equal to the 60 W IL by the manufacturers/vendors), the lamp that uses less electrical power is equivalent to the previously popular IL by the spectral properties as well as the produced illuminance; 4) to draw conclusions about LED lamps suitability for lighting working areas.

MATERIAL AND METHOD

Four different LED lamps (two typical LED lamps with glass cover, one LED consisting of six MCOB multi-LED chips, one lamp with 35 LED chips placed all around the surface of the lamp) and one IL were studied. Data of the lamps used has been given in table 1.

During three series of experiments several parameters were measured and analysed: I series – working temperature of luminaires [1 °C], illuminance [1 lx] and power [1 W]; II series – spectrum of light; III series – flicker produced by luminaires (according to the results obtained the frequency of the flickering and the modulation index were calculated).

The devices and computer programmes used during experiments are given in table 2.

Table 1. Lamps used in experiments

Lamp/ Type of LED	Manufacturer/ lamp series	Power, W	Power*, W	Colour tempe-rature, K	CRI	Luminous flux, lm	Dura-bility, h	Price €
1. 35LED	Set Lighting Apparatus CO AS/-	6.5	60	3,000	-	-	-	19.56
2. LED (LG)	LG Electronics / LED LAMP A19 12.8W	12.8	60	2,700	80	810	25,000	30.90
3. LED (OS-RAM)	OSRAM /Parathom ACL 60 ADV	13.0	60	2,700	90	810	25,000	38.47
4. 6MCOB	unknown/ 'A+'	7.0	60	2,700–3,500	-	560–630	> 40,000	19.91
5. IL	TUNGSRAM 60W	60.0	60	-	100	710	1,000	0.50–1.00
An idealised 'average' incandescent lamp		60.0	60	2,700	100	710	~1,000	-

*Power of an incandescent lamp that has equivalent illuminance value, according to the seller/producer of the lamp.
CRI – colour rendering index

Table 2. Devices and computer programmes used during experiments

Device	Specifications
Light meter	*Delta Ohm Photo-Radiometer* HD2302.0 (calibrated at Metrosert 31.01.2012, certificate no ATLC-12/0035);
Photodetector	*Delta Ohm LP471PHOT Probe* (corrected to wavelengths 400 nm to 1,050 nm), used together with the light meter to measure illuminance;
GLX interface	*Pasco Xplorer GLX* interface to connect a laptop (PC) and temperature sensors;
2 temperature sensors	*Pasco Fast Response Temperature Probe* PS-2135; range: -30 °C to 105 °C; accuracy: ± 0.5 °C; resolution: 0.01 °C, connected to GLX interface
Power meters	Brennenstuhl PM 230; Brennenstuhl PM 300 (for secondary control measurements if necessary);
Spectrometer	*Broad spectral range spectrometer* LR1 (factory calibrated, configuration A, range: 300 nm to 1,000 nm);
Light detector	A detector with optical fiber extension *Toshiba TCD1304AP linear array* (range 200 nm to 1,100 nm), used with the spectrometer;
Flickermeter	An experimental device created in Tallinn University of Technology, needs an oscilloscope to obtain readings;
Oscilloscope	*LeCroy Wavesurfer* 42 Xs 400 MHz *Oscilloscope;*
Computer programs	*ASEQ Spectra* – for spectral measurements *DataStudio CI-6870* – for temperature measurements;
A darkened chamber	with walls covered with dark non-reflective cloth and dimensions 24 × 22.5 × 30 cm, a E27 bulb holder attached to the middle of the floor of the chamber;
Other	A stand, a lighting fixture, a multimeter, a laptop (during flicker measurements acts as a battery for the flickermeter).

The first and the third series of experiments were held in a darkened room – illuminance 0 lx.

During the I series a luminaire was inserted into a darkened chamber. Temperature sensors were attached as follows: one to the body of the luminaire and the second to the inner wall of the chamber (about 8 cm from the lamp). The detector of the light meter was placed on a stand. The distance between the surface of the luminaire and the surface of the detector was 1 m. The power meter was attached between the wire of the bulb holder and receptacle. The temperature measurements were started before switching on the luminaire and the readings were saved to a computer continuously during the experiments. After the lamp was switched on, the indications on the light meter and the power meter were fixated, afterwards the chamber was closed. The readings on the power meter were fixated every 10 minutes. After 60 minutes of experiment the chamber was opened, the illuminance and power measured one last time. Then the temperature measurement was stopped.

While gathering information considering IL, the temperature was constantly monitored to stop the experiment at any time the temperature measured by either probe was exceeding 100 °C.

During the II series of experiments, the spectrum of light emitted by the illuminaires was investigated. As a measuring device an ASEQ spectrometer was used with an optical fiber extension. For data reading during the experiments, some information was entered to an ASEQ Spectra – exposure (40 ms), BoxCar (5), scans (3). The detector's extension was placed in front of the luminaire and pointed at it. The distance between the two was altered when the measured luminaire was changed, so the magnitudes of the intensities of the registered light would be comparable to each other. Each experiment lasted for about 5min and the lamps were not heated before measurements.

The results obtained of the first two series, were compared to results from a previous experiment on CFLs, preformed during 2009 and 2010 (the parameters of lamps investigated in previous experiments are shown in table 3).

Table 3. The results from a previous experiment on CFLs

No.	Manufacturer	Power, W	Power* W	Durability, h	Price, €	Average illuminance, lx	Luminous flux**, lm
1	Pila	11	60	3,000	2.29	118.35	580
3	Wodmeng	11	60	8,000	3.64	112.15	550
4	General Electric	11	60	6,000	4.22	92.45	600
5	OSRAM	11	60	6,000	5.05	115.15	600
7	TUNGSRAM	11	60	6,000	5.30	115.85	580
8	PHILIPS	11	60	8,000	6.84	112.4	600

*Power of an incandescent lamp that has equivalent illuminance value, according to the vendor/manufacturer of the lamp;
**Luminous flux – according to manufacturer.

During the III series of experiments the illuminaire was placed into the darkened chamber and the flickermeter's photodiode sensor directed to the illuminaire in a distance of 10 to 35 cm (for the same reasons mentioned above). The flickermeter was connected to a laptop (via USB, so the computer was used as a direct current power supply) and an oscilloscope (used to record the data and the graphs describing the flickering of the light). The flickermeter transformed the light into electrical impulses. In addition to the graphs obtained from the oscilloscope also the frequency of the flickering and the values of mean, peak-to-peak, minimum and maximum voltage were registered.

After flicker measurements, frequency was calculated from the graphs obtained from the oscilloscope.

RESULTS OF MEASUREMENTS

LED lamps create less heat and warm up slower than ILs. Comparing the LEDs and ILs heating of the surface of the lamps and heating of the environment, the results are conflicting – LEDs tend to heat the environment more than IL, but their own temperature remains at lower levels. This can be explained with the different working principles – ILs luminous power is greater the higher the temperature of the filament, LEDs emit more light the lower their own temperature is. Three LEDs out of four proved to have higher illuminance (measured in a distance equal to 1m from the surface of the lamp) values than IL or CFLs. The data obtained is shown in table 4.

Table 4. The changes in illuminance and temperature during the I series of experiments

Lamp:	P, W	Illuminance E, lx				Φ_m, lm	Temperature T, °C			
		E_0	E_{60}	ΔE	E_a		IT_0	T_{60}	ΔT	S/E
1. 35LED	6.5	39.2	37.9	1.3	38.6	-	21.0	24.4	3.4	S
							21.2	34.4	13.2	E
2. LED	12.8	262.8	215.1	47.7	239	810	21.7	27.5	5.8	S
							21.2	57.3	36.2	E
3. LED	13.0	293.6	209.4	84.2	251.5	810	21.9	28.5	6.6	S
							21.7	60.4	38.7	E
4. 6MCOB	7.0	179.6	167.7	11.9	173.7	560–630	23.0	26.2	3.2	S
							22.3	43.2	20.9	E
5. IL	60	81.7	83.1	1.41	82.4	710	23.4	100.8*	77.4	S
							22.5	38.5	16.0	E

P – Power; E_0 – illuminance in the beginning of experiment; E_{60} – illuminance in the end of the experiment; ΔE – change of illuminance during the experiment; E_a – average illuminance; Φ_m – luminous flux according to manufacturer; T_0 – temperature in the beginning of experiment; T_{60} – temperature in the end of the experiment; ΔT – change of temperature during the experiment; S/E – where the temperature measurements were taken from: S – surface of the lamp, E – environment in the darkened box.
*in case of IL the value T_{60} is actually measured only 10 minutes after the beginning of the experiment, because the experiment was discontinued after the temperature on the lamp surface exceeded 100 °C.

The LEDs proved to use more electrical power than CLFs but less than ILs. In the case of lamps number 1 and 4 extreme deviations were registered between the data provided by the manufacturers and the results of experiments considering electrical power. Results are shown in table 5.

Table 5. The changes in power during the I series of experiments (information considering IL is imperfect, since the experiment was discontinued after 10 minutes)

Lamp	P, W							P_a, W	P_m, W	ΔP, W
1. 35LED	13.90	16.24	16.24	16.24	16.24	16.24	16.31	15.92	6.5	9.42
2. LED	13.98	13.92	13.89	13.86	13.92	13.80	13.86	13.89	12.8	1.09
3. LED	16.42	13.92	13.86	13.92	13.92	14.04	14.04	14.30	13.0	1.30
4. 6MCOB	18.64	18.56	18.56	18.72	18.72	18.64	18.64	18.64	7.0	11.64
5. IL	60.06	60.32	-	-	-	-	-	60.19	60.0	0.19
T, s	0	600	1,200	1,800	2,400	3,000	3,600			

P – Power measured during experiments on different times, P_a – average power during experiments, P_m – used power according to manufacturer, ΔP – difference between P_a and P_m, T – the time when power measurements were taken.

All of the LED lamps provided spectrums that correspond with ILs full spectrums better (Fig. 1) than CFLs line spectrums do. Also the spectrums of different LED lamps are shaped quite similarly.

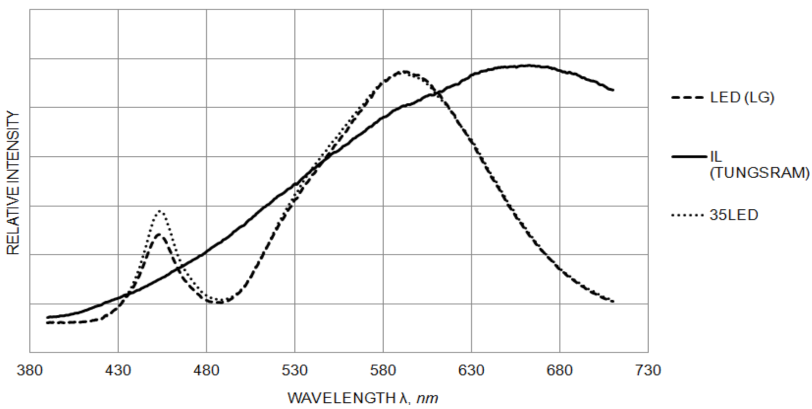

Figure 1. The spectrums of different LED lamps have quite similar shapes with one another and the spectrums of LED lamps also represent a full spectrum rather than a line spectrum.

While comparing the spectrums of LEDs and IL, some deviations can be observed considering the radiation intensities of some wavelengths. Some deficiency can be found in wavelengths from 440 nm to 540 nm. Also the wavelength of the most intensive light emitted has diminished (Table 5). The variations considering spectral properties can not be associated with neither the used power nor the price of the lamp.

The frequencies of the flicker are in a range where human perception is not able to register the variation of illuminance. LED lamps that have lower prices work on the same frequencies as IL. More expensive LEDs work on higher frequencies which should be more convenient to human perception. None of the lamps investigated achieved the MI values where a stroboscopic effect would manifest. The data considering flickering is given in table 6.

Table 6. The most intensely emitted wavelengths, flickering frequencies and modulation indexes of different lamps

Lamp:	1. 35LED	2. LED(LG)	3. LED(OSRAM)	4. 6MCOB	5. IL
The most intensely emitted wavelength λ, nm	591.50	604.97	631.11	592.64	659.97
Flickering frequency f, Hz	100	> 1,000	> 1,000	100	100
Modulation index E_{MI}, %	9	12	14	16	13

CONCLUSIONS

The objectives of the research were achieved. Results derived from the experiments indicated that investigated LEDs have better illuminance quality and their spectrums do not differ significantly from the incandescent lamps, although some deficiencies were registered. Aforementioned shortcomings most likely have no impact on people or the work efficiency, unless maximum colour rendering index (CRI = 100) is needed.

According to data obtained during the experiments (especially data on illuminance, spectrums and flicker) the lamps in question can be recommended for lighting of working areas.

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