Int. J. Metrol. Qual. Eng. 7, 407 (2016)
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DOI: 10.1051/ijmqe/2016025

Available online at:
www.metrology-journal.org

Illuminance and ultra violet emissions radiated from white compact fluorescent lamps

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Received: 30 May 2016 / Accepted: 7 November 2016

Abstract. During recent years, white compact fluorescent lamps (WCFLs) have played a key role in energy efficient campaigns worldwide. As the use of WCFLs becomes increasingly widespread so also increases the concerns relating to their mercury content and the associated hazards. While the risk associated with individual WCFLs is generally concerned negligible, the cumulative impact of millions of WCFLs does however becomes a more significant issue and could represent a potential risk to the environment. The present study aimed to focus on the most useable lamps in the Egyptian markets; white compact fluorescent lamps (WCFLs) and to evaluate relationships between UV emissions radiated and illuminance compact fluorescent lamps (WCFLs). Various parameters such as ultra violet irradiance (UVA), ratio of UVA irradiance to electrical power (η) and ratio of UVA power to luminous flux (K), for two groups of CFLs are studied to dedicate their performance. A set up based on NIS-Spectroradiometer ocean optics HR 2000 has been used for measuring the spectral power distribution white WCFLs with different Egyptian market. Second set up for NIS-UVA silicon detector for absolute irradiance measurements and relative spectral power distribution based on Spectroradiometer are used. The absolute irradiance in W/m^2 in UVA region of the lamps and their accompanied standard uncertainty are evaluated. Third set up based on NIS Luxmeter are used for measuring illuminance for these lamps. For all two groups under study, K parameter remains less than the safe limit for human health. Elios 32 watt WCFLs have smaller ratio (η) than Tiger 26 watt WCFLs. So, we recommended using Elios 32 watt WCFLs than Tiger 26 watt WCFLs at short distance in table lamps or other application and the distance more than 0.5 m. Uncertainty model includes all parameters accompanied with the measurements are calculated.

Keywords: white compact fluorescent lamps / illuminance / UVA radiation / irradiance / uncertainty

1 Introduction

The easiest method to achieve energy efficiency is to replace incandescent lamps with compact fluorescent lamps (CFLs) which are three to six times more efficient. Lighting is responsible for 19% of the electricity consumption [1]. Egypt, Saudi Arabia, Turkey and Iran are the largest consumers of electricity in Middle East. These four countries consume about 88% of the region's total electricity consumption, who have a very aggressive current program to promote CFLs [1,2]. One of the most important technologies in this century is energy saving that is an important item among the concept of environmental protection, economy, and improved science and technology [3]. There are various energy-saving products and compact fluorescent lamp (CFLs) is one of these products (Fig. 1).

Lighting energy can be saved in many ways, including improving the efficiency of the light source, improving the efficiency of the specific component of lighting system, typically the ballast and, improving the efficiency of the luminaries [4]. Replacing incandescent lamps with CFLs which have played an important role in both industrial and domestic lighting is one of the most obvious and easiest methods to achieve energy efficiency [5]. Replacing technology can occur at a very low cost and provide immediate results [1]. CFLs have many disadvantages. One of these emits higher acceptable levels of ultraviolet (UV) radiation [6]. Fluorescent light bulbs contain mercury, and the inside of the tube is coated with phosphors; the mercury gas inside the tube becomes excited when the electric current is switched on which emits UV radiation. This UV radiation then interacts with the chemicals on the inside of the bulb to generate light. Ideally, conversion of UV to visible light should be 100%; however, due to the defect in phosphor it contains trace amount of UV radiation [7–12]. To emphasis on use of energy saver CFLs, it is necessary to analyze the effect of radiation especially UV radiation on human health. UV radiation is based on its effect on living tissue, and the wavelength is divided into three major groups: UVA (320–400 nm), UVB (290–320), and UVC (200–290) [13,14]. Light output in the CFLs is influenced by the mercury vapor pressure inside the lamp; if the pressure is either greater than or less than optimal, light

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Fig. 1. Compact fluorescent lamps.

output declines, and change in contain mercury vapor can change light output [15]. As change in the containing mercury vapor can change light output and UV irradiance; the present study aimed to evaluate relationships between UV emissions radiated and illuminance from compact fluorescent lamps.

1.1 Theoretical principles of UVA irradiance

Spectral irradiance in UVA region is defined as the power of electromagnetic radiation per unit area in $W/m^2/nm$ hence,

$$\text{UVA irradiance}\, I_\lambda(\lambda) = \int_{\lambda_1}^{\lambda_2} I(\lambda) d\lambda, \quad (1)$$

where, $I_\lambda(\lambda)$ is spectral irradiance in $W/m^2/nm$. On the other hand, spectral power distribution (SPD) measurement describes the power per unit area per unit wavelength of an illumination. More specifically, the concentration is a function of wavelength to any radiometric quantity or photometric quantity [16].

UVA irradiance per unit electrical power is defined as [17]

$$\eta = \frac{\int_{\lambda_1}^{\lambda_2} E_\lambda(\lambda) d\lambda}{P}. \quad (2)$$

Ultraviolet radiation power per unit lumen output is defined as [17]

$$K = \frac{\int_{\lambda_1}^{\lambda_2} E_\lambda(\lambda) d\lambda}{k_m \int_{380\text{nm}}^{780\text{nm}} E_\lambda(\lambda) d\lambda V d\lambda}, \quad (3)$$

- $E_\lambda(\lambda)$ is spectral distribution of the radiant flux (W/nm);
- $V(\lambda)$ is spectral luminous efficiency;
- K_m is photometric radiation equivalent (683 lm/W).

From equation (1) K is also defined as:

$$K = \frac{\int_{\lambda_1}^{\lambda_2} I_\lambda(\lambda) d\lambda}{k_m \int_{380\text{nm}}^{780\text{nm}} I_\lambda(\lambda) d\lambda V d\lambda}. \quad (4)$$

UV radiation in the output light of WCFLs has to be analyzed for its safe use, especially for indoor lighting, where the distance between the lamp and human being is small. One of the important parameters for analyzing the effect of CFLs on human health is UV irradiance (UV power per unit area), which depends on the distance between the source and area of exposure [17].

UV light has three wavelength regions UVA (315–400 nm), UVB (280–315 nm) and UVC (200–280 nm). Glass stop the UVB and UVC, while transpire portion of UVA [17–19]. In the present research, measurements of the spectral power distribution, absolute irradiance and illuminance to determine various parameters such as ultra violet irradiance (UVA), ratio of UVA irradiance to electrical power (η) and ratio of UVA power to luminous flux (K), for two groups of CFLs are studied to dedicate their performance and accompanied standard uncertainties are evaluated. UVA portion will be only concerned and the ratio of UV power to luminous flux is considered to be equal to the ratio of UV irradiance to illuminance [12,17].

2 Experimental set up and methods

In the present research, the study of two groups of three white compact fluorescent lamps the most usable in Egyptian market, one group is Elios 32 Watt (NIS-CFL-1, NIS-CFL-2 and NIS-CFL-3) and the second group is Tiger 26 Watt (NIS-CFL-4, NIS-CFL-5 and NIS-CFL-6). Different parameters such as ultra violet irradiance (UVA), ratio of UVA irradiance to electrical power (η), ratio of UVA power to luminous flux (K) and relative spectral power distribution), for two groups of CFLs are studied to dedicate their performance.

2.1 Measurement set up of the spectral power distribution of the lamps

The set up of measuring the spectral power distribution of the compact fluorescent lamps CFL is shown in Figure 2.

It measured directly using the photometric bench and spectroradiometer ocean optics HR 2000 at National Institute of Standards (NIS) with uncertainty 4.7% [20] with appropriate input optics is used to evaluate the spectral power distribution. Light to be measured is guided into entrance port of spectroradiometer through an optical fiber and the spectrum is output through the USB port to a PC for a data acquisition. An optical fiber that guides light input from compact fluorescent lamps allows a flexible measurements setup. Measurements were performed in a conditioned dark room and maintaining the temperature at $25 \pm 2\,°C$.

2.2 Measurement set up of the absolute spectral irradiance in UVA range

The absolute spectral irradiance level of each lamp in the UVA range at 0.5 m is measured using a NIS calibrated radiometer model 268 UVA from UDT Company shown in Figure 3. Measurements were performed in a conditioned dark room and maintaining the temperature at $25 \pm 2\,°C$.

The UVA detector was mounted on a translation stage and positioned at the same height as the light source (compact fluorescent lamp CFL) on the optical bench. Prior taking measurements, each compact fluorescent lamp

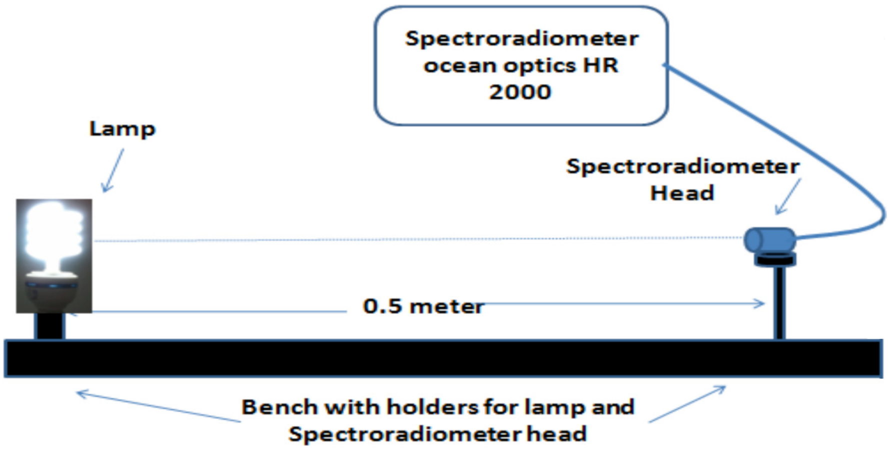

Fig. 2. Schematic diagram of NIS facility for measuring spectral power distribution.

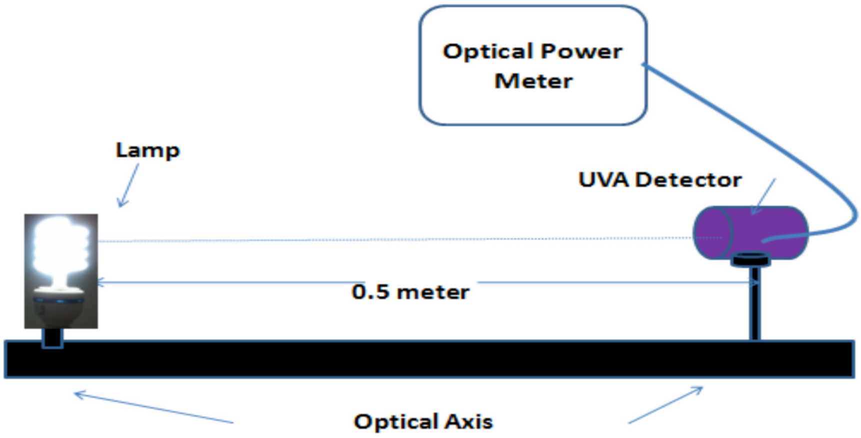

Fig. 3. Schematic diagram of NIS facility for measuring UVA irradiance using calibrated radiometer.

CFL was warmed up to 30 min. Measurements were repeated for each lamp and were finally averaged out. Finally, the uncertainty in irradiance measurements is calculated.

2.3 Measurement set up of the illuminance

The illuminance of each lamp is measured using a NIS calibrated Luxmeter LMT U1000 as shown in Figure 4.

Measurements were performed in a conditioned dark room and maintaining the temperature at 25 ± 2 °C. The Luxmeter was mounted on a translation stage and positioned at the same height as the light source (compact fluorescent lamp CFL) on the optical bench. Prior to taking measurements, each compact fluorescent lamp CFL was warmed up to 30 min. Measurements were repeated for each lamp and were finally averaged out. Finally, the uncertainty in irradiance measurements is calculated.

3 Results

Two different Egyptian brand groups of CFLs commonly used in Egyptian market in indoor lighting from Elios 32 Watt (NIS-CFL-1, NIS-CFL-2 and NIS-CFL-3) and Tiger 26 Watt (NIS-CFL-4, NIS-CFL-5 and NIS-CFL-6) are studied to assess their unwanted output in the UVA region, their Illuminance level and their spectral power distribution. These lamps are designed to emit their power in the visible region. In fact, they emit almost of their energy in the visible region but part of their energy is emitted in the UV region.

3.1 The relative spectral power distribution

The relative spectral power distribution was normalized for each compact fluorescent lamp so we can compare the lamps as shown in Figure 5. It is found that each group of the lamps has its own characteristics, and they emit most of their spectrums in the visible region with different spectral distributions for each of the two groups.

3.2 The UVA irradiance

UVA irradiance was measured absolutely at 0.5 m distance for the two groups of white CFLs of different wattage (32 W and 26 W) and the quantities presented in Figure 6. The irradiance level of each lamp measured at 0.5 m from its central vertical axis using NIS calibrated UVA radiometer. At this distance UVB and UVC irradiance could not be

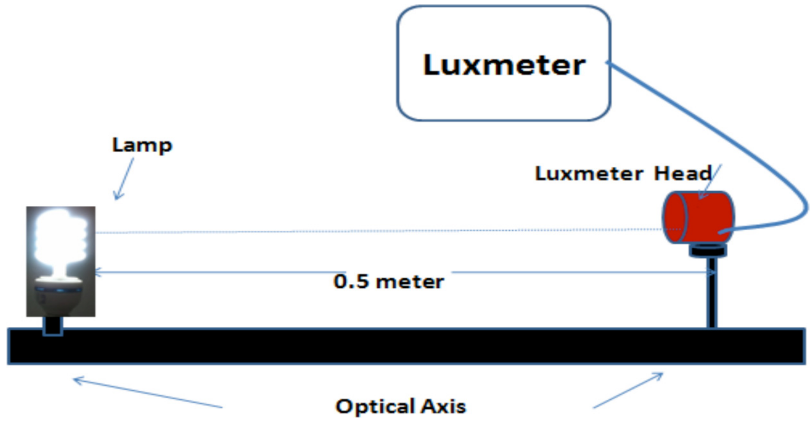

Fig. 4. Schematic diagram of NIS facility for measuring illuminance for CFLs.

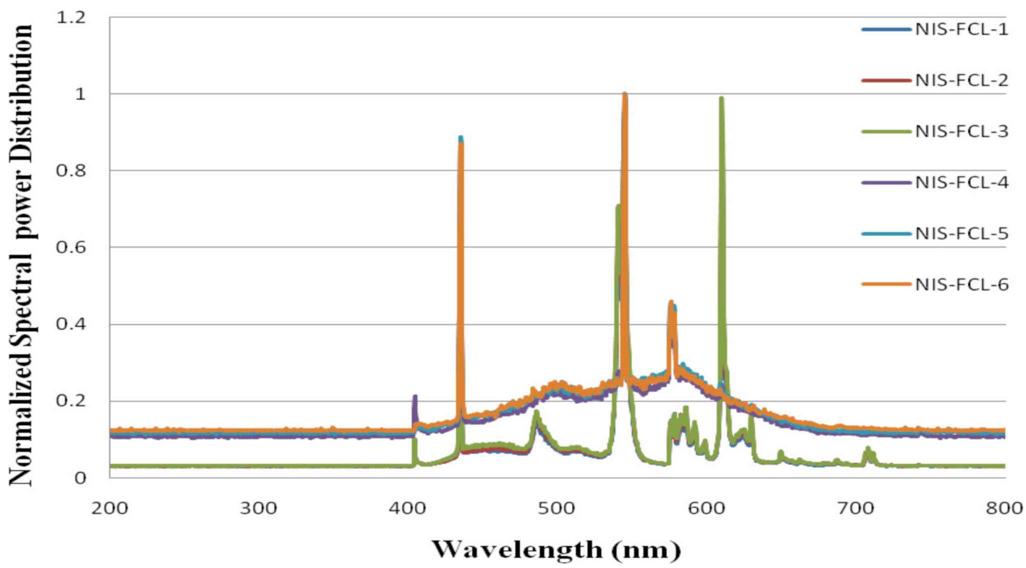

Fig. 5. Normalized spectral power distribution of six white compact fluorescent lamps.

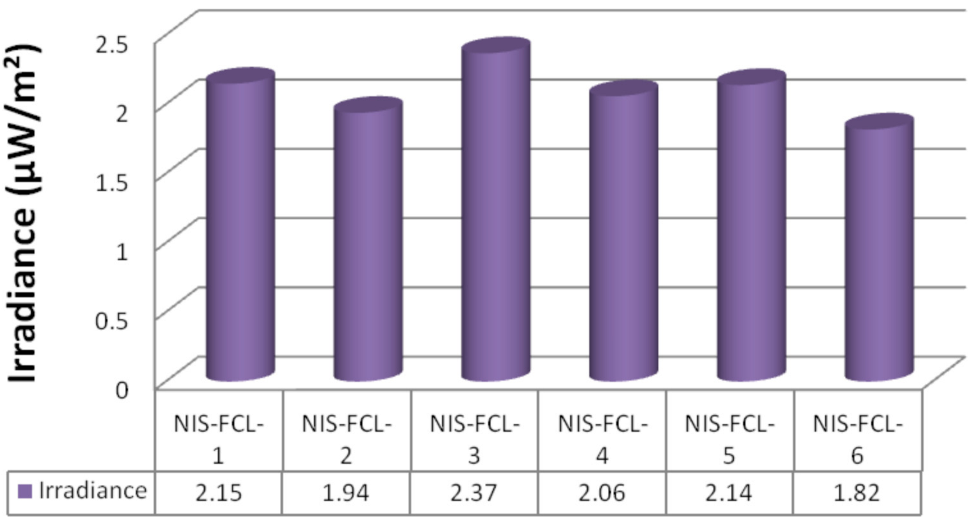

Fig. 6. UVA absolute irradiance levels using NIS calibrated UVA radiometer at 0.5 m.

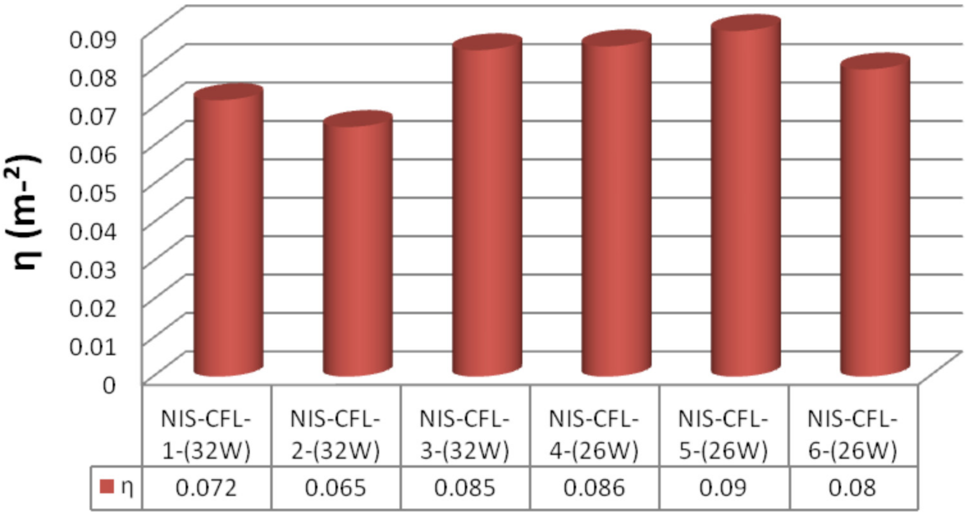

Fig. 7. UVA absolute irradiance levels per to electrical power of CFLs (η).

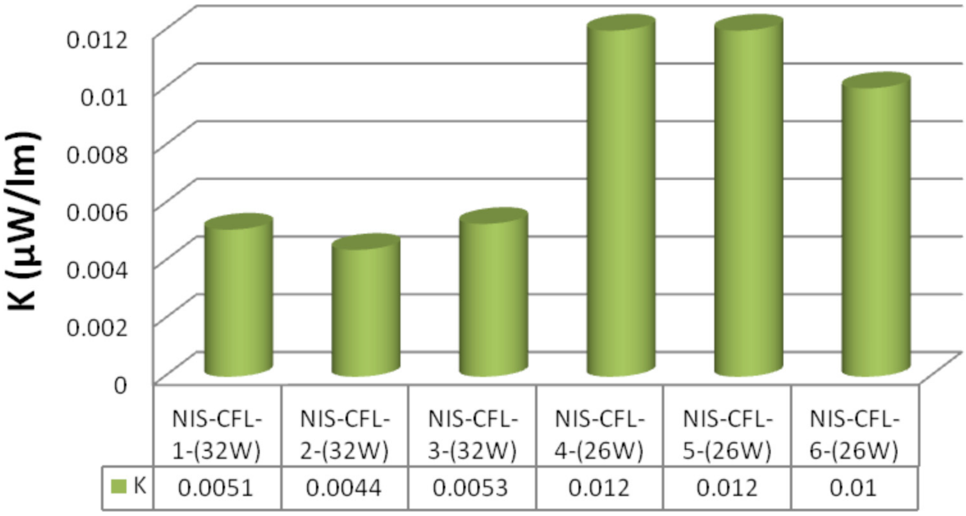

Fig. 8. UVA absolute irradiance levels per illuminance values (K) for white CFLs using NIS calibrated UVA radiometer and NIS calibrated luxmeter at 0.5 m.

detected. Figure 6 shows the comparison of UVA irradiance values at 0.5 m distance to the white CFLs at different wattage.

3.3 The ratio of UVA irradiance to electrical power (η)

Figure 7 shows the histogram for comparison of η values to the white CFLs at different wattage.

3.4 The ratio of UVA power to luminous flux (K)

The amount of illuminance for CFLs is measured at distance 0.5 m and the quantities presented in Figure 8 as ratio K which is UVA absolute irradiance levels per illuminance values for CFLs.

4 Discussion

A set up based on NIS Spectroradiometer ocean optics HR 2000 and the photometric bench, UVA standard NIS radiometer and NIS calibrated Luxmeter for relative spectral power distribution, absolute irradiance measurements and illuminance measurements are used, respectively. Two different Egyptian brand groups of CFLs commonly used in Egyptian market in indoor lighting from Elios 32 Watt (NIS-CFL-1, NIS-CFL-2 and NIS-CFL-3) and Tiger 26 Watt (NIS-CFL-4, NIS-CFL-5 and NIS-CFL-6) are studied to assess their unwanted output in the UVA region, their Illuminance level and their spectral power distribution. The absolute irradiance measurements at 0.5 m in W/m^2 in UVA region from each lamp are obtained, using UVA standard NIS radiometer with maximum responsivity at 365 nm.

Figure 5 shows the spectral power distribution for Elios 32 Watt (NIS-CFL-1, NIS-CFL-2 and NIS-CFL-3) and Tiger 26 Watt (NIS-CFL-4, NIS-CFL-5 and NIS-CFL-6). It is found that each group of the lamps has its own characteristics, and they emit most of their spectrums in the visible region with different spectral distributions for each of the two groups.

Figure 6 shows the histogram for comparison of UVA irradiance values at 0.5 m distance to the white CFLs at different wattage (32 W and 26 W). As is obvious [17], UVA irradiance increases with increase in lamp electrical wattages. The UVA irradiance for Elios 32 Watt (NIS-CFL-1, NIS-CFL-2 and NIS-CFL-3) varies from 1.94 μW/m^2 to 2.15 μW/m^2 and Tiger 26 Watt (NIS-CFL-4, NIS-CFL-5 and NIS-CFL-6) varies from 1.82 μW/m^2 to 2.14 μW/m^2.

To make a better comparison in UV concentration, it would be more appropriate to analyze UVA irradiance per electrical wattages (η). In general [17], the value of η should remain invariant, provided the phosphor and the mercury content used in CFLs are in the same proportion. Also, large variation may due to non-uniformity in coating of phosphor. Smaller value of η is safe for human being. Figure 7 shows the histogram for comparison of UVA absolute irradiance levels per to electrical power of CFLs (η) of white CFLs at different wattage (32 W and 26 W). The values of η for Elios 32 Watt (NIS-CFL-1, NIS-CFL-2 and NIS-CFL-3) varies from 0.065 m^{-2} to 0.085 m^{-2} and Tiger 26 Watt (NIS-CFL-4, NIS-CFL-5 and NIS-CFL-6) varies from 0.08 m^{-2} to 0.09 m^{-2}.

UVA irradiance to illuminance ratio (K), is of more interest for analyzing the white CFLs radiation characteristics. Figure 8 shows the histogram for comparison of UVA absolute irradiance levels per illuminance values (K) for white CFLs at 0.5 m at different wattage (32 W and 26 W). The values of K for Elios 32 Watt (NIS-CFL-1, NIS-CFL-2 and NIS-CFL-3) varies from 0.0044 μW/lm to 0.0053 μW/lm and Tiger 26 Watt (NIS-CFL-4, NIS-CFL-5 and NIS-CFL-6) varies from 0.01 μW/lm to 0.012 μW/lm. The maximum detected value 0.012 μW/lm is less than the safe limit for human health [17].

5 Uncertainty analysis

Evaluation of the uncertainty is done by the Guide to the expression of uncertainty in Measurement (GUM) method. This method is adopted and described in details by International Organization for Standardization (IS) [21]. The standard uncertainty $u(x_i)$ to be associated with input quantity x_i is the estimated standard deviation of the mean [21,22]

$$u(x_i) = s(\overline{X}) = \left(\frac{1}{n(n-1)}\sum_{k=1}^{n}(X_{i,k} - \overline{X})^2\right)^{1/2}. \quad (5)$$

The combined standard uncertainty $u_c(y)$ is obtained by combining the individual standard uncertainties u_i these can be evaluated as Type A and Type B. That is,

$$u_c^2(y) = \sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i). \quad (6)$$

Table 1. Estimated uncertainty of spectral power distribution for the two groups of CFLs.

Uncertainty component	Relative standard uncertainty (%)
Calibration of spectroradiometer	4.7
Current regulation of lamps	0.001
Distance measurements	0.01
Repeatability	0.02
Relative expanded uncertainty ($K = 2$)	**9.4**

Table 2. Estimated uncertainty budget of UVA irradiance for the two groups of CFLs.

Uncertainty component	Relative standard uncertainty (%)
Irradiance responsivity calibration of standard radiometer	2.5
Current regulation of lamps	0.001
Distance measurements	0.01
Repeatability	0.02
Relative expanded uncertainty ($K = 2$)	**5**

Uncertainty model used for the determination of the UVA irradiance $E_{UVA}(\lambda)$ is [19,23]:

$$E_{UVA}(\lambda) = E_S(\lambda) + \delta E_l + \delta E_c + \delta E_r, \quad (7)$$

where,
- $E_S(\lambda)$, uncertainty due to reference spectral irradiance UVA standard radiometer (obtained from the calibration certificate);
- δE_l, uncertainty due to distance effect on the irradiance measurements (calculated by using the inverse square law);
- δE_r, uncertainty due to repeatability of the measurements (standard deviation of repeated 5 times);
- δE_c, uncertainty due to current regulation of lamps.

The uncertainty must be quoted whenever the results of a measurement are reported, it tell us about the precision with which the measurements were made. The uncertainty budget of the spectral power distribution (SPD), the absolute irradiance and illuminance measurements are shown respectively in Tables 1–3 with expanded uncertainty with confidence level 95% (coverage factor $K = 2$).

Finally, the uncertainty in spectral power distribution (SPD), UVA irradiance, and illuminance measurements are calculated. As discharge lamps are lesser stable in terms of electrical current and output values, in comparison to incandescent lamps, these output values exhibit larger uncertainties.

Table 3. Estimated uncertainty budget of illuminance for the two groups of CFLs.

Uncertainty component	Relative standard uncertainty (%)
Illuminance responsivity calibration of standard photometer	2.7
Current regulation of lamps	0.001
Distance measurements	0.01
Repeatability	0.02
Relative expanded uncertainty ($K=2$)	**5.4**

6 Conclusions

Measurements for UVA content present in the radiation of two different Egyptian brand groups of CFLs commonly used in Egyptian market in indoor lighting were studied to assess their unwanted output in the UVA region, their illuminance level and their spectral power distribution. These lamps are designed to emit their power in the visible region. In fact, they emit almost of their energy in the visible region but part of their energy is emitted in the UV region. The absolute irradiance measurements at 0.5 m in W/m^2 in UVA region from each lamp are obtained, using UVA standard NIS radiometer with maximum responsivity at 365 nm. UVA absolute irradiance levels per illuminance values for CFLs using NIS calibrated UVA radiometer and NIS calibrated luxmeter at 0.5 m. The measurements were performed under control of environmental conditions and good regulation of electrical power. Human being can be exposed to a significant amount of UVA radiation from white CFLs light if exposed for long time and at very short distance. It is recommended to use these lamps indoor with minimum safe limit distance 0.5 m. Different parameters such as ultra violet irradiance (UVA), ratio of UVA irradiance to electrical power (η), ratio of UVA power to illuminance (K) and relative spectral power distribution (SPD), for two groups of white CFLs are studied to dedicate their performance. For all two groups under study, K parameter remains less than the safe limit for human health [17]. Elios 32 watt white CFLs have smaller ratio (η) than Tiger 26 watt white CFLs. So, we recommended using Elios 32 watt white CFLs than Tiger 26 watt white CFLs at short distance in table lamps or other application and the distance more than 0.5 m.

Uncertainty model includes all parameters accompanied with the measurements are studied. The accompanied uncertainty in the spectral power distribution measurements (9.4%), the absolute UVA irradiance measurements (5%) and in the illuminance measurements (5.4%) are calculated respectively in Tables 1–3 with confidence level 95% ($K=2$).

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Cite this article as: Manal A. Haridy, Sameh M. Reda, Abdel Naser Alkamel Mohmed, Illuminance and ultra violet emissions radiated from white compact fluorescent lamps, Int. J. Metrol. Qual. Eng. **7**, 407 (2016)