Experimental study on the cooling performance of high power LED arrays under natural convection

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Abstract. This paper presents on the cooling performance of high power light emitting diode (LED) arrays under natural convection condition. A series of experiments with different type of LED array arrangements with a commercial heat sink were performed to evaluate their thermal performance. An analytical thermal resistance model was used to calculate thermal resistance. The results reveal that thermal resistance and junction temperature are affected by the type of array. The triangular array of the high power LED revealed the highest heat transfer coefficient with 3.86% compared to the most common square array. It indicates that array arrangement of the LED significantly affect on the excellent performance.

1. Introduction
High power LED known as the fourth generation of light source and dominated the lighting market nowadays. It offers a numerous advantages over conventional lighting sources due to lower power cost, longer lifetime and high efficiency [1]. LEDs have been widely used in various lighting solutions, including street lighting, traffic light, indoor lighting and LED TV. The luminous efficiency of LEDs has risen to a certain level in response to the applications. However, the output level is still insufficient for some devices. In order to utilize LEDs in universal application, the implementation of multiple LEDs is required. However, it is reported that operating LED beyond the allowable junction temperature could shorten the lifetime, depreciate the light output and decreased the efficacy of the LED[2]. In addition, efficiency and reliability of LED are not only affected from the environment heat, but also the heat generated by the LED itself. In contrast to other conventional lighting, where the majority of the heat generated from the light source is dissipated to the ambient via radiation, approximately 90% of the heat generated by the PN junction in a LED is dissipated away by conduction [3]. Furthermore, due to the small size factor, LED package is unable to effectively dissipate heat through convection. It is generally known that thermal characterization of LEDs in an array need to account more constraint compared to a single package LED [4]. Apart from the effect of environment temperature, the effect of thermal interaction between LEDs in the array can escalate junction temperature of each LED at the same time.

As the efficiency and reliability of LED are a strong function of temperature, successful thermal management becomes highly important [5]. System with poor thermal design could shorten the
lifetime of LED with excellent thermal performance. Despite of many thermal management approaches and solutions, a typical high power LED lighting system must deal with design considerations, such as cost, reliability, energy efficiency and noise, which lead to a limited cooling design options [2, 6-10]. There are a lot of researches reported on thermal management of high power LED at package level focusing on the selection of high performance materials and improvement on package structure in order to enhance heat dissipation [11]. Another direct solution to improved heat dissipation of high power LED is to use high conductivity substrate such as metal and ceramic in printed circuit board (PCB) where LEDs are soldered on [12-14]. In the case of multiple LEDs on a board, several researchers have reported the study on the spacing and placement of LED in order to get uniform luminance and good thermal performance [2,4]. Due to the small form factor, a thermally good design of LED packages and great thermal performance of PCB is insufficient to dissipate enough heat; an additional cooling means is needed [12] such as passive and active cooling. However, passive cooling is the most desired since it offers simple structure and low cost [15].

In consideration of these, present research performs a thermal analysis of high power LEDs soldered on a metal core printed circuit board (MCPCB). A heat sink is attached on LED array system module which acts as a passive cooling solution. The effect of LED placement design in array on thermal removal ability under natural convection condition is then analyzed.

2. Experiments
Commercial high power LEDs (Golden Dragon) manufactured by OSRAM Opto Semiconductors are used in the experiments. The arrays consist of six high power LEDs and soldered on 59 mm × 83 mm MCPCB in four different arrangements as shown in figure 1. The arrays applied the basic grid shapes of square, hexagonal, triangular and circular namely as A, B, C and D. The LEDs are electrically arranged in a typical series/parallel electrical array to account for forward voltage (Vf) variations between the LEDs and ensure a reasonable current distribution. Figure 2 shows the structure of the Golden Dragon LED which is mounted on the MCPCB and heat sink. The size of the heat sink dimension used in the experiments is 59 mm × 83 mm × 33 mm.

Array A: Square grid

Array B: Hexagonal grid

Array C: Triangular grid

Array D: Circular grid

Figure 1. Photograph and schematic of LED arrangement.
Figure 2. LED structure and mounting method.

Figure 3 shows the experimental setup schematic diagram. The LED arrays are powered using a regulated digital DC power supply, and its power is 15.2 W. One LED on the MCPCB is selected as device under test (DUT). The temperature of solder point, MCPCB and heat sink are measured using K-type thermocouples. The thermocouples are connected to a data acquisition system and then to a computer to record the temperature at 60 seconds interval till the temperature of the system achieved steady state condition.

3. Results and discussion

In the experimental set up, junction temperature could not be measured directly. However, it is feasible using solder point temperature to check the thermal behavior of the system since it also increases in same proportion with the junction temperature. Figure 4 shows the temperature variations of solder point with time for each array. It can be seen that the solder point temperatures for each array increase sharply in similar pattern up to 73.9 °C. Figure 5 compares the solder point temperature rise for each array. It is obvious that the solder point temperature rise is higher for array A and lowest for array C. This is due to the effect of better placement shape of LEDs in the array which leads to the reduction in thermal interaction effect between LEDs in the array.
The total thermal resistance of multiple LEDs in array is the sum of each individual thermal resistance and can be well explained using parallel thermal resistance model as describes in figure 6. The thermal resistance from junction to board, $R_{th/B}$ for multiple LED array is expressed by using parallel resistance equation as:

\[ R_{th/B} = \sum R_{th,i} \]

Here, $R_{th,i}$ is the thermal resistance of individual LED in the array.
Since all of the LEDs used are the same type and exhibit the same characteristics, equation (1) is simplified as:

$$R_{thJB, total} = \frac{R_{thJB}}{n}$$

(2)

Thus, the total thermal resistance is expressed as:

$$R_{thJA} = \frac{R_{thJB}}{n} + R_{thBH} + R_{thHA}$$

(3)

where $R_{thJA}$, $R_{thJB}$, $R_{thBH}$, $R_{thHA}$ are the thermal resistance from junction to ambient, thermal resistance from junction to board, thermal resistance from board to heat sink and thermal resistance from heat sink to ambient respectively. Equation (3) can be interpreted as the increase in the number of unit LED in a system leads to the decrease in total thermal resistance due to the total power is distributed among the LEDs.

**Figure 6.** Thermal resistance model for multiple LED array.

Knowing the value of total thermal resistance, junction temperature could be easily calculated by following equation:

$$T_j = T_A + (P_H \times R_{thJA})$$

(4)

where $T_j$ and $T_A$ are the junction temperature and ambient temperature respectively and $P_H$ is the total heat input.

Figure 7 represents the total thermal resistance and junction temperature for each type of array. Array A with the most common square grid shape produced the highest total thermal resistance.
followed by array B, D and C array with value of 5.49°C/W, 5.33°C/W, 5.25°C/W and 5.32°C/W, respectively. This pattern is similar to the junction temperature whenever it plots against type of array.

Heat transfer coefficients for all arrays are then summarized in figure 8. It depicts that the heat transfer coefficient (h) is very limited due to the convection is only relied on the natural movement of hot air, which is very slow. The maximum convection coefficient recorded was as high as 2.65 W/m²·°C for the LEDs in array C. This pattern was followed by 2.62 W/m²·°C, 2.60 W/m²·°C and 2.58 W/m²·°C for array D, B and A, respectively. It clearly shows that the best thermal convection performance for array C produced the highest increment over array A by about 3.86%.

Figure 7. Total thermal resistances for different array.
4. Conclusion
The cooling performance of high power LED arrays attached with heat sink under natural convection has been studied. Four types of array composed with six high power LEDs in different arrangement were considered. Thermal resistance and heat transfer coefficient models were used to calculate thermal resistance and convection from the measured temperature for each array. The triangular array of the high power LED (namely as Type C) shows the highest heat transfer coefficient with 3.86% compared to the most common square array. Therefore, the array arrangement of LED significantly demonstrated has influences the performance of the system.

Acknowledgement
The authors would like to thank the Universiti Malaysia Perlis (UNIMAP), Universiti Sains Malaysia (USM) and UniKL MSI for the financial and facilities support for this research work.

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