Numerical Study of Optimization of the Volume and the Emplacement of Phase Change Material Employed for Power LED Lamp Cooling

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ABSTRACT

The purpose of this paper is to optimize the volume and the emplacement of PCM in the heat sink for improving the cooling performance of LED with economizing of PCM amount. A numerical model is developed to simulate the PCM melting process with considering natural convection. The incorporation of PCM in the heat sink permit to reduce the junction temperature during melting time and to store an amount of energy which will be evacuated to the ambient accommodation. Different configuration of heat sink with PCM were proposed, and their temperature reduced were compared. The importance of the emplacement of PCM with the same volume was investigated.

Keywords: LED; Heat sink; PCM; Average temperature; Comsol Multiphysics.

1. INTRODUCTION

Nowadays, light emitting diodes lamp becomes the most interesting lamp (Zhua and Sun, 2016). It replaces mercury discharge lamp (Ben Hamida ***et al.*** (2012, 2013, 2015a, 2015b)) and metal halide lamp (Ben Hamida ***et al.*** (2015c, 2016)) thanks to its instantaneous ignition, its low consumption and its high lifetime, which can reach fifty thousand hours. However, it converts more than 80% of the electric power into heat. If this heat is not properly dissipated outside, it can affect the lifetime and the luminous flux.

The first mode of heat transfer from the LED die is the conduction. For that reason, several works insisted on the important of the materials used in the packaging of the LED: Christensen ***et al.*** (2009) perform a ceramic packaging architecture to eliminate the resistance due to the epoxy isolation layer. Heo ***et al*** present an application of high thermal conductivity aluminum nitride (AlN) films to replace low thermal conductivity epoxy resin or alumina substrates (Heo ***et al.*** (2013)). Yang ***et al.*** (2014) reduce the thermal spreading resistance by 14% by using graphite substrate instead of aluminum. Ben Abdelmlak ***et al.*** (2016, 2017) notify the grave effect of thermal conduction path deficiency between the thermal grease and the heat sink. The heat sink will guaranty the dissipation of the heat by convection in the surrounding environment. Many other investigators study experimentally the effect of orientation of heat sink on the heat transfer for example Costa who upgrade radial heat sink (Costa ***et al.*** 2014) and Tari ***et al.*** (2013) who gives numerical study of inclined plate fin heat sink. Huang combined pin fins and oblique fins (Huang ***et al.*** 2016). He found the two optimum number of plate fins in each model (7 in OPF oblique-plate fin heat sink and 8 in PPF pin-plate fin heat sink). Seung-Hwan Yu studied experimentally and numerically the natural convection in a radial heat sink, composed of a horizontal circular base and rectangular fins (Yu ***et al.*** 2010).

However, sometimes, passive cooling methods are deficient for the heat charge generated during long periods of manipulation due to some restrictions such as limited thermal conductivity of air for convection or small space reducing the performance. For that reason, other researchers resort to active method, Hsu and Hang showed high performance of LED with forced convection cooling fluid airflow (Hsu ***et al.*** 2016).

The problem of active method is that it requires other moving parts and additional energy. In this work, a thermal management technique for cooling LED using Phase Change Materials is proposed.

PCMs are effectively used as passive thermal energy storage for several applications such as air conditioning (Zalba ***et al.*** 2004) and glazed windows (Li ***et al.*** 2016; Lia ***et al.*** 2018). To ameliorate the PCM reliability, some works use a metal foam/PCM (Zheng ***et al.*** 2018; Esapour ***et al.*** 2018), others use multi-PCM (Aldoss ***et al.***, 2014) or composite of PCM (George ***et al.*** 2018).

2. GEOMETRY AND GOVERNING EQUATIONS

The figure 1 shows the simplified structure of LED package and the structure of the heat sink (Minseok ***et al.*** 2012).

The dimensions of the structure and the proprieties of materials are summarized in table 1.

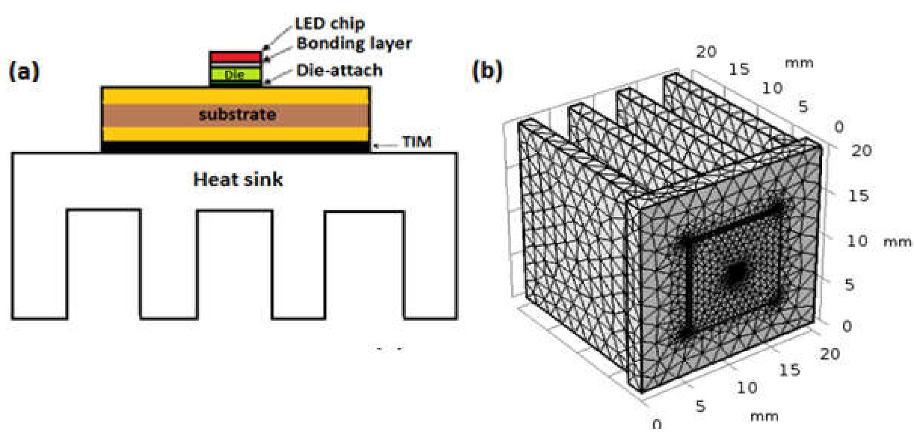


Fig. 1: (a) The structure of the LED package (b) Dimensions of the heat sink

Table 1: Structural dimensions and thermal conductivities at 25°C

	Thickness	Size	Materials	Thermal conductivity (W/m^2K)
LED-chip	4 µm	1 mm × 1 mm	GaN	130
Metallization	10 µm		Au-Si eutectic bonding	27
Die	375 µm		Si	124
Die-attach	50 µm		Au-20Sn	57
Substrate	127 µm	1 cm × 1 cm	Copper	385
	381 µm		DBC : AlN	180
TIM	50µm	1 cm × 1 cm	Thermal grease	3
Heat sink	-	-	Al	150

The energy equation is:

$$\frac{dH}{dt} = \nabla \cdot (\lambda \cdot \nabla T) \quad (1)$$

Where, H is the enthalpy and λ the thermal conductivity of the PCM

$$H(T) = \int_{T_m}^{T} \rho \cdot C_p \cdot \partial T + \rho \cdot L_{PCM} \cdot \beta(T) \quad (2)$$

Where, L_{PCM} is the latent heat of the PCM and β is the liquid fraction expressed as:

$$\beta(T) = \begin{cases} 0 & if \quad T \le T_{sol} \\ \dfrac{(T - T_{sol})}{(T_m - T_{sol})} & if \quad T_{sol} \prec T \prec T_m \\ 1 & if \quad T \ge T_m \end{cases} \quad (3)$$

Where T_m is the melting temperature and T_{sol} is the solidus temperature

3. ASSUMPTIONS AND BOUNDARY CONDITIONS

The initial temperature is 25 °C.

On top of the die there is a uniform heat flux (q = 1 W) and other surfaces around the die, the die attach and the substrate are adiabatic.

To study the effect of a thermal shock on our LED structure, the heat transfer coefficient is taken as dropped from $h = 200 \ W/(m^2K)$ to $h = 5 \ W/(m^2K)$ at t = 0 s.

The thermos-physical characteristics of the PCM are independent of temperature as detailed in table 2

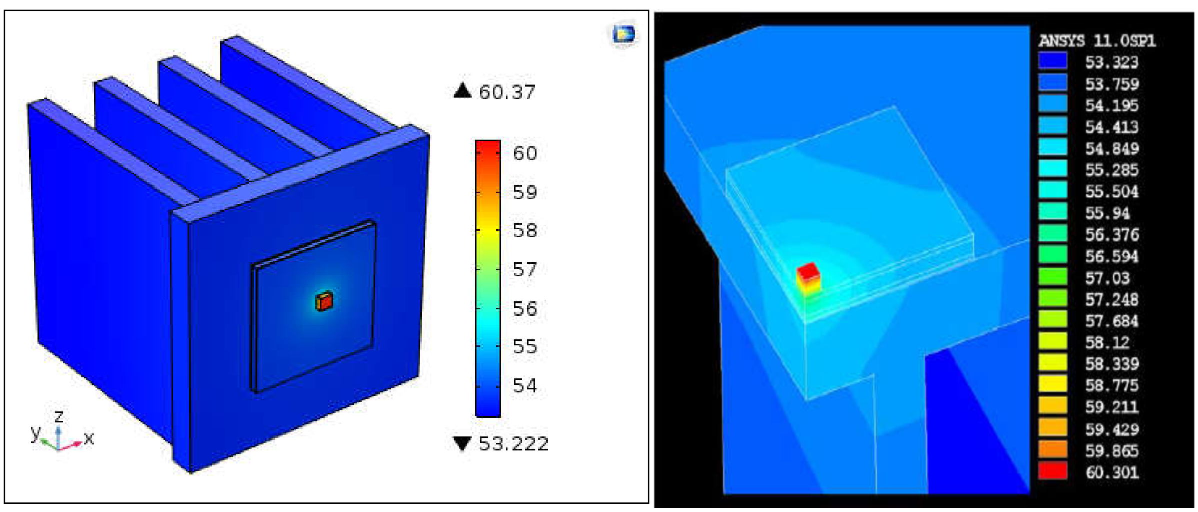
Table 2: Thermo-physical characteristics of RT42 (Saad ***et al***.,2013)

Solidification/Melting temperature, $T_{s/m}$	38-42 °C
Latent heat of fusion, L	165 (kJ/kg)
Specific heat, C_p	2 (kJ/kg K)
Thermal conductivity, k	0.2 (W/m K) (solid); 0.2 (W/m K) (liquid)
Density, ρ	880 (kg/m^3) (solid); 760 (kg/m^3) (liquid)
Dynamic viscosity, μ	0.0235 (Pa.s)
Coefficient of thermal expansion, β	0.0001 (1/K)

4. NUMERICAL PROCEDURE AND VALIDATION

The commercial simulation software Comsol Multiphysics 5.3, which is based on finite technical elements, is used as the computational platform in which the applied modules are used for solving the physical model. The mesh used and adequate to satisfy the accuracy of the results contains 147836 elements. Additional elements give a difference of 0.002 ^{0}C in the junction temperature.

Figure 2 shows the temperature profile of the LED package in stationary state with zero volume of PCM. With the same conditions taken by Minseok ***et al.*** (2012) : power 1 W, ambient temperature 25°C and heat transfer coefficient $h = 10 \ W/(m^2 K)$, the maximum and the minimum temperature are 60.37°C and 53.22°C respectively. Compared with those found by Minseok, which are 60.30°C and 53.32°C respectively, the difference is about 0.1%.



(a) (b)

Fig. 2: Temperature distribution of the LED package: (a): our code (b): Minseok [25]

5. RESULTS AND DISCUSSIONS

5.1 Incorporation of PCM in the cavities of heat sink

The initial structure of our LED heat sink was presented in figure 1 and it was given by Minseok ***et al.*** (2012): $20 \times 20 \times 2$ mm of Aluminum base attached to 4 parallel plate fins having 1,5 mm of thickness and separated by 3 cavities with 4 mm width.

For improving the thermal management of our LED devise, we consider only the symmetric emplacement to assure the uniformity of temperature distribution in the structure.

For a better study and optimization, 5 possible cases of PCM location within the cavities of heat sink heat shown in the figure 3.

5.2 Evolution of solid-liquid interface and time for complete melting

The figure 4 is a capture of the solid liquid interface at t = 5000 s. The figure 5 displays the evolution with time of the melt volume fraction. The red color represents fluid PCM phase, while blue for solid PCM phase.

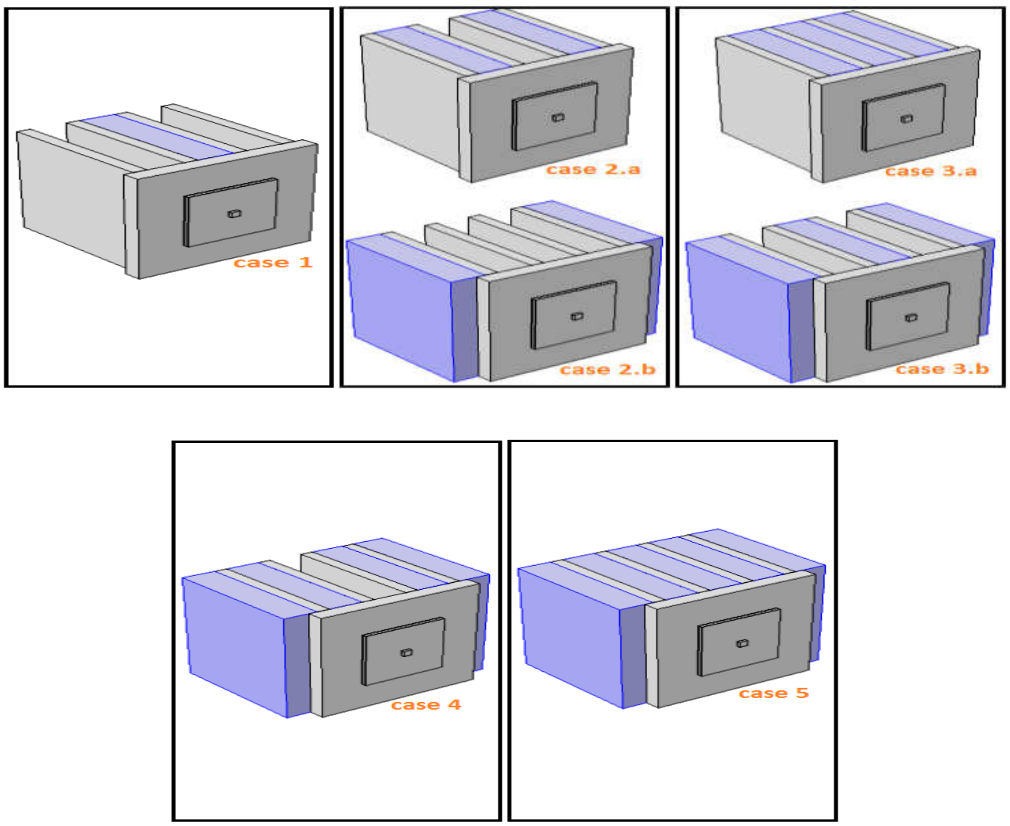


Fig. 3: Different configuration of LED with PCM

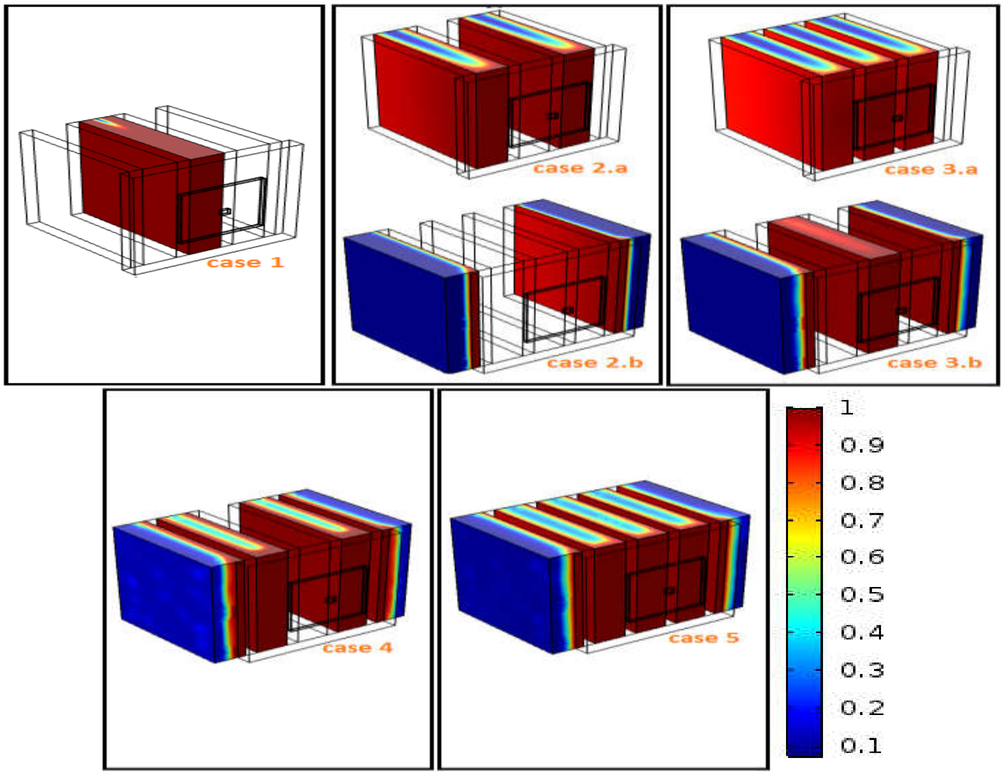


Fig. 4: Liquid PCM volume fraction distribution at t = 5000s

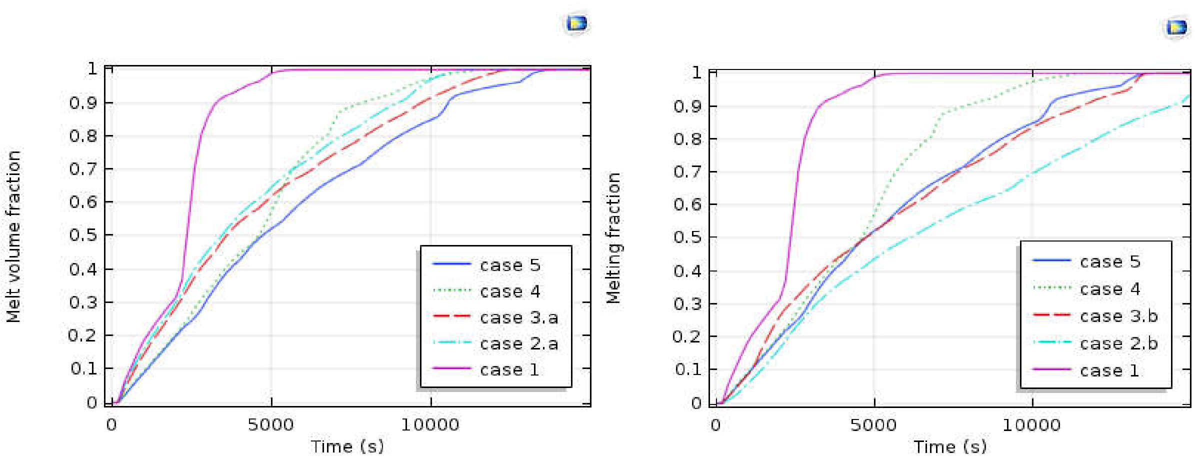


Fig. 5: Evolution of PCM melt volume fraction with time

From these figures, we conclude that: when the PCM is putted inside the heat sink it melts faster than when it putted outside because the majority of heat absorbed by PCM is coming from fins by conduction.

If the PCM is enclosed between fins it has large surface of heat conduction. For that reason, the solid liquid interface in case 2.b moves the most slowly.

The liquid fraction of PCM starts from the base of the heat sink due to heat conduction from the base. The increase of the number of PCM layer enhances the uniformity of temperature distribution in the walls of the heat sink.

5.3 Transient temperature variation

Figure 6 displays the evolution of average temperature with time for different configuration of heat sink with PCM. For the case without PCM, the average temperature attains quickly the stationary temperature 54°C. For the cases with PCM, the average temperature increases moderately to the melting point of PCM. When the PCM is melting the average temperature still constant. It is reduced by 15% in case 5 and 4, with 11% in case 3 and 2 and with 5% in case 1.

Increasing the amount of PCM help to absorb more the heat and to reduce more the temperature but there is no large difference between cases from 2 to 5. There is an increase of 60% of amount of PCM but only 4% of difference in reducing the average temperature.

Therefore, we can economize on PCM and use only two layers of PCM to decrease the mass of heat sink and guaranties the same results.

When the PCM is fully melted, the average temperature will increase gradually to the steady state temperature finally. The inclusion of PCM stabilizes the average temperature at the desired value only if the PCM has not melted fully.

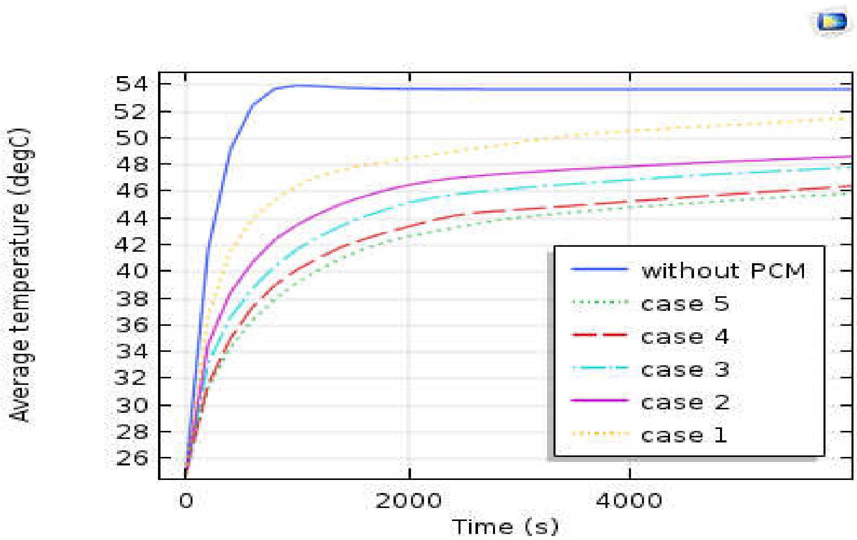


Fig. 6: Evolution of average temperature with time for various configurations

6. CONCLUSIONS

The incorporation of PCM in the heat sink of the Light emitting diodes permit the absorption of heat to delay the peak temperature and to store the energy which will be evacuated to the ambient accommodation.

To predict these numerical models is developed and validated with previously published works.

The main results of the numerical analysis led to the following conclusions:

- The central chip is the origin of heat, so using one central layer of PCM has no effect on reducing the temperature because its little volume melt very fast and it is insufficient to absorb more of heat.
- With the same volume of PCM the emplacement is very important: the layer enclosed between fins melted fast and absorb the energy faster because the heat is coming by conduction from the fin surface.
- The use of PCM in the heat sink permit the reduction of temperature by 11% with 2 or 3 layer and 15% with 4 and 5 layers.

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