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Improvement of thermal and optical behavior of multi-chip LEDs package

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HIGHLIGHTS

- Study of the effect of substrate and chips shapes on LEDs thermal and optical behavior.
- Effect of chips disposition on rectangular and circular substrates are compared.
- Circular substrate shape provides lower junction temperature and higher lamp lifetime.
- Small chip spacing generates temperature and lifetime difference between chips.

ARTICLE INFO

Keywords:
Multi-chip LED package
thermal management
Chips spacing
circular design
rectangular design

ABSTRACT

Thermal management of light emitting diodes (LEDs) packages is indispensable to maintain lower operating temperature. The present paper reports a numerical analysis of 45W LEDs module. Two forms of substrate and chips are compared. Results show that circular chips mounted on circular substrate provide lower junction temperature of the package thanks to the elimination of slide effects. Moreover, the disposition of chips is studied. In fact, junction temperature decreases by 8.72% when the pitch increases from 1 to 14 mm in the rectangular design, and it decreases by 7.46% when increasing the pitch from 1 to 12 mm in the circular design. However, it is found for both rectangular and circular configurations that the chips spacing causes a temperature difference between chips of the same package. The latter does not affect the light output but it causes a significant difference of chips lifetime: a difference of 1354 h between central and outer chips is noted with rectangular configuration, and 1331 h with circular configuration. This may cause a drop of the light output of the lamp when central chips fail and result in an optical discomfort for users.

Nomenclature

h	Convective exchange coefficient [W/m.K]
L_f	Lamp lifetime [hour]

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pitch	Chips spacing [mm]
T	Temperature [°C]
(x,y,z)	Cartesian coordinates

Greek Symbols

α	α
β	β

Subscripts

j	junction
amb	amb
avg	average

1. Introduction

Recently, light emitting diodes (LEDs) have started to monopolize the world of lighting thanks to their flexibility of use, their robustness, their high energy efficiency etc. But, despite their versatility and their continuous progress, LEDs still suffer from a thermal problem related mainly to the increase of its junction temperature. In fact, 85% of the consumed power is transformed into heat [1], which causes a serious rise of the junction temperature. The latter causes the drop of all LEDs performances if it is not evacuated to the outside of the lamp. In fact, under high junction temperature, the luminous flux, the lifetime and the energy efficiency of the lamp decrease considerably [2]. So, thermal management of LEDs lamps is a decisive criterion to ensure higher performances of the LED.

Heat sinks are commonly used to cool LEDs lamps by natural convection. Several research works are developed numerically and experimentally to optimize the geometry of the heat sinks and provide higher level of free heat transfer rate [3–10]. Empirical correlations were then carried out to express the Nusselt number as function of different heat sink dimensions and orientations.

Other research works are focused more on the design and the performances of the active part of the lamp such as the choice of the substrate material [11,12], the thermal interface material (TIM) properties [13,14]. In fact, Yin et al. [11] tested three different substrate materials. They found that an AlN substrate provides the best heat transfer rate and the lowest junction temperature. Xia et al. [12] presented in their work a selection of COB substrates according to different packaging densities. Tang et al. [13] were interested in the thermal interface material part because of its considerable effects on the temperature evolution of the lamp. Graphene based thermal interface material was found to guarantee lower junction temperature than conductive silver past and tin alloy solder [13]. Besides, Ben Abdelmlek et al. [14] studied numerically the case of deficient thermal interface material (TIM). The defection was modeled as a thin air layer between the heat sink and the TIM. Their results showed that an air layer of 150 μm is able to destroy the lamp.

The optimization of the design of the active part such as the substrate design, the chips number and the chips distribution on the substrate seems to be indispensable for multi-chip LEDs packages. Cheng et al. [15] carried out an optimization of temperature distribution on different chips constituting the LEDs package under study. Ben Abdelmlek et al. [16] showed in their numerical study that there is an optimal chips number and spacing that provides better thermal and optical distribution on the package. Moreover, the same researchers [17] determined an optimal substrate design that maximizes the amount of heat exchanged.

In the majority of developed works, researchers treated the case of rectangular configuration of both substrate and chips. However, the circular design is commonly used in various lighting applications such as decorative lighting and residential lighting. So, it must be of major importance in the thermal studies of LEDs package to provide better lamp operation. A comparison between the two configurations is then developed in the present work in order to release the impact of the chips positions on the thermal behavior of the source as well as on its optical properties.

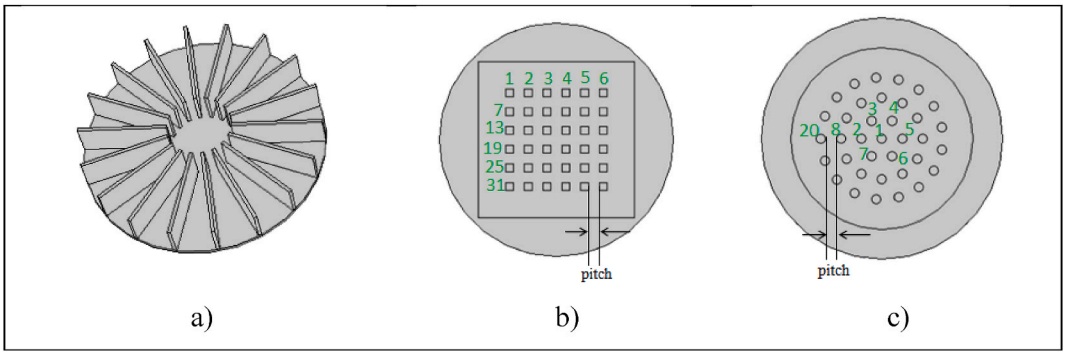

Fig. 1. a) geometry of the heat sink, b) Rectangular design of substrate and chips, c) Circular design of substrate and chips.

Table 1
Geometric and thermal properties of the lamp components.

	Height (mm)	length × width (mm^2)	Materials	Thermal conductivity (W/m^2K)
Die	425.10^{-3}	25	Si	124
Die-attach	50.10^{-3}	25	Au–20Sn	57
Substrate	381.10^{-3}	10^4	Copper	385
	127.10^{-3}		AlN	180
	381.10^{-3}		Copper	385
TIM	50.10^{-3}	10^4	Thermal path	3
Heatsink	Base: 2	Base: R = 75 mm	Al	150
	Fin: 21.3	Fin: 55mm × 2 mm		

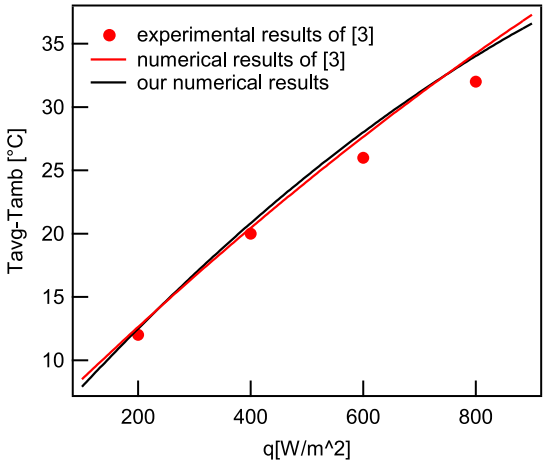

Fig. 2. Comparison between numerical results and previous experiments.

2. Mathematical modeling

2.1. Geometry

The multi-chip LEDs lamp tested in this modeling contains 36 COB (Chip on board) LED chips. An Au–20Sn based die attach is used to fix different chips on the substrate, and a thermal interface material (TIM) is used to embed the lamp on its heat sink.

The heat sink shown in Fig. 1 a) is made of a circular base and twenty rectangular fins arranged uniformly on the base. All geometric and thermal properties of different package components are cited in Table 1.

Two configurations are developed in this work: rectangular and circular configuration.

a) Rectangular configuration

Fig. 1 b) shows the rectangular configuration where a 100 × 100 mm^2 rectangular substrate is used. The 36 LEDs are arranged at regular intervals as 6 × 6 on the substrate, and numbered from one to thirty six. The distance between two adjacent chips (illustrated in Fig. 1 b)) is named pitch.

b) Circular configuration

In this configuration, substrate and chips have circular forms and have the same surfaces of the rectangular configuration (ie. Substrate surface = $10^4 mm^2$, chip surface 25 mm^2). Circular chips are arranged in three circles around a central chip. The first circle contains 6 chips, the second one is composed of 12 chips and the outer one contains 17 chips. The pitch illustrated in Fig. 1 c) is defined as the distance between two adjacent circles formed by chips. LEDs mounted on the radial substrate are ordered from one to thirty six.

2.2. Assumptions and governing equation

In order to simplify the numerical modeling, we consider the following assumptions:

- The state is steady,
- the LEDs lamp converts into heat approximately 85% of the electrical power consumed,
- the heat sink exchanges heat with the outside by natural convection.

Based on these assumptions, the governing equation is then as follows:

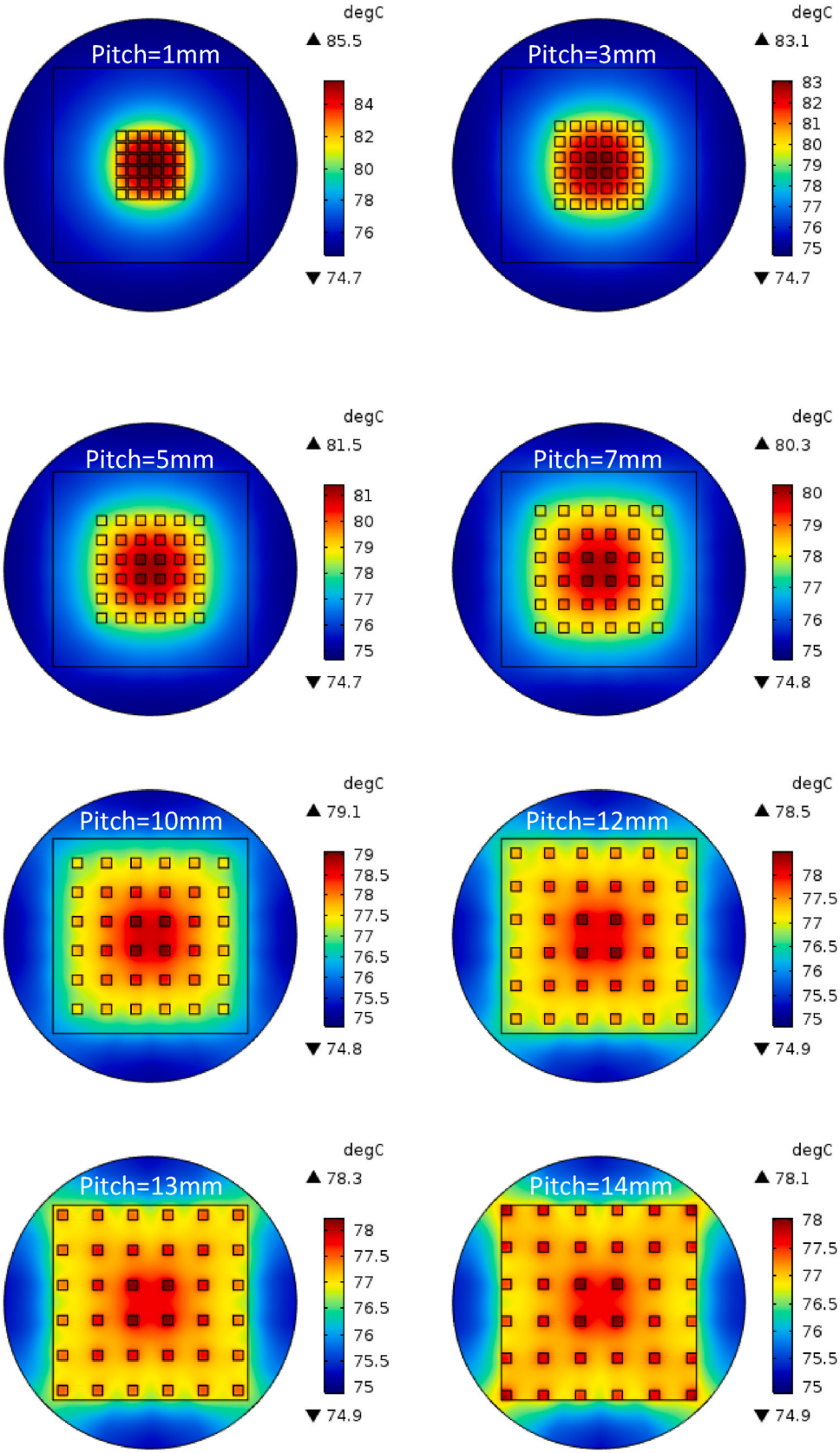

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Fig. 3. Temperature evolution on the LEDs package for different pitches: rectangular configuration.

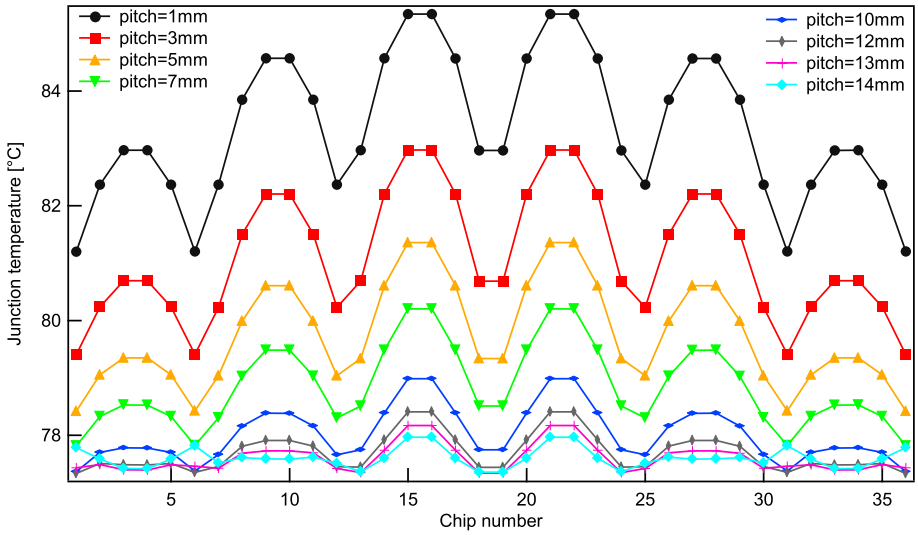

Fig. 4. Effect of pitch on junction temperatures of different chips of the package: rectangular configuration.

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}=0 \tag{1}$$

2.3. Boundary conditions

- The lamp modeled in this analysis has a power of 45W. Taking into account the above assumptions, 85% of the input power is injected as heat on different chips.
- For the natural convection heat transfer from the heat sink to the outside:
  ✓ The heat transfer coefficient: h = 10 W/m·K,
  ✓ The ambient temperature T_{amb} = 25 °C

2.4. mesh sensitivity

To solve the partial differential equations, the numerical simulation was elaborated using COMSOL Multiphysics®. The selected grid is composed of 210826 domain elements, 91487 boundary elements and 5186 edge elements because it was found that additional elements had no effect on the temperature variation.

3. Results and discussion

3.1. Validation

The CFD code was validated against both experimental and numerical results of Yu et al. [3]. Fig. 2 illustrates the evolution of temperature difference between the heat sink and the ambient for various injected power on the radial heat sink base. The comparisons show good agreement.

3.2. Rectangular configuration: effect of chip spacing

The effect of the chip spacing (noted pitch) on the local thermal evolution of the package is illustrated in Fig. 3 for the case of rectangular configuration. The pitch varies from 1 to 14 mm. Smaller pitches result in higher junction temperature because of the accumulation of heat at the center of the package. As the pitch increases, we note an amelioration of the heat spreading at the substrate level. With higher pitches (pitch = 13–14 mm), the heat is spread over the entire substrate and the heat transfer to the heat sink is improved especially at the corners of the substrate. What is noteworthy here in temperature distribution is that the junction temperature is not uniform on the package. In fact, the central chips have higher temperature than those located at the ends of the chips array. This can lead to a variation of the light produced by the lamp and its lifetime, which causes discomfort for users. Fig. 4 highlights the junction temperature of different chips ordered from one to thirty six for different pitches tested in this work. As illustrated, the maximum junction temperature decreases by about 8.72% when increasing the pitch from 1 to 14 mm. In addition, the variation in junction temperature is considerable with smaller pitches. In fact, for pitch = 1 mm, we note a difference of almost 5% between central chips and those located at the ends of the array. The temperature difference decreases well with the increase of the pitch and the junction temperature becomes uniform on different chips with higher pitches.

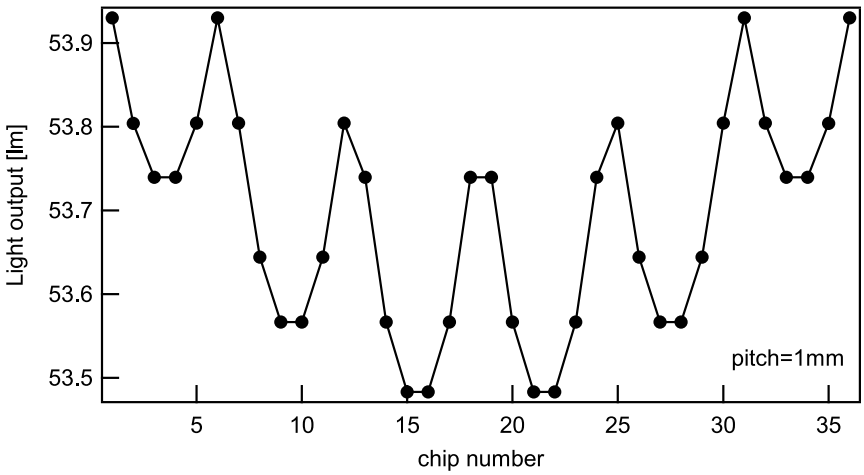

Fig. 5. Light output of different chips of the package for the case pitch = 1 mm: rectangular configuration.

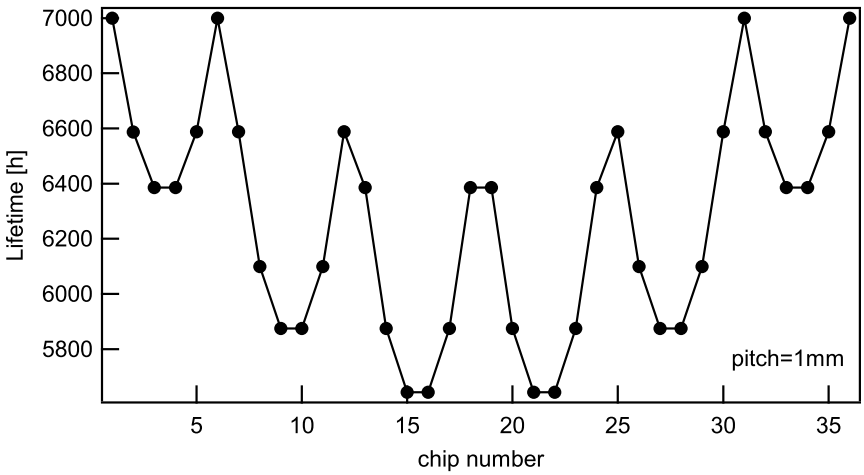

Fig. 6. Lifetime of different chips of the package for the case pitch = 1 mm: rectangular configuration.

Since smaller pitches cause a considerable variation in the junction temperature of different chips of the same package, so it seems to be important to explore the effect of pitch on the optical properties of the LEDs module. The LED chips used in this study have a power of 1W and emit a luminous flux of 60lm under optimal operating conditions (junction temperature = 25 °C, forward current of 350 mA). Assuming that for each degree of junction temperature rise, the chip's light output decreases by 0.108lm [18], we present on Fig. 5 the light output emitted by different chips of the package for the case of pitch = 1 mm. As it can be seen, the variation of the light output in the package is very small (about 0.35%). So, the difference of junction temperature in the LEDs module has not an effect on the light output, and the light emitted by the lamp can be considered as uniform.

Fig. 6 depicts the effect of temperature difference on the lifetime of different chips constituting the lamp for the case pitch = 1 mm. The lifetime L_f of the LEDs package is calculated as follows:

$$L_f = \alpha exp^{-\beta T_j} \tag{2}$$

where α = 477377, β = 0.052 and T_j designates the junction temperature [19].

The effect is found to be significant. In fact, there is a lifespan difference of 1354 h between the central chips and those located at the ends of the array. This period of time is equivalent to the lifespan of an incandescent lamp [20]. Thus, the degradation of some chips of the package will cause a decrease of the luminous flux of the light source and cause discontinuity of the emitted light.

3.3. Circular configuration: effect of chip spacing

The local distribution of temperature on the package for different pitches is explored in Fig. 7 for the case of circular configuration. The pitch varies from 1 to 12 mm. Firstly; note that circular design provides lower temperature than rectangular design thanks to the

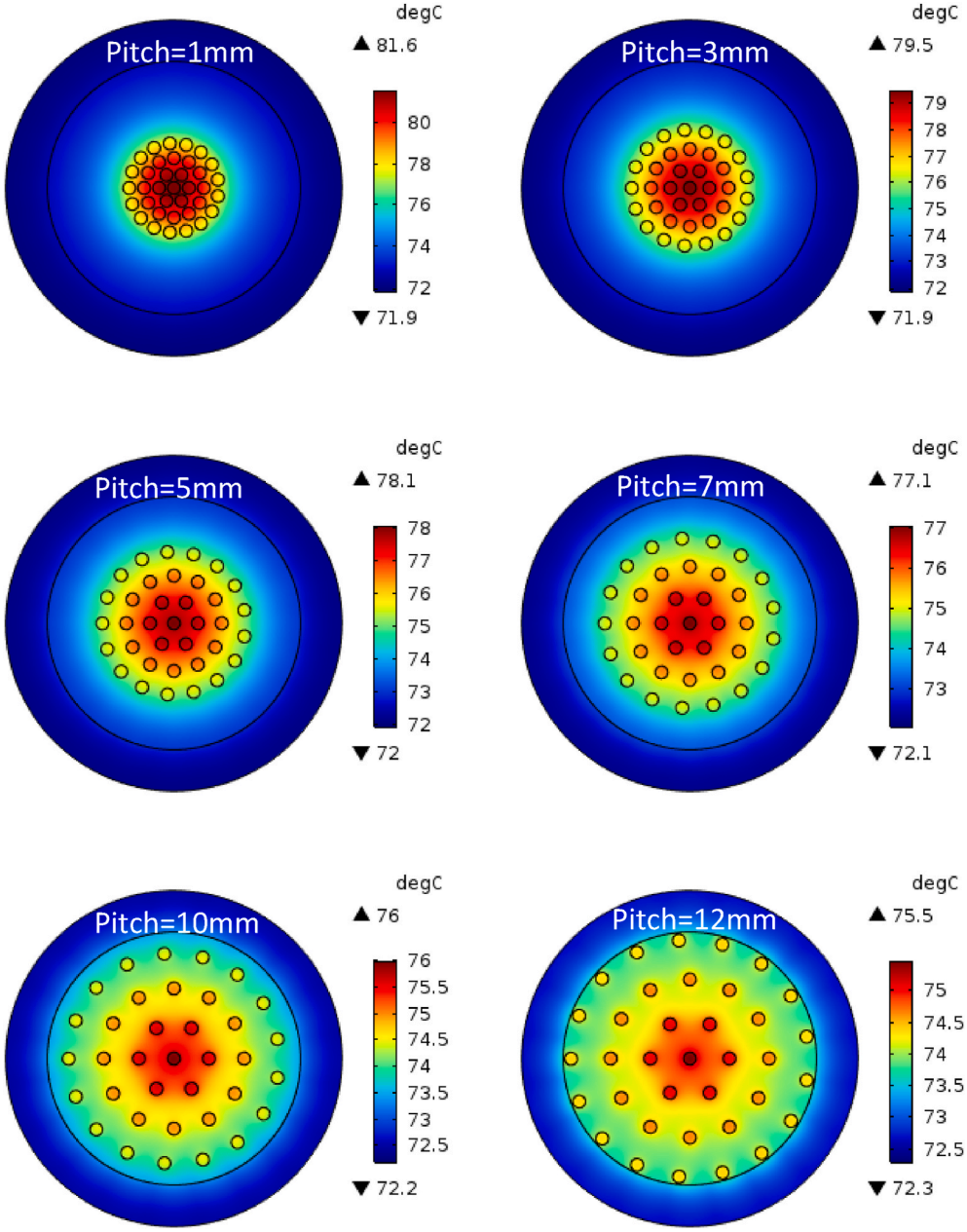

Fig. 7. Local thermal evolution on the LEDs package for pitch ∈ [1,12] *mm*: circular configuration.

elimination of side effects. In addition, for smaller pitches, the maximum junction temperature is located at the majority of chips except for the bigger circle formed by chips. As for the case of rectangular configuration, the heat spreading is ameliorated with the increase of the pitch. This leads to an amelioration of the heat transfer rate and a reasonable decrease of the chips temperature.

Fig. 8 displays the chips temperature for different spacings developed in this study. The temperature difference between chips is important with smaller pitches. In fact, for pitch = 1 mm, there is a temperature difference of 4.16% between the central chip and those located at the outer circle. In addition, we note that chips forming the same circle have the same temperature thanks to the radial heat spreading. With higher pitches, the temperature difference is more and more decreasing. In fact, the maximum junction temperature; which is located at the central chips; decreases by 7.46% when increasing the pitch from 1 to 12 mm, and the temperature is considered uniform with a pitch = 12 mm. Compared to the rectangular configuration, note that the circular configuration provides lower junction temperature despite that the pitch can not exceed 12 mm.

Fig. 9 shows the light output of different chips of the package for the case pitch = 1 mm. As for the case of rectangular configuration, the temperature difference has no considerable effect on the light output of the global package. However, the effect is found to be

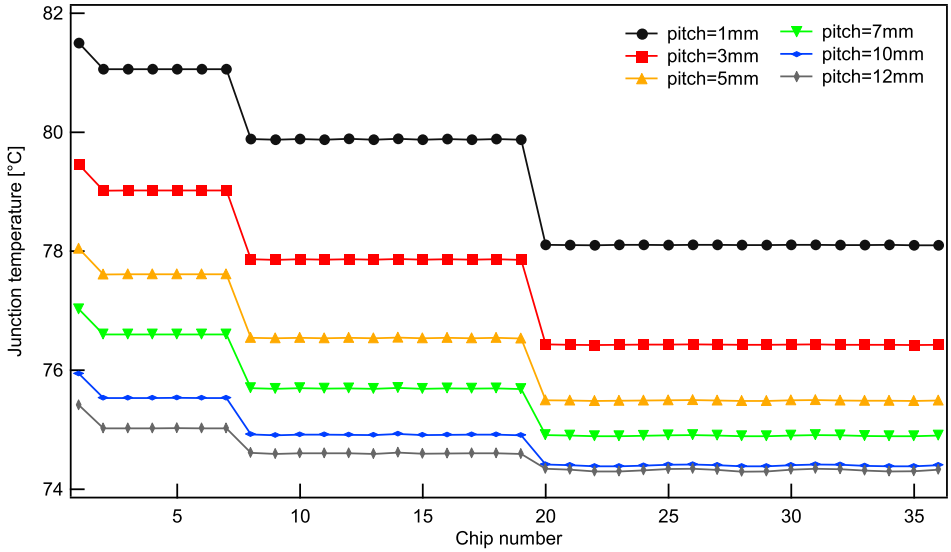

Fig. 8. Effect of pitch on junction temperatures of different chips of the package: circular configuration.

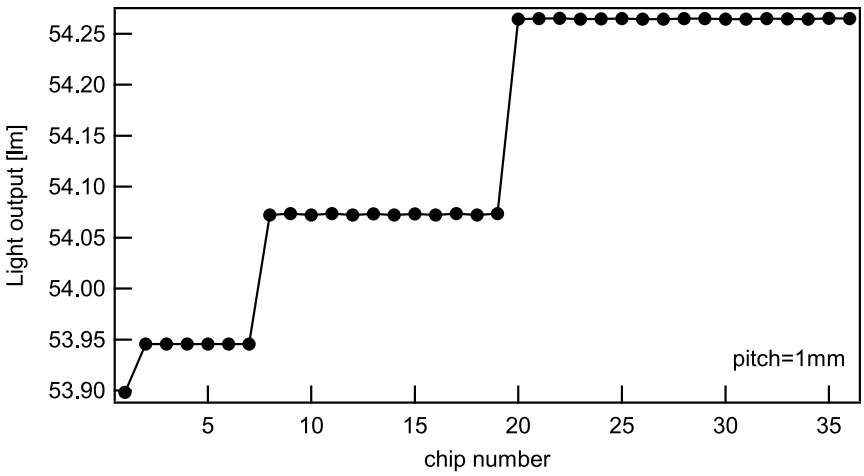

Fig. 9. Light output of different chips of the package for the case pitch = 1 mm: circular configuration.

important on the lifetime of different chips. In fact, as illustrated in Fig. 10 there is a difference of 1331 h between the lifespan of the central and the outer chips. This difference can make an optical problem and a discontinuity of the light emitted by the source when central chips fail.

4. Conclusion

Thermal and optical behavior of multi-chip LEDs lamp has been numerically investigated. Two configurations were developed: rectangular configuration where the substrate and chips have rectangular forms and circular configuration where the substrate and chips have circular forms. In the two configurations studied, the surfaces of the substrate and chips are the same. Numerical simulations were conducted to compare the two package designs and highlight the effect of the disposition of chips on the substrate. Results showed that circular configuration provides lower junction temperatures on different chips. Concerning the effect of the chips disposition, it was found that; for the two configurations studied; small pitches cause temperature difference between chips of the same package. It was about 5% and 4.16% of temperature differences for rectangular and circular design, respectively. Despite that it did not affect the light output of the light source, temperature difference between chips showed an important effect on the lifetime of chips. In fact, the lifespan difference between central and outer chips of the same lamp was about 1354 h for rectangular configuration and 1331 h for circular one. This period is equivalent to the lifespan of an incandescent lamp and may cause optical problem for users when central chips fail.

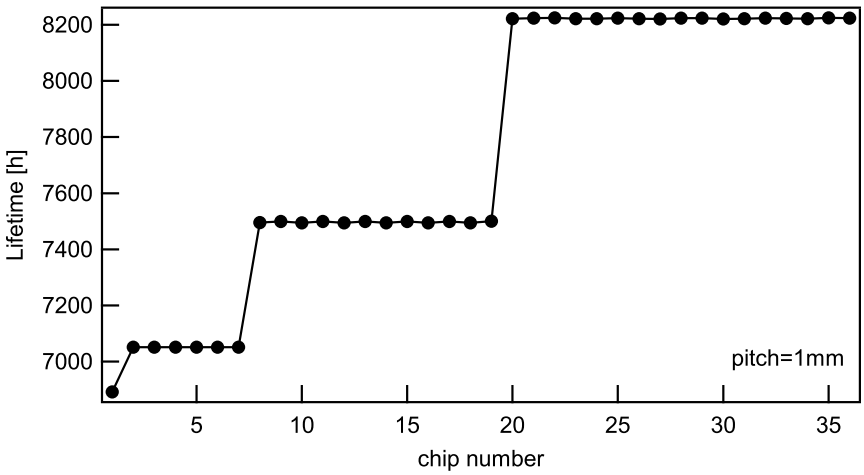

Fig. 10. Lifetime of different chips of the package for the case pitch = 1 mm: circular configuration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

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