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EVALUATION OF DISCOMFORT GLARE FROM LED LIGHTING SYSTEMS

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Abstract: *Along with concerns for energy efficiency, the increase in the efficacy of LEDs has accelerated the utilization of LED lighting systems in general lighting applications. In designing general lighting solutions with LED lighting systems, a very important aspect is visual comfort. Discomfort glare is a crucial component of visual comfort. The most widely used glare rating system is the Unified Glare Rating (UGR) system developed by the CIE The last addition to the current formulas evaluating discomfort glare have been made in 2002 and therefore do not include the novel developments in the field of lighting with the introduction of LEDs as interior lighting sources. The lighting market on the other hand is aiming at replacing incandescent lamps with LED retrofits. In this study, two important parts of the glare rating formulas, position index and apparent area are elaborated for LED light sources with non-uniform luminance distributions. For this aim, luminance measurements of an LED retrofit have been made and the results have been used for calculations and interpretations of the glare created by the light source. During the process, several important questions have been raised and the importance of further research on the subject of discomfort glare from LED lighting systems has been emphasized.*

Keywords: LEDs, discomfort glare, UGR, position index, apparent area.

1. Introduction

Lighting constitutes 19% of the World's and 14% of the European Union's total energy consumption [1]. With the 2020 energy initiative and the phase-out of incandescent lamps in Europe, energy efficient lighting technologies gained more importance. The EU has recently published the Green Paper "Lighting the Future – Accelerating the Deployment of Innovative Lighting Technologies", proposing to launch new policy initiatives in Europe on the deployment of Solid State Lighting Products [2]. Along with concerns for energy efficiency, the increase in the efficacy of LEDs has also accelerated the utilization of LED lighting systems in general lighting applications. In designing general lighting solutions with LED lighting systems, a very important aspect is visual comfort. It is crucial for the energy efficient lighting system to meet the necessary visual comfort conditions; without users being content with

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their lighting environment, the energy savings potential is of no use.

Discomfort glare is a very important component of visual comfort. CIE 117:1995 defines discomfort glare as “glare which causes discomfort without necessarily impairing the vision of objects”. The literature on glare includes different formulas and glare rating systems developed over the years with the introduction of different light sources into lighting applications. The most widely used glare rating system is the Unified Glare Rating (UGR) system developed by the CIE which combines features of the glare rating formulas of Einhorn and Hopkinson and also incorporates the Guth position index [3]. The UGR system was further developed in 2002 with CIE 147:2002, with new formulas and recommendations for the calculation of UGR for small, large and complex sources [4]. Unfortunately, this was the latest development on the UGR formula and therefore the current formulas do not include the novel developments in the field of lighting with the introduction of LEDs as interior lighting sources.

As been stated in the work of CIE TC 3-50 Lighting Quality Measures for Interior Lighting with LED Lighting Systems, for luminaires in which the LED distribution is clearly visible as in LED arrays or systems with optics, the small sized light sources with high brightness appear to be causing more glare than traditional light sources, making the utilization of the current UGR formulas inconvenient [5]. In this study, two important parts of the glare rating formulas, the position index and the apparent area are elaborated for LED light sources with non-uniform luminance distributions and the importance of further research on the subject for LED lighting systems is emphasized.

2. Unified glare rating

The CIE Unified Glare Rating (UGR) formula is given by:

$$UGR = 8log\left[\frac{0,25}{L_b}\sum\frac{L^2\omega}{p^2}\right] \quad (1)$$

and the UGR formula for small sources are given by:

$$UGR = 8log\left[\frac{0,25}{L_b}\sum 200\frac{I^2}{r^2p^2}\right] \quad (2)$$

where L_b is the background luminance in cd/m^2, L is the luminance of the luminous parts of each luminaire in the direction of the observer’s eye in cd/m^2, ω is the solid angle of the luminous parts of each luminaire at the observer’s eye in sr and p is the Guth position index for each luminaire, I is the luminous intensity toward the eye in cd, and r the distance between the observer’s eye and the light source in m.

The UGR formula for small sources, which is the category that includes the majority of LED lamps has been developed on the grounds that the original UGR formula produced results that would be deemed as ‘intolerable’ by the users even though the glare they caused was “somewhat tolerable”. Originating from this argument, the CIE report 147:2002 Glare from small, large and complex sources sets the size of a small source with a projected area A_p<0,005 m^2 (corresponding to a disk of 80 mm in diameter) equal to 0,005 m^2 and calculates the luminance of the source as:

$$L = \frac{I}{A_p} = 200 \cdot I \quad (3)$$

Looking at the size and the luminous intensity distributions of LED lighting systems, it appears that this addition to the UGR formula for small sources could be applicable. However, the UGR formula for small sources comes from the research of Paul et al., a study in which the glare source was a 200 W incandescent lamp [6]. Whether this research would apply for the LED lighting systems is a question mark.

3. Position index

Position index is defined as the change in discomfort glare experienced relative to the angular displacement of the source from the observer's line of sight [7]. An early study from 1925 by Luckiesh and Holladay showed that the glare sensation was changing in relation to the position of the light source in the visual field [8]. Luckiesh and Guth went further with this study in 1949 and created what they called the BCD criterion – the sensation at the borderline between comfort and discomfort. In their study, an extended visual field of uniform brightness and sources of circular geometry, uniform luminance distribution and constant spectrum were used. The subjects were initially asked to set the luminance of a test source directly in the middle of their field of view to a value that they found at the border of comfort and discomfort. From these luminance values, an average luminance value was calculated and this value was deemed as the BCD luminance. Using this luminance value, the BCD luminances of the sources as they were displaced at various angular distances from the line of vision were determined. The relationship between the obtained values was named as the position index [9]. In 2007, the study of Luckiesh and Guth was repeated by Kim et al. with similar conditions plus an addition of the lower visual field. The study showed a similar value for the BCD sensation but the position index values obtained from the study were smaller compared to Guth's position index [10].

In both of the aforementioned studies, the BCD luminance and the position index were determined using sources with uniform luminance distributions, a set circular geometry and a constant spectrum. When it comes to using LEDs as interior lighting elements, this is not the case. The biggest part of the LED market is aiming at replacing incandescent lamps with LED retrofits by bringing together a number of power LEDs to match the luminous flux of existing light sources and fitting these into the most suitable design that would allow for the suitable luminous distribution and correct thermal management. Other concerns include resemblance to current sources and a perfect fit for the existing electrical connections. In order to satisfy all these needs, power LEDs with very small sizes and very high luminances are arranged in different configurations, with or without optical systems, most of the time creating non uniform luminance distributions. Examples of luminance photos from two LED retrofits can be seen in Figure 1.

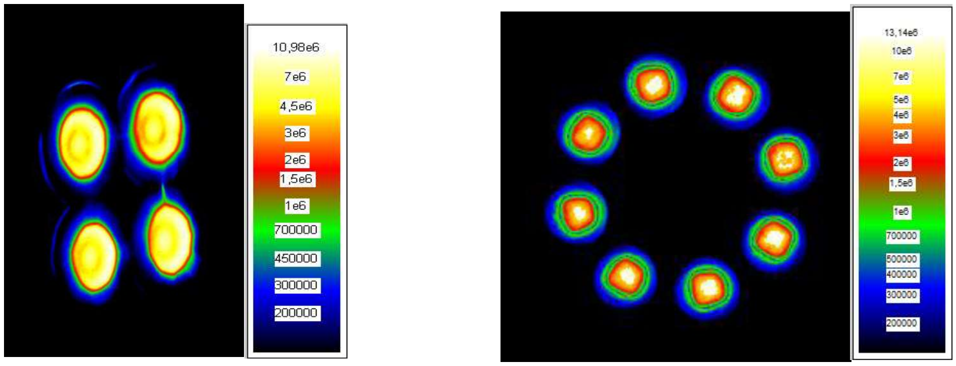


Figure 1 Examples of luminance distributions from LED retrofits systems

A study by Takahashi et al., examining the position index for a matrix light source where the luminance distribution is non-uniform, provided the results that for central vision, the matrix light source caused more discomfort glare than the uniform light source while the discomfort ratings for peripheral vision were similar from the non-uniform to the uniform source [11]. The study by Waters et al. examining non-uniform sources of luminance on the other hand showed again more glare in the central vision but less glare in the peripheral vision from the uniform source to the non-uniform source. The results of these two studies are contradictory for the peripheral vision, which constitutes an important part of the glare calculations considering interior lighting distances [12]. These issues rise the question of whether it is correct to use the position index of 1949 in the glare calculations made with the technology of today. It is important to emphasize at this point that further research on the position index should be made in order to ensure the correct utilization of UGR formulas for the prediction of glare from LED lighting systems.

4. Apparent area and the estimation of luminance

As been previously discussed, in calculating the UGR value from a light source, the background luminance, the source luminance, the solid angle and the position index are taken into consideration. The luminaire luminance, L, is generally derived from dividing the luminous intensity of the luminaire in the direction of the observer, I, to the projected area of the luminaire, A_p, as been given in formula (3).

The calculation of the luminance value in such a fashion induces the utilization of an average luminance value in the calculation of the glare rating index. For light sources with LEDs, due to the high luminances of the LED light source itself, taking the average luminance value into consideration constitutes a problem. While a retrofit which looks like an opal incandescent lamp, hiding the LEDs inside diffusing cover may have a uniform luminance distribution, the same is not true for systems in which the LEDs and the optics are visible. Going back to the luminance distributions given in Figure 1, it is possible to see the extent to which the non-uniformity can reach for systems with power

LEDs. For the first luminance photo, the maximum luminance value reaches $11.0 \cdot 10^6$ cd/m^2, creating four extremely bright spots in the users' field of view. Similarly, the maximum luminance value for the second LED system reaches $13.2 \cdot 10^6$ cd/m^2, this time creating eight bright spots in the field of view. One question that comes into mind is whether it is a correct approach to take the corresponding intensity value from the luminous intensity distribution and divide it into the apparent area or whether these bright spots should be evaluated as single light sources in the calculation of glare rather than taking the whole system as a single light source.

In calculating the glare from LED lighting systems, the shape and configuration of the light source creates a challenge as well. Due to thermal and optical concerns, the designs of these sources are diversified. This diversity in design makes it difficult to estimate an apparent area in the calculation of luminance from luminous intensity measurements. In order to communicate this difficulty of estimation of luminance for different viewing angles, luminance photos have been made for an LED retrofit, as the biggest part of the LED market is aiming at replacing incandescent lamps with LED retrofits. A photo of the chosen retrofit has been given in Figure2.

Figure 2 The retrofit

As can be seen from the photo, the light source includes four power LEDs, which have been embedded in the heat sink and covered by an optical system of diameter 12.5 mm. The diffusing glass has a diameter of 38.3 mm in total and the diameter of the retrofit is 60 mm. To enable efficient air movement, the heat sink has been equipped with air channels at the sides. The retrofit has been photographed using the Techno Team LMK 98-3 luminance camera from the front, at 45 degrees and from the side. The luminance photos and their legend in cd/m^2 have been given in Figure 3.

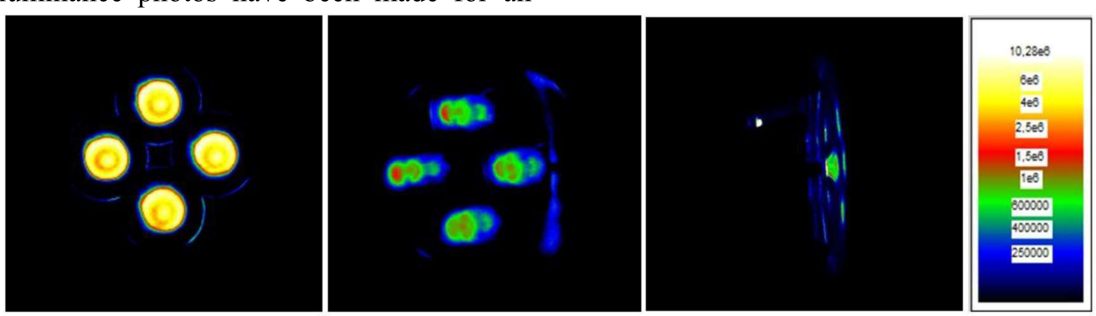


Figure 3 Luminance distributions of the Retrofit from the front, 45 degrees and from the side [cd/m^2]

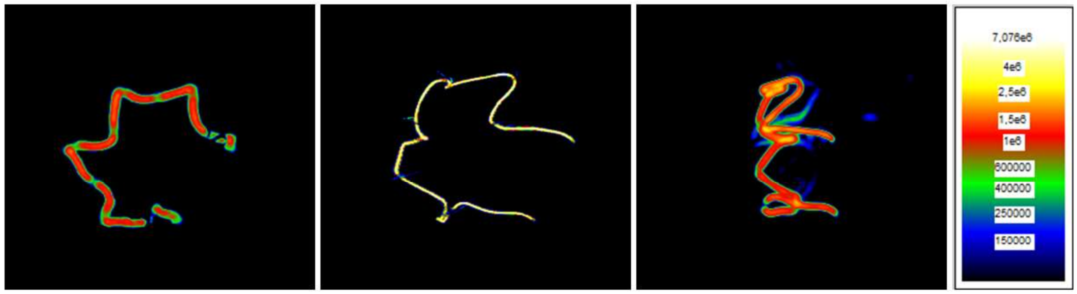


Figure 4 Luminance distributions of a 200 W incandescent lamp viewed from the front, from 45 degrees and from the side [cd/m^2]

The legend for the photo of the side view is reduced to 10^{-2} of the legend for the photos from the front and from 45 degrees.

While the luminance photo from the front reveals all the LEDs in their full brightness, the situation is different for other angles of view. Due to the shape of the heat sink, the luminance photo for 45 degrees includes reflections from the inner sides of the sink itself. The photo for the side view of the retrofit shows light coming out of one of the air channels of the heat sink on the upper side. The special form and configuration of the source creates an important challenge for the estimation of apparent area. The maximum and average luminance values in cd/m^2 obtained with the luminance camera have been given in Table 1. The average values have been computed only using the full area that includes the four LEDs and this area has been referred to as the surrounding area. The measurement results show that the maximum luminance value starts at $10.28 \cdot 10^6$ cd/m^2, a very high value attributable to the direct facing of the power LEDs; drops down to $1.97 \cdot 10^6$ cd/m^2 for 45 degrees and $0.23 \cdot 10^6$ cd/m^2 for the side view. If the average values for these luminance distributions are calculated, the values drop down to $0.99 \cdot 10^6$ cd/m^2, $0.10 \cdot 10^6$ cd/m^2 and $0.008 \cdot 10^6$ cd/m^2 respectively. There are two question marks at this point.

- Are the average values the correct values to use in the calculation of the glare index?
- Which area should be used in the computation of luminance from the luminous intensity distribution?

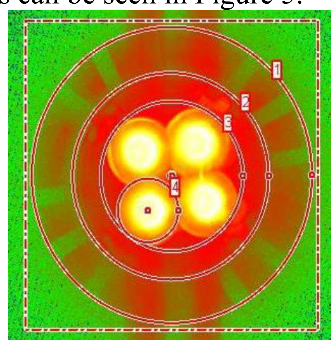
Another important question is which UGR formula is to be used for the calculation. As the size of the retrofit falls into the category of "small", is the apparent area accepted as 0.005 m^2 and the glare

Table 1. Maximum and average luminance values for the retrofit and the incandescent lamp according to orientation of view

Light Source		Front	At 45 degrees	Side
Retrofit	L_{max} / 10^6 cd/m²	10.28	1.97	0.23
	L_{avg} / 10^6 cd/m²	0.99	0.10	0.008
Incandescent lamp	L_{max} / 10^6 cd/m²	1.69	7.08	2.70
	L_{avg} / 10^6 cd/m²	0.14	0.21	0.29

rating calculated using the small UGR formula? It must be kept in mind that the small Glare Formula was produced through an experiment using a 200 W incandescent lamp. With a clear incandescent lamp, the tungsten wire is exposed to the eye in all viewing angles, while this is not the case with most of the novel LED retrofits surrounded by optics and heat sinks. Figure 4 shows the luminance distributions of a 200 W incandescent lamp photographed from the front (the bottom of the lamp), from 45 degrees and from the side. It is possible to see from the photos that in all viewing angles, the maximum luminance value is in the range of 10^6 due to its special form with the tungsten wire in the middle of the glass cover. Looking back at Figure 3, it can be seen that the LED retrofit has a totally different luminance distribution than the incandescent lamp, once again raising the question of whether the formula created by the research of Paul et. al. is convenient for LED light sources as well. To see the UGR rating produced by the light source at hand and to analyze the different results that can be obtained by changing the apparent area taken into consideration, an exemplary calculation similar to the conditions given in CIE 147:2002 for small light sources has been repeated. The report gives a numerical example, calculating the glare created by a 15 W bare incandescent lamp, placed two *m* above and four *m* away from the subject's eye, with a background luminance of 30 cd/m^2. The intensity is taken as 160 cd with the filament luminance $4 \cdot 10^6$ cd/m^2, making the projected area $4 \cdot 10^{-5}$ m². In such an example, the original formula results in a UGR rating of 39, while the small formula predicts a UGR of 22, where the difference between the two values are drastically.

To provide a better understanding of the questions that have been raised in the paper, this calculation has been repeated using the values from the chosen LED retrofit instead of the 15 W incandescent lamp. For the calculation with the original UGR formula, three different apparent areas have been selected. These areas have been defined as the emitting area of one LED with its optics, the surrounding area of all four LEDs with optics, and the whole retrofit. The defined areas can be seen in Figure 5.



1 – Whole Retrofit; 3 – Surrounding Area; 4 – Emitting Area

Figure 5 Areas used in the calculation

The position in the example calculation corresponds to the luminous intensity value at 26.5 of 110 cd. The results have been given in Table 2. It can be seen that the numerical values of UGR are showing important differences when the apparent areas are changing. In order to emphasize the importance of these results, the UGR values have been further expressed as subjective evaluations, with the assumption that the retrofit is being analyzed for the interior lighting of an office room. *EN 12464-1:2011 Light and lighting - Lighting of work places - Part 1: Indoor work places* defines the maximum UGR value for writing, typing, reading and data processing in an office as 19 [13].

Looking at the values obtained by using the whole retrofit, which includes the LEDs as well as the heat sink and the optics, the subjective evaluation would be comfortable, as the UGR value is below the maximum value in the standard. If the surrounding area of the LEDs is taken into consideration, the UGR value rises up to 23, exceeding the maximum value for offices, making it uncomfortable for the office user. Finally, when only the emitting area is used for the calculation and the four LEDs are considered as four separate light sources, the UGR value rises up to 25, creating a very uncomfortable situation for the office user. When the UGR formula for small sources is used on the other hand, the UGR values become 17, 17 and 21, corresponding to the subjective evaluations of comfortable, comfortable and uncomfortable for the respective areas.

Table 2. Calculation of luminance from apparent area and luminous intensity

Part	Whole Retrofit	Surrounding Area	Emitting Area
d **[mm]**	60	27.9	4x 12.5
Area **[m²]**	28.2×10^{-4}	6.11×10^{-4}	4.91×10^{-4}
I_0 **[cd]**	833	833	833
$L_{0\ calculated}$ **[cd/m²]**	0.30×10^{6}	1.36×10^{6}	1.70×10^{6}
$L_{0\ measured}$ **[cd/m²]**	0.29×10^{6}	1.13×10^{6}	1.46×10^{6}
I_{26° **[cd]**	110	110	110
L_{26° **[cd/m²]**	0.04×10^{6}	0.18×10^{6}	0.23×10^{6}
UGR*	17	23	25
ie. Office Lighting**	Comfortable	Uncomfortable	Very Uncomfortable
UGR_{small}	17	17	21
ie. Office Lighting**	Comfortable	Comfortable	Uncomfortable

**UGR* values calculated assuming the apparent area changes according to the cosine law

**According to EN 12464-1:2011 Light and lighting - Lighting of work places - Part 1: Indoor work places

With the results of this calculation, it is possible to say that the uncertainty in defining the apparent area creates an important uncertainty in the UGR results as well. Is the light source in hand adequate for a glare free environment? Unfortunately the answer is not certain. Keeping this difficulty in mind, the reader is invited to go back to Figure 1 and reflect on the estimation of the apparent area for the LED retrofit with eight LEDs, positioned in a circular configuration, with a big area of very low luminance in the middle. How is the apparent area and therefore the average luminance computed in this case?

5. Further discussion and conclusion

To conclude, it is a question mark whether the available glare rating formulas are suitable for the novel light sources using LED technologies. The position index calculated in 1949 with sources of uniform luminance distributions, a set circular geometry and a constant spectrum appears to be inconvenient for today's technology with

LED lighting systems having a wide variety of luminance distributions. Later studies on the position index have provided contradictory results and there is no study conducted using actual LEDs. In addition to the position index, the shape of the novel light sources, along with their configuration makes the calculation of luminance from the luminous intensity distribution and apparent area very difficult. It is not easy to define the apparent area for the majority of LED light sources, especially with those which have complex heat sink designs and embedded optics. The fact that the current LED products in the market are evaluated according to the available UGR formulas is a major problem for the end user. While an LED product with non-uniform luminance distribution may prove to be "glare-free" according to the current formulations, the user who eagerly purchases the product despite its high price, thinking that it's energy efficient and environmentally friendly, may take it home and end up resenting the product because at the end it may not be "glare-free" at all. It is important to mention that the lighting simulation programs are also dependent upon the current formulations and may be producing faulty results for the calculations including LED lighting systems. This turns the trustworthiness of the calculations into a big question mark. With the information in hand, it is not certain that the current glare rating formulas can be used with LED lighting systems and further research into this field is extremely necessary.

References

1 CELMA, *Guide on the Importance of Lighting*, 1st Edition, July 2011, Belgium.

2 European Comission, *Green Paper: Lighting the Future – Accelerating the Deployment of Innovative Lighting Technologies*, Brussels, December 2011.

3 CIE 117:1995, *Discomfort Glare in Interior Lighting*, Vienna, 1995

4 CIE 147:2002, *CIE Collection on Glare, Glare from small, large and complex sources*, Vienna, 2002

5Knoop, M., *Lighting Quality Measures for Interior Lighting with LED Lighting Systems*, CIE 27th Session Proceedings, pp.219-225, July 2011, Sun City, South Africa.

6 Paul, B.M., Einhorn, H.D., *Discomfort glare from small light sources*, Lighting Research and Technology 31(4) 139-144, 1999.

7 Wienold, J., Christoffersen, J., *Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras*, Energy& Buildings, 2006, 38, pp. 743–757.

8 Luckiesh, M., Holladay, L.L., *Glare and visibility*, Trans. Illumin. Eng. Soc., 20 (3) 1925, pp. 221–252.

9 Luckiesh, M., Guth, S. K., *Brightness in visual field at borderline between comfort and discomfort (BCD),* Illum. Eng. 1949, 44, 650-670.

10 Kim, W., Han, H., Kim, J. T., *The position index of a glare source at the borderline between comfort and discomfort (BCD) in the whole visual field*, Building and Environment 44 (2009), pp. 1017-1023.

11 Takahashi, H., Kobayashi, Y., Onda, S., Irikura, T., *Position index for the matrix*

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light source, J. Light & Vis. Env., 2007, 31(3):10-15.

12 Waters, C. E., Mistrick, R. G., Bernecker, C. A., *Discomfort glare from sources of non-uniform luminance*, Journal of the Illuminating Engineering Society, 1995. 24(2):73.

13 EN 12464-1:2011 *Light and lighting - Lighting of work places - Part 1: Indoor work places*, 2011.

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