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Thermal management of honeycomb heat sink filled with phase change material for smart lighting applications

Khaoula Ben Abdelmlek¹, Zouhour Araoud¹, Alaeddine Amor², Laurent Canale³, Kamel Charrada¹, Georges Zissis⁴

¹ Laboratory studies of Ionized and Reactive Media (EMIR), Monastir, Tunisia

² VTL group, Nabeul, Tunisia

³ CNRS, LAPLACE UMR 5213, Toulouse, France

⁴ Université Toulouse 3, LAPLACE, UMR 5213, Toulouse, France

Abstract

Recently, thermal management of LEDs lamps has become increasingly essential due to the widespread integration of LEDs in smart lighting applications. In this work, we focus on the thermal analysis of convective heat transfer using a honeycomb heat sink designed for LEDs lamp cooling. Three different heat sink geometries were examined: an aluminum-filled honeycomb radiator, a hollow honeycomb radiator, and a hollow honeycomb radiator incorporating a phase change material (PCM) layer. The results obtained from numerical simulations using COMSOL Multiphysics® showed that the third heat sink geometry, when employed in short-duration lighting applications, led to a 25% reduction in temperature for a 20W power lamp. We also determined the optimal operational time, during which the temperature drop is maximum. Moreover, we observed that the integration of a PCM-filled honeycomb radiator in cyclic lighting applications (involving on/off cycles and high/low power settings) significantly mitigates temperature rise in the lamp by leveraging the PCM's heat storage capacity. This approach effectively prevents thermal shocks, ensures prolonged LEDs performance, and contributes to energy savings in the lighting sector. By addressing the thermal management challenges associated with LEDs lamps through innovative heat sink designs and the utilization of PCM, our research offers valuable insights for enhancing the overall performance and efficiency of LED lighting systems.

Keywords Thermal management, LEDs lamp, Smart lighting, Phase change material

I. Introduction

Given the rapid adoption of LEDs lamps in the lighting sector, their dominance in general industrial and road lighting, and their impressive advancements in terms of performance and integration with the Internet of Things, LEDs lamps have emerged as the top choice for the smart lighting challenge and the transition towards smart cities. However, it is undeniable that LEDs still face thermal issues that need to be addressed in a serious manner. Failure to do so can result in sudden overheating, performance degradation, reduced lifespan of the light source, and even complete luminaire failure [1-2].

Several research studies have been dedicated to addressing the thermal management of LED lamps, similar to cooling electronic devices, with the aim of reducing the junction temperature and designing reliable and durable luminaires. Passive cooling of LEDs primarily relies on natural convection heat transfer. The heat generated by the LED chips is conducted to a heat sink integrated within the lamp, which then dissipates the heat to the surrounding environment through natural convection. The optimal design of the heat sink geometry, taking into account the operating conditions of the lamp, is crucial for effective heat dissipation.

Numerous research studies have focused on passive cooling of LEDs, aiming to experimentally or numerically evaluate the heat transfer rate as a function of geometric parameters and non-dimensional numbers such as Rayleigh, Prandtl, and Grashoff numbers [3-6]. The geometric parameters of the heat sink, including fin length, thickness, spacing, number and orientation play a significant role in LEDs thermal management [7-9]. For instance, Park et al. [7] developed an optimization of a radial heat sink within chimney design a LED downlight lamp. Similarly, Jang et al. [8] successfully optimized the geometry of a radial heat sink by varying the fin shape without increasing the total mass of the heat sink. Ben Abdelmlek et al. [9] studied experimentally the effect of heat sink orientation on the thermal performances of the light source. They experimentally showed that the horizontal upside fins heat sink is the best orientation to minimize the junction temperature of the device.

Additionally, various research works have focused on critical lighting scenarios such as oven or showcase lighting. In these specific cases, the heat sink is located within confined spaces. Previous studies have shown that this significantly affects the heat transfer rate from the heat source [10-11]. Authors have numerically investigated the impact of cavity height and orientation on heat transfer through rectangular heat sinks. They demonstrated that beyond a height equivalent to five times the fin height, the heat transfer rate becomes constant [11].

Certainly passive cooling of LEDs helps mitigate the risks of overheating and luminaire failure. However, it is important to acknowledge that the cooling rate achieved through natural convection is significantly lower compared to that achieved through forced convection. Active cooling techniques offer sophisticated methods to enhance heat transfer rates and maximize the lifespan of the light source. Naquiuddin et al. [12] developed an overview of microchannels for the thermal management of heat released by high heat flux applications. Ghaneifar et al. numerically investigated the impact of airflow passing hole diameter within curved microchannels on the thermal performance of vertical LEDs using nanofluid [13]. They demonstrated a significant reduction in the average temperature of the heat sink and an improvement in its thermal coefficient, particularly when employing microchannels with greater curvature. Another method of thermal management of LED devices is thermoelectric cooling (TEC), which utilizes the Peltier effect [14]. TEC modules have recently been integrated into LEDs luminaires to effectively dissipate heat from the LED junction. Wang et al. [15] integrated a thermoelectric module into a high power LED lamp. The purpose of their study was to convert the heat given off by the lamp into electrical energy. They found considerable improvements in the thermal and optical performance of luminaires. Lin et al. [16] compared three different solutions for the thermal management of LEDs: Thermoelectric cooler (TEC), microchannel heat sink (MHS), and the combination of these two technologies. Their study demonstrated that the third method, which involves the combination of TEC and MHS, proved to be the most efficient for dissipating heat from the LED lamp.

Simple microspray systems [17-18] have also shown a considerable effect on lowering the junction temperature of LED modules. However, it is important to note that active cooling of LEDs is not always advantageous. It can be cumbersome, requiring additional energy and space, and generally comes with a higher cost for the user.

The integration of phase change materials (PCM) in LED luminaires offers a means to efficiently transfer a substantial amount of heat generated by the chips to the external environment. When the lamp is in operation, the PCM initially exists in a solid state. As the lamp heats up, the temperature of the PCM gradually increases until it reaches its melting temperature. At this point, a phase change occurs, converting the PCM from a solid to a liquid state. During this phase change, a significant amount of heat is absorbed by the PCM in the form of latent heat of fusion, and stored within the material. When the lamp's temperature begins to decrease, the PCM undergoes a reverse phase change from a liquid back to a solid state. During this transition, the stored heat is released, aiding in the cooling process of the LED

luminaire. This property of PCM allows for effective heat management by exploiting the high heat storage capacity and latent heat properties of the material. The integration of PCM in LED luminaires provides an additional mechanism for thermal management, enhancing the overall heat dissipation capability and improving the reliability and longevity of the luminaires [19]. Several numerical and experimental works were carried out to study the effect of PCM integration in thermal management systems [20-22]. Debich et al. [20,21] developed an experimental and numerical thermal study of a PCM-filled rectangular heat sink for cooling mechatronic devices. Their parametric study highlighted the effect of input power, PCM type and its volume fraction. They showed that filling the heat sink with PCM (mainly if it is n-Eicosane) leads to an improvement in terms of thermal management. Later, the same authors developed an optimization, following the reliability based design optimization (RBDO) approach, of the PCM-filled heat sink geometry.

By integrating LEDs in smart lighting, the lamp will undergo periodic thermal stress or also will operate intermittently following on/off cycles or also high/low power cycles. This would require a higher level of thermal management in order to control the behavior of the lamp in the face of sudden temperature rises that can damage the lamp and reduce its thermal and optical performances. In this context, Wu et al. [22] also studied the thermal behavior of a rectangular heat pipe radiator filled with PCM intended to cool a high power LED lamp. RT52 supplied by Rubitherm Technologies GmbH was used as PCM. The heat sink temperature is measured for different input powers and different cycling modes. Experimental results showed that the addition of PCM slowed the heating rate and peak temperature of the lamp. In addition, the heat sink achieves the best anti-thermal shock ability in LED intermittent working modes. Yang et al. [23] presents a numerical model validated by another analytical dealing with the heat transfer by natural convection around a heat sink containing a PCM layer at the level of its base. The performance of the radiator has been analyzed in the face of transient thermal shocks. Baby et al. [24] quantified experimentally the heat transfer through n-Eicosane filled heat sink. Three geometries were compared: a finned radiator filled with PCM, a finned radiator without PCM, and a radiator filled with PCM but without fins. The authors were interested in the cases of intermittent heating and they showed that in this case the addition of PCM slows down considerably the rise in temperature and reduces the peak temperatures.

Based on the literature review conducted above, the cooling of LEDs using heat sinks filled with PCMs has primarily focused on traditional heat sink geometries. However, there are alternative geometries that have proven to be efficient in heat transfer. One such geometry is

the honeycomb heat sink, which has been utilized in the thermal management of lithium-ion batteries [25] and the cooling of LEDs lamps (via forced convection) [26]. Honeycomb heat sinks are known for their robustness, compactness, and ability to provide a larger surface area for heat exchange compared to traditional radiators of the same volume. In the context of cooling lithium-ion batteries, this geometry has demonstrated significant temperature reductions when filled with PCM, effectively preventing battery failures.

In this work, we propose to numerically investigate the effectiveness of a hexagonal honeycomb heat sink geometry for cooling LED modules used in smart lighting applications. Three different heat sink geometries are studied: a honeycomb heat sink filled with aluminum, a hollowed honeycomb heat sink, and a honeycomb heat sink filled with E-BiInSn PCM. Additionally, three input powers and four cycles of intermittent operation are tested to analyze the thermal behavior of the heat sink under varying conditions. By exploring the thermal performance of these honeycomb heat sink configurations, we aim to contribute to the development of effective cooling strategies for LEDs in smart lighting applications.

II. Numerical modeling

1. Geometry

Because smart lighting has become a challenge for both manufacturers and consumers, it is essential to integrate sophisticated technologies to cool LED lamps. In this work, we propose to test the effectiveness of a honeycomb heat sink in cooling LED lamps. The honeycomb heat sink is a robust and compact geometry that has demonstrated its effectiveness in cooling various electronic devices.

Three different geometries are tested in this study, as depicted in figure 1. The first geometry is a honeycomb heat sink with a height of 10 mm, consisting of an array of regular hexagons filled with aluminum. The dimensions of the regular hexagon, as detailed in figure 2, are $a = 4.5$ mm and $2t = 0.8$ mm. The second geometry is a honeycomb heat sink that occupies the same volume as the first geometry, but with empty hexagons that allow for airflow between them. The third geometry involves adding a 1 mm thick layer of phase change material (PCM) between the different hexagons, as shown in figure 1.

For all three heat sinks tested in this study, LED chips are embedded within the heat sink, and they are distributed over the seven central hexagons.

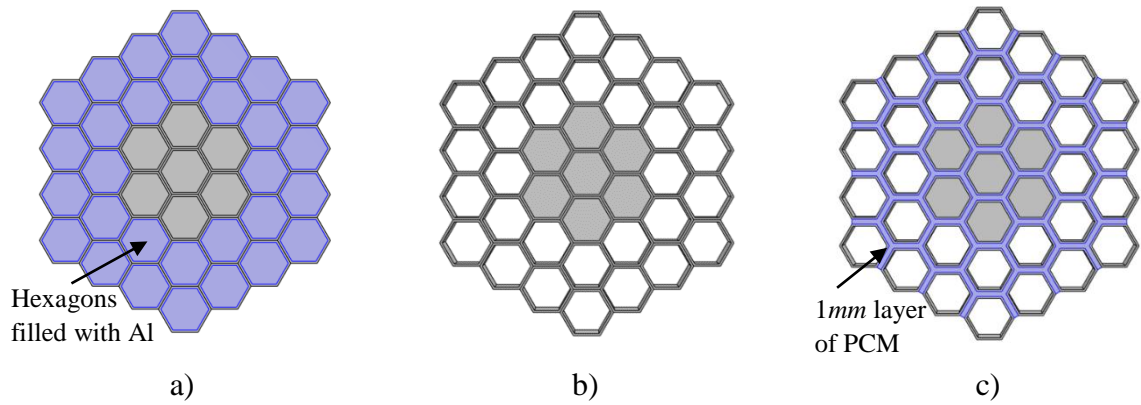


Figure 1 Different honeycomb geometries tested: a) Honeycomb heat sink filled with Aluminum, b) Hollowed Honeycomb heat sink, and c) Honeycomb heat sink filled with PCM

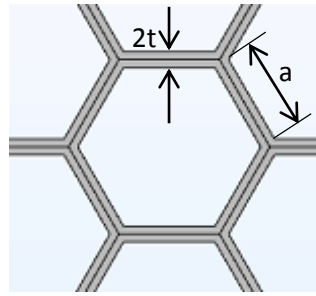


Figure 2 Dimension of a hexagonal cell

2. Governing equations

The governing equations for the three dimensional modeling in Cartesian coordinates are as follows:

✓ Continuity:

$$\frac{\partial(u)}{\partial x} + \frac{\partial(v)}{\partial y} + \frac{\partial(w)}{\partial z} = 0 \quad (1)$$

Where u , v and w are the velocity components in the x , y and z directions respectively.

✓ Momentum equations in (x,y,z) directions:

$$\rho \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = -\frac{\partial P}{\partial x} + \mu \left(\frac{\partial u}{\partial t} + u \frac{\partial^2 u}{\partial x^2} + v \frac{\partial^2 u}{\partial y^2} + w \frac{\partial^2 u}{\partial z^2} \right) + S \quad (2)$$

$$\rho \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = -\frac{\partial P}{\partial y} + \mu \left(\frac{\partial v}{\partial t} + u \frac{\partial^2 v}{\partial x^2} + v \frac{\partial^2 v}{\partial y^2} + w \frac{\partial^2 v}{\partial z^2} \right) + S \quad (3)$$

$$\rho \left(\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = -\frac{\partial P}{\partial z} + \mu \left(\frac{\partial w}{\partial t} + u \frac{\partial^2 w}{\partial x^2} + v \frac{\partial^2 w}{\partial y^2} + w \frac{\partial^2 w}{\partial z^2} \right) + S +$$

$$\rho g \beta (T - T_{\infty}) \quad (4)$$

Where ρ is the liquid PCM density (note that the liquid PCM is assumed to be incompressible and Newtonian fluid), P is the pressure, μ is the dynamic viscosity, g is the gravitational acceleration, t is the time, β is the thermal expansion coefficient, and T_∞ is the ambient temperature.

The source term S in the momentum equations is written as follows:

$$S = -\frac{(1-f_{PCM})^2}{f_{PCM}^3 + \varepsilon} A_m, A_m = 10^4, \varepsilon = 10^{-10}$$

Where A_m is the mushy zone constant, f_{PCM} is the liquid fraction, and ε is a small scalar to avoid division by zero [27].

Energy equation:

$$\rho C_p \left(\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) - \rho L \frac{\partial f_{PCM}}{\partial t} \quad (5)$$

$$\text{Where } f_{PCM} = \begin{cases} 0 & \text{if } T < T_s \\ \frac{T - T_s}{T_l - T_s} & \text{if } T_s < T < T_l \\ 1 & \text{if } T > T_l \end{cases}$$

T_s is the solidification temperature, T_l is the melting temperature, and L is the latent heat of melting.

3. Boundary conditions

- A high power LED lamp was chosen to be tested in this work. This light source is composed of seven LED chips on which the total electrical power consumed is equally divided. Three level of total power are tested in this work : $P_{tot}=20,10$ and 5 W
- The exterior surfaces of the heat sink exchange heat with the outside by natural convection with a convective heat transfer coefficient $h = 10 \frac{W}{m^2.K}$ at an ambient temperature $T_\infty = 298K$ and ambient pressure $P_{atm} = 1 atm$
- 70% of the electrical power consumed by the lamp is converted into heat [28]. So, to provide the amount of heat generated at the level of different chips, a heat flux is imposed equally on the seven LEDs chips : $q = 0.7P_{tot}$
- The lamp is initially at ambient temperature T_∞ .

4. Numerical procedure and mesh sensitivity

The different partial differential equations (1)-(5) were solved numerically using COMSOL Multiphysics®, a CFD software based on the finite element method. A mesh test was also conducted in order to have higher results precision. The selected mesh is composed of 384174 domain elements and 136436 boundary elements (see figure 3). Additional mesh elements have no significant effect on the results precision.

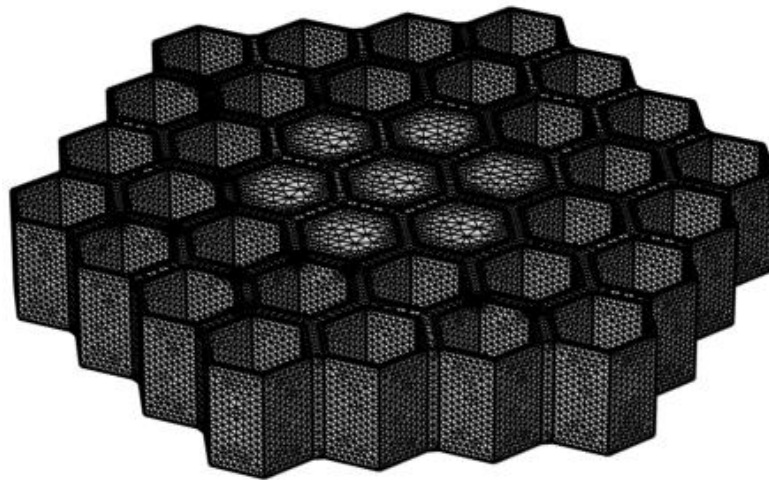


Figure 3 Mesh of the computational domain

III. Results and discussion

1. Validation

In order to validate the accuracy of our numerical model in predicting the thermal behavior of the lamp with and without the integration of phase change materials, we compared our numerical results with the analytical results presented by Yang et al. [25] for the case of a rectangular heat sink. Two cases were examined: firstly, the case of a heat sink without PCM was compared to the results of Yang et al. [25] to ensure that our numerical model accurately describes heat transfer through natural convection. Secondly, the numerical model incorporating a layer of PCM beneath the heat sink baseboard was compared with the analytical results of Yang et al. [25] to verify the precision of our numerical solution for the system of partial differential equations when including the equations describing phase change of the material. Figure 4 illustrates the temperature profile of the heat sink at $t = 1200s$, and figure 5 presents the variation of heat sink temperature over time. During the initial 20-minute period,

$t \in [0, 1200s]$, the heat sink is subjected to a heating power of 4W. In this phase, the temperature rise of the heat sink is almost identical in the presence or absence of PCM since the PCM has not yet reached its melting temperature. However, integrating the PCM layer results in a slight decrease in temperature values, attributed to the enhanced surface area for heat exchange.

Following this, a thermal shock power ($P = 40W$) is applied for the next 100s, i.e., within the range [1200, 1300s], causing a significant increase in heat sink temperature. At this point, the PCM reaches its melting temperature and transitions into a liquid state. Finally, the heat sink returns to its initial heating power of 4W within the interval [1300, 3600s]. During this phase, it is obvious that the temperature drop of the heat sink differs between the cases with and without PCM. Specifically, in the presence of PCM, the heat sink gradually cools until it reaches its solidification temperature. At this temperature, the phase change occurs isothermally, and then the cooling process of the heat sink continues gradually until it reaches a steady state.

The comparison between our numerical results and the analytical results demonstrates satisfactory agreement, confirming that our numerical model accurately predicts heat transfer through natural convection in the presence and absence of a phase change materials layer.

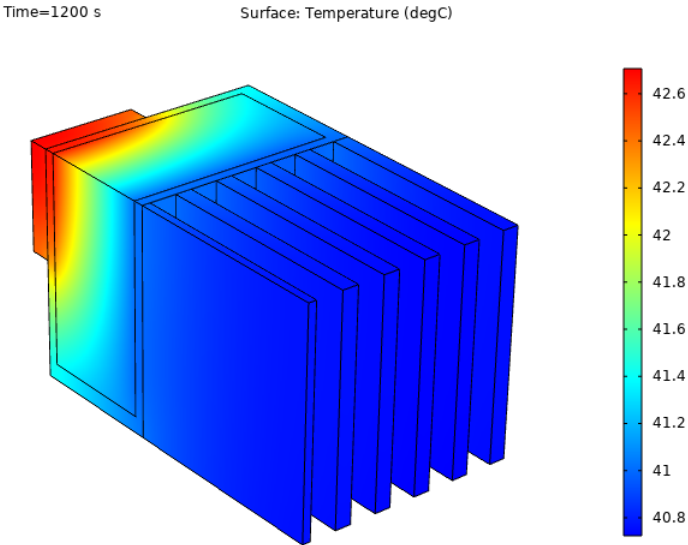


Figure 4 Validation of the temperature profile on the rectangular heat sink with results of [28]

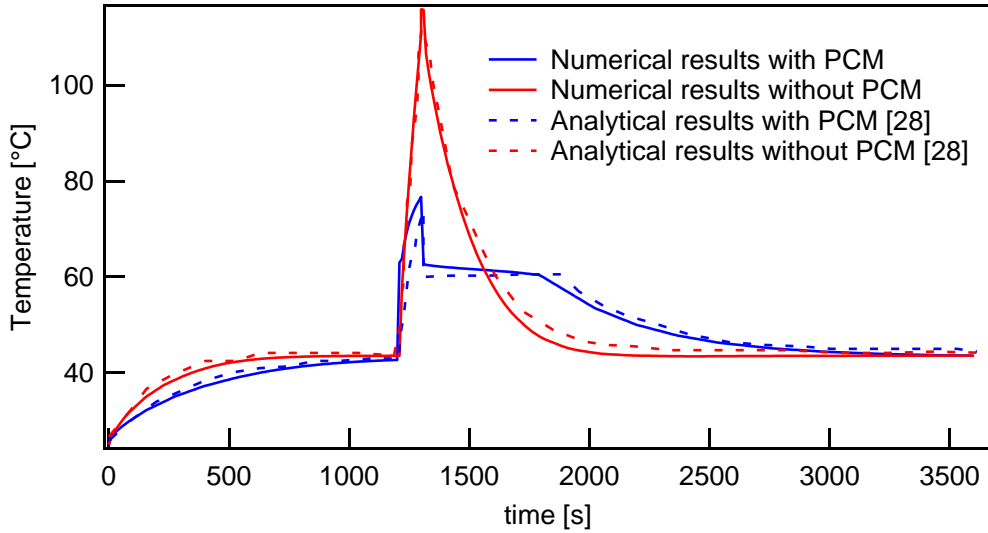


Figure 5 Validation of the evolution of temperature as a function of time [28]

2. Comparison between different geometries

2.1. Filled Aluminum honeycomb heat sink vs. hollowed honeycomb heat sink

In this part, we propose to compare the three geometries of heat sinks of this study. Figure 6 illustrates a comparison of the temperature profile for the case of honeycomb heat sink filled with aluminum and hollow honeycomb heat sink. Two different total powers were tested: $P_{\text{tot}} = 5, 10 \text{ W}$. For reasons of convergence of the numerical model, note here that the LED chips are represented by hexagonal flat surfaces given their very low thickness (which is of the order of a few micrometers). The junction temperature is then assumed equal to that on the chips surfaces.

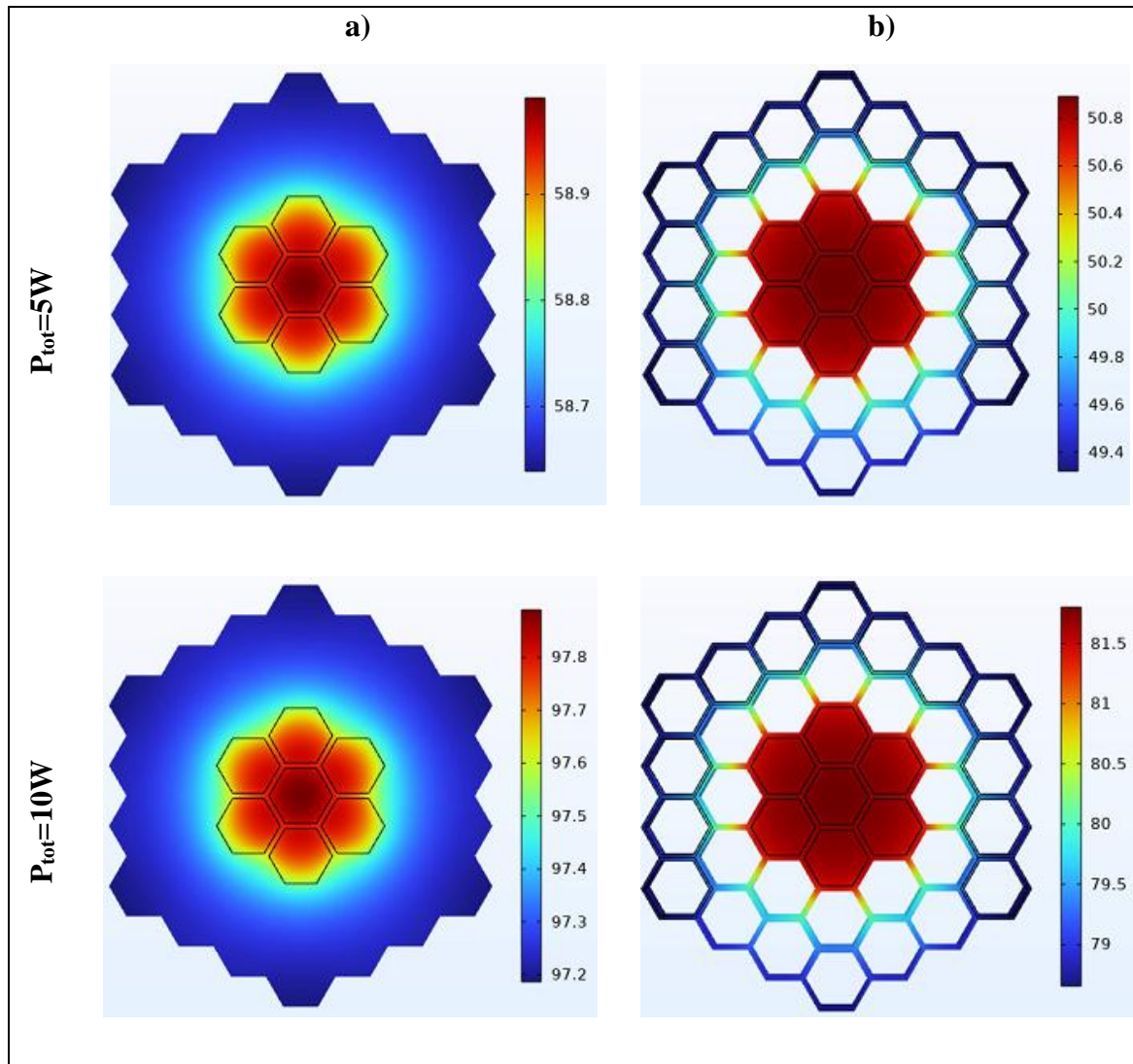


Figure 6 Temperature profile on (a) honeycomb heat sink filled with aluminum and (b) on honeycomb hollowed heat sink

According to the figure 6, using a hollow honeycomb heat sink instead of the one filled with aluminum, it allows to reduce the maximum junction temperature by 13.75% and 16.66% for total powers $P_{tot}=5$ and 10W, respectively. In fact, besides significantly reduce of the heat sink weight, the hollow honeycomb geometry allows efficient air circulation between fins. The amount of heat exchanged with the outside via natural convection improves considerably which provides lower junction temperature. Such an intact and robust geometry should be an effective solution for lighting applications where the weight of the heat sink must be reduced, the design must be attractive and robust, and without affecting the efficiency of the light source.

2.2.Heat sink without PCM vs heat sink with PCM

The comparison between the second and the third geometries is illustrated in the figure 7 for total powers $P_{tot}=10W$ and $P_{tot}=20W$ over an operating time of 20 minutes. The rise in temperature is less acute in the presence of PCM. In addition, the junction temperature remains relatively lower than that without PCM. This reduction in temperature although it is small, it leads to considerable gains in terms of lamp lifetime. For example, the junction temperature reduction by 6 degrees for the case $P_{tot}=10W$ results in 2445 hours of additional lamp operation (about twice the life of an incandescent bulb [1, 29]).

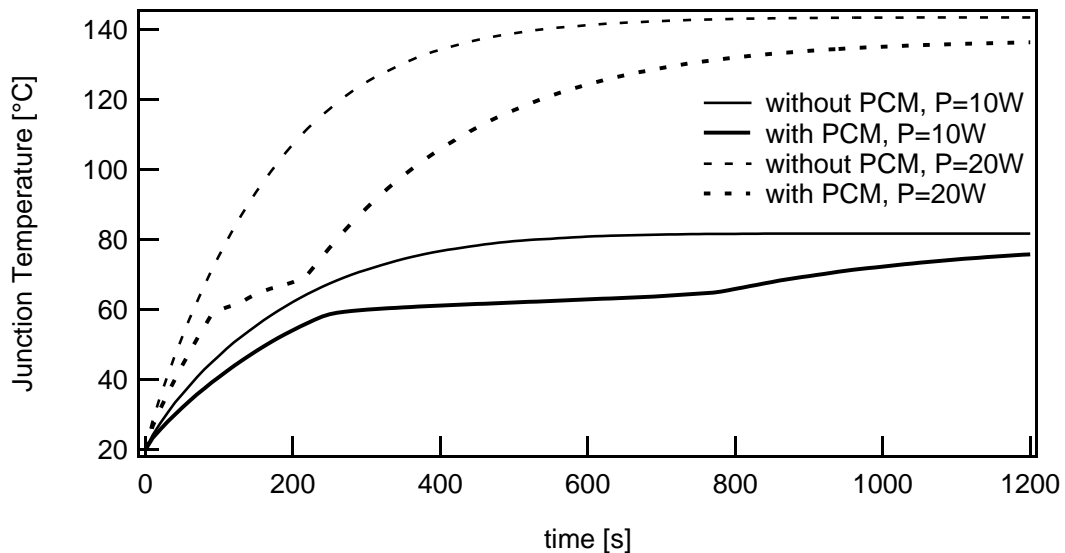


Figure 7 Temperature evolution as a function of time for hollowed honeycomb heat sink and hollowed honeycomb heat sink filled with PCM

Although the effect of adding a PCM layer allows a considerable temperature reduction in steady state and avoids the failure of lamp, the effect seems to be most significant over the first 400 seconds of the lamp operating time, mainly for very high power lamps $P_{tot}=20W$. Indeed, with this power, the maximum reduction of the junction temperature is about $36^{\circ}C$ by adding a 1mm layer of PCM. This undoubtedly allows benefiting from the performance of the lamp for longer since this drop in junction temperature will extend its lifetime and improve its flux and its luminous efficiency.

Since the effect of adding PCMs to the LED lamp is more significant on a reduced operating time, it would be interesting to take advantage of this effect in short duration and intermittent

lighting applications. Smart lighting is the first candidate to propose in this context since the integration of PCMs would be effective for the smart city.

2.3. Comparison of photometric parameters

In addition to the junction temperature, the photometric properties of the LED serve as crucial indicators of the light source's performance. In this section, we aim to compare the luminous flux, luminous efficacy, and lamp lifespan for the three studied radiator configurations. Considering an emission of 60 lm per LED chip at a junction temperature of 25 °C, each chip exhibits a luminous degradation coefficient of -0.108 lm/°C. The lamp comprises a total of 7 of these chips, and the total luminous flux emitted by the lamp is then calculated by aggregating the individual fluxes of each chip [6]. Luminous efficacy of the LED is defined as the ratio of its luminous flux to its total electrical power. Finally, the lamp's lifespan is determined using the formula (6) provided below [30]:

$$L_f = Ae^{-\theta T_j} \quad (6)$$

where $A = 477377$, $\theta = 0.052$ and T_j is the junction temperature.

Figures 8 and 9 respectively depict the evolution of flux, luminous efficacy, and lamp lifespan for a 10W lamp, varying with the cooling system's geometry. It is worth noting that the first configuration (denoted as 1 in the figures) refers to a filled aluminum honeycomb heat sink, the second configuration (denoted as 2) signifies a hollowed heat sink without PCM, and the third configuration represents a hollowed heat sink with a PCM layer.

According to Figure 8, a notable enhancement in both flux and luminous efficacy is observed when transitioning from a heat sink filled with aluminum to a hollowed honeycomb with PCM, resulting in a 16lm increase in flux. This improvement is also reflected in the lamp's lifespan. In fact, according to figure 9, the impact on the lifespan is substantial, marked by a noteworthy enhancement. Shifting from the first to the second configuration yields a remarkable improvement of 3785 hours, and progressing from the second to the third configuration results in an additional substantial gain of 2445 hours in enhanced lifespan.

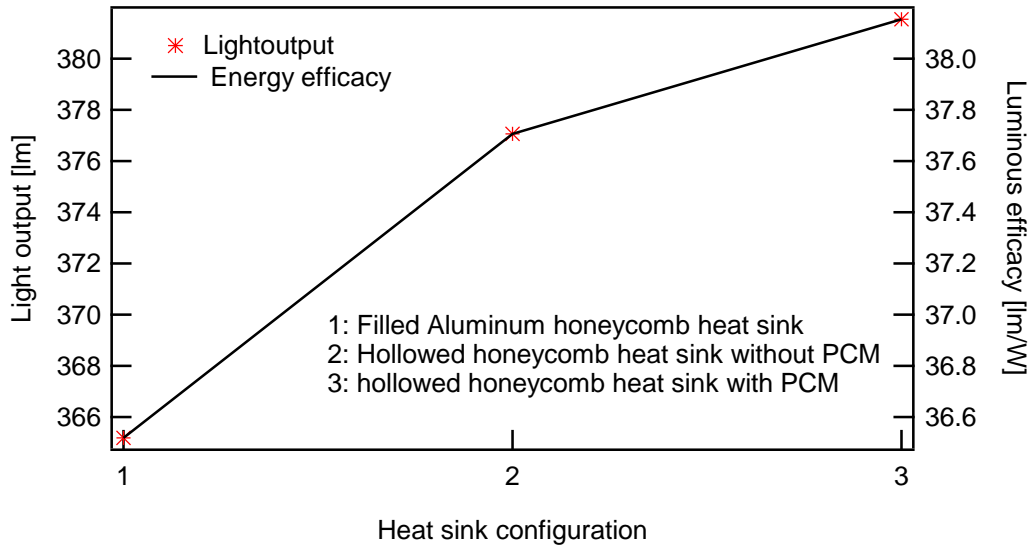


Figure 8 Light output and luminous efficacy of the lamp for different heat sink configurations

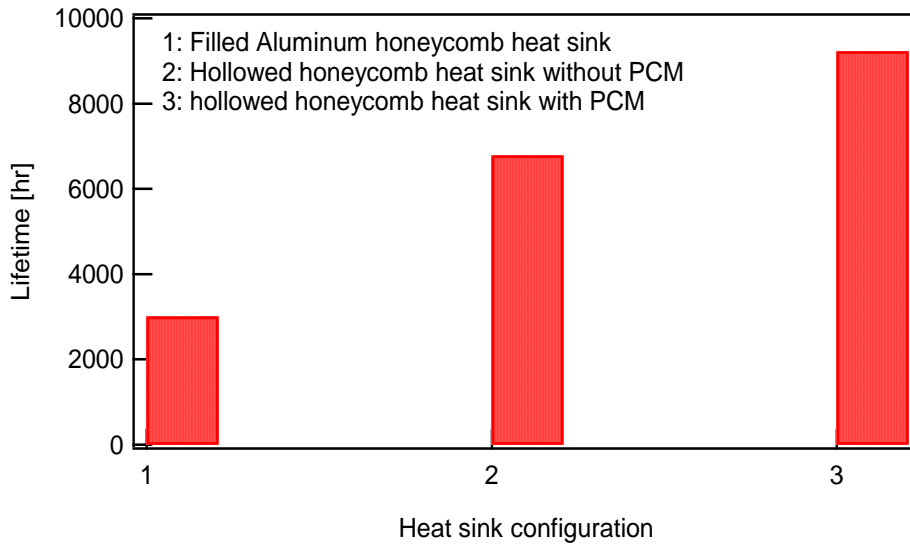


Figure 9 Lamp lifespan for different heat sink configurations

3. 20W LEDs lamp for smart lighting: Determination of optimal operating time

Figure 10 shows the evolution of the maximum junction temperature as a function of time over a 5-minutes interval. The aim here is to determine the optimum operating time that will guarantee a junction temperature within the standards over an acceptable time interval.

According to the figure 10, for the case of hollowed honeycomb containing a PCM layer, the maximum temperature increases slightly if we increase its operating time from 1.5 min to 3.5 min. Indeed, over this interval, the junction temperature is between 58°C and 68°C. The temperature difference between the latter and the threshold (120°C) set by the manufacturers is about 50°C. This largely sufficient difference guarantees proper operation of the lamp over said

time interval, essentially for smart lighting applications, which require a high degree of robustness and performance.

On the other hand, for lighting applications of short duration such as corridor lighting in hospitals, companies, hotels, university residences, smart road lighting etc., the operating time should be greater than 3 min to guarantee user safety and security. Thus, the optimal operating time chosen in this study is 3.5 min.

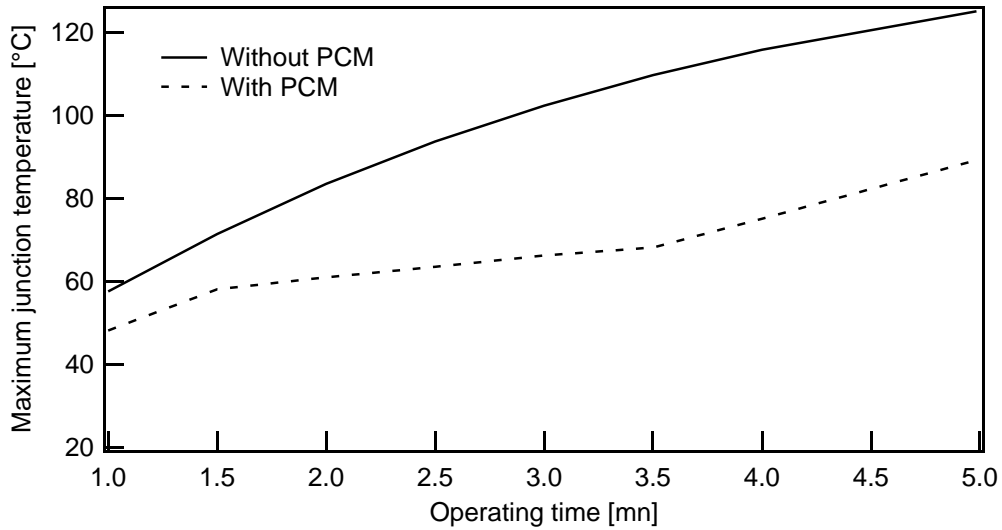


Figure 10 Evolution of maximum junction temperature as a function of operating time

4. 20W LEDs lamp for smart lighting: thermal behavior following on/off cycles

At the heart of the challenges of the energy crisis, several municipalities as well as users have opted for smart lighting, in order to guarantee total control of lighting, to manage the activation and intensity of lamps efficiently according to needs, and to reduce the percentage of energy waste in the lighting sector. In this dynamic, we are interested in this part in the thermal study of a 20W power lamp that undergoes on/off cycles for a total duration of one hour. One can meet this lamp in the lighting of corridors for example, where the turning-on and the intensity of light are controlled and personalized according to the presence of individuals. In this study, the variations of the total power lamp P_{tot} during the cycle are represented by a rectangular signal characterized by the following parameters:

$$\left\{ \begin{array}{ll} t_{on} & \text{time during which the lamp is on} \\ t_{off} & \text{time during which the lamp is off} \\ T_s = t_{on} + t_{off} & \text{signal period} \end{array} \right.$$

In this study, t_{on} is fixed to be equal to 3.5 min. In addition, four different signal periods are evaluated: $T_s=20, 15, 10$ and 5 min. The maximum junction temperature reached by the lamp, for each signal period, are then depicted in figures 11-15.

One can notice on figure 11 that the profile of the junction temperature of each period can be divided into two: a phase of PCM charging, and another of PCM discharging. Initially, the junction temperature is equal to the ambient temperature of the external environment. Once the lamp is on, its junction temperature begins to rise. Since PCM is initially in the solid phase, it begins its phase change after 100s of operation when the junction temperature reaches 60°C (PCM melting temperature). Thanks to the thermo-physical properties of the PCM, the increase in junction temperature slows down, mainly during the phase change of PCM. Finally, the junction temperature reaches its maximum value at the end of its operating period and the PCM becomes completely in the liquid phase. This temperature remains relatively acceptable and guarantees proper operation of the light source.

To summarize, the junction temperature rise in the presence of PCM occurs in three phases of PCM: solid phase, followed by a latent heating phase and a liquid phase.

When the lamp is off, $t \in [210s, 1200s]$, the drop in temperature is accompanied by the discharge of the PCM, which boosts the cooling of the lamp and helps it to regain a junction temperature equal to the ambient temperature. This allows the following periods of the cycle to also trigger with a low junction temperature and to reach acceptable maximum temperatures as depicted in figure 12 (equal to those of the first period of the cycle), which guarantee correct operation of the light source .

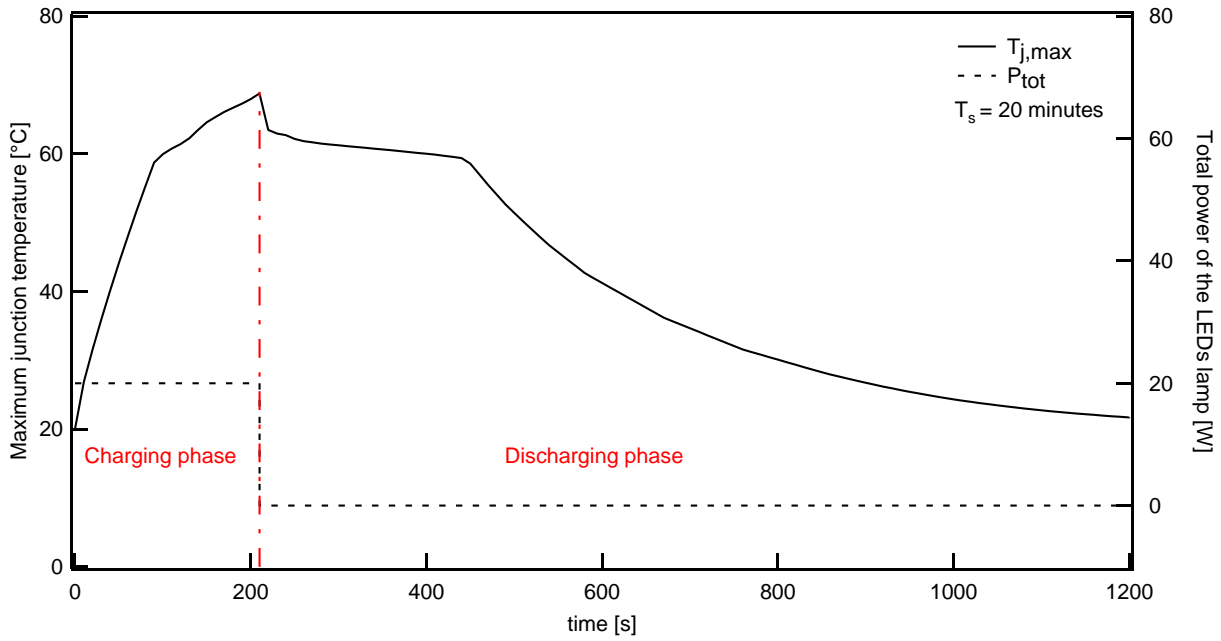


Figure 11 Temperature profile on the time range [0, 1200s]

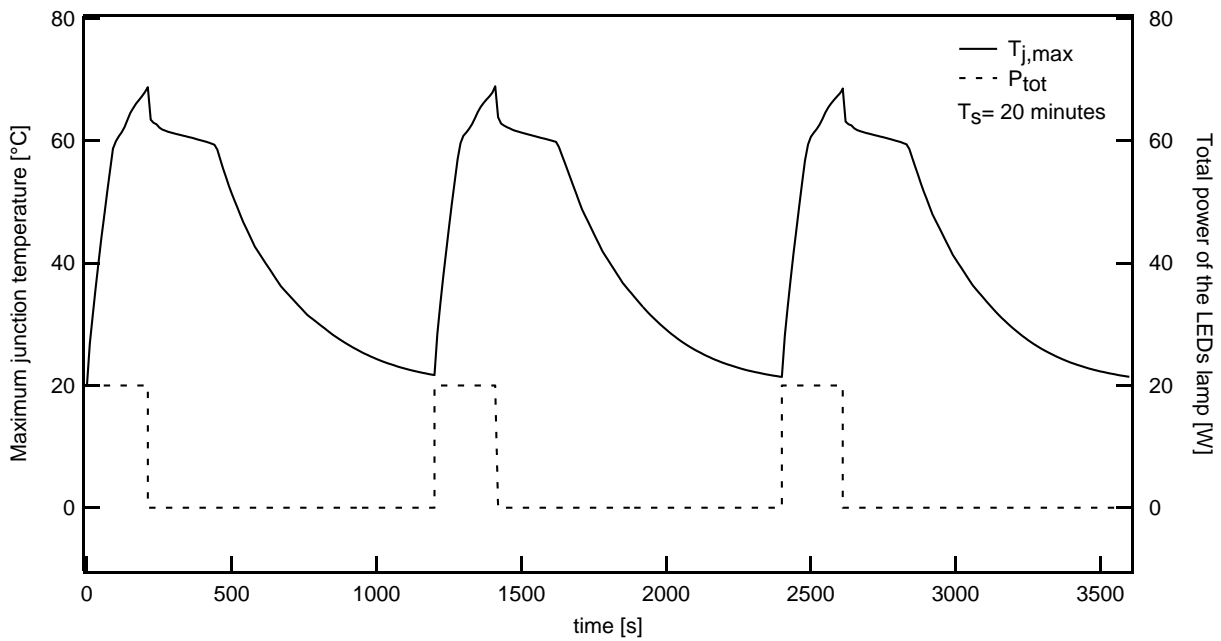


Figure 12 Temperature profile for ON/OFF cycle, $T_s=20$ min

By decreasing the signal period to $T_s=15$ min (figure 13), we notice that; on the first period of the cycle; the maximum temperature of the lamp follows the same evolution as that with $T_s=20$ min during the rise in temperature ($T_{max} = 69^\circ\text{C}$ at the end of the turning-on period). The difference lies in the discharging phase, the duration of which is $T_{off} = 690$ s. During this turning-off period, the lamp cools and its maximum junction temperature decreases to 25°C . The following cycle periods begin then with this last temperature, which is higher than the ambient

temperature of the external environment. This leads to a slight increase in the maximum temperature at the end of each turning-on period ($T_{\max}=72^{\circ}\text{C}$).

With $T_s=10$ min (figure 14), the duration of the extinction decreases further and the lamp has no longer enough time to cool down. This causes a remarkable increase in the onset temperature of subsequent cycles ($T=39^{\circ}\text{C}$) and their maximum temperatures reached ($T_{\max}=79^{\circ}\text{C}$).

For shorter signal periods (i.e. $T_s = 5$ min), as it can be seen in Figure 15, the maximum junction temperature of the lamp is low only during the first period of the cycle where the lamp starts at room temperature. As the lamp undergoes subsequent on/off cycles, the maximum temperature fluctuates between 83°C and 115°C . Relatively high operating temperatures degrade the performance of the light source, such as the quality of its emitted light, its luminous efficiency and its lifespan. Thus, according to the results obtained, it is strictly inadvisable to use this lamp when the on/off frequency is too high.

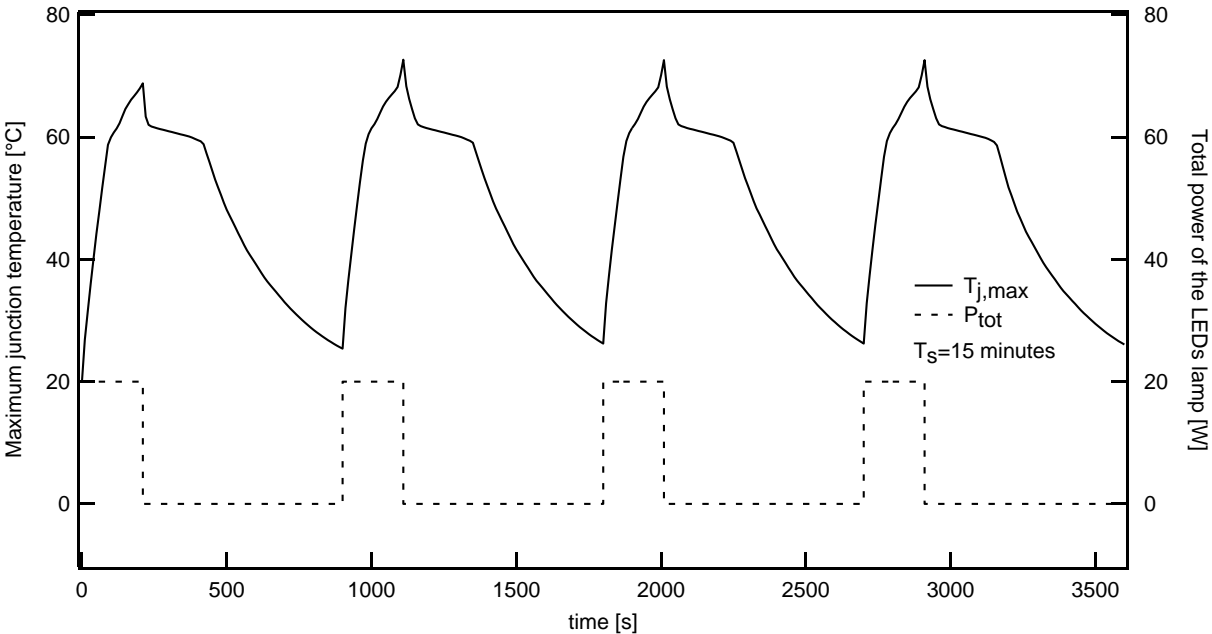


Figure 13 Temperature profile for ON/OFF cycle, $T_s=15$ min

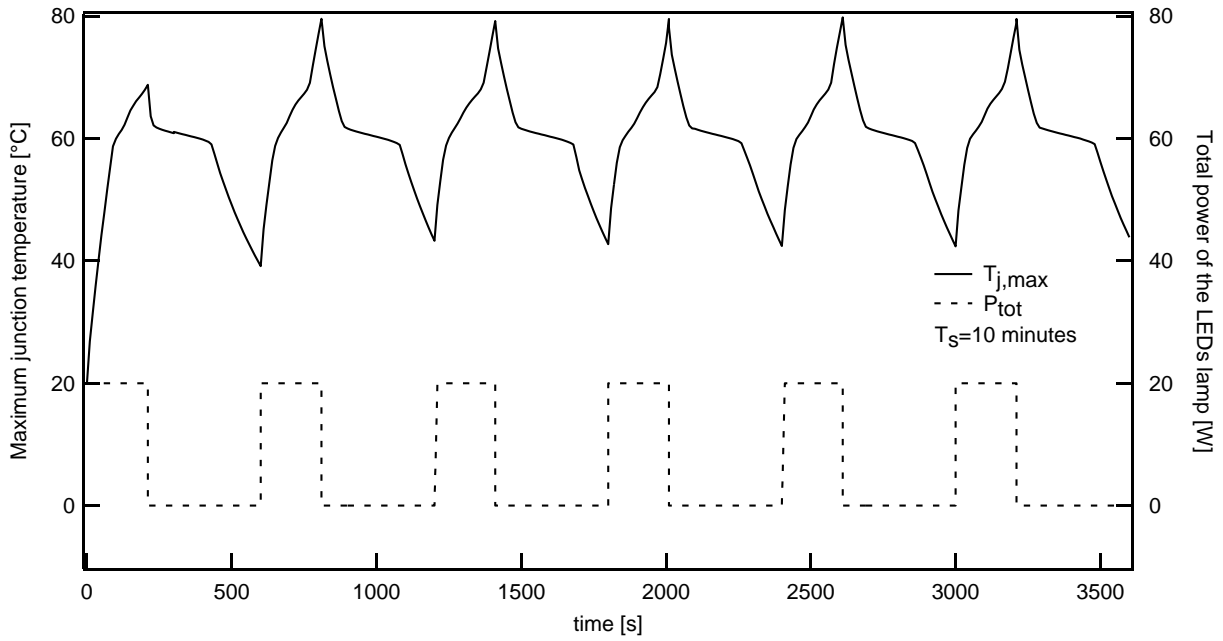


Figure 14 Temperature profile for ON/OFF cycle, $T_s=10$ min

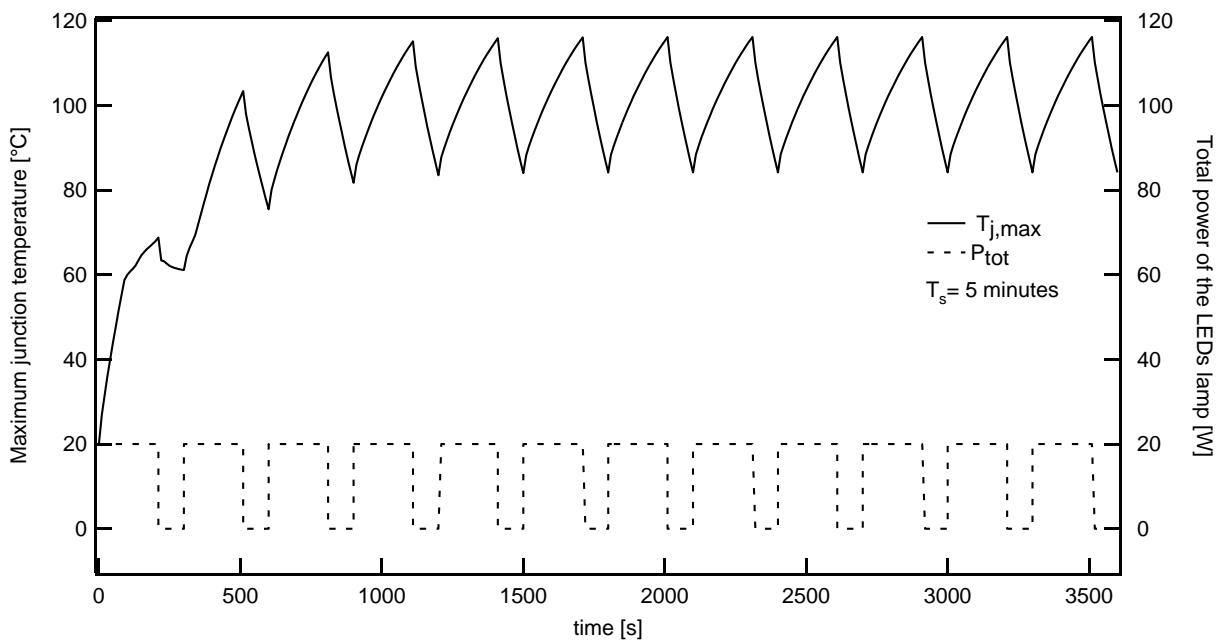


Figure 15 Temperature profile for ON/OFF cycle, $T_s=5$ min

5. 20W LEDs lamp for smart lighting: thermal behavior according to high/low power cycles

For reasons of safety and/or user comfort, smart lighting offers the possibility of controlling the amount of the light produced by the lamp. The latter can then; according to the needs of the

user, switch between low and high powers (night light mode / high power lamp mode). In this part of our numerical study, we deal with the thermal behavior of LEDs lamp according to high/low power cycles over a total duration of one hour. The power of the lamp under study fluctuates between 20W and 2W. The evolution of the maximum junction temperature is summarized in figure 16 for different periods of the high/low intensity cycles: $T_s=20, 15, 10$ and 5 min. Similarly to the previous section, we can characterize the power of the lamp by a rectangular signal defined by the following parameters:

$$\left\{ \begin{array}{ll} t_{on} & \text{time during which } P_{tot} = 20W \\ t_{off} & \text{time during which } P_{tot} = 2W \\ T_s = t_{on} + t_{off} & \text{signal period} \end{array} \right.$$

It is noted that for $T_s= 20,15$ and 10 minutes, the PCM integrated in the lamp follows successive charging and discharging cycles, thus favoring the slowing down of the rise of the junction temperature of the lamp. According to the results found, the longer the low power period, the lower the junction temperature of the LED. Thus, to promote the proper operating of the light source, it will be necessary to prolong the periods of low power as much as possible to allow the lamp to cool down and find fairly low junction temperatures before starting the high power mode.

On the other hand, for $T_s =5\text{min}$, the PCM only undergoes phase changes during the first period of its cycle. Indeed, at the start of the cycle, its junction temperature increases and reaches the PCM melting temperature. Then, during the low power phase which lasts only 1.5 minutes, the PCM does not have enough time to regain its solid state. It is then in changing phase before starting the second period of the cycle. During the latter, the junction temperature increases further, exceeds 100°C and cannot decrease beyond 80°C since the low power mode does not last long. The junction temperature undergoes then oscillations between 86 and 115°C over all the other periods of the cycle.

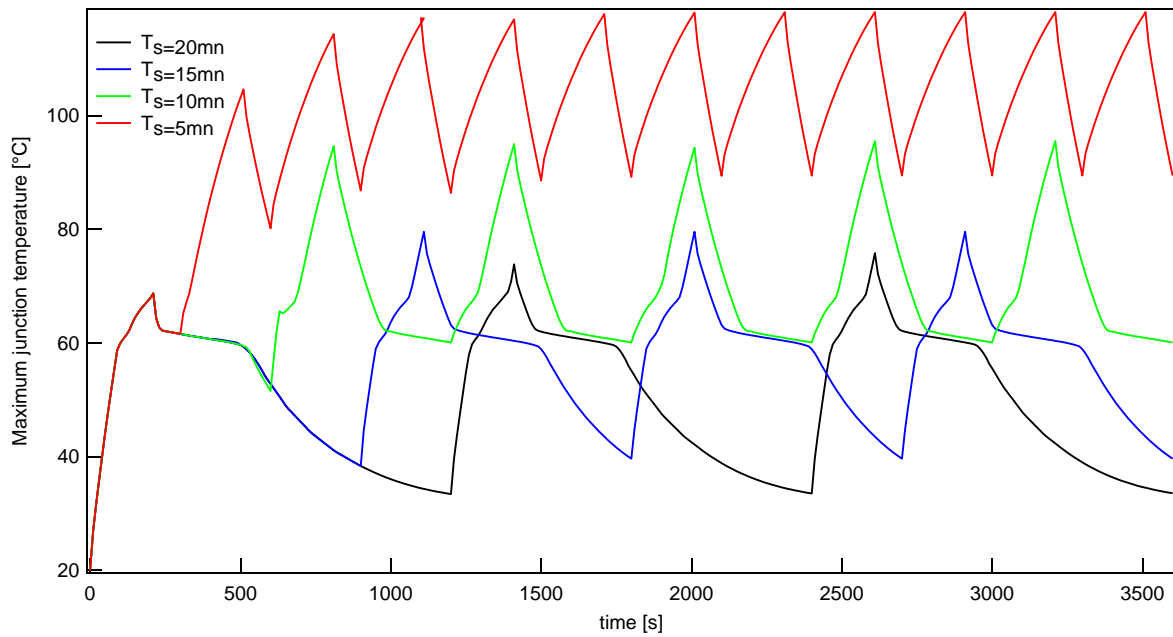


Figure 16 Temperature profile for high/low power cycle, $T_s=20, 15, 10, 5$ minutes

Conclusion

In this three-dimensional numerical analysis, we compared three honeycomb heat sink geometries for the thermal management of LEDs. Hollowed honeycomb heat sinks are more advantageous as they provide a larger surface area for heat exchange and allow for better heat dissipation. The integration of E-BiInSn PCM into hollowed honeycomb heat sink has shown a significant improvement in reducing junction temperature, particularly when used in short-duration lighting applications. The PCM's heat storage capability, especially during its phase change, effectively prevents excessive overheating and potential lamp failure. In fact, for a 20W power lamp, the junction temperature has decreased by 25% compared to the scenario without PCM.

In the context of smart lighting applications, we conducted a thermal study in the second part of this work, focusing on honeycomb heat sink filled with PCM during short on/off cycles and high/low power cycles. The heat sink model employed demonstrated remarkable performance when the cycle period did not exceed 10 minutes. It was observed that very brief intermittent periods should be avoided to fully leverage the lamp's performance, extend its lifespan, and prevent any potential failures.

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