

EXPERIMENTAL CHARACTERIZATION REGARDING TWO TYPES OF PHOSPHOR-CONVERTED WHITE HIGH-BRIGHTNESS LEDs: LOW POWER AND HIGH POWER DEVICES

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Abstract – This paper describes an experimental photometrical analysis regarding two mainstreams inside the high-brightness LED family: the power devices, so-called high power LEDs, and the low power devices. Focus is given to white phosphor-converted LEDs, which are used in LED-based luminaires for indoor and outdoor lighting. Data from several LEDs used in available luminaires are compiled and provided as photometrical references for the design considerations in light output of LED drivers which employ power electronic converters.

Keywords – High-Brightness LEDs, Light-Emitting Diodes, Photometry, Phosphor-Converted White LEDs, Power White LEDs, Solid-State Lighting

I. INTRODUCTION

Lighting systems have been experiencing a huge evolution, specifically in the past decades, underpinned by the use of power electronics in the process of driving newer light sources which aim energy efficiency. By the last and present decades, a new lighting concept has emerged: the use of white LEDs as light source. This new Solid-State Lighting (SSL) concept arises with the promise of being an efficient, durable and environmentally friendly technology.

Estimations are that energy consumption for producing artificial lighting could be reduced up to 50% [1] using them to substitute filament or gas discharge-based lamps.

Technological advances allowed LEDs to reach a luminous efficiency¹ of 150 lm/W [2], high color rendering index (CRI) and long lifespan. These features accredit LEDs to a position of prominence and allowed them to find place both in indoor and outdoor applications, i.e. street lighting, since the nature of the emitted light shows to be suitable for low-mesopic conditions (typical of street lighting) [3].

Most of currently commercially available white LEDs are made of nitride-based semiconductors (InGaN, GaN) [4]. These devices emit blue light (approximately 440 nm) and a cerium-doped yttrium-aluminum garnet (YAG) phosphor coat ensures the white light emission [5]. For this reason, these LEDs are called PC-LED (Phosphor-Converted LED).

The currently commercially available LED luminaires can be divided into two main groups: those which use low power high-brightness LEDs (HB LEDs, 20 mA at nominal flux, typically), and those which use high power high-brightness

LEDs (HP LEDs, typical currents for nominal flux of 350 mA to 1000 mA). Fig. 1 shows some indoor and outdoor light products using HB and HP LEDs. Fig. 2 shows these two types of LEDs in detail.

For maintaining the overall efficiency of a lighting system employing LEDs, power electronics is the main choice for drivers. But for the power electronic converter, the LED is only an electrical load (a non-linear one).

The photometrical characterization of LEDs is then of great value, considering that electrical power measurements alone cannot determine the light output of an LED module, luminaire or device, or other important characteristics for the human observer, such as color sensation and color rendering indexes (CRI). Flux measurements play an important role on determining the perceived light output.

For instance, the greater lumen output of a more efficient device can greatly reduce the amount of electrical power that needs to be managed by the power electronic converter (driver), while still maintaining the desired light output of the whole lighting equipment (e.g., a LED-based luminaire).

In this sense, power electronics and photometry must be used side by side for determining the performance of an LED-based lighting equipment. One of the main objectives of this work is then to interface these two areas of knowledge, providing important photometric data for the development of power electronic LED drivers.

This paper brings an analysis concerning electrical and photometrical characteristics of these two types of LED. LEDs from different generations were selected in order to experimentally show the evolution of the devices. All photometric data were obtained using an integrating sphere. Three HB LEDs of different manufacturers and six different HP LEDs from four manufactures were analyzed.

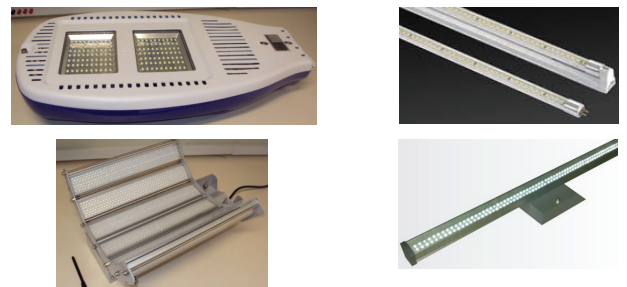


Fig. 1. Commercially available LED-based luminaires, separated by types and technologies: on the top, a street lighting (left) and an indoor lighting (right) luminaires, both based in power white PC-LEDs. On the bottom, a street lighting (left) and an indoor lighting (right) luminaires, both based in low power PC-LEDs.

¹ Following the explanation given in [4], this paper employs the terminology “luminous efficiency” instead of “luminous efficacy”.



Fig. 2. HP (left) and HB (right) LED types.

II. PACKAGING AND THERMAL CHARACTERISTICS AND DIFFERENCES

The currently available LEDs convert 15% to 25% of electrical power into visible radiation, emitting low levels of IR or UV radiation (or none at all) [6]. Therefore, the rest of the power not converted into light is wasted as heat.

The efficiency and the lumen output of the devices are strongly dependents on its junction temperature. If no thermal dissipation is provided, the LED can overheat, causing degradation of the photometrical characteristics, shortening of its lifetime or even catastrophic failure [4].

According to [7], an LED-based equipment becomes interesting for illumination when its luminous flux reaches 1200 to 1500 lumens, while still maintaining reliability. Consequently, the equipment purposed for lighting often requires the spreading of many LEDs in a limited surface or heat sink, what brings up the thermal issue.

HB LEDs nominal currents are fairly low (ca. 20 mA). For this reason, as can be seen on Fig. 2, its package has no heat dissipation structure. This type of package is the same type of those employed on the early models of LEDs and has a high thermal resistance, for about 250 K/W.

On the other hand, HP LEDs' packaging has a thermal path for heat dissipation, like a metal slug in which the substrate sits. With the evolution of the devices, different packages were designed by the manufacturers. Currently, packages using heat sink slugs of Al or Cu are popular [8]. These structures are used to transfer heat from the chip to a metal core printed circuit board or heat sink. Typical thermal resistances range from 6 to 12 K/W, much lower than the HB LEDs [4], allowing these devices to withstand higher power levels, while still managing thermal stress.

III. SELECTED LEDs

Several different technologies of white PC-LEDs can be found on the market. They differ from each other in many characteristics like packaging, rated current, correlated color temperature (CCT), etc. For this reason, the task of selecting LEDs for an experimental characterization might be hard.

On this study, nine different devices were selected, from which six are classified as HP LEDs and the other three are HB LEDs (two of these HB LEDs are actually used on commercially available luminaires). Table I brings the selected LEDs' name, the manufacturer, the correlated color temperature informed on datasheet and the year of fabrication of each one, whenever known, in order to show its generation.

These LEDs were all subjected to the experiments described on next section.

TABLE I
Selected LEDs

LED Number	LED name	Manufacturer	CCT (K)	Year of Fabrication
HP LEDs				
1	Luxeon III Emitter LXHL-PW09 ^[9]	Philips LumiLEDs	5,500	2006
2	Apollo XZCW10X106W ^[10]	SunLED	N/A	2008
3	EHP-AX08EL/GT01H-P01 ^[11]	Everlight	5,650	2009
4	EHP-AX08EL/LM01H-P01 ^[12]	Everlight	3,250	2009
5	Golden Dragon Oval Plus LCW W5PM ^[13]	Osram	3,500	2010
6	Golden Dragon Oval Plus LUW W5PM ^[14]	Osram	6,500	2010
HB LEDs				
7	LL1503SEWW1-301 ^[15]	Ledman	7,800	2005
8	LUW503F43 ^[16]	Wenrun	N/A	2006
9	Generic Brand*	N/A	N/A	N/A

N/A – information not available.

* commonly found in electronic stores.

IV. EXPERIMENT DESCRIPTION AND DATA

Each LED was fed with a controlled DC current source. The current level was increased slowly. At each step, measurements of device voltage, forward current, photopic luminous flux, average CRI and CCT were taken.

For HB LEDs, the current was varied from 5 mA to 50 mA in steps of 5 mA. For HP LEDs, the current interval analyzed was from 100 mA to 700 mA with steps of 100 mA. In the case of the HP LEDs, only one device was mounted on a heat sink and inserted in the integrating sphere, which is 40 inches (ca. 1 meter) in diameter. For the HB LEDs, series strings comprising 25 devices of each brand were used in order to match the power level of the HP LEDs.

Table II brings some photometrical data, in which the LEDs were fed with rated current. Temperature measurements were done on the heat sink of the HP LEDs and on the terminals of the HB LEDs, using a laser thermometer. Room temperature was measured 28° C.

TABLE II
Summary of Measured Data

LED Number	Luminous Flux	CCT	CRI	Temperature
HP LEDs @ 350 mA				
1	30.22 lm	7,741 K	77.5 %	32,0 °C
2	55.37 lm	6,962 K	73.8 %	31,0 °C
3	92.73 lm	6,455 K	75.2 %	33,5 °C
4	54.47 lm	3,061 K	81.7 %	32,0 °C
5	84.05 lm	4,023 K	84.8 %	31,0 °C
6	104.50 lm	5,950 K	71.9 %	31,0 °C
HB LEDs @ 20 mA				
7*	70.28 lm	5,940 K	79.2 %	41,0 °C
8*	101.50 lm	6,797 K	77.9 %	37,0 °C
9*	62.90 lm	63,571 K	82.6 %	37,0 °C

* series strings comprising 25 devices of each type.

The luminous fluxes of the HP LEDs were all obtained for a 350 mA current, thus all devices were operating with roughly the same power, since the forward voltage of all LEDs is closely the same at this current. From the table, large variations of flux between devices can be noticed, which implies obvious differences on luminous efficiency.

The CRI for all HP LEDs is roughly the same, with the exception of the warm-white types (LEDs 4 and 5). It seems that warmer LEDs tend to have better CRI, indeed. The color temperature for all cool-white HP LEDs is above 5500 K, in all cases, sometimes higher than 6500 K.

Great deviation of rated parameters (from Table I) was noticed for some of the LEDs, especially for the older models, such as LEDs no. 1 and 7.

For LED no. 9, a generic brand, great discrepancy of CCT can be noticed, compared to the other devices. This points to a very poorly constructed LED, with a very thin or inefficient phosphor coat to properly shift blue radiation to longer wavelengths, giving away light with a bluish aspect. This unidentified LED is one of the many that can be readily bought in electronic stores. These LEDs seem to be not manufactured aiming controlled and precise photometrical outputs, and therefore are not indicated for use in LED luminaires.

It is interesting to observe that the temperature measured on the HB LEDs is higher than the temperature of the HP LEDs. This might be because the HB LEDs have no appropriate means of heat dissipation. Additionally, the power fed to HB LEDs strings is about 27 % higher than the power fed to the HP LEDs (ca. 1.1 W for the HP and 1.5 W for the HB LEDs). Thus, this result is expected, since major part of the delivered power is converted into heat, as already addressed.

Figures 3 and 4 show the relative spectral power distributions (SPD) for all of the LEDs tested, each figure for one of the two main kinds subdivided for this experiment. Figures 5 to 7 depict the on-state electrical characteristics of all LEDs used in the experimental assessments, the voltage points being plotted for each measured currents.

Other interesting data to depict is how does the luminous efficacy (lm/W) correlates to increasing currents. It can be shown by Figures 8 and 9 that a typical phenomenon called “droop” [17] takes place, reducing overall efficiency when operating the LED in higher currents.

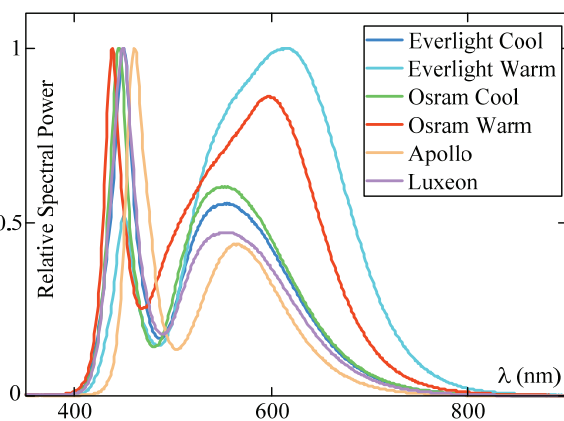


Fig. 3. Relative SPDs for the power HB LEDs (HP LEDs) tested.

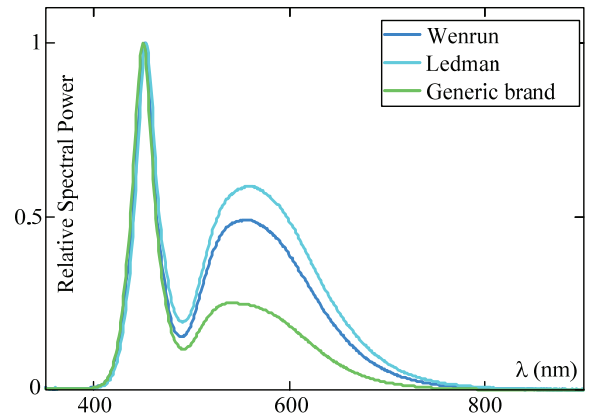


Fig. 4. Relative SPDs for the low power (HB) LEDs tested.

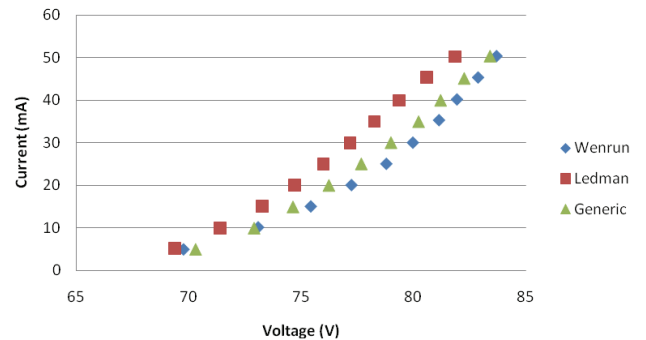


Fig. 5. On-state voltage vs. current characteristics of the HB LEDs strings (series associated).

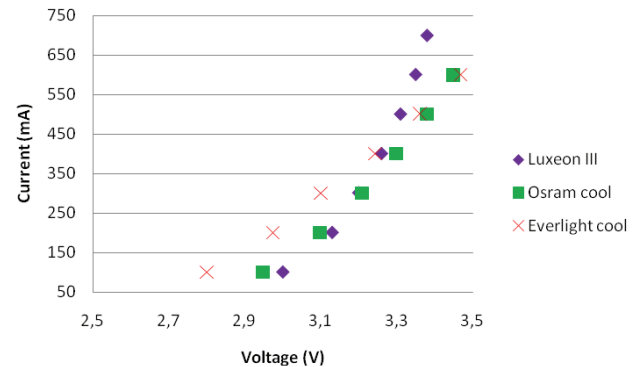


Fig. 6. On-state voltage vs. current characteristics of the first three HP LEDs from Table I.

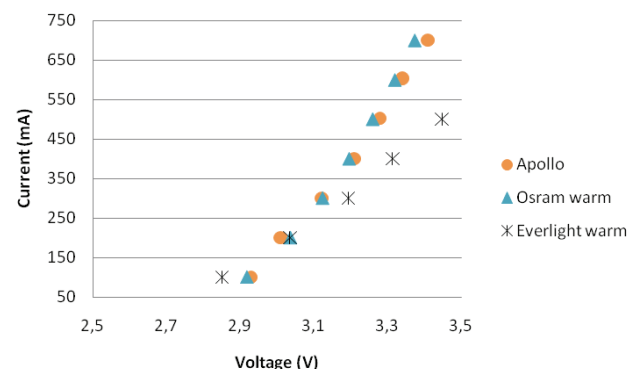


Fig. 7. On-state voltage vs. current characteristics of the last three HP LEDs from Table I.

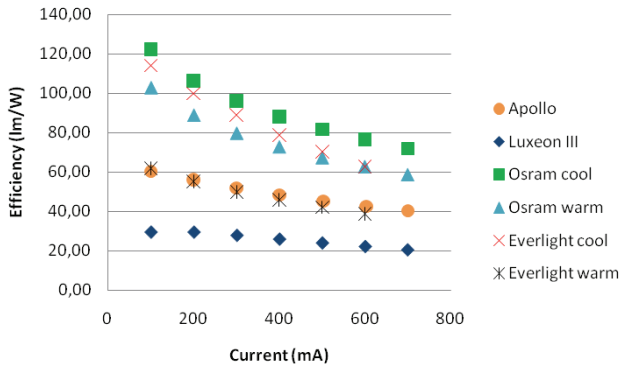


Fig. 8. Efficiency droop for the HP LEDs.

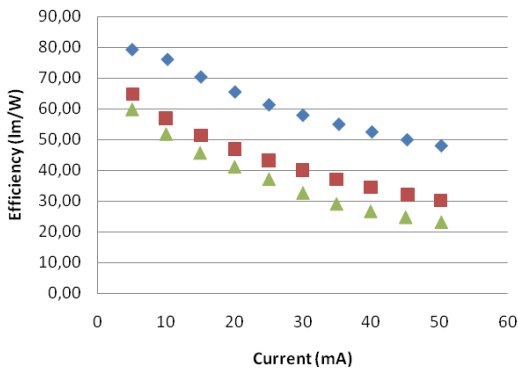


Fig. 9. Efficiency droop for the HB LEDs strings.

It is obvious from the above figures that the most recent LEDs, of the same kind and color temperature, present greater efficiencies than older ones. This is the expected trend of the technology, and could be easily verified in this experiment.

Also important to stress is that when one compares a warmer LED (i.e., with lower CCT) and a cooler LED (i.e., with greater CCT), if both are the same generation, type and model, as in the case of the Osram and Everlight brands tested, the efficiency of the warmer LEDs is always lower than the efficiency of the cooler LEDs. This is because warmer LEDs use a thicker phosphor coating in order to shift more of the blue light to longer wavelengths, a not very efficient process, reducing overall luminous efficiency. This wavelength shift can be clearly seen on Fig. 3, where the warmer LEDs present an increased peak close to 600 nm, compared to the cooler ones.

The time evolution of efficiency in the past half-decade can be more clearly verified in Fig. 10 and Fig. 11, which present the luminous fluxes at rated current for all the tested HP LEDs and their respective generations.

V. A DESIGN METHODOLOGY EXAMPLE

A design methodology for electronic LED drivers could be derived employing the data gathered regarding these two types of LEDs. This methodology could be applied in order to decide whether it is more adequate to employ one or the other LED type on a luminaire, i.e., HB or HP LED strings and their respective drivers.

For this design example, let it be supposed that one wishes to design a luminaire to replace one common fluorescent luminaire which employs two tubular fluorescent T8 lamps

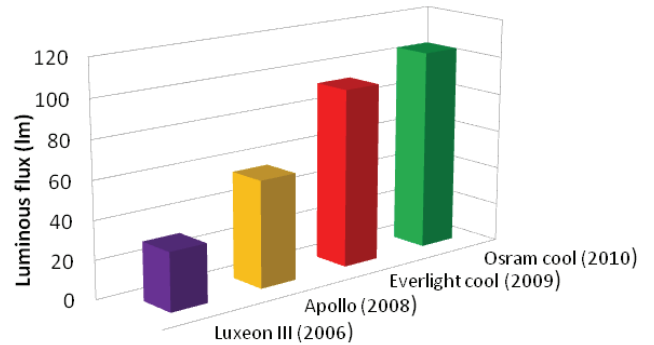


Fig. 10. Measured luminous fluxes at rated current of HP PC-LEDs from experiment (cool white only).

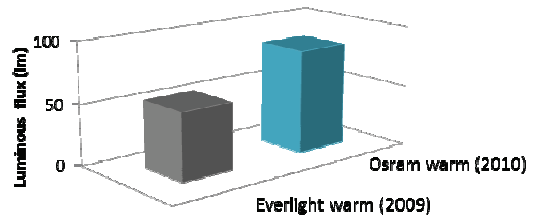


Fig. 11. Measured luminous fluxes at rated current for warm white HP PC-LEDs of two different generations.

of 32 W each, used commonly for indoor lighting. This luminaire should yield almost 6,400 lumens, considering the typical efficiency of 100 lm/W for the lamps operated at high frequency, driven by electronic ballasts [18].

The desired color temperature chosen will be somewhere between 5,800 K and 6,800 K. The input voltage of the driver is chosen 127 V (AC) from mains, as commonly used in indoor lighting for this kind of luminaire.

Let it also be set that string voltage is restrained to an arbitrary maximum, limiting the amount of LEDs which can be associated in series, therefore creating a multi-stringed luminaire, which is more reliable – less flux loss in case of string failure.

For simplicity, a buck converter will be used as the driver for each string of the luminaire, without an input power factor corrector (PFC). The LEDs in each string are associated in series, in order to ensure that all devices share the same current, while each buck converter will have the task of ensuring a constant average current for its string, due to its current source output characteristic. This scheme ensures current equalization for all strings, and automatically for all LEDs.

This strategy of using paralleled buck converters could be easily and cheaply performed by small integrated-MOSFET monolithic switching regulators fed at high voltage, similar to the LM340xHV family [19], which only need few external components (inductor, free-wheeling diode, current sensing and supply resistors, bypass and bootstrap capacitors).

The proposed multi-string modular luminaire can be represented as in Fig. 12, where input DC-bus voltage V_B is the rectified-mains peak voltage, in this case ca. 180 V. The output voltage is arbitrated to be 120 V maximum, and two design methodologies will be drawn – one for an HP LED and the other for an HB LED.

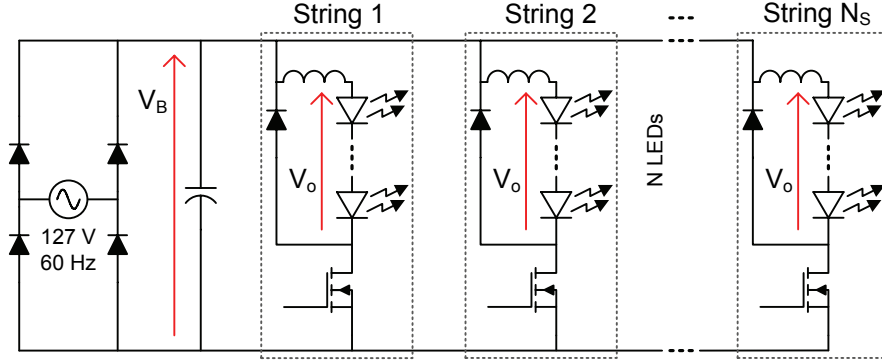


Fig. 12 – Proposal of a simplified multi-stringed LED luminaire, based on paralleled buck converters.

The design constraints for this luminaire are compiled in Table III.

TABLE III
Design Constraints for LED Luminaire

Parameter	Symbol	Value
Input voltage (rectified mains)	V_B	180 V
Maximum output voltage	$V_{o,max}$	120 V
Luminous flux output	F_o	6,400 lm
Overall color temperature	TCC	5,800-6,800 K
LED current	I_{LED}	LED-nominal

From these design constraints and choosing the two best (more efficient) LEDs, one of each kind of devices tested, the designer is left with the load parameters of Table IV.

TABLE IV
Parameters of Chosen LEDs (converters' load)

Parameter (one single device)	LED Chosen	
	Osram Cool White LUW W5PM	Wenrun Cool White LUW50F43
LED type	HP LED	HB LED
LED voltage – V_{LED}	3.26 V	3.1 V
LED current – I_{LED}	350 mA	20 mA
LED flux – F_{LED}	104.5 lm	4.06 lm
LED color – TCC_{LED}	5,950 K	6,797 K

The design steps are as follows.

For attaining the desired flux, the luminaire should comprise a determined number of LEDs – N , rounding up the result from (1).

$$N = \frac{F_o}{F_{LED}} \quad (1)$$

Then, the number of strings N_s is calculated from the maximum output voltage constraint, approximating the result from (2), also up.

$$N_s = \frac{N \cdot V_{LED}}{V_{o,max}} \quad (2)$$

The number of LEDs per string is then defined by (3).

$$N_L = \frac{N}{N_s} \quad (3)$$

And the output voltage at each string will be given by (4).

$$V_o = N_L \cdot V_{LED} \quad (4)$$

The buck conversion ratio, M , will be given by (5), where D is the duty cycle, considering a continuous conduction mode (CCM) operation.

$$M(D) = D = \frac{V_o}{V_B} \quad (5)$$

The output power at each string can be calculate from (6).

$$P_S = V_o \cdot I_{LED} \quad (6)$$

From which follows that the total power output is given by (7).

$$P_o = P_S \cdot N_s \quad (7)$$

The input power of the luminaire can then be found by (8), considering that each buck converter has an efficiency η .

$$P_{in} = N_s \frac{P_S}{\eta} = \frac{P_o}{\eta} \quad (8)$$

And the overall luminous efficiency of the luminaire (lm/W at the input) will be given by (9).

$$\eta_{lum} = \frac{N \cdot F_{LED}}{P_{in}} \quad (9)$$

From these equations, it is then possible to know the number of strings and converters, power input and overall luminous efficiency of the proposed modular multi-string LED luminaire.

A. Design Employing HP-LEDs

Using equations (1) to (9) and the parameters for the Osram LUW W5PM Cool White HP-LED from Table IV, the resulting design is as shown in Table V. The estimated efficiency for each buck converter is 95%.

TABLE V
Resulting Design Employing HP-LEDs

Luminaire Parameter	Calculated Value
Number of LEDs – N	62
Number of strings / converters – N _S	2
Number of LEDs per string – N _L	31
Voltage output at each string – V _o	101.06 V
Buck conversion ratio / duty cycle – M / D	0.5614
Power at each string – P _S	35.37 W
Total output power – P _o	70.74 W
Power at luminaire input – P _{in}	74.46 W
Total output flux – N.F _{LED}	6,479 lm
Overall luminous efficiency of luminaire – η _{lum}	87 lm/W

B. Design Employing HB-LEDs

Using the same equations and the parameters for the Wenrun LUW50F43 Cool White HB-LED from Table IV, the resulting design is as shown in Table VI. The estimated efficiency for each buck converter is also 95%.

TABLE VI
Resulting Design Employing HB-LEDs

Luminaire Parameter	Calculated Value
Number of LEDs – N	1,599
Number of strings / converters – N _S	41
Number of LEDs per string – N _L	39
Voltage output at each string – V _o	120.9 V
Buck conversion ratio / duty cycle – M / D	0.6717
Power at each string – P _S	2.42 W
Total output power – P _o	99.22 W
Power at luminaire input – P _{in}	104.44 W
Total output flux – N.F _{LED}	6,492 lm
Overall luminous efficiency of luminaire – η _{lum}	62 lm/W

Both of the designs have a luminous output within 1.5% of desired flux and both meet the color and maximum output voltage constraints.

But, in this case, from these two designs, compared side by side, there is good evidence in favor of the HP-LED technology – better overall luminous efficiency, reduced amount of LEDs, smaller number of strings and driving buck converters at each string (which reduces overall cost) and also lower energy consumption, since input power was lower due to higher efficiency of the LED devices themselves.

Though a design with more strings represents less flux reduction in case of a string failing, employing fewer compo-

nents (LEDs and drivers) turns out to be cheaper and easier to assemble into a luminaire. The reliability then also becomes another variable to be considered, when choosing between both designs.

VI. CONCLUSION

This paper brought an experimental analysis about the HP and HB LEDs' photometrical performances. Several devices were experimentally assessed, by using an integrating sphere and spectrophotometer to acquire relevant data. Electrical parameters were also taken to be correlated to some of the photometrical measurements. An analysis on the evolution of the technology was also drawn, based on the increase of luminous flux over time, for devices driven under same forward current.

It has also been shown that, when designing a LED-based luminaire, the electrical, photometrical and constructive differences between both types of LEDs become critical in choosing one in favor of the other.

It is possible to conclude that HP LEDs have better features for use in the majority of lighting applications, because they have a better luminous efficiency and emit more flux per device than HB LEDs, allowing the use of a reduced number of LEDs per fixture, properly mounted on heat sinks.

Thermal management issues are more easily worked on outdoor lighting fixtures, because, in general, the available space for the heat dissipation and the environmental conditions are favorable (i.e., natural convection). On the other hand, for environments where the conditions for thermal dissipation are more complicated (i.e., reduced space for heat sinking the LEDs), the use of HB LEDs in luminaires could be considered interesting, since indoor lighting often requires lesser power levels and offer limited options for heat dissipation.

This work has also verified that LED technology is being constantly improved over the years, causing the photometrical performance and reliability of this fairly new type of light source, in some cases, match or even supersede the current technologies for indoor or outdoor lighting.

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