DESIGN METHODOLOGY FOR LED LIGHTING SYSTEMS BASED ON PHOTO-ELECTRO-THERMAL INTERRELATIONSHIPS

Leandro Chies, Maicol F. de Melo, William D. Vizzotto, Rudimar Spannemberg Jr., Vitor C. Bender, Marco A. Dalla Costa
Federal University of Santa Maria, Santa Maria – RS, Brasil
e-mail: leandro.chies@ifsc.edu.br, maicolmelo@gedre.ufsm.br

Abstract – **This paper presents a design methodology for LED (Light-Emitting Diode) lighting systems based on photo-electro-thermal (PET) interrelationships. The proposed methodology uses only LED datasheet information, which makes experimental tests unnecessary to obtain the design parameters. The methodology allows identifying several design specifications, such as, luminous efficacy, heatsink thermal resistance, LED junction temperature and forward current, essential aspects to produce a satisfactory lighting system. Thus, it is possible to define the lighting system features based on standards requirements to obtain the desired system results. Initially, a review of several PET theories is presented, and a new mathematical analysis is performed, in order to highlight the main contributions of the methodology. An LED bulb lamp design is presented to exemplify the methodology. Finally, experimental tests with the proposed LED lamp resulted in a luminous flux of 1271 lm, with a luminous efficacy of 112 lm/W, and LED junction temperature of 79.67 ºC. The errors between calculated and measured luminous flux, luminous efficacy and LED junction temperature were 3.70%, 1.88%, and 3.85%, respectively. These results validate the proposed methodology.**

Keywords – **Design Methodology, Light-Emitting Diodes, Photo-Electro-Thermal Theory.**

I. INTRODUCTION

Nowadays the search for more efficient and environmentally friendly lighting systems presents a great social acclaim. In this scenario, the more traditional lighting technologies, such as incandescent and compact fluorescent lamps (CFL), are conceding space for new lighting possibilities, like as LED-based lamps. LEDs present lifetime up to 100,000 h, luminous efficacy higher than 150 lm/W, high color rendering index, robustness, driver simplicity and other advantages [1].

In addition, LEDs have great potential to save energy, the United States Department of Energy (DOE) estimates that the growth of solid state lighting (SSL) may be responsible for saving between 261 and 395 terawatt-hour in 2030 compared to a no SSL scenario, only in United States territory [2].

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However, a proper design is required during the LED lamp conception, and it requires a modeling that integrates photometrical, electrical and thermal (PET) parameters, once these interrelations have influence in the LEDs´ features [3]-[8]. Thus, the hard task in LED lamp conception is the PET design, which can guarantee a long lifetime with a desired luminous efficacy and low cost.

The literature presents many PET theories. For example, [9]-[12] propose the luminous flux determination. In [9], the luminous flux is estimated considering two functions: relative emitted flux vs. LED junction temperature and relative emitted flux vs. forward current. Reference [10] performs an improvement over [9], estimating the junction temperature by ambient temperature, electrical and thermal parameters. Moreover, algorithms to maximize the luminous flux for an optimal forward current, or to minimize the heatsink size, were also proposed. The work proposed in [11] estimates the luminous flux through the relation of luminous efficacy and LED power, where electrical and thermal parameters are used to estimate the luminous efficacy. Furthermore, it also presents a method to achieve the maximum luminous flux at an optimal power. Reference [12] improves the former theory, it uses a variable k_h coefficient (percentage of electrical power transformed in heat). Nevertheless, a difficult factor to use PET theory is that most of these theories require experimental tests in expensive equipments to obtain the PET theory parameters, for example an integrating sphere. References [13] and [14] presented a strategy to obtain the PET theory parameters trough the LED datasheet information.

In order to improve the state of art in PET theory, this paper proposes a methodology to design LED lighting systems based only on LEDs datasheet information, without any experimental or simulation tests. This methodology consists in three steps, organized in the following sections: PET parameters determination, Section II; equation of LED lighting system specifications, Section III; and graphical analysis using a design example, Section IV. Section V presents the experimental results obtained for the design example, while Section VI shows the main paper conclusions.

II. PHOTO-ELECTRO-THERMAL PARAMETERS ACHIEVEMENT BASED ON LED DATASHEET

The PET theory has been widely explored in the literature, which is based on the following equations, presented by [11]:

$$\phi_v = N_{ld} P_{ld} E \tag{1}$$

$$E = E_0 \left[1 + k_e (T_a - T_0) + k_e k_h P_{ld} (N_{ld} R_{hs} + R_{jc}) \right] \tag{2}$$

$$\phi_v = N_{ld} E_0 \left\{ \left[1 + k_e (T_a - T_0) \right] P_{ld} + \left[k_e K_h (N_{ld} R_{hs} + R_{jc}) \right] P_{ld}^2 \right\}. \tag{3}$$

Equation (1) calculates the luminous flux of the system by multiplying the number of LEDs (N_{ld}) by the LED power (P_{ld}) and efficacy (E). Replacing (2), that presents the luminous efficacy, in (1), it results in a complete expression for the luminous flux estimative (3). Table I presents the general PET parameters used in this study.

TABLE I
General PET Parameters

Symbol	Meaning	Unity
N_{ld}	LEDs quantity	-
E	Luminous efficacy	lm/W
ϕ_v	Luminous flux	lm
P_{ld}	LED electrical power	W
E_0	Reference efficacy in T_0	lm/W
T_0	Reference temperature	ºC
T_a	Ambient temperature	ºC
v_e	Negative coefficient that represents the E reducing rate with T_j increase.	1/ºC
T_j	LED junction temperature	ºC
k_h	LED electrical power percentage transformed in heat	%
R_{jc}	Junction to case thermal resistance	ºC/W
R_{hs}	Heatsink to ambient thermal resistance	ºC/W

The improvement proposed in this work, compared to other theories presented in the literature, is that the ϕ_v estimation is achieved using a variable E_0 jointly with a k_h estimative performed through LED datasheet. Besides, P_{ld} is related to thermal parameters and LED forward current, which is performed in Section II.C.

A. Variable Reference Efficacy (E_0)

The LED luminous efficacy depends on the LED junction temperature and forward current (I_f). One of the main parameters used to determine ϕ_v is E_0. In [11], E_0 is held constant during P_{ld} and ϕ_v variations. However, E_0 changes according to I_f at T_0, because of the droop effect [15]. Thus, the parameter E_0 can be represented as I_f dependent, $E_0(I_f)$, which can be modeled through the LED datasheet information, where the LED manufacturer shows graphically a curve of ϕ_v vs. I_f and another curve of forward voltage (V_f) vs. I_f. Both curves are obtained under T_0.

The process to obtain $E_0(I_f)$ depends on modeling ϕ_v and V_f as function of I_f at T_0, as shown in Figures 1 and 2, respectively. These curves are approximated by a polynomial interpolation, where $p_\phi(I_f)$ represents the polynomial generated by ϕ_v vs. I_f and $p_v(I_f)$ by V_f vs. I_f. Thus, $E_0(I_f)$ can be given by:

$$E_0(I_f) = \frac{p_\phi(I_f)\phi_0}{I_f p_v(I_f)} \tag{4}$$

where ϕ_0 is the reference flux used to normalize the ϕ_v vs. I_f, according to Figure 1.

Polynomial degree may vary depending on the desired accuracy level. A third degree polynomial is used in this case, enabling a satisfactory approximation model in the whole range of I_f. The graphs presented in Figures 1 and 2 and the respective polynomial approximation refer to Luxeon 3535L (MxA8-PW40-4000K) LED model. The polynomials coefficients of $p_\phi(I_f)$ and $p_v(I_f)$ are, respectively, d_0, d_1, d_2 and d_3, according to (5) and v_0, v_1, v_2 and v_3, according to (6)(6). Section II.D describes the values of these coefficients. Figure 3 shows the variation of E_0 vs. I_f, for the chosen LED model.

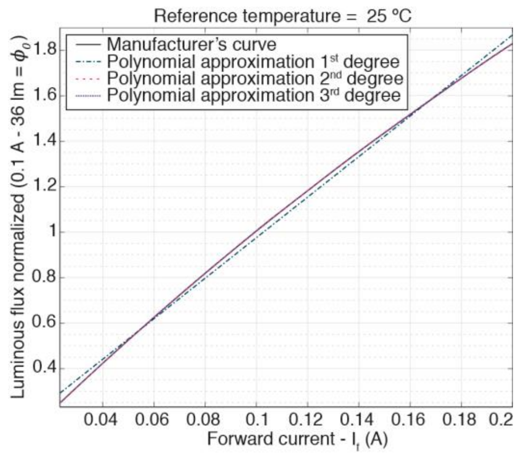

Fig. 1. Normalized ϕ_v as function of I_f (adapted from [16]).

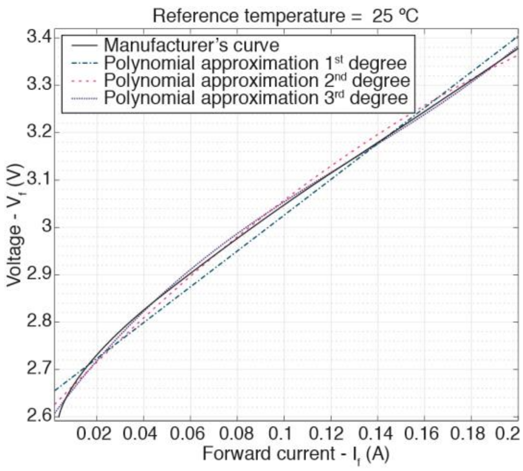

Fig. 2. Vf as function of If (adapted from [16]).

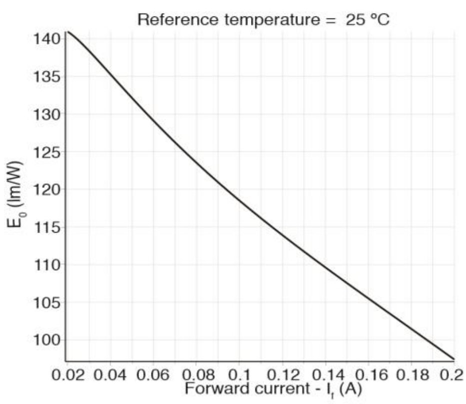

Fig. 3. E0 variation as If function for LED Luxeon 3535L.

$$p_\phi(I_f) = \left(d_3 I_f^3 + d_2 I_f^2 + d_1 I_f + d_0\right) \quad (5)$$

$$p_v(I_f) = \left(v_3 I_f^3 + v_2 I_f^2 + v_1 I_f + v_0\right) \quad (6)$$

B. k_h Coefficient Estimative

The coefficient k_h relates the percentage of electrical power transformed in heat. The methods to obtain k_h are empirical value estimation, as in [10], or performing experimental tests in one integrating sphere, as in [11] and [12]. However, these methods require expensive equipments. Therefore, a method to determine the k_h coefficient without experimental test is highly desirable, saving time and cost in the design. Thus, this study presents a method to obtain the coefficient k_h through the LED datasheet data, avoiding laboratory tests.

It is estimated by spectral power distribution $\varnothing_r(\lambda)$ (SPD) at temperature T_0 provided in the LED datasheet, which is normalized and represented by $\varnothing_{rn}(\lambda)$. As the white LED light radiant spectrum is predominantly in the visible wavelength range, the lumen definition (7) originates a modified lumen definition (8). The modified lumen definition allows determining the coefficient k_n, which reverses the radiant spectrum normalization coefficient. This coefficient is isolated in (8), resulting in (9), where ϕ_v is the total luminous flux at test current (usually the same as ϕ_0), obtained from the LED datasheet. Once the 1931 CIE photopic luminosity function, $V(\lambda)$, can be found in [17], the LED manufacturer datasheet presents the additional necessary data to find k_n. The k_h can be obtained substituting (10) and (11) in (12), since (10) defines the total radiant power ϕ_r, and (11) defines the thermal power P_h, which represents the amount of LED electrical power turned into radiant energy and into heat energy, respectively.

Thus, in order to determine k_h, the normalized values of radiant SPD for each wavelength of the observer $V(\lambda)$ must be obtained, considering the photopic vision. The LED datasheet presents some wavelength corresponding values of the SPD in graphic form, and then the radiant SPD can be approximated by fitting three Gaussian functions, according to (13) where a_i is the amplitude, b_i is the centroid (location), c_i is related to the peak width of a Gaussian function. Section II.D describes these coefficients´ values. Figure 4 presents the approximation results for Luxeon 3535L.

$$\phi_v = 683\int \phi_r(\lambda)V(\lambda)d\lambda \quad (7)$$

$$\phi_v = 683\int K_n \phi_{rn}(\lambda)V(\lambda)d\lambda \quad (8)$$

$$k_n = \frac{\phi_v}{683\int \phi_{rn}(\lambda)V(\lambda)d\lambda} \quad (9)$$

$$\phi_r = k_n \int \phi_{rn}(\lambda) \quad (10)$$

$$P_h = P_{ld} - \phi_r \quad (11)$$

$$k_h = \frac{P_h}{P_{ld}} \quad (12)$$

$$\phi_{rn} = a_1\left(\exp\left(-\left((x-b_1)/c_1\right)^2\right)\right) + a_2\left(\exp\left(-\left((x-b_2)/c_2\right)^2\right)\right) + a_3\left(\exp\left(-\left((x-b3)/c_3\right)^2\right)\right) \quad (13)$$

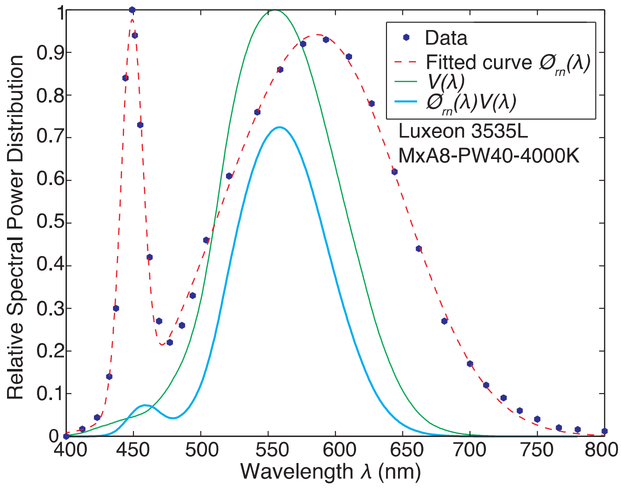

Fig. 4. Radiant spectral approximation for Gaussian functions under T_a=25ºC, and 1931 CIE photopic luminosity function V(λ).

It is important to highlight that, physically, the k_h coefficient varies according to T_j and I_f. However, this effect can be also represented by the $E_0(I_f)$ variation. Although, in this methodology, k_h is considered as constant and its variation is intrinsic to the E_0 variable.

C. Variable Electrical Power (P_{ld})

The LED forward voltage (V_f) decreases quasi-linearly with T_j increase [18]. Therefore, (6) can be rewritten to take into account T_j variation, as shown in (14) [10]. Where k_v is a negative coefficient that represents the ratio of the V_f variation with T_j, presented directly or graphically in the LED datasheet. By inserting (15), found by [11], in (14), and solving for V_f, it is possible to get the voltage as current and thermal parameters function, according to (16). Multiplying (16) by I_f, it results the electrical power (17).

$$V_f = p_v(I_f) + k_v(T_j - T_0) \text{ for } T_j > T_0 \quad (14)$$

$$T_j = T_a + k_h V_f I_f (N_{ld} R_{hs} + R_{jc}) \quad (15)$$

$$V_f(I_f) = \frac{p_v(I_f) + k_v(T_a - T_0)}{1 - k_v k_h I_f (N_{ld} R_{hs} + R_{jc})} \quad (16)$$

$$P_{ld}(I_f) = \frac{p_v(I_f) + k_v(T_a - T_0)}{1 - k_v k_h I_f (N_{ld} R_{hs} + R_{jc})} I_f \quad (17)$$

D. Technical Data

As previously cited, this work employs the LED Luxeon 3535L, model MxA8-PW40 4000K. Table II shows the parameters obtained directly from datasheet and indirectly, through the procedures presented in the former sections.

TABLE II
Parameters Obtained From Luxeon 3535L Datasheet

Method	Symbol	Value
Indirectly obtained Parameters	a_1	0.8866
	b_1	448.9
	c_1	11.29
	a_2	0.9184
	b_2	590.6
	c_2	84.62
	a_3	0.1236
	b_3	514
	c_3	57.56
	d_3	11.5556
	d_2	-12.8667
	d_1	11.3053
	d_0	-0.0082
	v_3	74.5589
	v_2	-28.8816
	v_1	6.7364
	v_0	2.5946
	k_e	-0.0015919[1]
	k_h	0.54
Directly obtained Parameters	$Ø_0$ (lm)	36
	R_{jc} (ºC/W)	33.33
	k_v (mV/ºC)	-3
	T_0 (ºC)	25

E. Estimated Luminous Flux With Variable E_0

The estimated luminous flux with variable efficacy, $E_0(I_f)$, presented in (18), has been validated through an LED bulb lamp tested in an integrating sphere (200 cm diameter) of Inventfine™, according to Figure 5. The proposed theory with variable $E_0(I_f)$ keeps the trend of the measured flux, which makes clear an improvement, once for fixed E_0 the curve behavior would be linear.

$$\phi_V(I_f) = N_{ld}E_0(I_f)\left\{ \begin{array}{l} \left[1+k_e(T_a-T_0)\right]P_{ld}(I_f)+ \\ \left[k_e k_h(N_{ld}R_{hs}+R_{jc})\right]\left(P_{ld}(I_f)\right)^2 \end{array} \right\}. \quad (18)$$

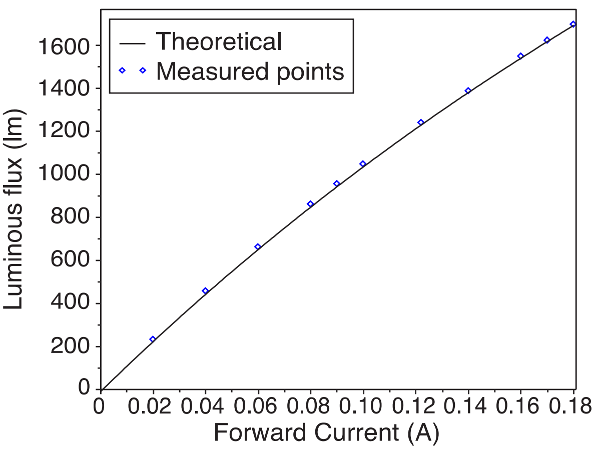

Fig. 5. Comparison between theoretical and experimental luminous flux for an LED bulb lamp with R_{hs}=0.73 ºC/W.

This section presented a procedure to obtain the PET parameters necessary to start a LED system design. However, a second step is necessary, the LED lighting system specifications, which is addressed in Section III.

[1]Linearization between 25ºC and 105ºC.

III. LED LIGHTING SYSTEM SPECIFICATIONS

Three important specifications for a suitable LED lighting system design are: the heatsink thermal resistance, the LED junction temperature, and the overall system luminous efficacy. These specifications are defined considering LEDs' quantity and LEDs' forward current.

Thus, since the designer knows these specifications, it is possible to perform different designs with distinct targets. For example, the focus can be the lamp lifetime, the system luminous efficacy or even the system cost. Another important possibility is to visualize different lighting systems, as different LEDs` quantity or LEDs` current, maintaining same performance and quality requirements.

Therefore, a complete design of a LED lighting system can be performed satisfactorily, where E, T_j, N_{ld}, I_f, total luminous flux, electrical power consumption, lifetime and system cost can be previously estimated.

In order to determine these three specifications, the following mathematical procedure is proposed:

1) Heatsink thermal resistance (R_{hs}): The R_{hs} definition is performed inserting (4) and (17) into (18), resulting in:

$$R_{hs}(I_f,N_{ld}) = \frac{-\left\{ \begin{array}{l} N_{ld}E_0(I_f)I_f\left[\begin{array}{l} p_V(I_f)k_e k_V(T_0-T_a)+k_V p_V(I_f) \\ +k_V^2(T_a-T_0)-k_e(p_V(I_f))^2 \end{array} \right] \\ +2K_V\phi_V(-1+k_V k_h I_f R_{jc}) \\ -\sqrt{(-k_V T_a-p_V(I_f)+k_V T_0)^2 N_{ld}I_f E_0(I_f)A} \end{array} \right\}}{2\phi_V k_V^2 k_h N_{ld}I_f} \quad (19)$$

where,

$$A = N_{ld}E_0(I_f)I_f\left(k_V^2-2k_e k_V p_V(If)+k_e^2(p_V(I_f))^2\right)+4k_V\phi_V k_e. \quad (20)$$

2) LED junction temperature (T_j): The LED junction temperature T_j is estimated inserting (16) into (15) and R_{hs} is replaced according to (19), resulting in:

$$T_j(I_f,N_{ld}) = T_a+\left(R_{jc}+R_{hs}(I_f,N_{ld})N_{ld}\right)k_h \left(\frac{p_V(I_f)+k_V(T_a-T_0)}{1-k_V k_h I_f\left(N_{ld}R_{hs}(I_f,N_{ld})+R_{jc}\right)}I_f\right). \quad (21)$$

The assumption of k_h constant to estimate T_j is an approximation. The error caused by this approximation is not significant, due the small temperature ranges of the system. However, if higher accuracy is desired, the variable k_h parameter can be obtained as presented in [12], which demands experimental tests.

3) System luminous efficacy (E): The system luminous efficacy E is calculated inserting (17) into (2) and R_{hs} is replaced according to (19), resulting in:

$$E(I_f, N_{ld}) = E_0(I_f)\left[\begin{array}{c} 1 + k_e(T_a - T_0) + k_e k_h (R_{jc} + R_{hs}(I_f, N_{ld}) N_{ld}) \\ \left(\dfrac{p_v(I_f) + k_v(T_a - T_0)}{1 - k_v k_h I_f (N_{ld} R_{hs}(I_f, N_{ld}) + R_{jc})} I_f\right) \end{array}\right]. \quad (22)$$

In this methodology stage, it is possible to perform a graphical analysis and predict the design results. Figure 6 shows the three parameters (R_{hs}, T_j, E) variation as I_f function considering just one LED. This estimative considers T_a of 30 ºC and different possibilities for the luminous fluxes, distinguished by different line colors. The ordinates axis represents, simultaneously, the R_{hs}, T_j and E.

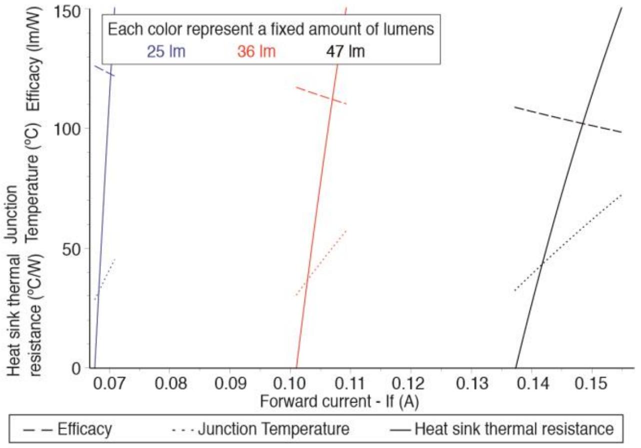

Fig. 6. PET parameters (R_{hs}, T_j, E) variation as forward current function (Luxeon 3535L).

A. Proposed Methodology Resume

Aiming to resume the proposed methodology, Figure 7 presents a methodology flowchart. The first step is to obtain the parameters from the LED datasheet (Table II). After that, the coefficients are calculated to be used in the system specifications (data process – Section III). Finally, the results are graphically presented (design space), enabling the designer to define the system characteristics.

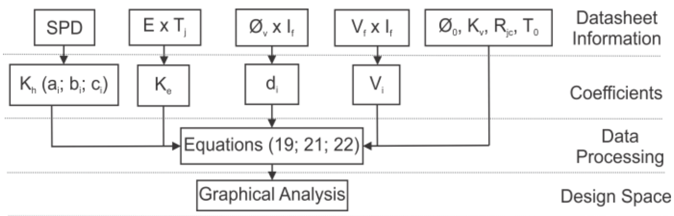

Fig. 7. Methodology flowchart.

IV. DESIGN EXAMPLE

An LED bulb lamp that employs the LED Luxeon 3535L, model MxA8-PW40-4000K, is used as a methodology design example. This lamp must comply with the requirements present by 389 INMETRO ordinance and Energy Star requirements [19]-[21] besides obtaining the energetic efficiency Procel Seal. Therefore, LED lamp must provide a luminous flux of 1100 lm with a luminous efficacy higher than 80 lm/W. Table III presents the main requirements that the LED lamp must comply.

TABLE III
LED Bulb Lamp Requirements

Requirement	Value
Minimum Efficacy	80 lm/W
Minimum Lifetime	25000h
Maximum variation of chromaticity coordinates	0.007
Luminous Flux to replace a 75W incandescent lamp	1100 lm

Considering the diffuser efficiency equal to 90% and the electronic driver efficiency equal to 85%, according to Figure 8, the LEDs must provide approximately a luminous flux of 1223 lm and a minimum luminous efficacy of 110 lm/W, aiming to result in a lamp with luminous efficacy of 85 lm/W and a total luminous flux of 1100 lm.

Other important parameter is the LED lifetime, which is related to T_j and I_f. For this LED model, T_j must be below 105ºC and the maximum I_f is 150 mA, to guarantee a lifetime of 25,000 hours, according to lumen maintenance and reliability LED LM-80 manufacture report [22]. Furthermore, considering these values, the chromaticity change is 0.0054 after 6,000 hours tests, which is in conformity with IES-LM-80, approved method for measuring lumen maintenance of LED light sources. Once defined the parameters and performance requirements, a design space for the LED bulb lamp is generated, as shown in Figure 6. It is important to mention that the bulb presents a preset R_{hs} = 7.7 ºC/W. Thus, there are two parameters to be analyzed, E and T_j, which are related to I_f and N_{ld}. Table II presented the used parameters to generate the design space. The maximum lamp N_{ld} possible is 50, considering physical space of the lamp bulb.

Figure 9 presents that for $E \geq 110$ lm/W the minimum N_{ld} is 41. Therefore, for achieving the required E, considering the space limitation, it is feasible an LED bulb lamp with N_{ld} between 41 and 50. Regarding T_j, for the N_{ld} possibilities, all range is in agreement with the requirement of T_j below than 105 ºC, according to Figure 10. Then, it was defined an LED bulb lamp with 41 LEDs connected in series, supplied by a forward current I_f of 94 mA.

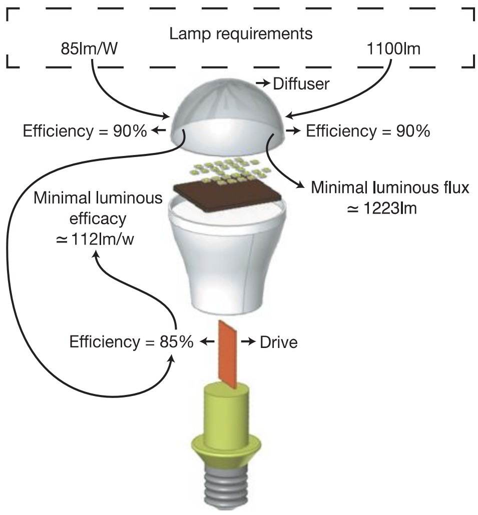

Fig. 8. LED bulb lamp: requirements and losses.

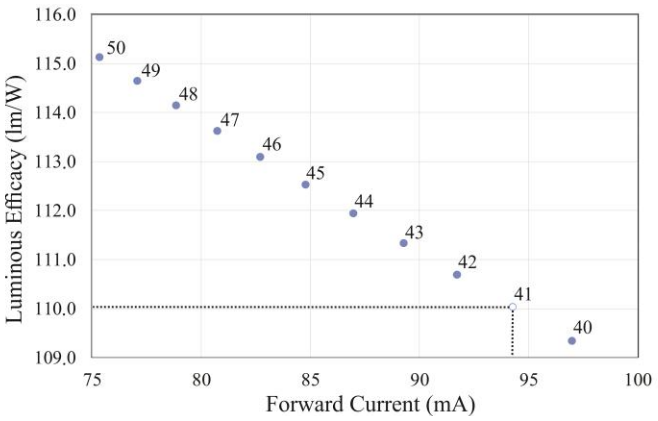

Fig. 9. Luminous efficacy, forward current and LEDs` quantity, for a LED lamp with 1100 lm.

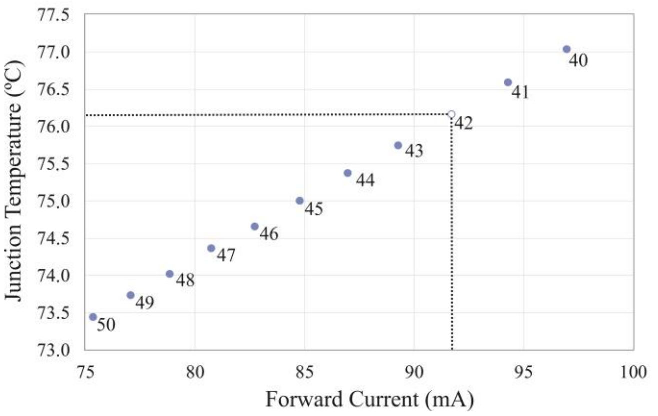

Fig. 10. Junction temperature, forward current and LED´s quantity, for a LED lamp with 1100 lm.

V. EXPERIMENTAL RESULTS

The results obtained in the design example were used in order to validate the previously analysis, an LED bulb lamp (R_{hs} = 7.77 ºC/W) composed by 41 LEDs, with I_f equal to 94 mA was built and experimentally verified. With these specifications, a luminous efficacy of 110 lm/W, a total luminous flux of 1223 lm and a junction temperature of 76.6 ºC are expected, which are according to the design example presented in Section IV.

Experimental tests were performed using an integrating sphere with a spectrophotocolorimeter. The junction temperature was estimated by measuring the LED pad temperature with a k-type thermocouple, using the power applied and the resistance R_{jc}, as in [23]. At least two measurements were performed, at 15 minutes intervals, checking if the variation between the measurements of voltage and luminous flux were smaller than 0.5%. This ensures the system stabilization, as described in [24].

Figure 11 represents a comparative graphic between theoretical and experimental ϕ_v related to I_f, which shows a high accuracy level. A small deviation between theoretical and experimental values are observed for high forward current values. This effect occurs due the approximations considered in some parameters, e.g. k_h and k_v coefficients, and variations in thermal resistances, which are more significant under high currents.

Figure 12 presents thermography image for defined I_f, which shows the temperature distribution among the LEDs. Table IV shows theoretical and experimental results and the respective errors, according to (23). As can be observed, the experimental results validated the proposed methodology, presenting a luminous flux of $\phi_v = 1271$ lm with $E = 112$ lm/W.

$$error(\%)= \frac{(measured - calculated)}{measured} * 100 \quad (23)$$

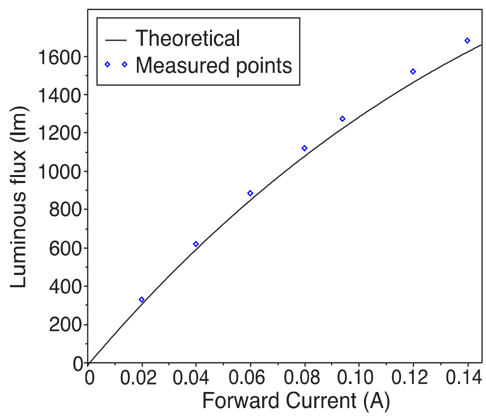

Fig. 11. Theoretical and experimental Øv vs. If for the lamp.

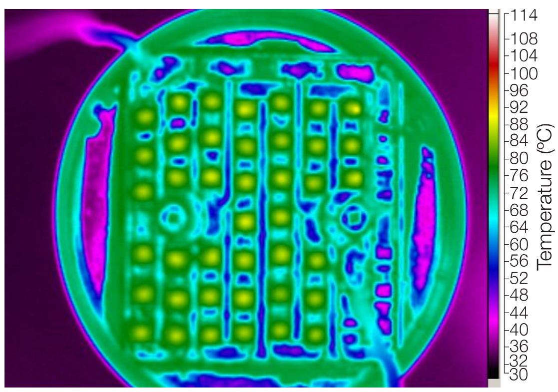

Fig. 12. Thermography image of bulb lamp for If equal to 94mA.

TABLE IV
Comparison Between PET Methodology Design and Experimental Results

Number of LEDs	Ambient temperature (ºC)	R_{hs} (ºC/W)	Forward current (A)	Luminous flux (lm) calculated	Luminous flux (lm) measured	Luminous flux (lm) error (%)	Luminous efficacy (lm/W) calculated	Luminous efficacy (lm/W) measured	Luminous efficacy (lm/W) error (%)	Junction temperature (ºC) calculated	Junction temperature (ºC) estimated	Junction temperature (ºC) error (%)
41	24.3	7.77	0.094	1224.65	1271.7	3.70	110.25	112.36	1.88	76.6	79.67	3.85

VI. CONCLUSION

This paper presented an alternative to obtain the PET parameters that avoids any experimental test or simulation to perform LED lighting system design. The PET theory allows the designer previously define the system specifications. The main improvements of the proposed methodology are obtaining k_h coefficient without experimental tests, based only on datasheet information; definition of a dynamic E_0, which is dependent on forward current; and equations optimization to obtain the LED lighting system specifications.

An LED bulb lamp (R_{hs} = 7.77 ºC/W) design example was performed considering some important standards to define the system features, as system efficacy, lifetime, total luminous flux, among others. For contemplating these requirements three main specifications were considered (R_{hs}, T_j and E) as functions of the LEDs` current and LEDs` quantity. Experimental results prove the feasibility of the proposed methodology, through the analysis of the following specifications: luminous flux, luminous efficacy, and LED junction temperature. The errors between calculated and experimental values for these variables were 3.70%, 1.88%, and 3.85%, respectively.

Therefore, the proposed methodology facilitates the optimization and the previously definition of the desired features of lighting systems. Moreover, the design methodology provides time and energy savings, cost reductions due an optimized design, among others benefits. Thus, it is possible to define the minimum system requirements and to design the system with emphasis in the desired characteristics.

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BIOGRAPHIES

Leandro Chies, born in Caxias do Sul, Brazil, in 1983. He received the B.S. degree in automation and control engineering from University of Caxias do Sul, in 2013 and M.Sc. degree in electrical engineering from the Federal University of Santa Maria, Brazil, in 2016. Since 2015 he is Professor at the Federal Institute of Santa Catarina, Brazil. His research interests include light-emitting-diode systems and image processing.

Maicol Flores de Melo, born in Cacequi, Brazil, in 1989. He received the B.S. and M.Sc. degrees in electrical engineering from the Federal University of Santa Maria, Santa Maria, in 2012 and 2014, respectively. Currently, he has been working toward the Ph.D. in the Gedre - Intelligence in Lighting research group. Since 2015 he is Professor at the Federal Institute Sul-rio-grandense, Brazil. His research interests include dc/dc converters, power factor correction stages, lighting systems based on LEDs, renewable energy systems and integration of renewable energies and lighting systems.

William Dotto Vizzotto, born in 1993. He received the B.S. degree in electrical engineering from the Federal University of Santa Maria in 2017. He is researcher at Gedre - Intelligence in Lighting research group since 2011. He has as main research topics: intelligence in lighting, DC-DC converters, LEDs, RGB LEDs, renewable energies and street lighting.

Rudimar Spannemberg Junior, born in Santa Maria, Brazil, in 1993. He is currently pursuing the Degree in electrical engineering at the Federal University of Santa Maria. He have been carrying out the activities of research with the Gedre - Intelligence in Lighting research group since 2014. His main areas of interest are LEDs, LED drivers, street lighting, renewable energy and DC-DC converters.

Vitor Cristiano Bender, born in Panambi, Brazil, in 1987. He received the B.S. degree in Electrical Engineering from Regional Northwest University of Rio Grande do Sul State (UNIJUI) in 2011 and M.Sc. and PhD. degree from the Federal University of Santa Maria (UFSM) in 2012 and 2015, respectively. From 2015 to 2017 he was a professor at the Federal University of Pampa (UNIPAMPA). Currently, he is a professor in Federal University of Santa Maria where he has been working as researcher with GEDRE – Intelligence in Lighting Research Group, at Santa Maria, Rio Grande do Sul, Brazil. His research interests include: lighting systems, electronic ballasts, LED and OLED drivers, LED and OLED modeling and thermal design.

Marco Antônio Dalla Costa, born in Santa Maria, Brazil, in 1978. He received the B.S. and M.Sc. degrees in electrical engineering from the Federal University of Santa Maria, Brazil, in 2002 and 2004, respectively, and the Ph.D. degree (with honors) in electrical engineering from the University of Oviedo, Gijón, Spain, in 2008. From 2008 to 2009 he was Associate Professor at the Universidade de Caxias do Sul, Brazil. Since 2009 he is Professor at the Federal University of Santa Maria, Brazil. Dr. Dalla Costa is coauthor of more than 50 journal papers and more than 100 international conference papers, and is holder of 2 Spanish patents. He is also the Vice-Chair of the Industrial Lighting and Displays Committee (ILDC) from the IEEE Industry Applications Society and serves as reviewer for several IEEE Journal and Conferences in the field of power electronics. His research interests include dc/dc converters, power factor correction, lighting systems, high-frequency electronic ballasts, discharge-lamp modeling, light-emitting-diode systems, renewable energy systems, solid state transformers, and visible light communications.