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Thermal study on novel spokes fin for high power LED

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Keywords: LED lights, junction temperature, radiation, spokes fin, heatsink

Abstract

High Power LED (HPLED) lights are popular today in industrial, residential, and consumer applications. In this work, under natural cooling considerations, on a commercial (size 17.85 × 17.85 × 3 mm) heatsink base, a novel spokes fin model was introduced and the temperature has been investigated and compared with rectangular and circular fin models. Using commercial FEA tool, the effect of heat transfer has been explored for a single and six HPLED arrays integrated on the top of the heat sink base and for different fin lengths, about 60 mm, 70 mm and 80 mm and junction temperatures 130 °C, 110 °C, 90 °C, 70 °C and 50 °C. The results revealed that the novel spokes fin is effective at about 4.72% (6 °C) on the upper part of the fins and 5.87% (13 °C) on the lower part of the fins. The heat dissipation from the HPLED junction to the atmosphere is effective using novel spokes compared to rectangular fins for both single and six HPLED array configurations. At the same time, the rectangular fin is effective in dissipating the heat for a single HPLED operation compared to the circular fin about 2.85% on the upper fins, 3.66% on the lower fins and has an equal dissipation effect while used for six HPLED array configurations. During the simulation, the mesh independence test is conducted and the radiation effect is also considered.

Nomenclature

Symbols

LED	Light emitting diode
HPLED	High power LED
FEM	Finite element method
STP	Standard temperature and pressure
Q	Heat flow (W)
T	Temperature
h	heat transfer coefficient (W m^{-2}K)
k	thermal conductivity $(W\ mK)^{-1}$
Nu	Nusselt number
Gr	Grashof number
Ra	Rayleigh number
LF	Lower fins (exposed to the atmosphere)
UF	Upper fins (Attached to the heat sink)
e	the emissivity of the object Subscripts and Superscripts
Al	Aluminium
Cu	copper

L	length of the fins
D	diameter of the fins

1. Introduction

HPLEDs are the fourth-generation lighting sources commonly known for their high efficiency, reliability, and long lifetime. It is commercially used for various applications such as street lighting, floodlights, automotive headlamps, etc. Efficient thermal management is one of the most crucial factors for reducing the lifetime failure and degradation mechanism of LED lamps. In addition to temperature, the other main factors which can reduce the performance of LED are the darkening of the diffusive bulb, alteration of the chromatic properties of the phosphors and a reflector, etc [1, 2]. LEDs are used in automotive and street lighting and have non-uniform temperature distribution throughout the module affecting the internal quantum efficiency as well as the chromatic characteristics of the white light emitted due to changes in the spectrum. Moreover, the fatigue life of the HPLED decreases during continuous operation due to a rise in the junction temperature. To overcome this, various active and passive cooling systems have been suggested to dissipate junction temperature and thereby increase reliable operation. Natural convection using fins is one of the most effective techniques due to no moving parts, being lightweight, and no maintenance.

Xin *et al* carried out a novel cooling system of HCPS (Heat transfer conductive plate) coupled with a heat sink cooling system for a multi-chip LED module. The factors affecting the LED junction temperature were validated using a thermal resistance network structure. The heat sink with HCPS showed better thermal performance compared with the only heat sink. Besides, the optimal length of HCPS was found to be 47 mm. Experimental results were validated with the numerical method, and results indicate that forced airflow had an immense effect on dissipating the LED junction temperature [3].

Adhikari *et al* focussed on determining optimal fins based on design parameters such as fin spacing, height, and length using steady-state, laminar, and conjugate heat transfer CFD simulations. The fin parameters significantly affected the flow through the fin channel ends, the thermal gradient, and heat transfer from the fin surfaces. It was found that effective heat transfer occurs within a narrow range of fin spacing in the case of longer fins and vice versa. Moreover, at optimal fin spacing, both the thermal gradient and air velocity at the fin channels increased [4].

Taye *et al* presented a mathematical model to compare the radiation effects for the heat flow through a rectangular profile. It was observed that fins with radiation effects had better fin thermal performance than those without radiation effects [5].

Liao *et al* investigated a suitable D/L ratio for an optimized LED chip package. With the correct encapsulated lens, the radiation angle could be adjusted from 90 to 170 degrees. Based on the analysis, an optimized LED module with improved heat transfer dissipation was found, in which the light output intensity was enhanced by 7.1%, the LED junction temperature was reduced by 5.1 °C, and the thermal resistance was 3.34 K/W smaller as compared to the worst of the three arrangements [6].

Mishra *et al* developed a numerical model to identify the safer operating conditions of an automobile LED headlamp. Two models were designed, the square aluminum heat sinks with a cylindrical plate placed at the top and an LED module, and the second, with the same provision as the first model but with 25 fins added. Heat dissipation, junction temperature, and heat flux were estimated using ANSYS 16.0 for different ambient temperatures and LED power dissipation. It was investigated that percentage of failure was around 38% and is reduced to 21.4% in the second model with fins. Moreover, for temperatures between 30 and 80 °C, heat flow between 0.5 and 1.25 W was found to be within safe working conditions [7].

Effendi and Kim performed CFD simulations for hybrid fin heat sinks under natural convection for different orientation angles and later compared the results with pin fin heat sinks. The results revealed the lowest thermal resistance was found at an orientation angle of 45° [8]. Wong *et al* developed a rapid heat sink evaluation method by using the Implicit Finite difference mathematical model for predicting the heat conduction of the LED heatsink module. This technique provides a simple way to evaluate the peak temperature change for various designs [9].

Han-Kuei Fu *et al* established a simulation model and measurement of the initial model to derive the structured analysis of heat dissipation of the LED module based on the interaction of heat and input power [10]. Yung *et al* investigated the optimal thermal performance and efficacy for different LED array configurations. The thermal conductivity of LED material has shown a profound effect on the heat dissipation factor in the LED array [11].

Simulation for single unit cooling fins Aluminium flat plate heat pipe is carried out by varying fin thickness, the number of fins, and fin height variables. The heat dissipation performance is examined for U bending and plus-shaped folding structure. Results revealed that thermal performance is mainly affected by fin height and optimal fin height is around 35 mm. Also, the cooling range is limited to a fin thickness of 1.5–2 mm and a height of 30–35 mm [12].

Mueller *et al* analyzed the thermal performance of heat sink configurations commonly used in power electronic devices and found that the increase in surface area and high thermally conductive material such as Aluminium played a significant role to improve the heat dissipation capacity [13].

Subahan *et al* carried out CFD simulations for heat sinks with various fin arrangements such as rhombus prism and pyramid using Ansys workbench fluent solver. It was observed that heat sink with rhombus prism pin fins was found to be most effective mainly due to high surface area [14]. Wengang *et al* investigated the thermal performance of high-power LEDs' by designing a heat sink array under natural convection conditions. The influence of parameters on thermal performance such as the number of fins, fin height, heat flux, synergy angle, and radiance was studied. The increase in the number of fins led to a reduction of the thermal resistance and average heat transfer coefficient. Moreover, the flow rate is reduced due to the blockage of fins and the increase in fin height enhanced heat dissipation and heat transfer. However, the heat transfer coefficient decreased due to airflow resistance with an increase in fin height [15].

Jeon and Byon conducted a numerical analysis to study the thermal performance of plate-fin heat sink with dual height configurations under natural convection. The results reveal that the thermal performance of the given configuration decreases with a decrease in secondary fin height. Moreover, the thermal performance per unit mass can be enhanced by decreasing the secondary fin height suggesting that it can be used for various practical applications [16]. A numerical investigation was conducted to evaluate the rate of heat transfer from an upward-facing radial heat sink under free convection. It was observed particular fin thickness had a minimal role in thermal performance. Moreover, other geometric parameters such as fin height had diminishing performance above a certain height limit [17]. Huang *et al* studied the effects of perforations in the fin base on the heat transfer performance by ventilating the cold air from below the fin base. The effects of perforation were analyzed. The thermal performance of longfin arrays is improved by applying fin-based perforations in the inner region. However, base plate perforations were not effective for shortfin arrays as compared to longfin arrays. The overall heat transfer coefficient increased with an increase in total perforation length [18]. Shih-Jeh Wu *et al* examined the junction temperature of LED lighting devices using CFD Ansys Fluent and found out that larger fin thickness slightly reduced the temperature. Also, the total area of the fins was the most effective factor for designing thermal performance [19].

The main objective of this work is as follows:

- Thermal performance of the three fins namely, circular, rectangular, and novel spokes fin attached to heat sink base and HPLED by measuring the temperature.
- To investigate the thermal performance of various junction temperatures of the HPLED along with varying the fin length.
- To compare the thermal performance at high junction temperatures with and without radiation effects on the heat sink and fins.
- The change in the value of Nusselt number for varying fin length and drop in junction temperature is investigated.
- To study an optimal heat sink along with the fins which are specific to HPLED applications.

2. Methodology

HPLED generates heat from its junction at which the input electric power is converted into light energy. The efficiency of an HPLED is about 25% and the remaining energy is dissipated as heat [20]. Dissipating the heat is essential to improve the life of the HPLED. The heat generated at the junction is dissipated to the heatsink and then to the fins through conduction, the remaining heat being dissipated by convection and radiation to the atmosphere [7]. Heatsink with fins can significantly reduce the junction temperature without the use of any external cooling aid due to its high surface-to-volume area, thus increasing the heat transfer from the source. This study uses Aluminium material which is generally used due to its low cost and lightweight properties. The commercially available heatsink base is considered with fins and modeled using commercial software ANSYS 19.2. In addition, a commercially available HPLED size of $17.85^{*}17.85\ mm^2$ is placed on the heat sink base using two different configurations and heat transfer is investigated by varying the fin lengths with three different fin types.

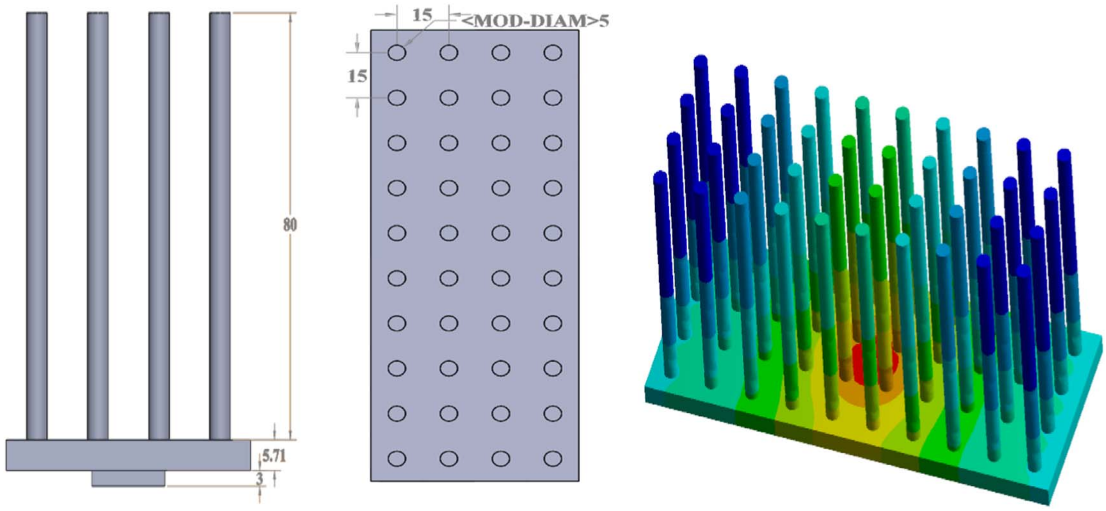

Figure 1. Circular fins dimensions and structure.

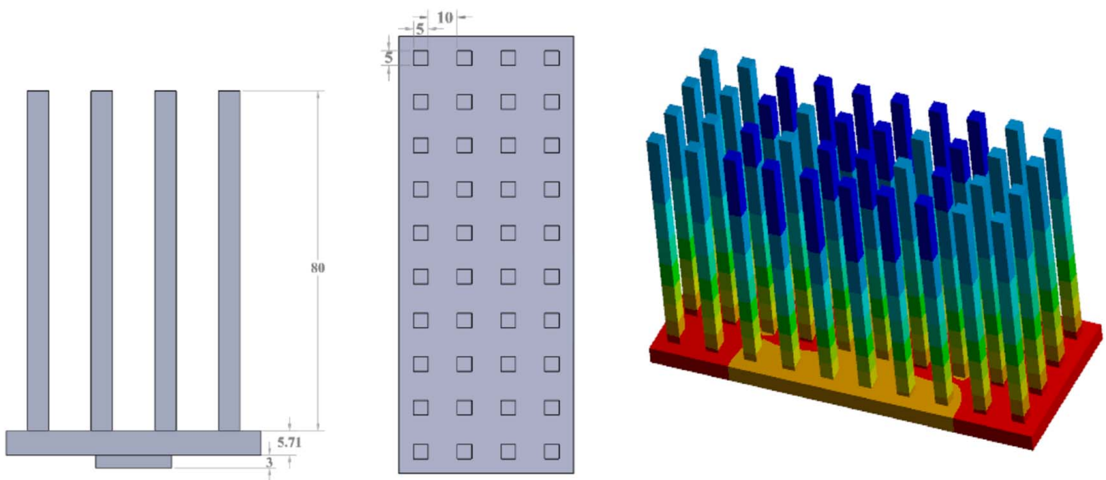

Figure 2. Rectangular fins dimension and structure.

2.1. Types of fins

In this work, three types of the fin are considered namely circular, rectangular and novel spokes fin to analyze the heat transfer from the HPLED junction temperature. It is evident that in all the three-pin types, the heat sink area is kept constant which is 150×60 mm^2 with a thickness of 5.71 mm. Figure 1 shows the 2D & 3D models of circular fins along with the heat sink base. The heat sink was embedded with 40 fins evenly distributed in a 10×4 array with equal spacing to optimize the airflow, uniformity, and even distribution of heat thus leading to better heat transfer [7]. The diameter (D) of the circular fin is 5 mm, the vertical (V) and horizontal distance (H) between the center of the fins are 15 mm and its distance from the edge of the heat sink is 5 mm on both sides. In addition to this, three different fin lengths of 60 mm, 70 mm & 80 mm are considered to investigate the heat dissipation performance.

Figure 2 shows the 2D & 3D dimensional models of rectangular fins. The cross-sectional area of the rectangular fin is 5^*5 mm^2, the distance between the two consecutive fins is 10 mm, and the distance from the edge of the heat sink is 5 mm on both sides.

Figure 3 shows the 2D & 3D representations of the novel spokes fin model. The existing circular fins are modified by adding spokes fins along the length of the fins with equal spacings of 9 mm.

2.2. High power LED configurations

In this work, two different models of LED configurations have been considered, namely single and six LED. The single and six LED performance has been investigated by varying the length of the fins and their various types.

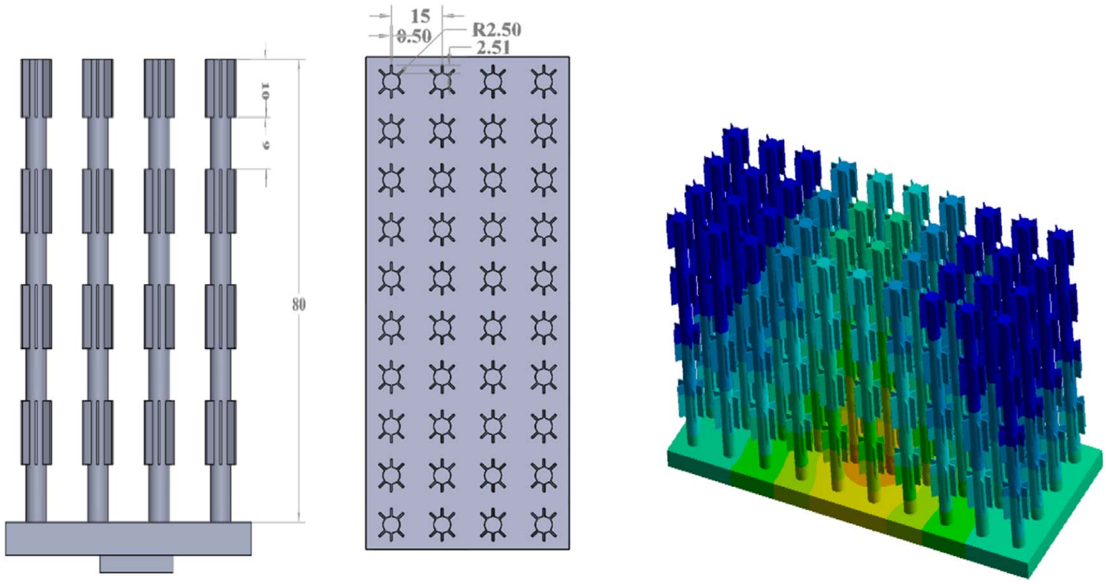

Figure 3. Novel Spokes fins dimension and structure.

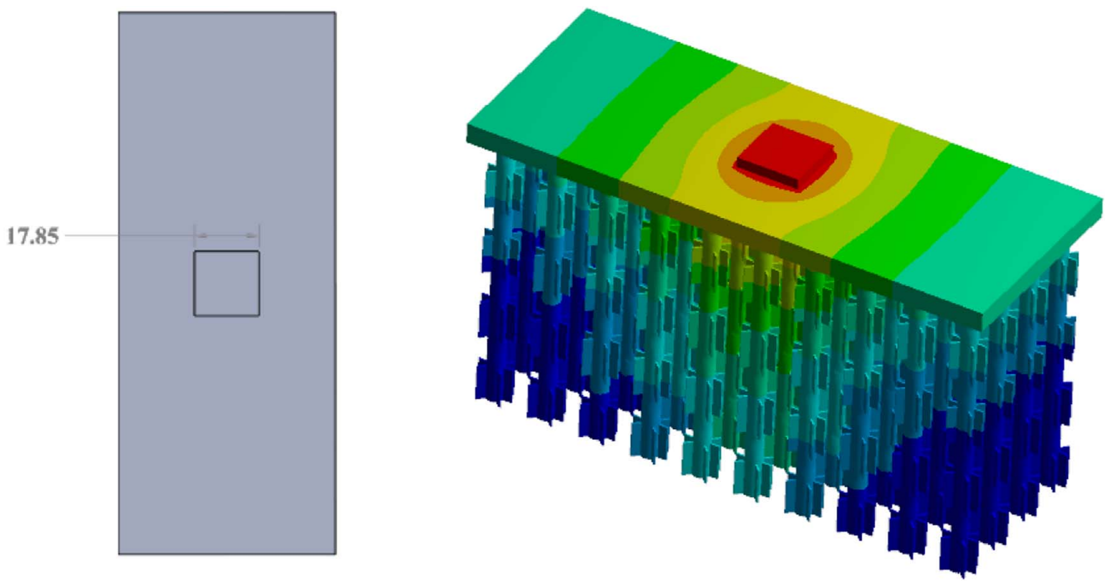

Figure 4. Single LED placement and heat profile.

Figure 4 shows the diagram of a single LED. The HPLED is mounted exactly at the center of the heat sink surface to facilitate uniform dissipation of heat leading to good fin performance. The heat sink has a cross-sectional area of 150*60 mm with a thickness of 5.71 mm. To simplify the model and computational complexity, the heat sink and the fins are composed of the same material as that of an LED module.

Figure 5 shows the orientation of six HPLEDs that have been utilized from similar work conducted by Rammohan *et al* [21] to determine the life of the HPLED array. The given six LED array has been distributed across the heat sink area by applying a basic grid shape of triangular to ensure uniform temperature distribution to all the fins thus enhancing the heat dissipation performance. LEDs are placed on a heat sink having dimensions 150 × 60 mm. LEDs of dimensions 17.85 × 17.85 mm are placed as shown in figure 5.

2.3. Temperature measurement on the fins

The present work aims to investigate heat sink (HS) by considering natural convection using fins. The solver used for the simulation is Steady-State Thermal. The Finite element method (FEM) is used to solve the governing equations followed by the Newton-Raphson method for the iteration process. Table 1 summarizes the boundary

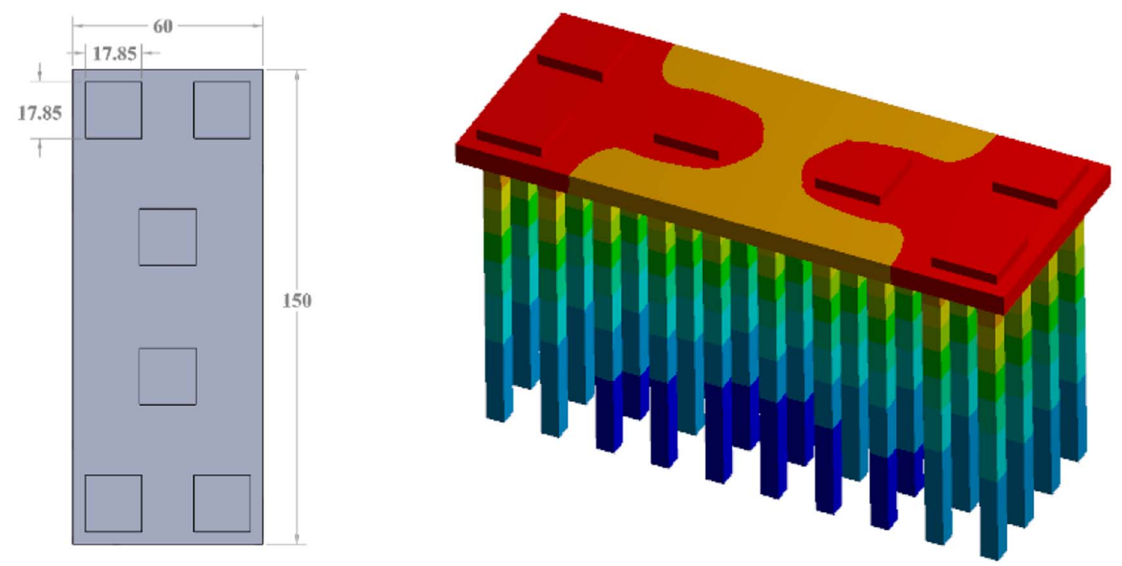

Figure 5. Six LED Array configuration and temperature profile.

Table 1. Boundary conditions.

Material Used	Aluminum Thermal conductivity of 237.5 W $m^{-2}K^{-1}$
Convection coefficient	Natural convection coefficient (h) is between 5–25 W m^{-2} K. Hence, 13 W $m^{-2}K^{-1}$ is considered
Density	2.7 g cm^{-13}
Emissivity	0.12
Heat capacity	887 J kg^{-1}.K

conditions including the structure of the mesh and simulation tool used. The optimal design of the heatsink for HPLED incorporated with circular (CIR), rectangular (REC) and novel spokes fin (PF) was simulated. Initially, the circular fin at different lengths such as 60 cm, 70 cm and 80 cm was investigated. Similarly, the rectangular and novel spokes circular fin fins at the same circular fin length for a single HPLED were also investigated. The heat flow is given on the LED modules, thereafter the heat transfer takes place by conduction to the heat sink. Since the fin-type arrangement is used in this study, heat transfer to the tip of the fins takes place by both conduction and convection. The Free convection simulations were carried out for all three fin types for increasing fin height from 60 & 70 to 80 mm. The material used here was aluminum which has a thermal conductivity of 237.5 W m^{-2}K.The value of heat flux is fixed at 1.5W for all the simulations and configurations. The convection coefficient was considered to be 13 W m^{-2}K since the range of natural convection coefficient (h) varies between 5–25 W $m^{-2}K^{-1}$ [7]. The ambient temperature and pressure were kept to be at an STP of 25 degrees and were applied to the whole body. To observe the effectiveness of the heatsink on radiating the HPLED temperature, the surface temperature is observed at the top (heatsink plate side), and the tip of each fin. This observance was repeated for HPLED junction temperatures such as 130 °C, 110 °C, 90 °C, 70 °C, and 50 °C respectively. To investigate the fin performance along its length, the fin temperature measurement is divided into two types namely, upper fin (LF) & lower fin (LF) where the upper fin is attached to the heat sink base and the lower fin is exposed to the atmosphere. Moreover, radiation effects were minimal for LED junction temperatures, Hence it was observed for the most effective heat sink design.

2.4. Boundary conditions and governing equations

The following assumptions have been considered during the simulation:

1. The flow is considered steady and 3-dimensional.
2. Uniform dissipation of heat in all directions from the heat source.

The Volume Fraction of the above-described configurations is given in table 2. The values are in percentage which indicates the volume fraction of a particular model in its different configurations.

Table 2. Volume fraction.

Values in % LED	Fins		
	Circular	Rectangular	Spokes fin
1	54.55	60.44	58.91
6	52.37	58.34	56.78

Equations governing natural convection, the Continuity equation [22] is given by:

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

The continuity equation is a mathematical representation of the principle of conservation of mass under a control volume. It states that, for steady-state flow, the mass flow rate into the volume is equal to the mass flow rate out.

When there is no heat generation, The steady-state conduction equation [7] can be represented as:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0 \quad (2)$$

Since heat generation inside the element is zero, the differential heat conduction equation will be replaced by the Laplace equation. The following equations are used to determine the Nusselt number (Nu) for validation:

A dimensionless number in heat transfer that approximates the ratio of the buoyancy to the viscous force due to temperature differences is called the Grashof number. It is mainly used in the study of situations involving natural convection [23].

$$Gr = \frac{g\beta(T_s - T_\infty)\delta^3}{v^2} \quad (3)$$

g = gravitational acceleration, m s^{-2}
β = coefficient of volume expansion,
δ = characteristic length of the geometry,
v = kinematics viscosity of the fluid, $m^2\,s^{-1}$
$T_s - T_\infty$ = Fin Temp.—Ambient Temp.

Rayleigh number is a dimensionless term used in the calculation of natural convection. The magnitude of Ra is used to determine whether the natural convection boundary layer is laminar or turbulent [23].

$$Ra = Pr.Gr = \frac{g\beta(T_s - T_\infty)\delta^3}{v^2} \quad (4)$$

The Nusselt number [23] in natural convection is in the following form:

$$Nu = C(Gr \cdot Pr)^n = CRa^n \quad (5)$$

A Nusselt number is a number used to represent heat transfer by pure conduction. A value between one and 10 is characteristic of slug flow or laminar flow. A larger Nusselt number corresponds to more active convection, with turbulent flow. The rate of heat transfer by emitted radiation is determined by the Stefan-Boltzmann law of radiation [23][24]:

$$Qt = \sigma eAT^4 \quad (6)$$

$\sigma = 5.67 \times 10^{-8}\,J\,s^{-1} \cdot m^{-2} \cdot K^{-4}$ (Stefan-Boltzmann constant),
A = the surface area of the object,
T = absolute temperature in kelvin,
e = the emissivity of the object is a measure of how well it radiates. An ideal black body radiator has e = 1, whereas a perfect reflector has e = 0. Real objects fall between these two values.

2.5. Mesh independence test

Mesh independence is a technique of exploring, whether the simulation results are liberated of the underlying mesh or not. The mesh independence is a balance between the correctness of the simulation and the computation time. The subsequent simulations of the proposed work is conducted on a CPU of 2.2 GHz and 8.0 GB of RAM capacity. The default 'physics-controlled' mesh producer is chosen, and an 'extra fine' size is designated. The degree of refinement is set to the maximum level. The built-in Hex-dominant meshing algorithms have been adopted for the segmentation of the domain due to their high effectiveness and robustness, resulting in stable solutions. The data presented in table 3 is for one LED circular fin of a length of about 60 mm.

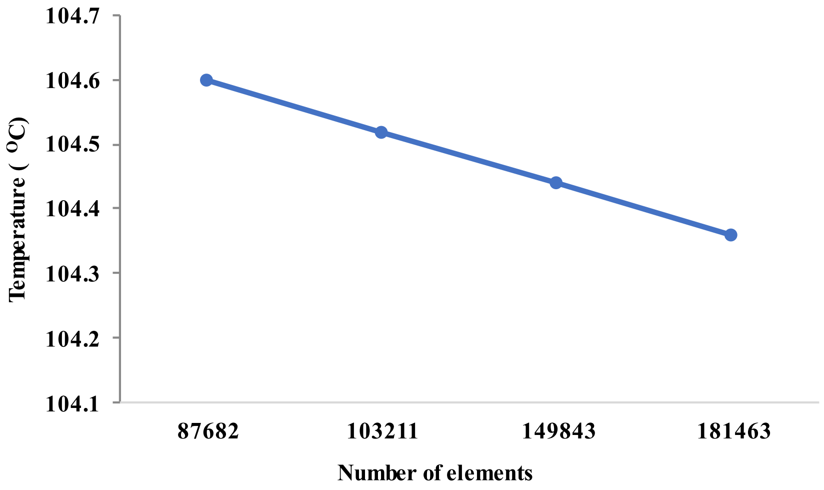

Figure 6. Graphical representation of mesh independence test.

Table 3. Mesh independence.

Resolution	Elements(n)	Minimum temperature				
		Ts = 50	Ts = 70	Ts = 90	Ts = 110	Ts = 130
4	87682	44	59.107	74.211	89.463	104.601
5	103211	43.933	59.08	74.226	89.373	104.52
6	149843	43.914	59.046	74.177	89.309	104.44
7	181463	43.895	59.011	74.126	89.242	104.36
Error % between resoulition 5 and 6		0.00019	0.00034	0.00049	0.00064	0.0008

Figure 6 depicts the graphical representation of the mesh independence test. The resolution of a surface mesh is the overall spacing between vertices that comprise the mesh. It is observed that the resolution is wide-ranging from 4 to 7 and the temperature varies from 50 °C to 130 °C. The elements considered during this independence are from 87682 to 181463.

Figure 6 shows that the temperature decreases while increasing the number of elements. It has been observed that at the minimum number of elements the observed temperature is 104.6 °C and at the same time at the maximum number of elements, the temperature is about 104.35 °C. The mesh independence test shows that we have reached a resulting value that is independent of the mesh resolution.

3. Results and discussion

To evaluate the performance of the heat sink and fins, the following considerations have been observed during the investigation.

- Fin temperatures 130 °C, 110 °C, and 90 °C are considered as higher temperatures (HT)
- Fin temperatures of about 70 °C and 50 °C are considered lower temperatures (LT),
- Upper Fin (UF) is considered to be the attached portion to the heat sink a
- Lower Fin (LF) is exposed to the atmosphere for analyzing the fin performance.
- Fin performance was examined for six HPLED and compared with a single HPLED.
- Fin number plotted from 1 to 40 in the X axis and fin temperature in the Y axis

3.1. Upper fin performance at a higher temperature for circular & rectangular fin

The fin performance is estimated based on the temperature variation on the fins attached to the heat sink base and the fins exposed to the atmosphere. The upper fin temperature is normally regarded as the base temperature

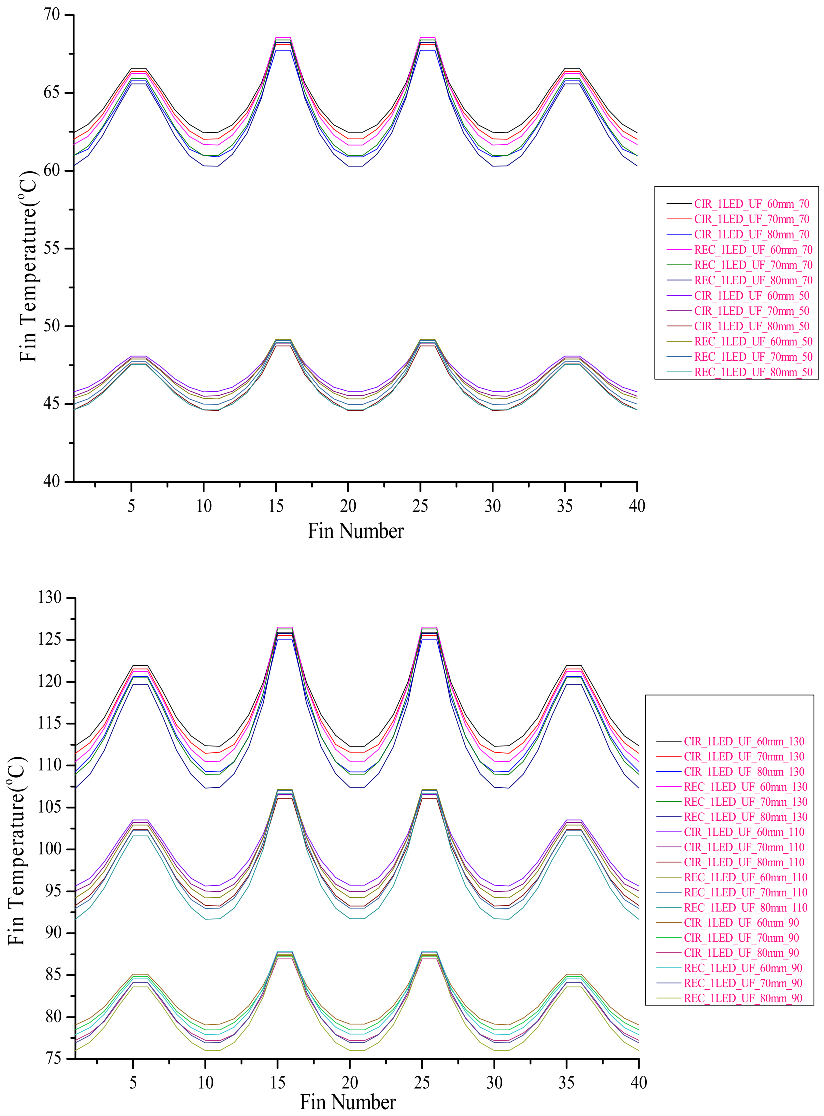

Figure 7. Temperature for single LED Circular and rectangular fins.

of HPLED; hence its thermal dissipation capacity should be high for good performance. Heat flux is almost uniform at the top of the LED module and it progressively increases towards the bottom where the value is the highest due to bottom edges and corners, thereafter the heat is diffused to the fins via a heat sink. Based on figure 7, the highest temperature from the HPLED junction is 130 °C which is considered as a heat source that loses its heat at about 4.98 °C on the heat sink base. When the heat flows by conduction towards the fins via the heat sink the temperature gradually decreases and is in the range of 109.25 °C − 125.02 °C for the upper fins. The remaining temperature is dissipated through 40 fins which are arranged with equal spacing of 10 mm.

For single HPLED, temperature variation is symmetric across the fin numbers with peak temperature at the 5th, 15th, 25th and 35th fin number. While considering a rectangular fin single LED of length 80 mm with 130 °C as junction temperature, all the fins dissipate an average heat of around 22 °C. The highest rise in temperature is observed for the 15th and 25th fin of 125.75 °C. At the same time, the remaining fins 1–15 & 25–40 dissipate the heat from the left side and the right side of the heat sink about 107.3–125.75 °C & 125.75–107.3 °C respectively. Further, the increase in the fin length from 60 mm to 70 mm and 80 mm reveals that the temperature has dropped from 105 °C to 98 °C at fin number 15 in the case of circular type. The fin base temperature was found to decrease with an increase in fin height for all LED junction temperatures. This occurs due to an increase in surface area, and the heat dissipation capacity of the fin increases. The variation or dissipation in temperature is improved for rectangular fins than circular ones across all fin numbers and also for increasing fin length. Overall, the upper surface temperature of the rectangular fin was found to be lower as compared to circular fins for the temperature, all the fins dissipate an average heat of around 9.77 °C at the highest same fin height. Moreover, the upper fin temperature across all rectangular fin numbers for 130 °C LED junction temperature is within the permissible limit, which shows safe operating conditions. The difference

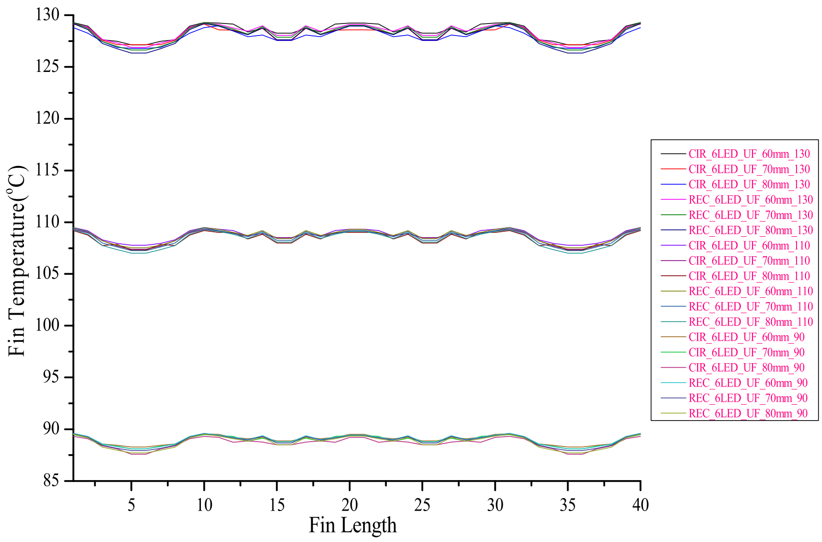

Figure 8. Temperature for six LED circular and rectangular.

between the highest and lowest temperature for the circular upper fins of length 80 mm at 130 °C junction temperature is 15.7 °C, whereas for 110 °C & 90 °C junction temperature difference is around 12.76 °C & 9.715 °C respectively. The Rayleigh number for circular and rectangular fin single LED of length 80 mm is numerically found to be 1.59×10^7 and 1.56×10^7 respectively. The temperature difference was found to be more for rectangular fins of around 18.45 °C for 130 °C junction temperature, followed by 14.97 °C & 11.5 °C for 110 °C & 90 °C respectively which shows rectangular fins are more efficient than the former.

3.2. Upper fin performance at a lower temperature for circular & rectangular fin

The above figure presents the numerical data of temperature distribution across upper fins at low HPLED junction temperatures. For a single LED rectangular fin of length, 80 mm and 70 °C LED junction rise in temperature is observed for the 15th and 25th fin of around 68.22 °C. At the same time, the remaining fins 1–15 & 25–40 dissipate the heat from the left and the right side of the heat sink in the range of 60.34–68.22 °C & 68.22–60.34 °C respectively. The fin base temperature was found to decrease with an increase in fin length and the reduction was found to be higher for rectangular fins due to more surface area.

3.3. Upper fin performance at a higher temperature for circular & rectangular fin 6 lED

For six HPLEDs, temperature variation across fins for all LED junction temperatures is uniform without many abrupt changes as in the case of a single LED shown in figure 8. While considering six LED rectangular fins of length 80 mm and 130 °C junction temperature, all the fins dissipate an average heat of around 3.66 °C. The highest rise in temperature is observed for the 1st and 10th fin at around 129.97 °C and the peak temperature is more pronounced for higher LED junction temperatures. Temperature is scattered throughout the LED heat sink base uniformly so that all the fins are conducting an equal performance in terms of heat dissipation. Therefore, it is easy to estimate the temperature variation across fins at both the top and bottom.

At the same time, the remaining fins 1–15 & 25–40 dissipate the heat from the left and the right side of the heat sink in the range of 129.18 °C − 127.62 °C & 127.62 °C − 129.18 °C. Further, increase with the increase in fin length from 60 mm to 70 mm and 80 mm, the temperature has dropped from 128.26 °C to 127.56 °C in the case of circular fins at fin number 15. While comparing to the rectangular fin, the reduction in temperature is better than circular fins across all fin numbers and also for increasing fin length. Overall, the upper fin temperature of the rectangular fin was found to be lower as compared to circular fins for the same fin height.

The difference between the highest and lowest temperature for the circular upper fins of length 80 mm at 130 °C junction temperature is 2.02 °C, whereas for 110 °C & 90 °C junction temperature it is around 1.9 °C & 1.75 °C respectively. The temperature difference was found to be more for rectangular fins of around 2.84 °C for 130 °C junction temperature, followed by 2.29 °C & 1.801 °C for 110 °C & 90 °C respectively which shows rectangular fins are more efficient than the former. The temperature variation across all fins for 50 °C junction temperature is nearly uniform. The Rayleigh number for circular and rectangular fin six LEDs of length 80 mm is numerically found to be 1.82×10^7 and 1.56×10^7 respectively.

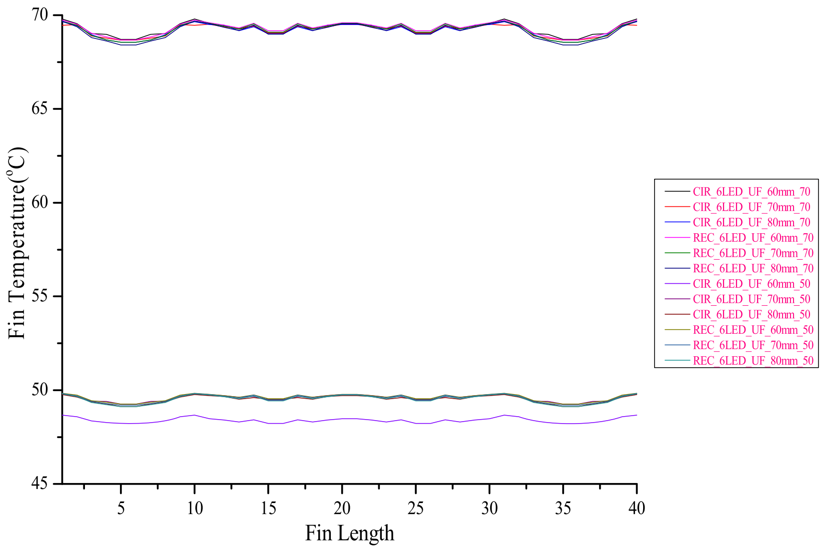

Figure 9. Temp. for upper fin 6 LED circular and rectangular.

3.4. Upper fin performance at a lower temperature for circular & rectangular fin 6 LED

While considering rectangular six LEDs of length 80 mm at 70 °C junction temperature, all the fins dissipate an average heat of around 1.6 °C. The highest rise in temperature is observed for the 1st and 10th fin of around 69.673 °C as shown in figure 9. At the same time, the remaining fins 1–15 & 25–40 dissipate the heat from the left and the right side of the heat sink in the range of 69.673 °C −68.996 °C & 68.996 °C −69.673 °C respectively. Further, an increase in the fin length from 60 mm to 70 mm and 80 mm reveals that there is a temperature drop from 69.4 °C to 69 °C in the case of the circular fin at fin number 15. While comparing to the rectangular fin, the dissipation of temperature is better than circular fins across all fin numbers and also for increasing fin length. Overall, the upper surface temperature of the rectangular fin was found to be lower as compared to circular fins for the same fin height. In short, the rectangular fin is better than the circular for the same LED junction temperature and fin length due to high heat dissipation capacity.

3.5. Upper fin performance for rectangular versus spokes fin single LED

Figure 10 depicts the temperature distribution across upper fins for single LED rectangular and spokes fin designs. The curves clearly show that the 60 mm Spokes fin outperforms 80 mm rectangular for all LED junction temperatures. The 60 mm spokes fin & 80 mm rectangular weigh around 292.03 gm & 355.88 gm respectively.

The Rayleigh number for spokes fin single LED of length 80 mm is numerically found to be 1.67×10^7.

3.6. Upper fin performance at lower & high temperatures for rectangular versus spokes fin six LED

Figure 11 describes the temperature distribution across 6 LED rectangular and spokes fin for all LED junction temperatures. It is observed that fin numbers 3–8 and 33–38 were found to have less temperature as compared to the other fins. Fin was found to have the highest temperature of 128.76 degrees. 60 mm spokes fin had better heat dissipation than 80 mm rectangular for all lengths for both upper and lower junction temperatures which clearly shows that the spokes fin is best among the given fin types. Moreover, the 80 mm spokes fin curve for 110 °C, 90 °C, and 70 °C LED junction temperature had more temperature difference than any other curves of 0.6 degrees between 70 and 80 mm whereas 0.15 degrees between 60 and 70 mm for fin number 4. At 50 °C junction temperature, fin temperature is nearly the same across all fin lengths for both rectangular and spokes fin. Therefore, it is optimum to use a spokes fin for high LED junction temperature, whereas rectangular for the low LED temperature as it is economical and easy to manufacture. The Rayleigh number for spokes fin six LED of length 80 mm is numerically found out to be 1.81×10^7.

3.7. Temperature difference for single and six LED array

Figure 12 shows the temperature difference between the upper and lower fin for a single LED configuration of height 80 mm along with 130 °C junction temperature. The ΔT is symmetric for all three fin types in the case of a single LED, with the spokes fin having more dissipation than the other two fin types. The temperature change for circular and rectangular is nearly the same across all fin numbers which is around 11.52 °C whereas for spokes fin variation is rather erratic with the highest change observed at fin number 17 which is close to 23 °C. Also, maximum temperatures were observed for fin numbers 8 & 37 which is around 20 °C. For six LEDs, ΔT

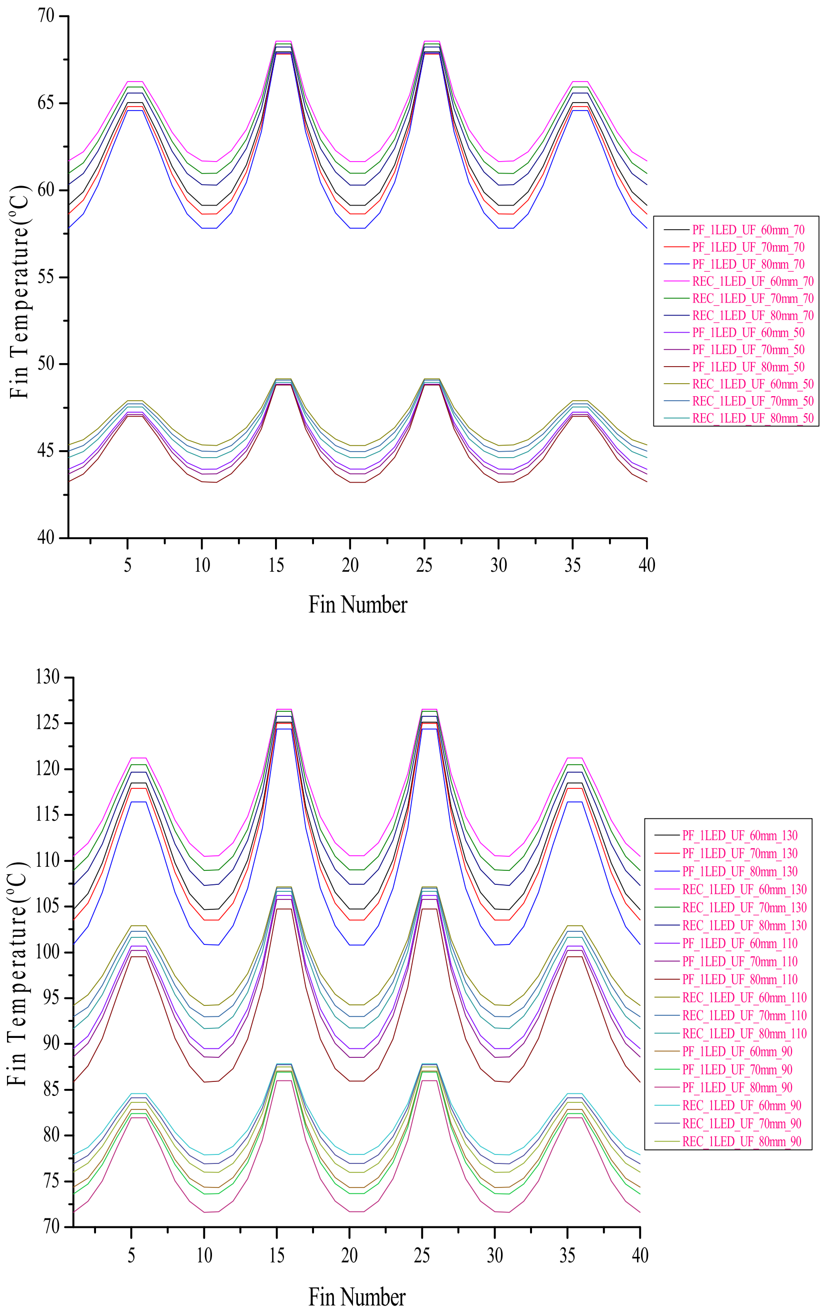

Figure 10. Temperature for the single LED spokes fin and rectangular fin.

variation is nearly constant for all three fin types with the spokes fin having the highest change of 23.58 °C, as all the six LEDs are placed in a basic grid shape of triangular thus enhancing the heat dissipation performance. Rayleigh number was found to decrease with an increase in fin length and decreasing LED junction temperature for all LED fin configurations.

3.8. Temperature data at the upper fins with and without radiation at higher LED junction temperature

Figure 13 depicts the temperature values at the upper fins with and without radiation at higher LED junction temperatures for the three fin lengths. The radiation effect is more pronounced for high LED junction temperature, hence the graph is plotted for 130 °C junction temperature. It is noticeable that there is a fall of around 1 °C temperature at the upper fin for all the given lengths while considering the radiation effect. Nusselt number is the enhancement of heat transfer as a result of convection to conduction across the same medium. It is observed that for effective cooling under natural convection the corresponding Nusselt number should decrease with increasing fin length [21][25]. The variation in Nusselt number for declining LED junction temperature for all three fin types along with the varying length is shown in figure 14. It shows the drop in value of the Nusselt

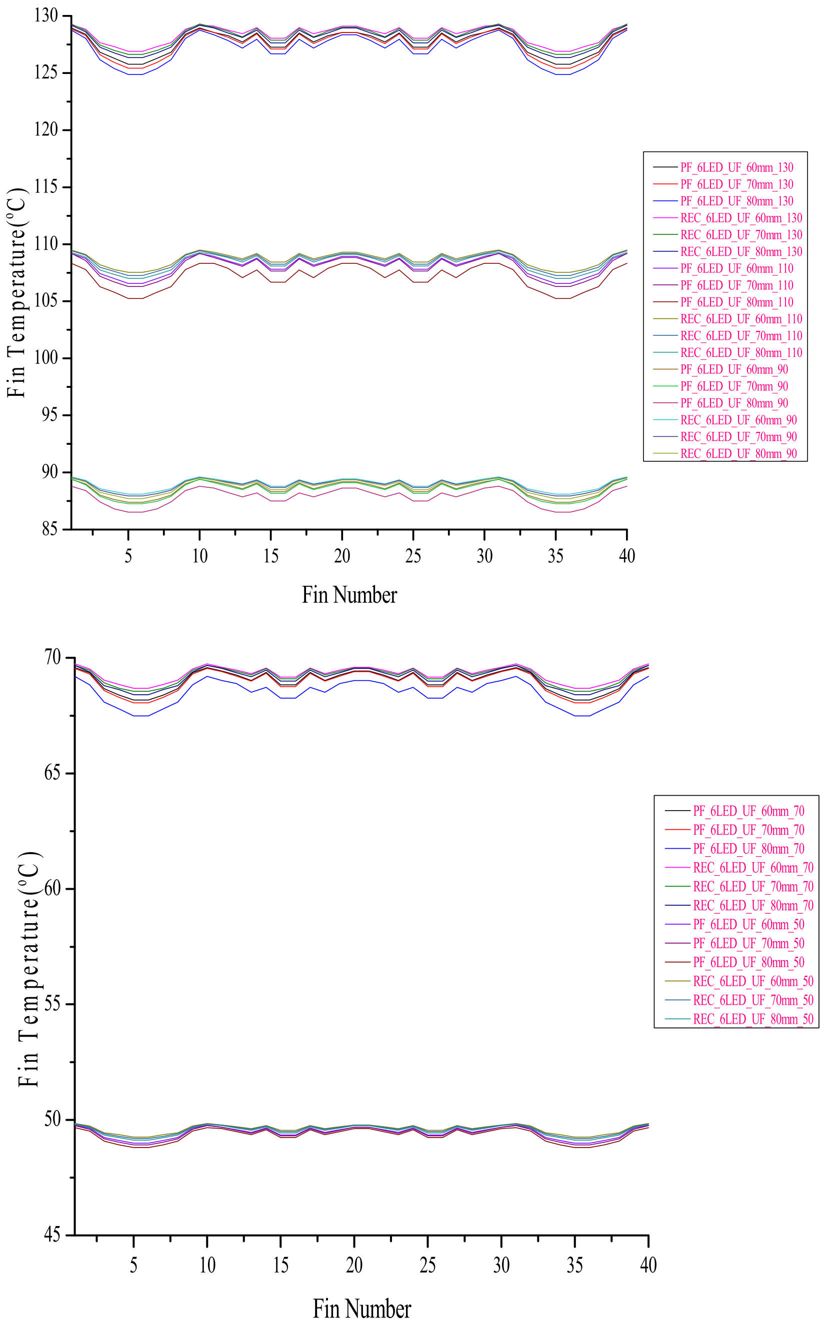

Figure 11. Temperature for six LED spokes fin and rectangular.

number for declining LED junction temperature for all the fin types. It is noticeable that at every junction temperature, 80 mm fins outperform the other two lengths and the drop is insignificant from 130 to 110 °C.

Moreover, the reduction in Nu increases as it approaches the ambient temperature. There is a small difference in Nusselt number of circular and rectangular fin-type, whereas the value of Nu number for 60 mm spokes fin is less than both circular and rectangular fins of length 80 mm which shows it optimum efficiency. Moreover, the Nusselt number decreases with an increase in the length of the fins, which is visible for lower fin single LEDs for all fin types as well.

Figures 15(a) and (b) show the decrease in Nusselt number for the lower and upper fin for six LED configurations with the drop in LED junction temperature. There is a significant difference in the values of Nu for rectangular and spokes fin type designs which indicated that spokes fin type is superior to rectangular, whereas there is no substantial difference in their Nu values for six LEDs between circular and rectangular.

In the case of six LED upper fins, there is a negligible difference in the values of Nu values for all LED junction temperatures as observed in figure 16.

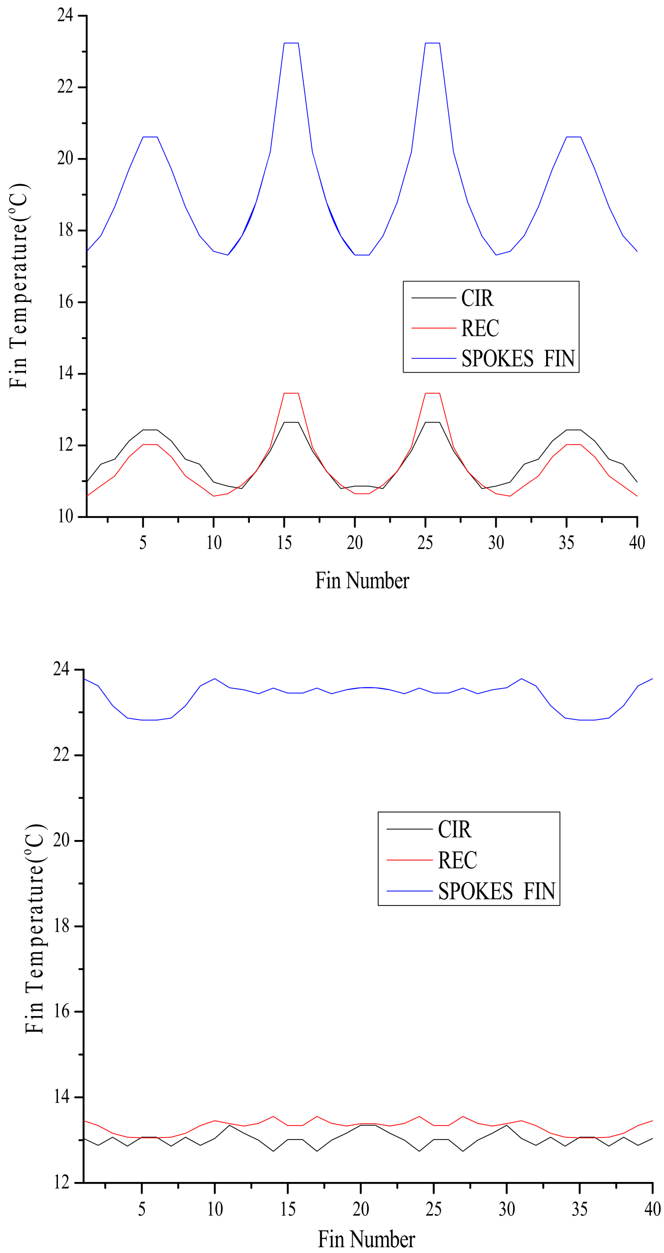

Figure 12. Temperature difference for circular, rectangular and novel spokes fin.

3.9. Thermal resistance model for single and six HPLED

Thermal resistance is a resistance that resists the flow of heat from the HPLED junction to the ambient. Lower thermal resistance enhances the heat dissipation in the heatsink. The lower thermal resistance is obtained by choosing the optimum material and appropriate dimension of the heat sink. Figure 17 shows the thermal circuit of the proposed heat sink and spokes fin model for 6 LEDs in the array. The heat source from the HPLED dissipates from the LED junction to the solder point which is denoted as $R_{JN\ (1–6)\text{-}SP\ (1–6)}$.

The remaining heat is dissipated from the solder point to the heat sink upper surface which is denoted as $R_{SP\ (1–6)\text{-}HS}$.

The upper surface of the heat sink to the lower surface of the heatsink thermal resistance is denoted as $R_{HS\text{-}FINB}$. The thermal resistance from the upper fins which are integrated with the heat sink to the fin tip at the bottom which is exposed to the atmosphere is denoted as $R_{FINB\text{-}AMB}$.

The total thermal resistance is the resistance of all LEDs in addition to the heatsink and fins. The total thermal resistance of the entire heatsink pack along with the LEDs except the fins is found as 8.2 °C/W [21]. Considering the fins along with the heatsink and LEDs the total thermal resistance is numerically found as 8.87 °C/W. For the single LED, only one LED junction temperature is to be considered. The total thermal resistance of the single LED along with the heatsink and fins are found numerically as 5.098 °C/W. For different fin arrangements, the thermal resistance does not vary ±0.5 °C/W.

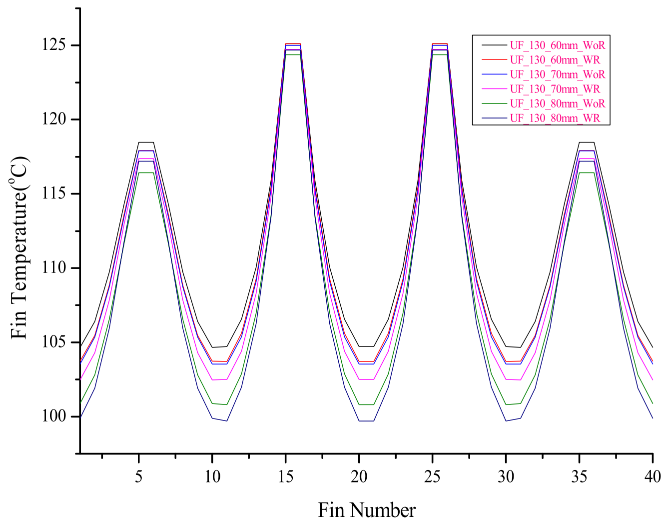

Figure 13. Temperature at the upper fins with and without radiation.

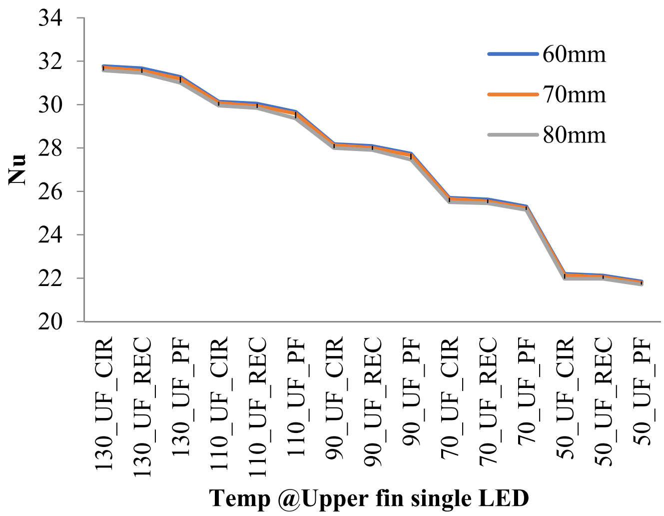

Figure 14. Nusselt number for upper fins single LED.

4. Conclusion

In the present study, thermal analysis of heat sink and three different fin types are carried out by using Steady-State ANSYS Workbench Solver. Three types of fin geometries namely, circular, rectangular and spokes fin are analyzed for varying fin lengths of about 60 mm, 70 mm and 80 mm and five LED junction temperatures namely 130 °C, 110 °C, 90 °C, 70 °C and 50 °C under natural convection conditions. Based on the results observed, the main conclusions from the current work are as follows:

- The fin base temperature was found to decrease by about 2.3 °C with an increase in fin length and the reduction was found to be about 1.7 °C for rectangular fins over circular fins, mainly due to more surface area.
- Novel Spokes fins are found to be the most effective for HPLED applications among the given three fin types with the highest heat dissipation capacity about 17.5% for the single LED and 2.8% for six LED array.
- For rectangular and spokes fin, it is observed that the 60 mm spokes fin is more efficient than the rectangular 80 mm on both the LF and UF for temperatures about 3.1 °C for the single LED and 2 °C for six LED array. Moreover, a novel spokes fin with a 60 mm length has 18% less weight than a rectangular fin of 80 mm, indicating it is more economical, and lightweight and hence making it a suitable choice for working at higher temperatures.

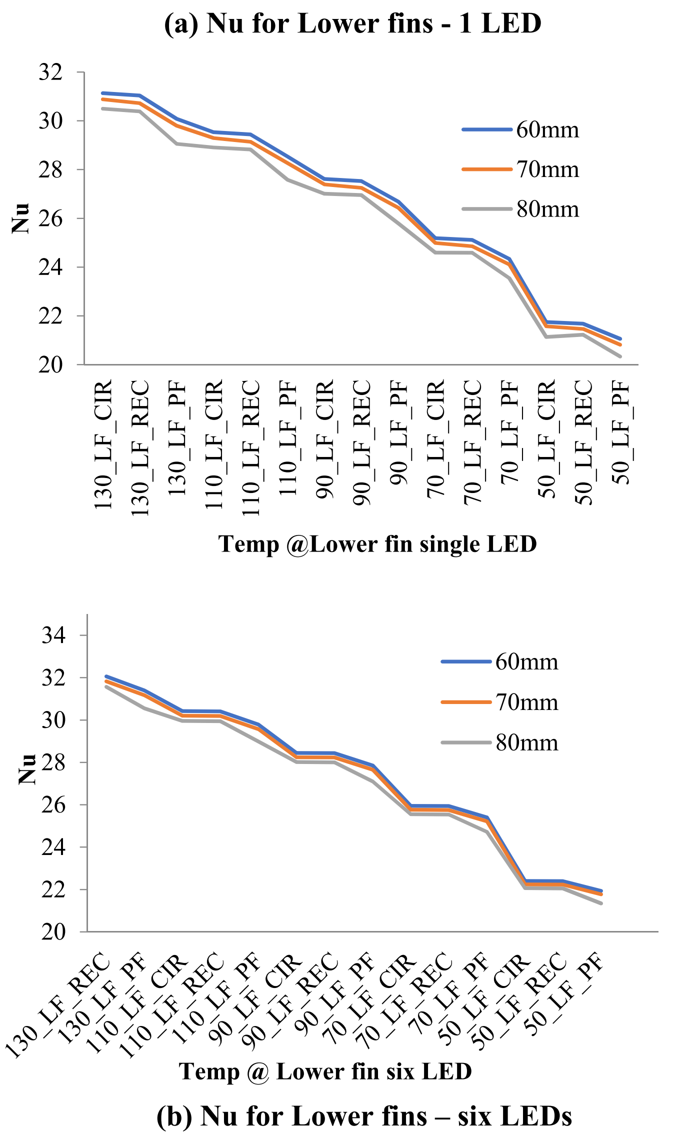

Figure 15. (a) Nu for lower fins – 1 LED 15(b) Nu for lower fins—six LEDs.

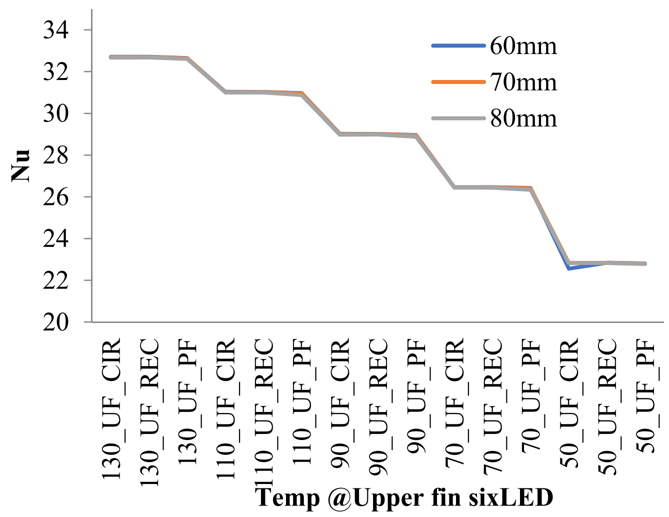

Figure 16. Nu for upper fins for six LED.

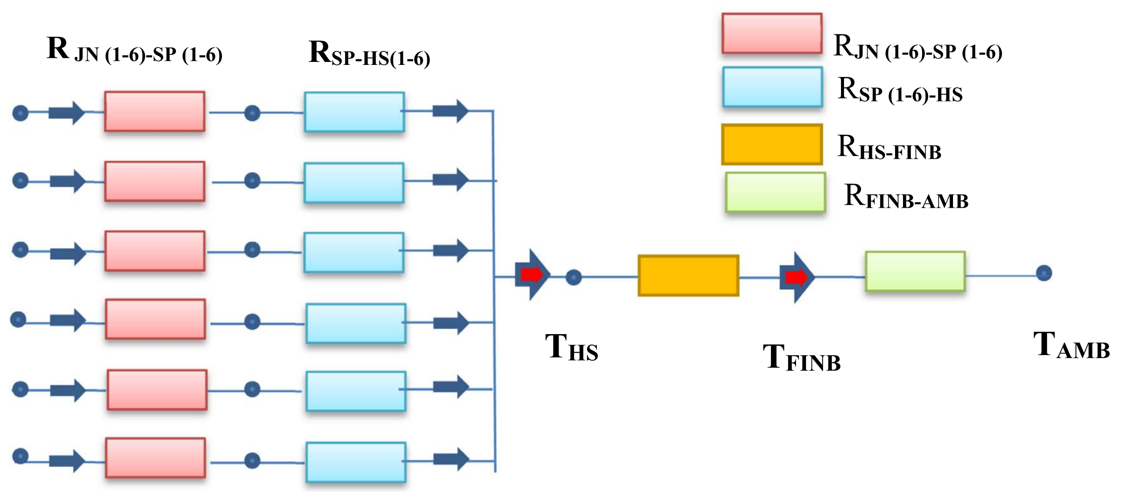

Figure 17. HPLED array thermal resistance model on a common heatsink.

- It is optimum to use a spokes fin for high LED junction temperatures of about 130 °C to 90 °C and whereas for lower junction temperatures of 50 °C to 70 °C, it is better to use a rectangular fin for six LED configurations as the fin performance is nearly the same for both.
- Temperature distribution among the upper fins for six LED configurations is nearly the same for all the fin types due to the triangular grid arrangement of LEDs placed on the heat sink base.
- The value of the Nusselt number was found to decrease by about 1.3% for the single LED and 0.8% for 6 LED. with an increase in fin length and was found to be least for spokes fin thus indicating its good thermal dissipation capacity of about 15.5% for the single LED and 4% for 6LED.

It is found the novel spokes fin proposed is best suitable for all High power LED applications which is low cost and lightweight and suitable for mass production during manufacturing. Also, the future scope of the proposed work can be extended by evaluating the available data using machine learning algorithms.

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Data availability statement

The data that support the findings of this study are available upon reasonable request to the corresponding author through email.

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Conflict of interest

We know of no conflict of interest associated with this publication.

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