Realization of luminous flux unit lumen at National Metrology Institute of Turkey (UME)

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Luminous flux calibration facility with an integrating sphere has been installed at the National Metrology Institute of Turkey (UME) in order to realize lumen. A LabView-based computer-controlled electrical system has been developed to operate light sources and to control electrical parameters. Owing to the corrections of the sphere system, inner coating reflectance, spatial non-uniformity, self-absorption factor and interior temperature variations have been characterized. The overall uncertainty in luminous flux measurement has been determined with an uncertainty of 1.14% ($k = 2$) in the range between 5–5000 lm.

Keywords: luminous flux, lumen, integrating sphere, illuminance, characterization, uncertainty.

1. Introduction

The photometry concerns the measurement of electromagnetic radiation in the range of wavelengths between 380 and 780 nm. The main parameter in photometry is luminous intensity, candela (cd), which is one of the base units in the International System of Units (SI). Other photometric quantities (lumen for luminous flux, lux for illuminance and $cd \cdot m^{-2}$ for luminance) are derived from luminous intensity. These photometric measurements are carried out by using the photopic weighting function $K(\lambda) = K_m V(\lambda)$, where K_m is the maximum luminous efficiency function whose value is 683 lm/W and $V(\lambda)$ function is an average action spectrum for the visual response of the human eye and also called the luminous efficiency function of a photopic vision.

The luminous flux is one of the most important quantities to be measured for light sources. It can be obtained either from illuminance $E(\theta, \varphi)$ or from luminous intensity $I(\theta, \varphi)$ distributions of a light source [1], [2]. The luminous flux is expressed in terms of photopic weighting function $K(\lambda)$ and spectral power distribution $\Phi_{e, \lambda}$ of a light source [3]

$$\Phi_V = K_m \int_0^\infty \Phi_{e,\lambda}(\lambda) V(\lambda) \mathrm{d}\lambda. \tag{1}$$

Physically, lumen can be defined in terms of a uniform point light source having 1 cd luminous intensity value that is positioned at the center of a sphere of 1 m radius. Then each 1 m^2 area of that sphere surface will receive a luminous flux of 1 lumen.

For the absolute realization of luminous flux, many national laboratories have been using goniophotometric techniques to measure the spatial illuminance distribution around the lamps and integrate it over the entire emission solid angle of the lamp [4]–[8]. Luminous flux can also be realized using an integrating sphere, both absolutely and relatively, which differ from goniophotometer technique. In the absolute integrating sphere method, the total luminous flux of a lamp inside the sphere is calibrated against the known amount of flux introduced into the sphere from the external source through a calibrated aperture [9]. In relative luminous flux measurements, luminous flux value of a source is measured with a substitution method in which the test lamp is compared with a known reference lamp, whereas spectral parameters of both lamps should be nearly the same to achieve correct measurements.

2. Theoretical considerations for the realization of luminous flux using an integrating sphere

Reference lamps are the basis for all measurements of total luminous flux in substitution principle. These measurements are performed by using an integrating sphere which should have a radius at least one order of magnitude higher than the largest dimension of the lamp. Inner surface walls of the sphere must be homogeneously coated with high diffuse reflection paint such as barium sulphate. The illuminance value of a lamp, which is placed in the sphere, changes depending on reflectance parameter of the coating [1]. In the first approach, luminous flux of the test lamp can be calculated from the following relation:

$$\Phi_T = \Phi_R \frac{E_T}{E_R} \frac{E_{AR}}{E_{AT}} \tag{2}$$

where Φ is luminous flux, E and E_A are the illuminance values of measured and auxiliary lamps (subscripts T and R refer to the test and to the reference respectively). Some portion of the reflected light is also absorbed by the lamp itself in the sphere, thus reducing the sphere responsivity (self-absorption). This parameter can be measured by using a stable auxiliary lamp. Finally, luminous flux unit, lumen, can be obtained either spectroradiometrically or photometrically as described in the following equations:

$$\Phi = \Phi_R \frac{E_T}{E_R} \frac{E_{AR}}{E_{AT}} \frac{\int_{380}^{780} S_T(\lambda)V(\lambda)\mathrm{d}\lambda \int_{380}^{780} S_R(\lambda)\frac{\rho(\lambda)}{1-\rho(\lambda)}s_{\mathrm{rel}}(\lambda)\mathrm{d}\lambda}{\int_{380}^{780} S_T(\lambda)\frac{\rho(\lambda)}{1-\rho(\lambda)}s_{\mathrm{rel}}(\lambda)\mathrm{d}\lambda \int_{380}^{780} S_R(\lambda)V(\lambda)\mathrm{d}\lambda} \qquad (3)$$

or

$$\Phi_T = \Phi_R \frac{E_T}{E_R} \frac{E_{AR}}{E_{AT}} \left(\frac{T_T}{T_R}\right)^{m_T}. \qquad (4)$$

In spectral calculation (Eq. (3)), $S(\lambda)$ is the spectral power distribution of the lamp (W), $s_{\mathrm{rel}}(\lambda)$ is the relative spectral responsivity of the detector (A/W) and $\rho(\lambda)$ is the spectral reflectance of sphere coating. In photometric calculation (Eq. (4)), T is color distribution of the lamp (K) and m_T is the mismatch index of distribution temperature.

3. Characterization of sphere

3.1. Temperature characterization

The temperature should not change inside the sphere during the measurements, if accurate luminous flux determination is aimed. Any variations in temperature will cause the reflection of the sphere coating affecting the illuminance value of the lamp. Four calibrated Pt-100 temperature sensors, which were located in different regions of the sphere, were used in order to characterize inner temperature distribution. The locations of temperature sensors (Fig. 1**a**) and experimental results that correspond to them are shown in Fig. 1**b**. The temperature variations were observed for one hour and changes were found of approximately 2 °C. As seen from Fig. 1, temperature variations
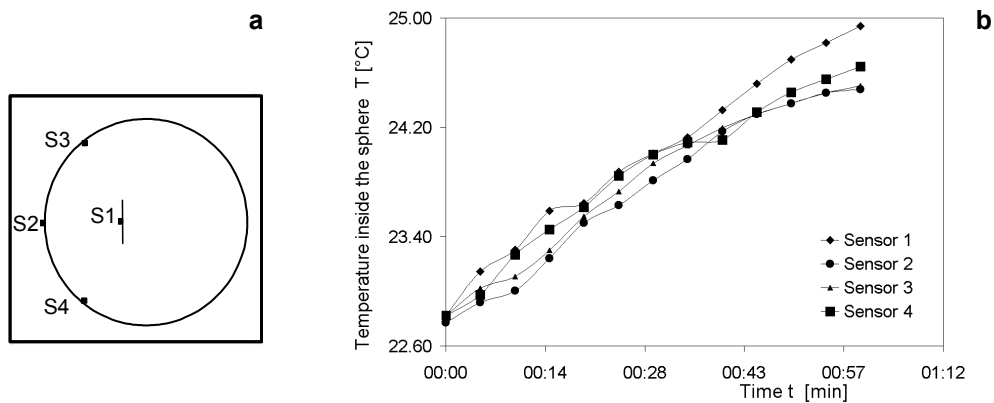

Fig. 1. Location of temperature sensors (**a**) and measurement results (**b**).

of the sensors are almost the same during the measurements. According to the CIE recommendations, luminous flux measurement should be performed within 1 °C temperature change [1]. Hence, taking this recommendation into account, measurements should be performed in approximately 30 minutes according to the temperature characterization graph (see Fig. 1).

3.2. Spatial non-uniformity characterization

The second characteristic measurement concerned the spatial non-uniformity of the sphere. Response of an integrating sphere is not uniform over the sphere wall. Some fragments such as a baffle, holder and gap between the two hemispheres have effects on reflections from the sphere walls [3]. Moreover, variations in incidence angle bring

T a b l e 1. Non-uniformity results of sphere.

Rotational angle of lamps	0°	90°	180°	270°	360°
Luminous flux values	173.12	173.16	173.18	173.19	173.13

about a change in the diffuse reflectance of sphere coating and sphere responsivity [10]. The spatial non-uniformity of the sphere was measured by a technique known as a scanning-beam source. A lamp, located at the centre of the sphere producing narrow beam, was rotated along the horizontal axis with angles from 0° to 360° in 90° steps and photocurrent of a photometer head was recorded at each position. Then luminous flux value was calculated for each position and non-uniformity results were obtained as shown in Tab. 1. The standard deviation depending on rotation was found to be 0.003% among the luminous flux values.

3.3. Reflectance factor characterization

Spectral irradiance measurement technique was chosen for the characterization of reflectance factor [3]. In the visible region, spectral irradiance value of the lamp was firstly measured inside the sphere by plugging a spectrophotometer to the sphere output port. Then it was carried out on a photometric bench. Having taken the ratio of two measurement results, spectral reflectance factor of sphere coating was found to be on the order of 95% as shown in Fig. 2 with an uncertainty of 0.71% ($k = 2$).

4. Luminous flux measurements

Luminous flux calibration facility, which allows calibration of test lamps by comparing luminous flux reference lamps with a 2 m diameter sphere, has recently been installed at UME. The basic components of the measurement system are: an integrating sphere coated with barium sulphate having 95% average reflectance in the visible range, a calibrated cosine-corrected photometer head, an auxiliary lamp and a baffle as depicted in Fig. 3.
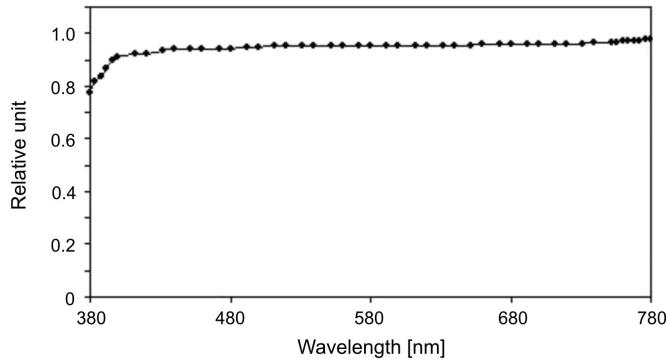
Fig. 2. Wavelength dependence of sphere coating.

Gas-filled incandescent lamp was used as a reference light source. In order to check the experimental measurement setup, three Polaron LF200W type reference luminous flux lamps, which were already calibrated by a goniophotometrer, were used. These lamps were classified into two groups: test and reference. Illuminance value of a lamp was measured by means of a temperature stabilized reference photometer head. A baffle was located between the photometer head and the lamp, so that direct illumination would be eliminated. Calibrated Pt-100 temperature sensor was used to monitor the temperature inside the sphere. This sensor was installed behind the baffle for shielding the direct illumination of the lamp. Integrating sphere was equipped with
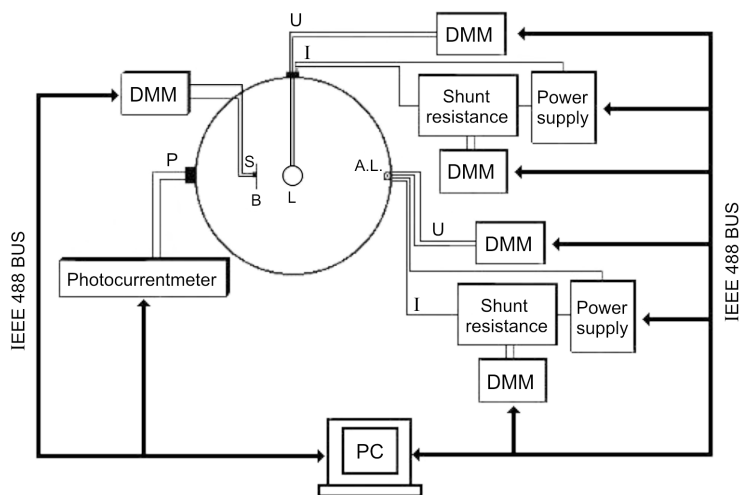

Fig. 3. Luminous flux measurement system; P – photometer head, S – temperature sensor, B – baffle, L – lamp, A.L. – auxiliary lamp, DMM – digital multimeter, I – lamp current, U – lamp voltage, PC – computer.

an auxiliary lamp, which was placed at the sphere wall opposite to the photometer head and used for absorption measurements.

Luminous flux lamps were operated with DC power at fixed polarity and at stabilized lamp current to get better accuracy of electrical measurements. Highly stable PTN 150-20 type Heinzinger power supply with stability of 10^{-5} was operated on a constant-current mode. In any case the electrical parameters of the lamp were measured using the four-pole-technique [11]. The lamp current was measured as the voltage across a calibrated reference resistor, which has a resistance of 99.9952 mΩ with a relative expanded uncertainty of 2 ppm at 2 A. The lamp current and voltage were recorded by using a calibrated HP 3458A multimeter (DMM) having high resolution ($8^{1/2}$ digit) and results were acquired by the computer. We have developed and used a LabView-based program to control the lamp current automatically with a computer -feedback system. It should be noted that stability of the lamp current was kept constant at about 5×10^{-5} A with an expanded uncertainty of 0.028% ($k = 2$).

Self-absorption factors of each lamp were measured with inside components of the sphere by using a stabilized auxiliary lamp and a photometer head in separate measurements for test and reference. After the determination of a self-absorption factor, illumination values of reference and test lamps were measured respectively in order to obtain lumen

$$\Phi_T \; = \; \Phi_R \frac{\Delta E_T}{\Delta E_R} \left(\frac{T_R}{T_T} \right)^{m_T} \frac{\Delta E_{AR}}{\Delta E_{AT}} \, c_R \, c_T \left(\frac{t_{OT}}{t_{OR}} \right)^{m_p + m_S} \tag{5}$$

where m_p and m_S are the mismatch indexes of the photometer head and integrating sphere, c is current correction factors of the lamp and t_0 is the ambient temperature inside the sphere. Measurements were repeated three times with remounting and reburning the lamps. Results of measurements are given in Tab. 2. As shown in table, luminous flux results, measured by the integrating sphere, were checked with certificate values. The average ratio between the integrated sphere and certificate results was found as 1.000329 and associated standard deviation was found to be 8×10^{-4}.

By using an established measurement system, we have participated in a bilateral comparison with PTB (Pysikalisch Technische Bundesanstalt, Germany). Six Polaron LF200 type lamps were used in the comparison. Our results were compared with a goniophotometric system, which is now being used at PTB. Results of this comparison

T a b l e 2. Luminous flux measurement results.

Lamp No.	Self-absorption measurements E [lx]	Luminous flux measurements		Ratio $\Phi_{\text{sphere}}/\Phi_{\text{gonio}}$
		Sphere method Φ [lm]	Goniophotometer method Φ [lm]	
P.254	242.80	1973	1975	0.998987
P.256	242.62	2038	2037	1.000491
P.259	242.93	2067	2065	1.000969

T a b l e 3. Comparison results of luminous flux with UME and PTB.

Lamp No.	Lamp ID	Lamp voltage U [V]		Luminous flux Φ [lm]		Absolute differences, UME/PTB-1	
		UME	PTB	UME	PTB	U [V]	Φ [lm]
UME.IA.04	LF200/355	89.558	89.555	2028.9	2032.0	2.9×10^{-05}	1.5×10^{-03}
UME.IA.08	LF200/351	85.765	85.772	1846.1	1848.8	7.7×10^{-05}	1.5×10^{-03}
UME.IA.09	LF200/352	85.971	85.970	1881.4	1885.0	9.7×10^{-06}	1.9×10^{-03}
UME.IA.10	LF200/353	87.591	87.579	1968.5	1968.6	1.4×10^{-04}	6.0×10^{-05}
UME.IA.11	LF200/354	86.284	86.273	1871.2	1874.1	1.2×10^{-04}	1.6×10^{-03}
UME.IA.12	LF200/356	89.617	89.616	2032.1	2033.4	1.6×10^{-05}	6.2×10^{-04}

are illustrated in Tab. 3. Average voltage difference (UME/PTB-1) of compared lamps was 4.0×10^{-5} with absolute standard deviation of 3.3×10^{-5} and average luminous flux difference was 1.2×10^{-3} with absolute standard deviation of 3.3×10^{-5} as seen in the table.

5. Measurement uncertainty

The uncertainty analysis for luminous flux measurement is presented in Tab. 4. All known uncertainty components have been included in the analysis regardless of

T a b l e 4. Uncertainty budget for luminous flux measurements.

	Source of uncertainty	Relative uncertainty [%]
Integrating sphere	Spatial non-uniformity	0.003
	Reflectance factor	0.354
	Mismatch index of sphere	**0.007**
	Absorption measurements	0.038
	Temperature measurements	0.065
	Temperature coefficient of sphere	0.039
Light source	Luminous flux of reference lamp	0.400
	Stability of lamp current	0.028
	Mismatch index of lamp current	**0.016**
	Temperature coefficient of shunt resistance	0.032
	Distribution temperature	0.004
	Mismatch index of distribution temperature	**0.092**
Photometer	Photocurrent measurements	0.041
	Mismatch index of photometer	0.003
	Repeatability	0.15
	Combined uncertainty ($k = 1$)	0.57
	Expanded uncertainty ($k = 2$)	1.14

whether they have a significant effect on the combined uncertainty. Combined measurement uncertainty is calculated using the following equation:

$$\Phi_T = \Phi_R \frac{\Delta y_T}{\Delta y_R} \left(\frac{T_R}{T_T} \right)^{m_T} \frac{\Delta y_{AR}}{\Delta y_{AT}} \left(\frac{V_T J_R}{J_T V_R} \right)^{m_I}$$

$$\times \left\{ \left[1 + \alpha (t_R - t_T) \right] \left[1 + \alpha_S (t_{0T} - t_{0R}) \right] \right\}^{m_p + m_S} \qquad (6)$$

where Δy is the photocurrent of the photometer head, V and J are voltage and current values of the lamp, m_I is the mismatch index of the lamp current, α and α_S are temperature coefficients of reference shunt resistance and sphere response, t and t_0 are temperatures around shunt resistance and inside the sphere (subscripts T and R refer to the test and to the reference).

This uncertainty budget is appropriate to the terminology of the BIPM, ISO [12], [13] and CIE TC 2-43 [14]. Uncertainty factors are categorized as type A and B. Type-A uncertainty is of random nature and is evaluated by statistical methods, and Type-B uncertainty is of systematic nature and is evaluated by other components. The standard uncertainty of the output value $u(y)$ is determined as combined uncertainty from contributions $u(y_i)$ of the standard uncertainties $u(x)$ of all input values.

5.1. Lamp-induced uncertainty components

Three reference luminous flux lamps, which were already calibrated at PTB using a goniophotometrer with standard uncertainty of 0.8% ($k = 2$), were used in the realization process. As a test lamp, the same type six Polaron LF200W lamps were used. The luminous flux Φ_T of all test lamps was measured by a substitution method under invariant circumstances.

The electrical parameters of reference lamps were given in the certificate for operating lamp at 2715 K distribution temperature with a standard uncertainty of 6 K. Distribution temperatures of test lamps were measured on the photometric bench at the same burning position by using a calibrated PR-650 model SpectraColorimeter (manufactured by Photo Research Inc.) with an uncertainty of 8 K. The uncertainty arising from reference and test lamps distribution temperatures was calculated as 0.008% ($k = 2$). The mismatch index m_T for changes in lamp current affecting the distribution temperature was calculated as 0.72 with an uncertainty of 0.092% ($k = 1$).

Standard and test lamps were operated with constant current and monitored by the lamp voltages across the contacts of the lamp cap using a calibrated Guildline 9230-15 type reference resistor. HP 3458A type multimeters were calibrated in the required current region with 5 ppm uncertainty by using known resistors and voltage measurements. The specified uncertainty value includes the uncertainty of these resistance and voltage measurements. Standard deviations in the voltage measure-

ments were found with an uncertainty lower than 7×10^{-5}. The lamp current was measured as the voltage across a calibrated reference resistor, which has a resistance of 99.9952 mΩ with a relative expanded uncertainty of 2 ppm at 2 A. The mismatch index m_I for changes in lamp current affecting the luminous flux was calculated as 6.87 with an uncertainty of 0.016% ($k = 1$).

5.2. Photometer-induced uncertainty components

The spectral responsivity scale is based on absolute optical power measurements using a cryogenic radiometer at three wavelengths, 488.1, 514.7, 632.8 nm and a silicon based reflection type trap detector. The responsivity scale was realized in the visible region by modeling the reflectance and internal quantum efficiency of photodiodes. Deviations between the measured and modeled responsivity at these wavelengths are within 0.05% ($k = 2$). Using a calibrated current-meter the photocurrent of the reference photometer head was monitored. The photometer head was located onto the sphere output port and 12 readings were taken for each lamp. Standard deviations in the photocurrent measurements were taken as a standard uncertainty of 0.029% ($k = 1$). The uncertainty arising from reference and test lamps photocurrents was calculated as 0.082% ($k = 2$). The mismatch index m_p determined from the reference photometer by using the same lamp at two different distribution temperatures was calculated as 0.018 with an uncertainty of 0.002% ($k = 1$).

5.3. Temperature-induced uncertainty components

Temperature measurements are of vital importance for electronic units and sphere coating reflectance measurements. It should be noted that the lamp current is measured through the voltage across a calibrated reference resistor, which is very sensitive to temperature variations. Therefore, temperature around the resistor must be stable. In order to perform accurate current measurement, the temperature of reference resistance was monitored using a calibrated temperature sensor. Then the temperature coefficient of reference shunt resistance was calculated as 5.4×10^{-4} with a standard uncertainty of 0.032% ($k = 1$). A photometer head and a calibrated Pt-100 sensor were used in order to calculate temperature dependence of sphere coating. The temperature coefficient was calculated from the analysis of data as 1.7×10^{-4} with a standard uncertainty of 0.039% ($k = 1$). The mismatch index m_S determined from the integrating sphere was calculated as 0.024 with an uncertainty of 0.007% ($k = 1$).

6. Conclusions

In UME, luminous flux unit of lumen was realized by using a substitution principle based on the integrating sphere. Measurements were performed according to illuminance value measurement for both the test and reference lamps by using a cosine-corrected reference photometer head. The sphere, which is the main parameter in the realization, was characterized in terms of the temperature distribution, spatial non-uniformity and reflectance factor of the coating. The temperature distribution in the

sphere was observed to change by about 2 °C within one hour. This variation is not suitable for accurate measurements of luminous flux. From the experimental data, it was decided that luminous flux measurements should be ended within 30 minutes (1 °C variation). Moreover, the spatial non-uniformity of the sphere showed that change in luminous flux in one degree was about 1.9×10^{-4} lm/deg and coating reflectance factors were 95%.

In these measurements, the most important parameter affecting the measurement results is, in general, the stability of the lamp current. That is why the lamp current was controlled automatically with a precisely developed computer-feedback system. It was kept constant at a current of about 5×10^{-5} A and the expanded standard uncertainty of the stability system was calculated as 0.028% ($k = 2$).

The overall uncertainty related to this type of measurement is estimated as 1.14% at $k = 2$ confidence level. This method has been successfully applied to the measurement of luminous flux in the range of 5 to 5000 lm by using different reference lamps. It is also possible to calibrate fluorescent type lamps by using the established system.

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