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Analysis of a passive heat sink for temperature stabilization of high-power LED bulbs

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Abstract. In this paper we present a numerical analysis and experimental measurements of the temperature stabilization of high-power LED chips that we have obtained by employing an aluminum passive heat sink, designed to be used in a compact light bulb configuration. We demonstrate that our system keeps the temperature of the LED chip well-below $70°C$ yielding long-term operation of the device. Our simulations have been performed for a low-cost device ready to install in public streetlights. The experimental measurements performed in different configurations show a nice agreement with the numerical calculations.

1. Introduction

The use of high-power light emitting diodes (HP-LED) for public illumination is an emerging subject, triggered by recent developments of different technologies including semiconductor materials[1, 2, 3], fluorescence techniques[4], driver electronics[5] or thermal control[6] among others[7, 8].

One of the key aspects concerning the performance and durability of HP-LED lighting systems is the adequate control of the temperature of the LED chip[9]. As it has been pointed by recent studies[10], LEDs have a high energy efficiency and long lifespan, however, a large amount of heat is dissipated during operation due to Joule effect; thus, cooling HP-LEDs is an important challenge in package designs, where a correct evacuation of the heat will substantially enlarge the lifetime of the device[11].

Besides the previous constraint, other practical aspects like a compact configuration, low cost, mass production or even esthetic considerations can play an important role in market-oriented products. Thus, in this paper we present a numerical analysis of the thermal stabilization of $30W - 50W$ LED chips attached to passive heat sinks, yielding a compact light bulb design that can be used for commercial purposes in the street lighting market. The system we propose keeps the temperature of the LED chip well-below 70^oC under realistic conditions, yielding long-term operation of the bulb, with the corresponding savings in energy consumption and maintenance.

After the numerical calculations performed, in order to compare the results of the computational simulations with experimental measurements taken in standard systems, a set of prototypes has been constructed in a compact and ready-to-install configuration. As we will

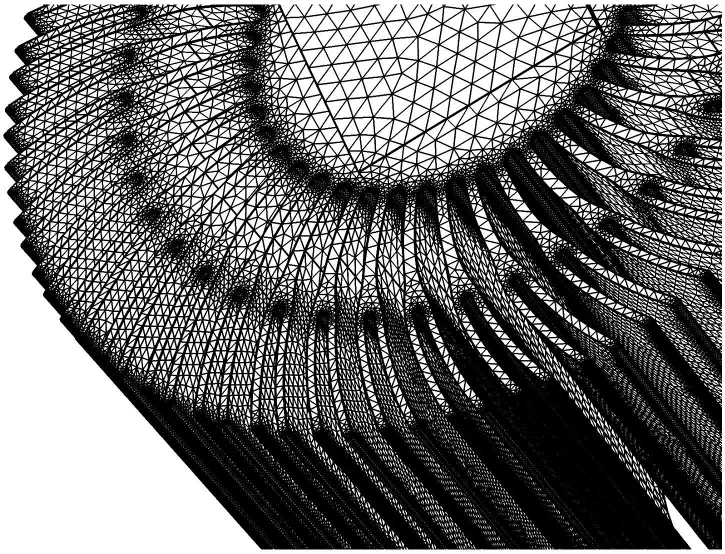

Figure 1. Detail of the computational grid used for the numerical simulations. The size of the real devices was $5cm$ and $10cm$ height and $9cm$ diameter. Details of the calculations are given in the text.

demonstrate, there is a nice agreement between the numerical simulations and the corresponding data obtained.

2. Numerical model

Our first aim is to calculate the steady-state temperature distribution over the surface of a heat sink with translational symmetry along one axis. This configuration is ideal for mass production at a very low cost via metal extrusion process. In our theoretical model, we have assumed that the heat sink is made of black anodized aluminum (Al 16061), which is surrounded by a laminar air flow of density (ρ) given by the ideal gas law. Thus, in the air side, the first expression that we formulate is the continuity equation:

$$\nabla \cdot (\rho \vec{v}) = 0, \tag{1}$$

being $\vec{v}$ the velocity of air. In addition we have the energy equation[12]:

$$\rho \frac{\partial \vec{v}}{\partial t} = -\nabla P + \mu \nabla^2 \vec{v} - \rho \vec{g}, \tag{2}$$

where t is the time, P the pressure and μ the dynamic viscosity of air. We assume that the acceleration of gravity $\vec{g}$, is parallel to the z-axis. Another formula to be added to the model is the moment equation:

$$\rho C_P \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \frac{\partial P}{\partial t}, \tag{3}$$

being C_P the specific heat, T the absolute temperature and k the thermal conductivity. On the heat sink we have the condition $\nabla^2 T = 0$. At the interface, for a black anodized surface with high emissivity (≥ 0.8), we can neglect the effect of the incoming radiation heat flux (W/m^2) and thus the outgoing flux ($\dot{q}$) is given by the Stefan-Boltzmann law:

$$\dot{q} = \epsilon \sigma T^4, \tag{4}$$

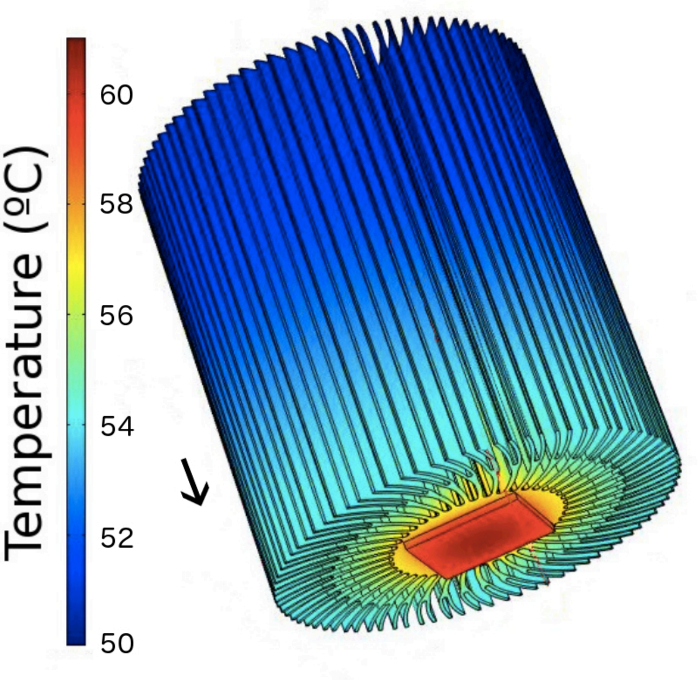

Figure 2. Numerical simulation of steady-state temperature distribution over the surface of a passive heat sink in vertical configuration corresponding to the geometry of Fig. 1. The color scale ranges from $50°C$ (blue) to $61°C$ (red). The arrow indicates the direction of the gravitational force, which in this case is parallel to the axis of symmetry of the heat sink. The system modeled is black anodized Al and the size used for the calculations was $10cm$ height and $9cm$ diameter. The LED power in this simulation is $50W$. Other details of the simulation are given in the text.

where ϵ is the emissivity of the aluminum wall, σ is the Stefan-Boltzmann constant and T is the absolute temperature of the heat sink.

We want to solve the previous problem for a heat sink made of black-anodized aluminum (Al6061) with the geometry shown in Fig. 1. To numerically integrate the previous set of equations, we have used COMSOL Multiphysics®, which is is a finite element analysis solver commercial package for various physics and engineering applications, especially coupled phenomena. In addition to conventional physics-based user interfaces, this software also allows for entering coupled systems of partial differential equations (PDEs). In particular, we have used the Heat Transfer Module which provides user interfaces for heat transfer by conduction, convection and radiation.

We have modeled the LED chip as a $1mm-$thick aluminum square plate which provides a constant heat flux at the base of the heat sink. For the chips under consideration the amount of waste heat can be estimated as 70% of the LED power[13]. The dependence on the grid density was investigated by changing the number of points. The final selection is shown in Fig. 1. The simulation corresponds to a heat sink $10cm$ height with a diameter of $9cm$. The diameter of the solid internal core is $4cm$.

The results of the numerical calculations are shown in Fig. 2 for a vertical configuration (i.e.: the symmetry axis of sink parallel to the direction of the acceleration of gravity $\vec{g}$) and simulating the effect of a $50W$ LED chip placed at the bottom of the heat sink. As it can be appreciated in the picture, the maximum of the temperature distribution is obviously located at the LED

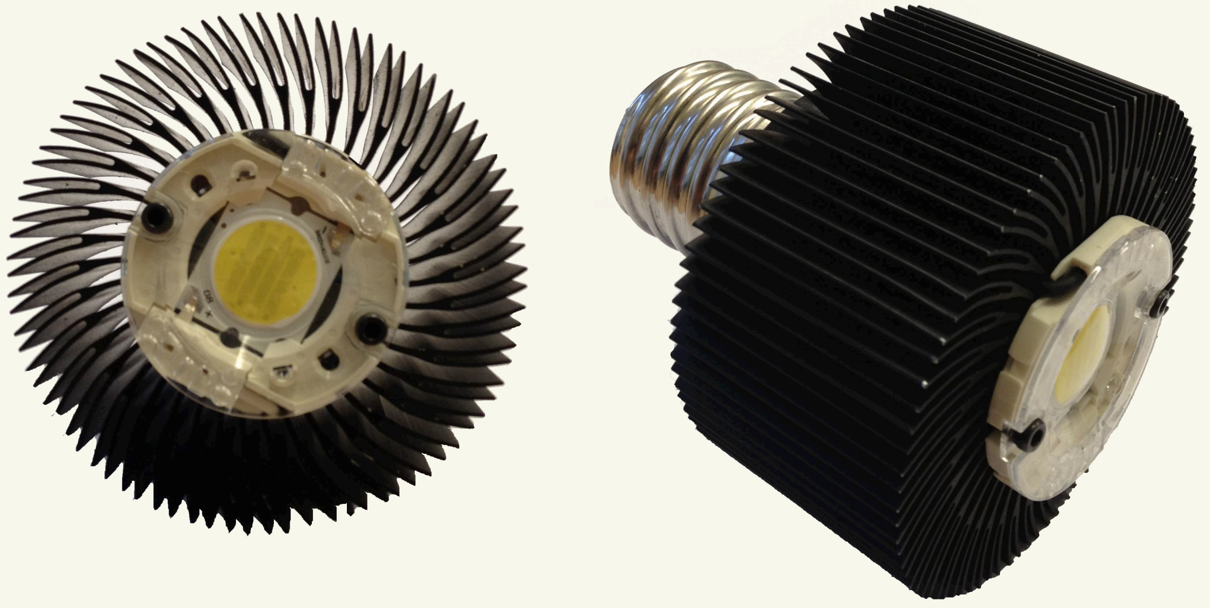

Figure 3. Front (left) and lateral (right) view of the real system composed of a black anodized aluminum structure in a compact LED bulb configuration. The height of the sink is $5cm$ and its diameter is $9cm$ the corresponding simulations and experiments for horizontal and vertical orientations with a 25W LED chip are shown in Fig.5 and Fig. 6, respectively.

chip and the values of T gradually diminish with the distance from the chip, showing a radially symmetric distribution around the axis of the cylinder. For an ambient temperature of $21°C$, the maximum of the resulting steady-state distribution calculated is $60.8°C$, well below the critical damage temperature provided by the LED manufacturer, providing thus a maximal lifetime of the device. As we will show below, this result is un good agreement with the experimental measurements performed in a real system. Of course, for higher ambient temperatures our predictions are still valid and in this case the gap with respect to the damage threshold is reduced accordingly[11] .

3. Experimental Setup

In order to check the validity of our numerical model, a series of experiments were made. Aluminum (Al6061) black anodized heat sinks with the same geometry as in Fig 1 and two different lengths ($5.0cm$ and $10.0cm$ were attached to a $25W$ and $50W$ LED chips respectively. In Fig. 3 we show a photo of one of the prototypes that we constructed to perform the experimental measurements.

In all the cases, to minimize the thermal contact resistance between the LED chip and the heat sink a graphite film of high thermal conductivity ($240Wm^{-1}K^{-1}$) was used. Finally, the light bulbs were mounted in several orientations in order to reproduce different operation conditions. The emissivity of the heat sink with the black-anodized surface treatment is 0.8. The geometric parameters of the experimental model are the same as in the numerical simulation described above and below. A temperature sensor with three different probe heads (DAQ-9172, NI9211), a power supply, a wattmeter, and a laptop were used in order to collect data.

The overall pattern for the air flow could be described as follows: the cooling air enters from the outer region of the heat sink and is heated while passing through the fins. The heated air rises upward in the inner regions of the heat sink due to the fact that the density of the air in

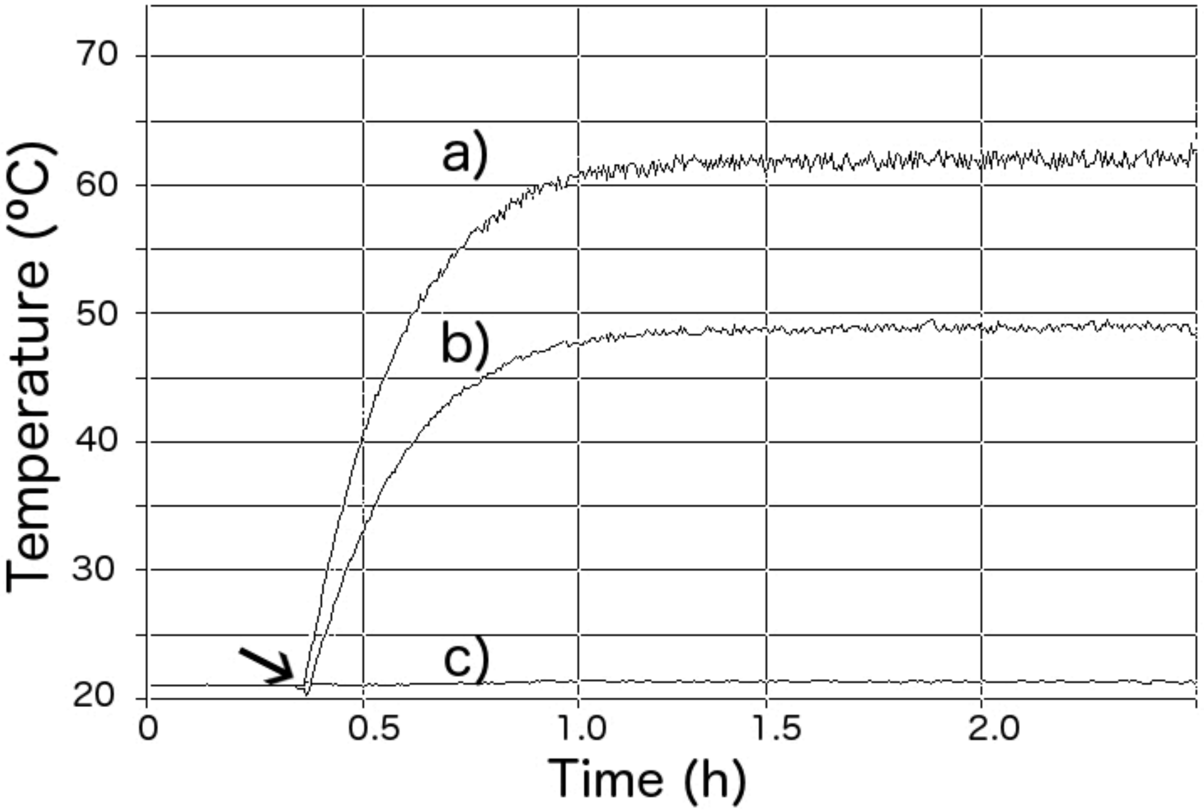

Figure 4. Experimental measurement of the temperature distribution in the vertical configuration (the axis of symmetry of the sink is parallel to the gravity force) corresponding to the numerical simulation of Fig.2. Curves a), b) and c) correspond respectively to the LED chip, the center of the top side of the heat sink and the ambient. Details of the experiment are given in the text. The arrow points to the instant when the power is switched on.

this zones became less than that of the surrounding air. In addition, a thermal boundary layer develops discontinuously, after some delay. Thus, a relatively high local heat transfer coefficient is expected in the inner regions of the heat sink.

The pin-fin heat sink will show uniform cooling performance in the case of natural convection considered. Repeated leading-edge effects will appear in the outer regions of the heat sink because the fins are arranged to keep the flow at a certain distance in the radial direction.

4. Results and discussion

In Fig. 4, we plot the experimental measurement of temperature values measured for a $50 - W$ LED chip in vertical configuration (the axis of symmetry of the sink is parallel to the gravity force) corresponding to the numerical simulation of Fig.2 with the chip placed at the bottom of the heat-sink. Curves a), b) and c) correspond respectively to the temperatures measured at the LED chip, the center of the top side of the heat sink and the ambient.

As it can be appreciated in the curves, once the power is switched on (indicated by an arrow) the temperature increases until saturation after less than one hour. The maximum values measured in curves a) and b) are respectively $63°C$ and $49°C$ which are in very good agreement with the numerical simulation of Fig. 2.

To determine the optimum configuration and the precision of the numerical model, we have simulated and measured different orientations and lengths of the heat sink. The results of the numerical calculations can be seen in fig. 5 for a 25W HPLED and $5cm$ height heat sink. The results show the simulation of the steady-state temperature for vertical (a) and horizontal (b) configuration, meaning these names that the acceleration of gravity ($\vec{g}$) is parallel or perpendicular to the symmetry axis of the heat sink, respectively.

The comparison of the numerical simulations of Fig. 5 with experimental values is shown in Fig. 6. In this figure we plot the temperature measured at the chip (a) and at the center of the opposite side of the heat sink (b). Line c) shows the ambient temperature during the experiment.

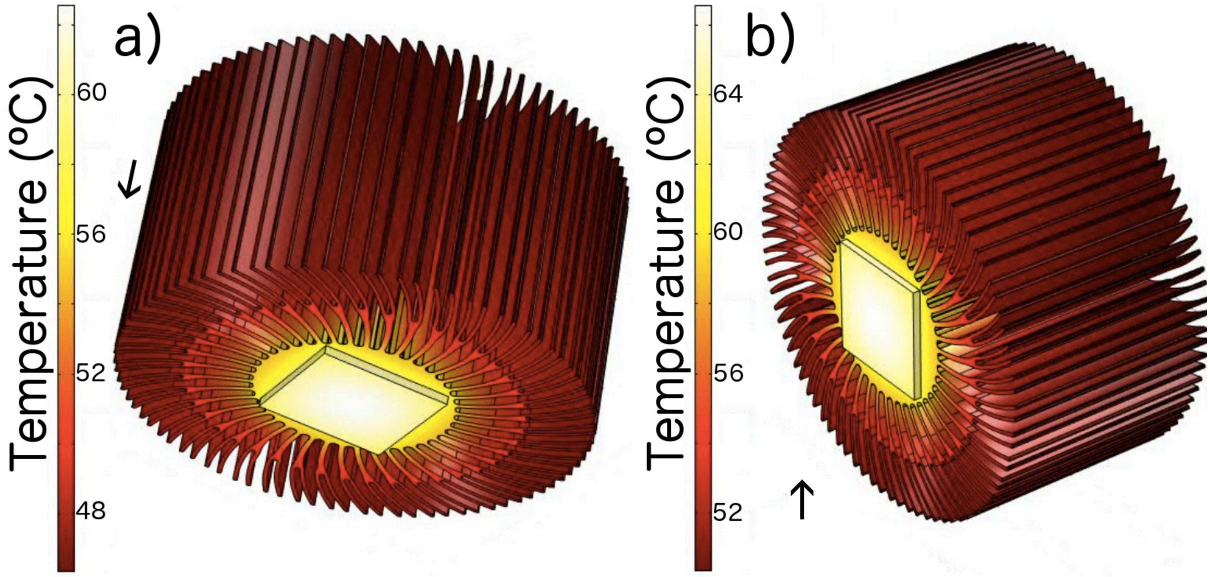

Figure 5. Numerical simulation of steady-state temperature distribution over the passive heat sink in horizontal (left) and vertical (right) configuration. The arrows indicate the direction of the gravitational force in each case. The color scale ranges are plotted in the left side of each simulation. The system modeled is black anodized Al as in Fig. 2. In this case the size used for the calculations was $5cm$ height and $9cm$ of diameter. The LED power is $25W$. Other details of the simulation are given in the text.

As it can be appreciated in the left non-shaded zone of Fig. 6, after less than one hour of operation of the LED, the system reaches a thermal steady state with a maximum temperaure in the chip of $63°C$, in excellent agreement with the simulations of Fig. 5-a. Once the temperature is stabilized, we rotate the system 90° which corresponds to a perpendicular orientation of the axis of symmetry of the heat sink with respect to the force of gravity (see Fig. 5-a). This situation is indicated by a dark-grey shading in the graph. It is obvious that this configuration is not the optimal one, yielding an increase of about $8°C$ in the chip temperature.

Then, we rotate the sink another 90° and thus, the axis of symmetry of the sink is aligned with the gravity force as in 5-b, however the chip is placed now at the top of the chip instead of the bottom. As it can be appreciated the temperature slightly decreases showing the important contribution of air convention along the pin-fins.

Finally, we restore the initial position and the temperature asymptotically recovers the steady-state value of the first zone of the graph. All the measurements made are in very good agreement with the numerical simulations shown in Fig. 5 for two different orientations.

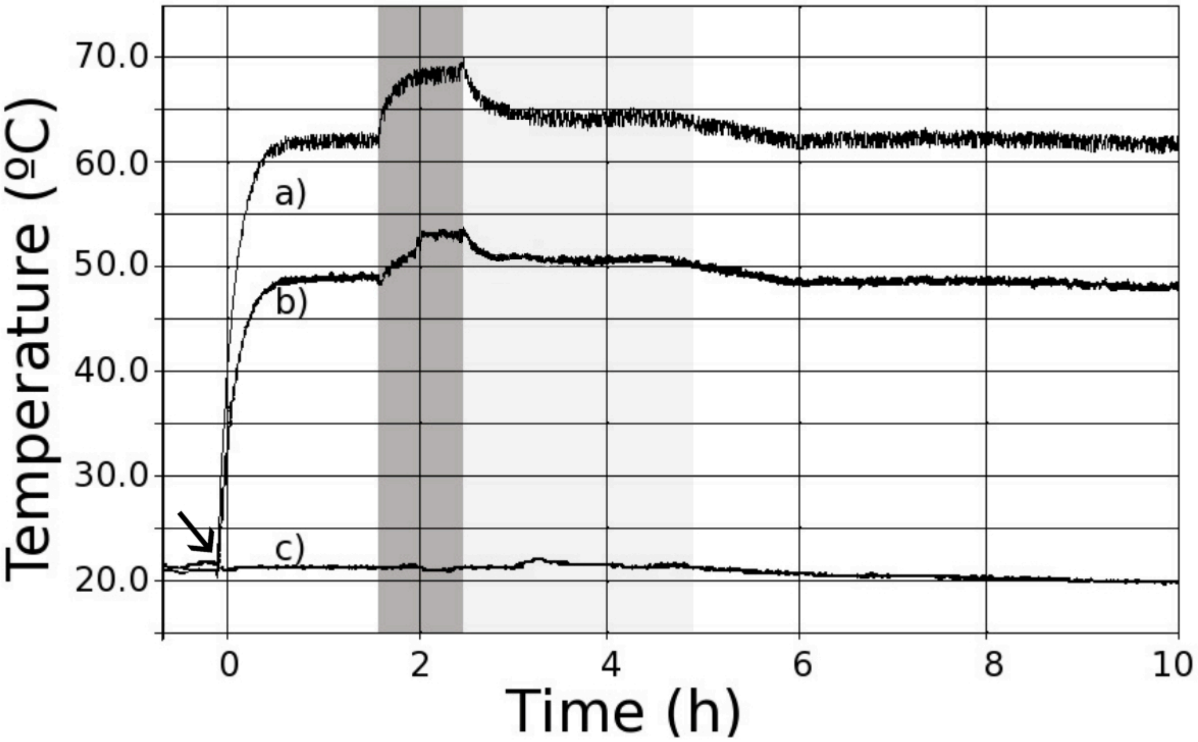

Figure 6. Experimental measurement of the temperature distribution measured at: a) the LED chip, b) the center of the back side of the heat sink, and c) the ambient. The non-shaded parts of the graph correspond to measurements made for parallel orientation of the symmetry axis of the heat sink with respect to the force of gravity and with the LED chip placed placed at the bottom of the heat sink corresponding to Fig. 5-a. The dark-gray zone displays the values obtained for perpendicular orientation (Fig. 5-b) and the light-gray region corresponds to the same orientation Fig. 5-a but with the LED chip place at the top of the sink. The rest of the parameters of the experiment are given in the text.

5. Conclusions

We have presented a numerical study of the steady-state temperature distribution of a realistic high-power light emitting diode (HP-LED) bulb. Our results have been compared with experimental data measured in a prototype fabricated under market considerations. A nice agreement has been found between the computer simulations and the measurements performed.

Therefore, from our analysis we can derive that aluminum low-cost passive heat sinks can be used to keep the temperature of $30W - 50W$ HP-LED chips below $70°C$, thus making it possible to reach life-times of $55.000h$ with the corresponding savings in energy consumption and maintenance.

Acknowledgments

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