

LIQUID COOLING FOR IMPROVED LED PERFORMANCE

Luigi COLOMBO¹, Alberto DOLARA², Roberto FARANDA³, Ștefania GUZZETTI⁴, Sonia LEVA⁵, Andrea LUCCHINI⁶

The main issue concerning the power LEDs is the thermal power generated during operation, which increases the junction temperature affecting the operating characteristics of the power LED and causing the reduction of: the useful life of the components, the luminous flux, the light efficiency and the forward voltage. Moreover there is an increase of the fundamental wavelength of emitted light.

Purpose of this study is to compare the heat transfer performances of finned surfaces, which represent a commonly used passive techniques for heat removal in the field of lighting power LED, with an innovative liquid cooling placing the LED in an enclosure filled with dielectric refrigerant.

Keywords: High-power LEDs; Thermal management; Refrigerating liquid; Heat dissipation; Luminous characteristics

1 Introduction

Light-emitting diode (LED) lights have recently attracted the attention of the illumination industry, due to their lower power consumption [1, 2]. In fact, due to rapid technological improvement, the illuminating efficiency of LED has grown beyond 100lm/W in commercial products and have demonstrated proven energy saving to traditional lightings, such as incandescent, fluorescent, and mercury [3]. Then, they are also considered one of the most valuable light sources in 21st century [4, 5] due to longer life and smaller structure than the other light sources.

However, their use presents a thermal problem, since about 70% of their total energy consumption is wasted as heat [6]. This is a big problem because, in addition to failure, the most critical thermal effects on LEDs are a reduction in lifetime, shifts in the emitted wavelength, and lower operational efficiency. Without appropriate thermal management, the efficiency of LEDs can be reduced from a theoretical 90% to values as low as 20% [7]. So, an efficient heat sink design is essential to solve this problem.

¹ Prof., Department of Energy, Politecnico di Milano, Milano, Italy

² Prof., Department of Energy, Politecnico di Milano, Milano, Italy

³ Prof., Department of Energy, Politecnico di Milano, Milano, Italy

⁴ Dott., Department of Energy, Politecnico di Milano, Milano, Italy

⁵ Prof., Department of Energy, Politecnico di Milano, Milano, Italy, e-mail: sonia.leva@polimi.it

⁶ Prof., Department of Energy, Politecnico di Milano, Milano, Italy

Purpose of this paper is to investigate the optimization of thermal management of LEDs using refrigerating liquid. In particular, this paper starts from the results obtained in a previous work [8] where a lighting prototype, characterized by an aluminum cavity where white power LEDs were fixed and gradually filled with refrigerating liquid was tested. The conducted experiments showed that the best thermal performances of the prototype was achieved by totally dipping LEDs into the refrigerating liquid. However, that configuration was negatively affecting the light characteristics, because wavelengths in the range 530 - 630nm were cut when the luminous radiation pass through the liquid.

In this paper the new solution studied, in order to better use the benefits of the refrigerating liquid, and the relative results obtained will be described. In particular, the most important change to the old solution is the replacement of white LEDs with specific blue LEDs. The light spectrum emitted by these LEDs is not influenced by the refrigerating liquid. The luminous and thermal performances of the new configuration were experimentally determined subsequently a thermal model was developed.

2 Experimental setup

The experimental measurements and analyses are focused on the prototype LED lamp showed in Figs. 1 and 2, which components (from top to the bottom) are: 1- the removable heat sink, 2- the pcb LED (6 high power, LUXEON Rebel ES Royal Blue LEDs, 700mA, 12.7W, by General Luminaire), 3- the upper closing plate, 4- the silicone gasket, 5- the lateral surface of the fluid enclosure, 6- the glass with phosphor cover (Round ChromaLit™ Phosphor Element, 3000K, 80 CRI, by Intematix), 7- the silicone gasket, 8- the lower closing plate.

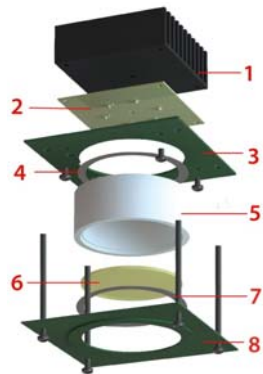


Fig. 1 3D model exploded

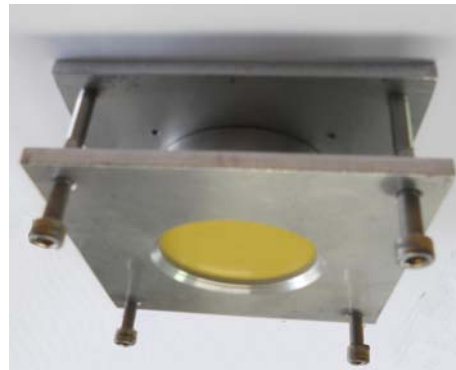


Fig. 2 Prototype

The prototype performances were quantified in terms of: illuminance output, voltage applied to the LEDs, electric current absorbed by the LEDs and operating temperatures of the LED junctions. The first quantity was measured by a portable luxmeter (uncertainty $\pm 1\%$) and two readings were recorded, one at the beginning of the experiment (single reading) and the other in steady state conditions (average of three values). For the others, on the contrary, a digital multimeter connected to a PC was employed to read and store data with a sampling frequency of 0.1Hz during the whole duration of the experiment (heating, steady state operation, cooling). The voltage measurement was carried out directly by the digital multimeter (uncertainty 1%) while the measurement of electric current and temperatures were indirect. The first is converted into a voltage by a Hall effect transducer and measured by a digital multimeter (uncertainty 1%), while the latter is measured by thermocouples (uncertainty $\pm 0.2^\circ\text{C}$) and converted to temperature by a multimeter. The temperature measurements were carried out in five different points to provided information about: the LED temperature; the temperature at the centre of the PCB; the fluid temperature; the temperature at the centre of the phosphor cover; the temperature of the air surrounding the lamp. The LED junction temperature is evaluated as:

$$T_j = T_b + P \cdot R_{\theta_{j-b}} \quad (1)$$

where, T_b is the LED temperature in its test point, T_j the junction temperature, P the LED power, and $R_{\theta_{j-b}}$ the thermal resistance from the junction to the board.

The criterion adopted to state the end of the transient is based on the temperatures of the lamp and its expression is respectively for heating for cooling:

$$(T_i - T_{air,i}) / [(\sum_{i=1}^{i+60} T_i) / 60 - T_{air,i}] \times [0.99; 1.01] \quad (2)$$

$$(T_s - T_i) / (T_s - T_{air,i}) \times [0.99; 1.01] \quad (3)$$

where T_i is the generic temperature of the lamp at the i -th sampling, $T_{air,i}$ is the generic temperature of the air at the i -th sampling and T_s is the generic temperature of the lamp in steady state. The values of the temperatures reported are the average values of 60 samplings (ten minutes of acquisition).

The experiments aimed to highlight the effect of the heat sink and the fluid between the LEDs and the glass with phosphor on the afore mentioned quantities. As heat sink a squared aluminium plate (side length 40 mm, thickness 1.5 mm) and a matrix (12 rows and 12 columns) of pins (height 16 mm, width 1.75 mm, thickness 1.2 mm) has been used. As filling fluid two options were considered: air and silicon oil (Dow Corning PV-6010 [8]). Consequently the configuration tested in the experiment were four and named as follows:

- a) AN: fluid: AIR; heat sink installed: NO;
- b) AY: fluid: AIR; heat sink installed: YES;
- c) OY: fluid: OIL; heat sink installed: YES
- d) ON: fluid: OIL; heat sink installed: NO.

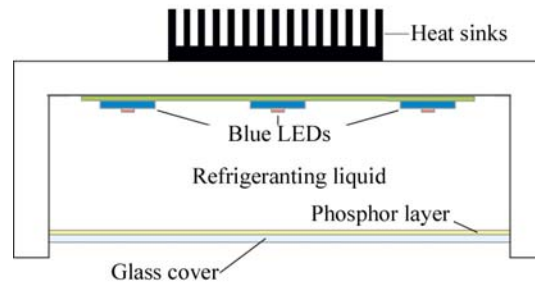


Fig. 3 OY configurations

3 Thermal model

A steady state model based on a thermal resistance network allows the estimation of the LED operating temperature and the assessment of the influence of various geometrical/physical parameters. Assuming axial symmetry, a simplified representation of the main heat flow paths is given in Fig. 4, where all the thermal resistances are displayed. Their meaning together with a proper definition is discussed in the following.

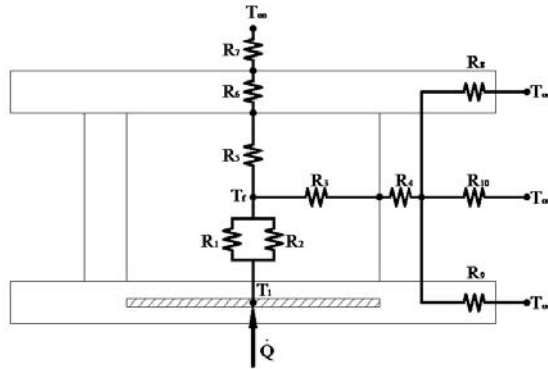


Fig. 4 Thermal network.

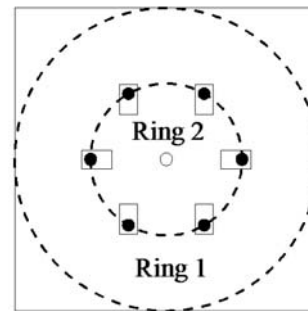


Fig. 5 Schematic of the PCB.

Resistances R_1 and R_2 account for the heat transfer from the LEDs to both the ambient air and the fluid within the enclosure through the PCB. This latter can be separated in two portions (Ring 1 and Ring 2) by the circle ideally connecting the electronic devices, as shown in Fig. 5. Under the assumption of axial symmetry, each ring behaves as a circular fin with the root at the LED temperature. Hence, the associated thermal resistance is given by [9]:

$$R_n = 1 / (\eta_f h_{tot} A_n), n = 1, 2 \quad (4)$$

where A denotes the heat transfer area and η_f is the fin efficiency defined as:

$$\eta_f = \frac{2r_i}{m(r_e^2 - r_i^2)} \frac{K_1(mr_i)I_1(mr_e) - I_1(mr_i)K_1(mr_e)}{K_0(mr_i)I_1(mr_e) - I_0(mr_i)K_1(mr_e)} \quad (5)$$

Here, I_0 and K_0 are the 0th order Bessel modified functions of first and second kind, respectively; I_1 and K_1 are the 1st order Bessel modified functions of first and second kind, respectively; r_i and r_e the inner and outer radii; m is the fin parameter given by:

$$m = \sqrt{2h_{tot} / (k_{FR-4}t)} \quad (6)$$

where t is the PCB thickness, k_{FR-4} is the thermal conductivity of the PCB material, mainly FR-4, and h_{tot} is the global heat transfer coefficient taken the sum of the average convective heat transfer coefficients on both sides of the PCB. These ones are calculated from suitable correlations.

Resistances R_3 and R_5 account for the convective heat transfer from the fluid in the enclosure and the surrounding walls. Their general definition is [9]:

$$R_{conv} = 1 / (hA) \quad (7)$$

where A is the heat transfer area. The heat transfer convective coefficient h is calculated from suitable correlations.

Resistances R_4 and R_6 account for conduction, respectively, in the enclosure side wall, made of Aluminium, and in the plastic window:

$$R_4 = \frac{1}{2\pi k_{Al}H} \ln \frac{r_e}{r_i} \quad (8)$$

$$R_6 = L / (k_p A) \quad (9)$$

where H is the wall height, r_i and r_e the inner and outer radii, L the thickness of the plastic layer and A the heat transfer area.

Resistances R_7 and R_{10} account for heat transfer from an external wall and the surroundings. In particular, the former is relative to the external side of the window whereas the latter refers to the outer surface of the enclosure. They are expressed as (7), but the heat transfer coefficient is the sum of the convective and the radiant component.

Resistances R_8 and R_9 account for the heat transfer through the Aluminium mounting flanges, considered as circular fins and modelled as described by (4). The four screws connecting the two flanges to seal the enclosure act as thermal bridges, but they are neglected since preliminary thermographic measurements showed that they are practically at ambient temperature. Most of the thermal resistances described above involve a convective heat transfer coefficient. As free convection occurs in the usual operating conditions, the coefficient is calculated from suitable correlations [9].

Table 1 reports the values of the thermal resistances along the main heat flow paths for DC-561 filling the enclosure compared with the manufacturer data relative to air cooling.

In particular,

$$R_{PCB} = R_1 R_2 / (R_1 + R_2) \quad (10)$$

is the thermal resistance through the PCB. Its value is 1.5 times lower than the junction to board thermal resistance claimed by the manufacturer.

$$R_{axial} = R_5 + R_6 + R_7 \quad (11)$$

is the thermal resistance from the fluid in the enclosure and the surroundings through the window;

$$R_{radial} = R_3 + R_4 + (1/R_8 + 1/R_9 + 1/R_{10})^{-1} \quad (12)$$

is the thermal resistance from the fluid in the enclosure and the surroundings through the sides of the enclosure and the mounting flanges. Finally,

$$R_{tot} = R_{PCB} + (1/R_{axial} + 1/R_{radial})^{-1} \quad (13)$$

is the junction to ambient thermal resistance, that results 0.8 times lower than the junction to board thermal resistance claimed by the manufacturer for air cooling. Hence, due to liquid cooling operating temperatures are expected to reduce by a factor ranging between 1.24 and 1.5. This prediction is in good agreement with the measured value equal to about 1.1.

Table 1

Thermal resistances			
	Manufacturer data	DC-561	Reduction factor
R_{PCB} [K/W]	21	14.1	1.5
R_{axial} [K/W]	-	65.1	-
R_{radial} [K/W]	-	3.0	-
R_{tot} [K/W]	>21	16.9	1.24

4 Results: thermal and electrical test

Fig. 6 shows the obtained results. Configuration OY shows the lowest operating temperature. The reason is related to the behaviour of air which acts like a thermal insulator, the combined effect of the heat sink, that reduces the thermal resistance with the surrounding air, and the oil inside the lamp, which is more suitable than air as heat transfer medium.

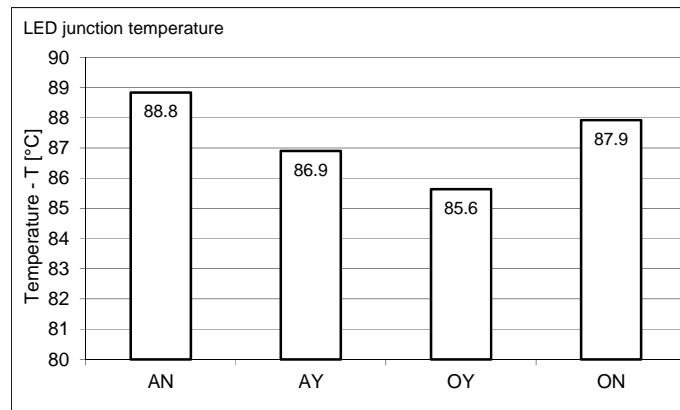


Fig. 6 Steady state LED junction temperature

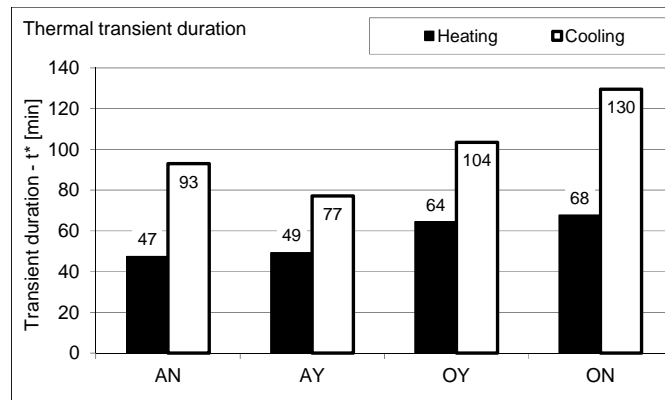


Fig. 7 duration of heating and cooling processes

Moreover it is possible to infer that the heat sink has a larger effect in the temperature reduction than oil because configuration AY has a lower operating temperature than configuration ON. Fig. 7 indicates that the duration of the transient, because of the larger heat capacity of oil than air, increases in presence of oil. Configuration OY shows heating and cooling transients 30% longer than configuration AY (characterized by the shortest transient time).

On the contrary the power consumption of the different configurations (AN, AY, OY, ON) is the same and equal to about 12 W.

5 Results: luminous radiation test

The tests about to the light radiation were performed considering only the quantity of light emitted from the prototype (illuminance in a specific point), investigating whether lower operating temperatures would guarantee a higher luminous efficiency. Instead, the quality of light (emission spectrum, color temperature and color rendering index) hasn't been investigated because already analyzed in a previous work [6]. In particular, the illuminance of the LED spotlight at point P has been detected (Fig. 8).



Fig. 8 Box to detect the illuminance

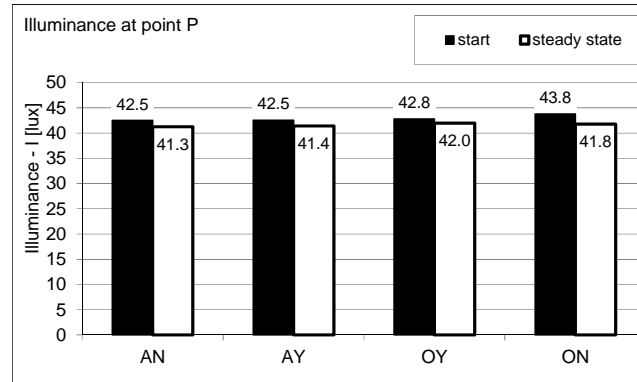


Fig. 9 Lamp illuminance at the starting instant and in steady state

The LED spotlight has been fixed in the hole at the center of the top face of a 1 meter cubic matt black box. The probe of the luxmeter was fixed in the center of the box's bottom face. The lux were detected both at switching time of prototype both in thermal transient completed. Each measurement was repeated three times at intervals of 10 seconds of each other.

Fig. 9 shows that the behavior of the bright spot is consistent with what was expected. Although with variations not particularly significant, the lux issued, at operating temperatures of the prototype lowest, are the highest.

6 Conclusion

A lamp prototype filled with oil and endowed with a heat sink to improve heat transfer of power LEDs is proposed and investigated in the present study.

This study shows that it is the combination of both that provides the best thermal performances (lowest junction temperature, this also means that a longer lifetime of the components could be achieved), even though the heating and cooling transients increases. This suggests that exists a tradeoff between thermal performances and transient duration, consequently a proper design of the heat sink and a careful sizing of the volume of oil have to be performed to get the optimal solution. Moreover LED blue and glass cover with a phosphor layer, guarantees high luminous efficiency and a uniform white light emission of the source. In addition a small increase in light flux are achieved too.

R E F E R E N C E S

- [1]. *A. Dolara, S. Leva*, "Power Quality and Harmonic Analysis of End User Devices", *Energies*, **vol. 5**, 2012, pp. 5453-5466
- [2]. *R Faranda, S. Guzzetti, C Lăzăroiu, S. Leva*, "LEDs lighting: two case studies" *UPB Sci. Bull., Series C*, **vol. 73**, 2011, pp. 199-210
- [3]. *B. J. Huang, C. W. Tang*, "Thermal -electrical-luminous model of multi chip polychromatic LED luminaire", *Applied Thermal Engineering*, **vol. 29**, no. 16, 2009, pp. 3366-3373.
- [4]. *J. Li, B. Ma R. Wang, L. Han*, "Study on cooling system based on thermoelectric cooler for thermal management of high-power LEDs", *Microelectronics Reliability*, **vol. 51**, no. 12, 2011, pp. 2210-2215.
- [5]. *J. H. Choi, M. W. Shin*, "Thermal investigation of LED lighting module", *Microelectronics Reliability*, **vol. 52**, no. 5, 2012, pp. 830-835.
- [6]. *S. H. Yu, K. S. Lee, S. J. Yook*, "Natural convection around a radial heat sink", *International Journal of Heat and Mass Transfer*, **vol. 53**, 2010, pp. 2935-2938.
- [7]. *T. Cheng, X.B. Luo, S.Y. Huang*, "Thermal analysis and optimization of multiple LED packaging based on a general analytical solution", *International Journal of Thermal Sciences*, **vol. 49**, 2010, pp. 196-201.
- [8]. *R. Faranda, S. Guzzetti, G. C. Lazaroiu, S. Leva*, "Refrigerating liquid prototype for LED's thermal management", *Applied Thermal Engineering*, **vol. 48**, 2012, pp. 155-163.
- [9]. *F. Incropera, D. P. De Witt, T. L. Bergmann, A. S. Lavine*, "Fundamentals of Heat and Mass Transfer", 6th Edition, Mar. 2006.
- [10]. *L. Jayasinghe, Y. Gu, and N. Narendran*, "Characterization of thermal resistance coefficient of high-power LEDs", in 6th International Conference on Solid State Lighting, **vol. 6337** of *Proceedings of SPIE*, New York, NY, USA, Aug. 2006.