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Datasheet-based methodology for CCT and luminous flux estimation in mixed-LED lighting sources

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Abstract: This work proposes a datasheet-based methodology to estimate the correlated color temperature (CCT) and the luminous flux of one or a combination of multiple white Light-Emitting Diodes (LEDs). This methodology is based on the interaction between the different domains (colorimetrical, optical, thermal and electrical) that control the LED's behavior. An experimental setup with LEDs of 4000K and 6500K CCT was built and tested under multiple operating conditions, in order to verify the accuracy of the proposed method. Results presented good correlation between estimated and measured data, with a maximum error of 1.05% for CCT and 3.13% for luminous flux.

Keywords: Circadian cycle; correlated color temperature; design methodology; lighting; Light-Emitting Diode; luminous flux; thermal modelling.

1. INTRODUCTION

With the advance of technology, mankind experienced a shift in its behavior, spending more time indoors. This caused an increase in the exposure to artificial light at the expense of lower solar light exposure. This shift can interfere with our health in a negative way. Humans have a 24-hour cycle called circadian cycle that is regulated mostly by light. Depending on the light exposure, this cycle can be disturbed, causing changes in the production of hormones such as melatonin and cortisol, and in the person's activity-rest pattern (Figueiro et al., 2018).

Being exposed just to solar light helps to synchronize the circadian cycle (Wright et al., 2013). However, in many situations this is not possible due to our daily routine and/or environment conditions. In these cases, it would be desired to have an artificial light that could change its luminous flux and correlated color temperature (CCT) throughout the day to mimic the solar irradiation pattern. Furthermore, a light source that can change these characteristics can also be used in different situations, such as with a low CCT characteristic to induce relaxation, or with a high CCT to induce alertness (Mills et al., 2007).

To keep up with the desired characteristics of such high-performance system, the chosen light source must also be optimized. Light-Emitting Diodes (LEDs) are considered nowadays the standard technology in lighting system due to their many advantages over traditional light sources, such as high efficiency, long lifespan and eco-friendly structure (Schubert, 2006). Moreover, LEDs are available in a wide range of CCT values and power ratings, making it suitable for many applications in different markets.

A key factor to be considered when using LEDs is the variation in its junction temperature during operation. Fluctuations in the current applied to the LED and its junction temperature can cause CCT and flux variations (Ohta and Robertson, 2005; Krames et al., 2007; Koh et al., 2011; Loo et al., 2011). Other parameters, such as forward voltage, desired optical output and ambient temperature should also be considered when using LEDs. This ensures that the device will operate within safe margins and provide the desired output characteristics. Therefore, having a mathematical model of the LED that take all these parameters into account can provide a better understanding of the system as a whole and help in the design process of the lighting fixture.

There are some past works that predict the correlated color temperature of two or more LEDs (Chen et al., 2014, 2015; Lee et al., 2016). However, these papers used experimental data to model the system or even consider the CCT constant regardless of the operating conditions (i.e., junction temperature) of the system.

In this paper, we propose an improved methodology for estimating the CCT and luminous flux of LED lighting sources. This method is based only on data obtained from the LED's datasheet, making the design process of lighting fixtures fast and cost-effective. Moreover, the final model is scalable for any power rating, as parameters such as the LED's junction temperature are included in the estimation.

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The rest of this paper is organized as follows: after the introduction, the methodology to estimate the correlated color temperature and luminous flux of one or more LEDs is presented in Section 2. Experimental results are shown in Section 3, aiming to validate the methodology. The last Section concludes the paper.

2. METHODOLOGY

To estimate the final CCT of the light source, the equivalent electric model of each LED used must be known. The simplified LED model consists of an independent voltage source V_0 in series with a resistance Rs and an ideal diode (Lin and Chen, 2009). These parameters can be derived from the LED's datasheet characteristic I-V curve, usually given for a reference temperature T_0, resulting in the expression described in (1).

$$V_f(I_f) = V_0 + R_s \cdot I_f \quad (1)$$

In this equation, V_f and I_f are the forward voltage and current of the LED, respectively.

Temperature effects in the LED operation can be added to this model as in (2), where k_v is the temperature coefficient. This parameter represents the drop in the forward voltage V_f due to changes in the junction temperature T_j (Xi and Schubert, 2005; Bender et al., 2013).

$$V_f(I_f) = V_0 + R_s \cdot I_f + k_v(T_j - T_0) \quad (2)$$

As in any physical system, part of the electric power applied to the LED is converted into heat instead of light. In order to keep its junction temperature under safe conditions, it is a common practice to attach the LED to a heatsink. Normally, between 65% and 85% of the LED's power is converted into heat (Farkas et al., 2004; U.S. Department of Energy, 2007; Hui and Qin, 2009; Liu et al., 2011; Chen et al., 2012). The coefficient k_h represents this amount and in most cases, it is not given in datasheet, but can be found as the inverse of radiant efficiency (Farkas et al., 2004). Equation (3) can be used to estimate the junction temperature in LED (CREE, 2004; Hui and Qin, 2009; Bender et al., 2013). The other parameters necessary to be known in this equation are the heatsink temperature T_{hs} and the thermal resistance between the LED junction and its case R_{jc}.

$$T_j(I_f) = T_{hs} + R_{jc} \cdot V_f \cdot I_f \cdot k_h \quad (3)$$

Even though some parameters (thermal resistances, coefficients k_h and k_v) have dynamic responses and can vary across the production lot, they were considered fixed in this methodology, aiming the simplification of the model (Yang et al., 2006; Kuo et al., 2008; Tao et al., 2010).

The next step is achieving an equation that relates the luminous flux ϕ in respect of current and temperature variations, as shown in (4) (Bender et al., 2013). This can be made by applying a linear regression in the data from the luminous flux versus current plot $\phi(I_f)$ and obtaining the linear and angular coefficients d_0 and d_1, respectively. After, the linear c_0 and angular c_1 coefficients can be obtained from the data of luminous flux versus junction temperature plot $\phi(T_j)$. The other parameters necessary are: the number of LEDs of the same model n, the nominal flux ϕ_{nom}, the ambient temperature T_a and the heatsink thermal resistance R_{hs}.

$$\phi(I_f) = n \cdot \phi_{nom} \cdot [c_0 + c_1 (T_a + (R_{jc} + n \cdot R_{hs}) \cdot k_h \cdot I_f \cdot \gamma(I_f))] \cdot (d_0 + d_1 \cdot I_f) \quad (4)$$

In the equation above, $\gamma(I_f)$ is defined as:

$$\gamma(I_f) = \frac{V_0 + R_s \cdot I_f + k_v(T_a - T_0)}{1 - I_f \cdot k_h \cdot k_v(R_{jc} + n \cdot R_{hs})} \quad (5)$$

The datasheet also provides data of chromaticity coordinates y and x. Using this information and the McCamy's formula, it is possible to evaluate the CCT curve (McCamy, 1992). CCT can be plotted with respect of y variation, as shown in Figure 1 to an LED of 6500K, in order to illustrate (CREE, 2017). A linear behavior is observed in this plot. Equation (6) represents this behavior, and using linear regression, the coefficients e_0 and e_1 can be determined.

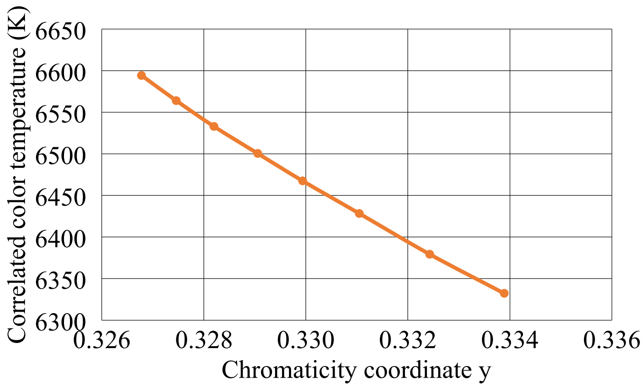


Figure 1. Correlated color temperature in respect of y variation to the LED with CCT of 6500K.

$$CCT(y) = e_0 + e_1 \cdot y \quad (6)$$

The following step is to use linear regression in the plots of chromaticity coordinate Δy in respect to forward current $\Delta y(I_f)$ and junction temperature $\Delta y(T_j)$ variations, both plots expressed in the datasheet. Thus, the coefficients a_0 and a_1 (from $\Delta y(T_j)$), and b_0 and b_1 (from $\Delta y(I_f)$) can be found. With these coefficients, the chromaticity coordinate y can be evaluated using (7). It is also necessary to know the center point of the plot y_{nom}.

$$y(I_f) = y_{nom} \cdot [a_0 + a_1 (T_a + (R_{jc} + n \cdot R_{hs}) \cdot k_h \cdot I_f \cdot \gamma(I_f))] \cdot (b_0 + b_1 \cdot I_f) \quad (7)$$

By combining (6) and (7), one can obtain the CCT of the LED for a given current. Thereby, with the equations seen before, it is possible to obtain both CCT and luminous flux of one LED (or more, if it is used the same model) in respect with the forward current applied to it.

To obtain the CCT of one or more different LED models, it is necessary to analyze colorimetry properties. At a given light source, the chromaticity coordinates x, y, z and the reference stimulus X, Y, Z have a relation as seen in (8) (Ohta and Robertson, 2005; Malacara, 2011). Using the combination of these stimulus, any color can be obtained. To mix m different light sources, the equivalent reference stimulus is the sum of the respective sources, as in (9) (Moreno and Contreras, 2007).

$$\frac{X}{x} = \frac{Y}{y} = \frac{Z}{z} = X + Y + Z \tag{8}$$

$$\begin{aligned} X_{mix} &= X_1 + X_2 + ... + X_m \\ Y_{mix} &= Y_1 + Y_2 + ... + Y_m \\ Z_{mix} &= Z_1 + Z_2 + ... + Z_m \end{aligned} \tag{9}$$

Using (8) and (9), it is possible to obtain the chromaticity coordinate y for a mix of m light sources:

$$y_{mix} = \frac{Y_1 + Y_2 + ... + Y_m}{\frac{Y_1}{y_1} + \frac{Y_2}{y_2} + ... + \frac{Y_m}{y_m}} \tag{10}$$

According to (6), the chromaticity coordinate y is proportional to the CCT. It is known that the stimulus Y (that represents luminance) is proportional to the luminous flux (Chen et al., 2015). Using these relations, equation (9) can be rewritten as (11). In this form, it can be used to estimate the CCT of a mix of different LED models, in respect with the current variation, just using data from the datasheet.

$$CCT_{mix}(I_1, I_2, ..., I_m) = \frac{\phi_1(I_1) + \phi_2(I_2) + ... + \phi_m(I_m)}{\frac{\phi_1(I_1)}{CCT_1(I_1)} + \frac{\phi_3(I_2)}{CCT_2(I_2)} + ... + \frac{\phi_m(I_m)}{CCT_m(I_m)}} \tag{11}$$

3. EXPERIMENTAL VALIDATION

To verify the accuracy of the proposed methodology, a mixed-LED system was built for experimental tests. In this system, two different LED models were used. The first has a CCT of 4000K (JK3030AWT-00-0000-000B0HL240E) and the later has a CCT of 6500K (JK3030AWT-00-0000-000B0HL265E). Both devices are manufactured by CREE (CREE, 2017). Seven LEDs in series of each model were used ($n = 7$), all of them attached to the same heatsink.

All the necessary parameters were obtained from the datasheets and are summarized in Table 1.

The measuring setup consists of an integrating sphere with spectrophotocolorimeter to evaluate optical parameters (luminous flux, correlated color temperature), one thermocouple attached to the heatsink and another inside the sphere to measure the ambient temperature, two current sources and a circuit to modulate the average current in the LEDs using pulse width modulation (PWM).

Tests were performed with each group of LEDs separately, at two different ambient temperatures, 25°C and 35°C. The current sources were set to a peak value of 150 mA and the values were measured with PWM duty cycles of 25%, 50%, 75% and 100% (average current of 25%, 50%, 75% and 100%, respectively). All the measurements were taken after thermal steady-state conditions were reached. The results for each group of LEDs are shown in the next sub-sections, with comparison between measured and calculated values. The error was calculated using (12).

Table 1. System Parameters

Parameter	Value	
Correlated color temperature CCT (K)	4000	6500
Forward voltage V_0 (V)	5.2863	
Series resistance R_s (Ω)	4.7246	
Temperature coefficient k_v (V/°C)	-0.0018	
Reference temperature T_0 (°C)	25	
Nominal current (A)	0.15	
Power conversion coefficient k_h	0.75	
LED Thermal resistance R_{jc} (°C/W)	11	
Heatsink thermal resistance R_{hs} (°C/W)	2.92	
Number of LEDs n	7	7
Linear coefficient c_0 from $\phi(T_j)$	1.064	
Angular coefficient c_1 from $\phi(T_j)$	-0.002	
Linear coefficient d_0 from $\phi(I_f)$	0	
Angular coefficient d_1 from $\phi(I_f)$	6.65	
Nominal luminous flux ϕ_{nom} (lm)	124	
Linear coefficient e_0 from $CCT(y)$	6899.3	18582
Angular coefficient e_1 from $CCT(y)$	-7652	-36704
Linear coefficient a_0 from $\Delta y(T_j)$	1.0169	1.0193
Angular coefficient a_1 from $\Delta y(T_j)$	-0.0002	
Linear coefficient b_0 from $\Delta y(I_f)$	1.0165	1.0189
Angular coefficient b_1 from $\Delta y(I_f)$	-0.1085	-0.1237
Center point y_{nom}	0.3665	0.3214

$$Error = \frac{Value_{measured} - Value_{calculated}}{Value_{measured}} \cdot 100\% \tag{12}$$

3.1 LED with CCT of 4000K

Figure 2 shows the junction temperature of the 4000K LED with ambient temperature of 24.2°C and 35°C. The estimated values were compared with calculated ones. To estimate the values, the heatsink temperature was measured with the thermocouple and the final value was obtained using (3). The average error was 2.99%, with a maximum error of 4.80%.

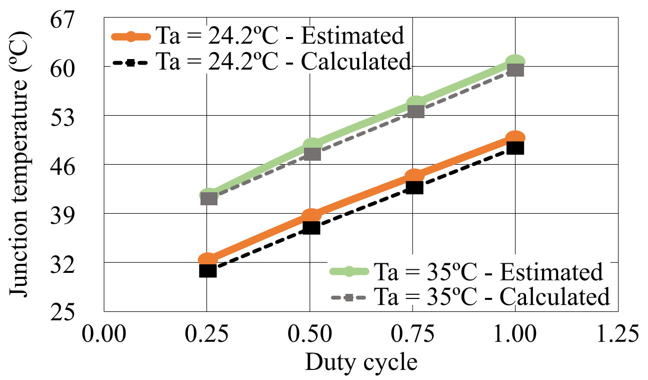
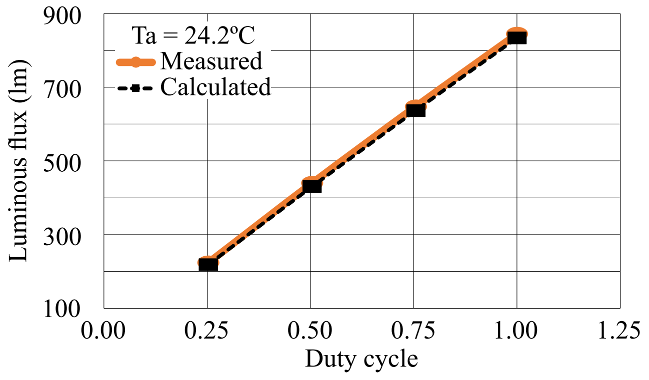
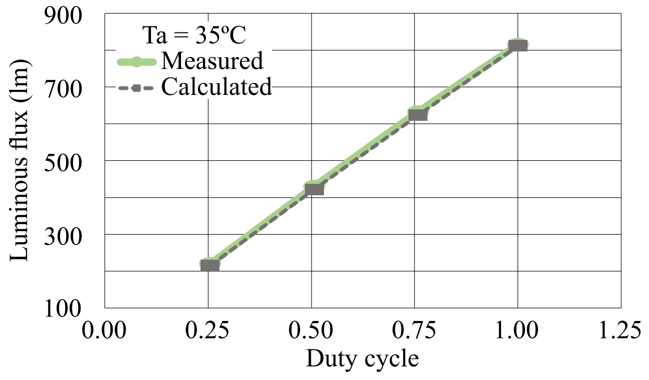


Figure 2. Comparison of estimated and calculated values of junction temperature to the LED with CCT of 4000K.

The comparison between the measured and calculated values for the luminous flux is shown in Figure 3a for ambient temperature of 24.2°C and Figure 3b for 35°C. The luminous flux was calculated using (4). The maximum error was 2.36%, with an average error of 1.65%.



(a)



(b)

Figure 3. Comparison of measured and calculated values of luminous flux in ambient temperature of (a) 24.2°C and (b) 35°C to the LED with CCT of 4000K.

Figure 4 shows the comparison for CCT. The values were calculated using (6) and (7). The blue dotted lines show the boundary of the Brazilian standard that express tolerance values to correlated color temperature. To a CCT of 4000K, the acceptable variation is 3985 ± 275K (INMETRO/MDIC 389:2014, 2014). The average error in the comparison is -0.15%, with a maximum value of -0.59%. The maximum difference between the values in absolute terms is 24K. It shows a good correlation comparing the methodology with the experimental data.

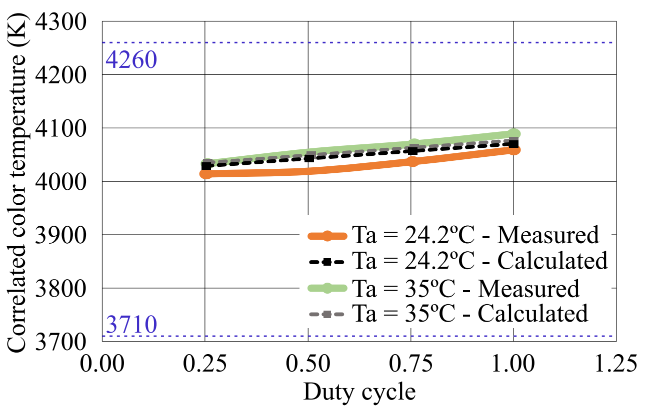


Figure 4. Comparison of measured and calculated values of correlated color temperature to the LED with CCT of 4000K.

The comparison in numerical values for junction temperature T_j, luminous flux ϕ and correlated color temperature CCT is shown in Table 2. The numerical values presented are for duty cycles (D) of 25, 50, 75 and 100%, and variations of approximately 10°C in ambient temperature.

Table 2. Comparison of measured and calculated values to the LED with CCT of 4000K

	Parameter	Measured	Calculated	Error (%)
D = 25%	T_j	32.4°C	30.8°C	4.80
	ϕ	223.9 lm	218.6 lm	2.36
T_a = 24.6°C	CCT	4014K	4029K	-0.37
D = 50%	T_j	38.7°C	36.9°C	4.58
	ϕ	439.8 lm	430.4 lm	2.14
T_a = 24.5°C	CCT	4019K	4043K	-0.59
D = 75%	T_j	44.4°C	42.7°C	3.72
	ϕ	647.3 lm	636.7 lm	1.64
T_a = 24.1°C	CCT	4037K	4057K	-0.49
D = 100%	T_j	49.8°C	48.4°C	2.89
	ϕ	844.4 lm	834.1 lm	1.22
T_a = 23.7°C	CCT	4059K	4070K	-0.28
D = 26%	T_j	41.6°C	41.2°C	1.16
	ϕ	220.1 lm	215.4 lm	2.11
T_a = 34.9°C	CCT	4033K	4035K	-0.05
D = 51%	T_j	48.8°C	47.5°C	2.60
	ϕ	429.9 lm	422.0 lm	1.85
T_a = 35.1°C	CCT	4055K	4049K	0.14
D = 76%	T_j	54.8°C	53.6°C	2.20
	ϕ	632.2 lm	623.0 lm	1.45
T_a = 35°C	CCT	4070K	4063K	0.17
D = 100%	T_j	60.7°C	59.5°C	1.94
	ϕ	814.9 lm	811.2 lm	0.45
T_a = 35°C	CCT	4089K	4077K	0.30

3.2 LED with CCT of 6500K

The comparison of junction temperature for the 6500K LED is shown in Figure 5 with ambient temperature of 24.5°C and 32.5°C. The average error was 2.51%, with a maximum error of 4.09%.

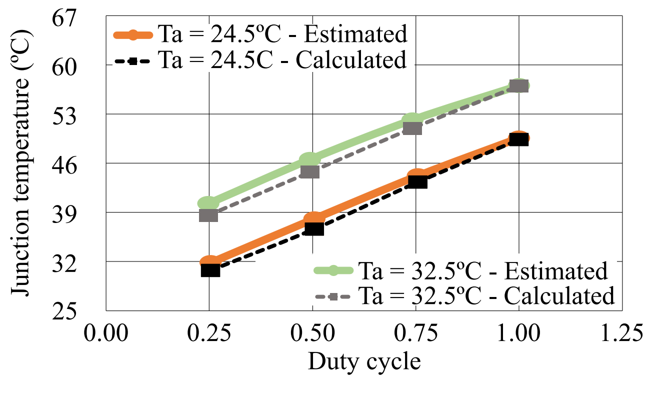


Figure 5. Comparison of estimated and calculated values of junction temperature to the LED with CCT of 6500K.

Results for luminous flux are shown in Figure 6a under T_a = 24.5°C and in Figure 6b for T_a = 32.5°C. The maximum error was 3.13%, with an average error of 1.67%.

Figure 7 shows the comparison of correlated color temperature. The blue dotted lines show the boundary of the Brazilian standard that express tolerance values to correlated color temperature. To a CCT of 6500K, the acceptable variation is 6532 ± 510K (INMETRO/MDIC 389:2014, 2014). The average error in the comparison is 0.36%, with a maximum value of 1.05%. The maximum

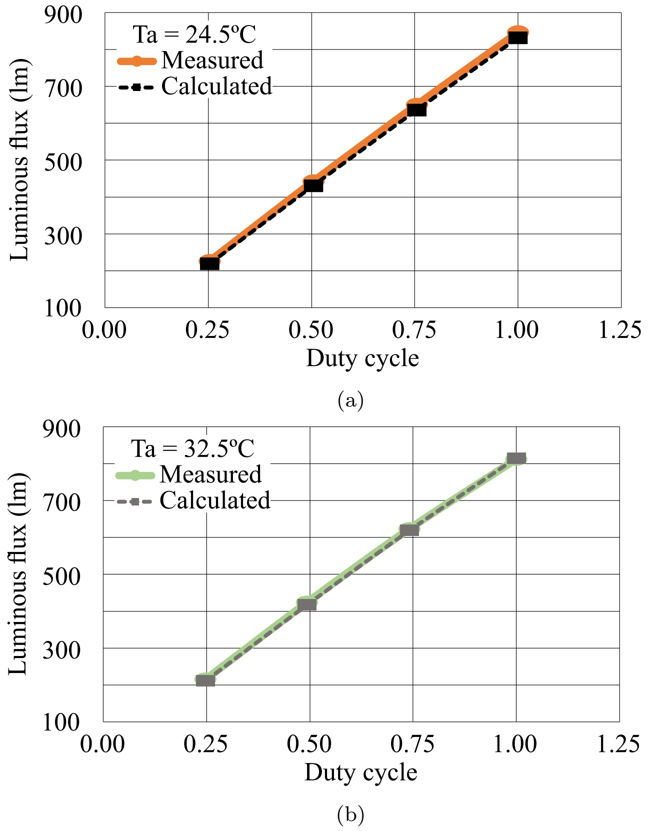


Figure 6. Comparison of measured and calculated values of luminous flux under ambient temperature of (a) 24.5°C and (b) 32.5°C to the LED with CCT of 6500K.

difference between the values is 69K. A ± 200K deviation in CCT is considered non-perceivable by human eyes (Chen et al., 2015).

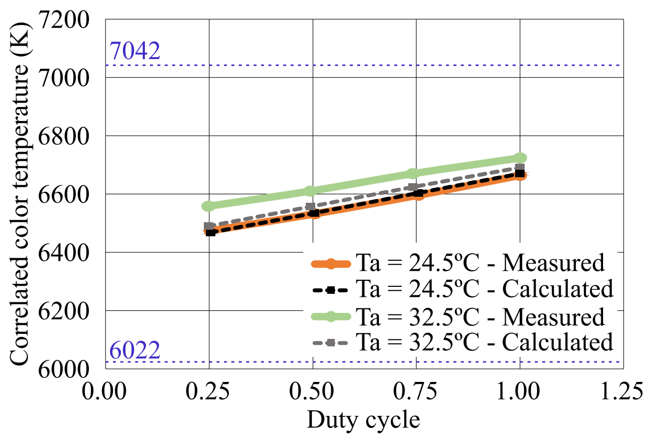


Figure 7. Comparison of measured and calculated values of correlated color temperature to the LED with CCT of 6500K.

The comparison in numerical values for junction temperature T_j, luminous flux ϕ and correlated color temperature CCT is shown in Table 3. The comparison was made for each value of duty cycle (D) and ambient temperature (T_a). Figure 8 shows the waveform of the current applied to the LEDs, in the case of $T_a = 32.6$°C and $D = 74.149\%$.

Table 3. Comparison of measured and calculated values to the LED with CCT of 6500K

	Parameter	Measured	Calculated	Error (%)
$D = 25\%$	T_j	31.8°C	30.7°C	3.43
	ϕ	225.9 lm	218.8 lm	3.13
$T_a = 24.5$°C	CCT	6474K	6468K	0.10
$D = 50\%$	T_j	38.1°C	36.6°C	3.83
	ϕ	442.1 lm	430.7 lm	2.57
$T_a = 24.2$°C	CCT	6532K	6535K	-0.04
$D = 76\%$	T_j	44.2°C	43.3°C	2.02
	ϕ	649.6 lm	636.0 lm	2.09
$T_a = 24.7$°C	CCT	6596K	6604K	-0.12
$D = 100\%$	T_j	49.6°C	49.4°C	0.48
	ϕ	846.1 lm	831.9 lm	1.68
$T_a = 24.7$°C	CCT	6664K	6670K	-0.09
$D = 25\%$	T_j	40.3°C	38.6°C	4.09
	ϕ	215.3 lm	211.0 lm	1.98
$T_a = 32.5$°C	CCT	6558K	6489K	1.05
$D = 49\%$	T_j	46.5°C	44.7°C	3.88
	ϕ	424 lm	417.5 lm	1.53
$T_a = 32.5$°C	CCT	6610K	6557K	0.81
$D = 74\%$	T_j	52.2°C	51.0°C	2.28
	ϕ	623.5 lm	619.0 lm	0.73
$T_a = 32.6$°C	CCT	6670K	6624K	0.69
$D = 100\%$	T_j	57.0°C	57.0°C	0.06
	ϕ	812.5 lm	815.5 lm	-0.37
$T_a = 32.5$°C	CCT	6724K	6691K	0.49

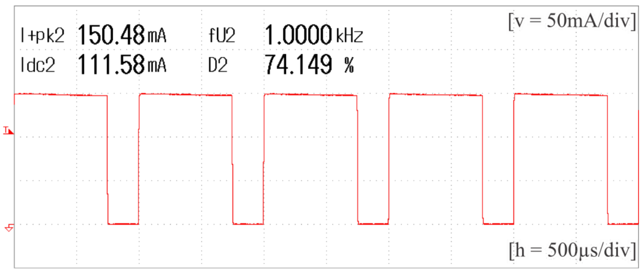


Figure 8. Waveform of the PWM current applied to the LEDs, in the case of $T_a = 32.6$°C and $D = 74.149\%$.

4. CONCLUSION

An improved methodology for estimating the correlated color temperature and luminous flux was proposed in this paper. By using the interaction between colorimetrical, thermal, optical and electrical characteristics of the LEDs, this method can be used to speed-up the design process of single or mixed-LED systems. Experimental results obtained with two different LED models verify the accuracy of the model. The maximum errors encountered are 4.8% for junction temperature, 3.13% for luminous flux and 1.05% for correlated color temperature, with an absolute value of 69K. The reduced error values shows the good agreements between the methodology predictions and experimental measurements. Additionally, all CCT results attended the Brazilian standard INMETRO/MDIC 389:2014, with errors lower than 200K, considered non-perceivable by human eyes.

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