EXPERIMENTAL AND NUMERICAL INVESTIGATION FOR COOLING PERFORMANCE OF HIGH POWER LIGHT EMITTING DIODE (LED) ARRAYS USING HEAT SINK

by

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"In the name of ALLAH, The Most Beneficent and The Most Merciful"

Praise is exclusively to Allah. The Lord of the universe and peace is upon the Master of the Messengers, his family and companions.

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NOMENCLATURES

SYMBOL	DESCRIPTION	UNIT
English Symbols		
A_t	Total heat sink surface area	m^2
c_p	Specific heat	J/kg·K
h	Channel height	mm
h_{avg}	Average heat transfer coefficient	W/m^2·°C
h_{local}	Local heat transfer coefficient	W/m^2·°C
I	Current	A
I_f	Forward current	A
k	Thermal conductivity	W/m·°C
L	Length of heat sink	mm
P	Pressure	Pa
P_{in}	Input power	W
P_H	Actual heat input	W
Q_{net}	Net heat flux	W
R_{thJX}	Thermal resistance between junction and specific environment	°C/W
R_{thJA}	Thermal resistance junction to ambient	°C/W
R_{thJS}	Thermal resistance junction to solder point	°C/W
R_{thJB}	Thermal resistance junction to board	°C/W

R_{thSB}	Thermal resistance solder point to board	°C/W
R_{thBH}	Thermal resistance board to heat sink	°C/W
R_{thHA}	Thermal resistance heat sink to ambient	°C/W
T	Temperature	K
T_X	Reference temperature	°C
T_J	Junction temperature	°C
T_S	Solder point temperature	°C
t	Time	s
V	Voltage	V
V_f	Forward voltage	V
U_{max}	Maximum velocity	m/s
U_∞	Approach air velocity	m/s
x, y, z	Cartesian coordinates	m

Greek Symbols

ρ	Density	kg/m^3
v	Kinematic viscosity	m^2/s
μ	Dynamic viscosity of fluid	N·s/m^2
η_p	Power conversion factor	-
ξ,η,φ	Uniform orthogonal computational space	-

LIST OF ABBREVIATION

SSL	Solid state lighting
LED	Light emitting diode
Re	Reynolds number
Nu	Nusselt number
2D	Two-dimensional
3D	Three-dimensional
CFD	Computational fluid dynamics
FDM	Finite difference method
FEM	Finite element method
MAC	Marker and Cell
NSE	Navier-Stokes equation
PCB	Printed circuit board
MCPCB	Metal core printed circuit board
IMS	Insulated metal substrate
COB	Chip on board
LTCC	Low temperature co-fired ceramic
TIM	Thermal interface materials
DC	Direct current
DUT	Device under test
SMD	Surface mounted device

HID	High-intensity discharge
JEDEC	Joint Electron Devices Engineering Council
GNF	Generalized Newtonian fluid
PIV	Particle image velocimetry

EKSPERIMEN DAN KAJIAN BERANGKA TERHADAP PRESTASI PENYEJUKAN SUSUNAN DIOD PEMANCAR CAHAYA (LED) BERKUASA TINGGI MENGGUNAKAN SINKI HABA

ABSTRAK

Penggunaan diod pemancar cahaya (LED) berkuasa tinggi semakin meluas dalam aplikasi lampu kerana kelebihan-kelebihannya yang ketara berbanding sumber cahaya konvensional. Antara kelebihan-kelebihannya ialah jangka hayat yang panjang, penggunaan tenaga yang rendah dan kecekapan yang tinggi. Dalam aplikasi lampu, beberapa LED perlu digunakan bagi mendapat jumlah cahaya yang standing dengan sumber cahaya konvensional. Walau bagaimanapun, penyelesaian ini akan meningkat suhu simpang, dimana keadaan ini akan menurunkan prestasi dan memendekkan jangka hayat LED dengan ketara. Oleh itu, pengurusan haba memainkan peranan yang amat penting dalam reka bentuk sistem lampu LED. Tujuan utama kajian ini adalah untuk menyiasat prestasi penyejukan susunan LED berkuasa tinggi yang menggunakan sinki haba tipikal sebagai alat penyejuk. Tujuan ini telah dicapai dengan melaksanakan penyiasatan eksperimen dan simulasi menggunakan empat jenis susunan LED. Susunan LED adalah berdasarkan bentuk-bentuk asas iaitu segiempat, bulatan, segitiga dan heksagon. Eksperimen telah dijalankan untuk menguji prestasi haba pemindahan susunan-susunan LED dengan aliran udara laminar pada pelbagai nombor Reynolds (Re) dengan julat dari 0 hingga 21173. Parameter seperti rintangan haba, pekali pemindahan haba dan nombor Nusselt (Nu) telah diperiksa dalam eksperimen tersebut. Kajian yang dijalankan ke atas kesan Re menunjukkan bahawa pemindahan haba keseluruhan prestasi sistem lampu meningkat dengan ketara untuk Re sehingga 15880 dan kurang kesan telah diperhatikan dengan meningkatkan Re kepada 21173. Seterusnya ujian telah

dijalankan ke atas kesan dari jenis susunan LED yang berlainan. Keputusan menunjukkan bahawa susunan C telah memberikan prestasi penyejukan yang terbaik apabila dikendalikan di bawah keadaan olakan tabii dan olakan paksa disebabkan oleh keupayaan pemindahan haba yang baik. Selain itu, ciri-ciri aliran, susutan tekanan dan pengedaran suhu telah diramalkan menggunakan kod tiga dimensi (3D) dinamik bendalir berkomputer (CFD). Aliran lamina stabil berdasarkan persamaan Navier-Stokes (NSEs) dan persamaan pemindahan haba telah diselesaikan dengan kaedah pembezaan terhingga (FDM). Kaedah "Marker and Cell" telah digunakan untuk menyelesaikan istilah tekanan. Perisian MicroAVS® telah digunakan untuk menggambarkan keputusan kajian berangka. Pekali pemindahan haba daripada penyiasatan berangka kemudiannya dibandingkan dengan penemuan eksperimen dan padanan yang munasabah telah diperolehi.

EXPERIMENTAL AND NUMERICAL INVESTIGATION FOR COOLING PERFORMANCE OF HIGH POWER LIGHT EMITTING DIODE (LED) ARRAYS USING HEAT SINK

ABSTRACT

High power light emitting diodes (LEDs) are increasingly used in many lighting applications due to their significant advantages over conventional light sources, which include long lifetime, low energy consumption and high efficiency. In order to match light output of conventional light sources, multiple LEDs are essential in application to lighting systems. However, this solution would escalate junction temperature, which significantly degrades the performance and shortens the lifetime of LED. Therefore, thermal management plays very important role in designing LED lighting system. The main aim of the present study is to investigate the cooling performance of high power LED arrays, attached to a typical heat sink as cooling means. This was accomplished by performing an experimental and numerical investigation using four different types of LED array arrangements. The LED placement incorporated the basic shapes of square, circular, triangular and hexagonal grid. An experiment set up was developed to test the heat transfer performance of the LED arrays with laminar air flow at various Reynolds number (Re) ranging from 0 to 21173. The parameters such as thermal resistance, heat transfer coefficient and Nusselt number (Nu) were examined in the experiments. Study carried on the effect of Re showed that the overall heat transfer performance of the lighting systems increased significantly for Re up to 15880 and less effects were noticed by increasing Re to 21173. Subsequent tests were carried out on the effect of different type of LED arrays. The results showed that array C was found to give the best cooling performance when operated under natural and forced convection conditions due to

the good heat transfer capability. Moreover, three dimensional (3D) simulations using Computational Fluid Dynamics (CFD) code has been used to predict the flow characteristic, pressure drop and temperature distribution. The code applied finite-different method (FDM) based on Navier-Stokes equations (NSEs) and heat transfer equations to solve the steady, laminar flow whereas the pressure term was solved using Marker and Cell (MAC) method. MicroAVS® software was utilized to visualize the numerical results. The temperature and heat transfer coefficient from numerical investigation was then compared with the experimental findings and a reasonable agreement was obtained.

CHAPTER ONE
INTRODUCTION

1.1 Overview

The first sub-chapter serves as the introduction to high power LED. The thermal challenges and the importance of thermal management in application of high power LED as lighting solution are discussed. The thermal problem statements are presented in the next sub-chapter. Finally, the detailed objectives of the study and scope of research works are highlighted in addition to the outline of the thesis.

1.2 Introduction to high power LED

Global warming and energy consumption have drawn worldwide attention for several years. LED is one of the viable solutions for environmental protection and energy conservation. LED is an application of solid-state lighting (SSL) technology which converts electricity into light by utilizing semiconductor. Due to a number of advantages compared to traditional lighting sources, LED technology has been researched and developed rapidly in the last 10 years. It is currently in focus in countries around the globe that are transitioning from traditional lighting towards high power LED in various lighting solutions such as street lighting, indoor lighting, traffic light and the infamous flat panel LED TV. It is also believed that SSL will dominate the lighting market and outperform firstly the incandescent and later the fluorescent lighting in the next decade, completely replacing traditional lighting sources.

However, high power LED provides greater thermal challenges than most other traditional lighting sources. Despite the high efficiency, LED also generates heat in addition to light. As LEDs are not 100% efficient at converting input power to light, some of the electrical energy will partly convert into light and partly into heat (Huaiyu et al., 2011). Approximately 85% of the power that is applied to LED is converted into heat and must be transferred to the ambient (Petroski, 2004). Unlike incandescent light bulbs, high-power LED does not radiate heat energy within the light beam. Instead, LED conducts heat from the LED die to the underlying circuit board, heat sinks, housings or luminaire body structure and is subsequently released to the environment. The heat generated by the chip heats up the device itself leading to a phenomenon called self-heating. If the heat isn’t managed properly and junction temperature rises, the LED lifetime will be shortened and the LED will be less efficient.

Thermal management has been essential requirement in ensuring reliable quality of high power LED performance. Thus, various studies on thermal management of high power LED have been performed from package to system level. Despite many investigations on new high power LED related thermal solutions, heat sink is the most preferred cooling medium to remove heat involving only passive heat transfer. Passive heat sink cooling is obviously advantageous for its reliability, energy-free and noise-free operation. However, with advances in high power LED, the thermal load is too high to be dissipated sufficiently by passive heat sink alone; this situation calls for the addition of active cooling solution. There are many types of active cooling system that have been developed. However, most of these solutions still have constraints on technical and economical factors. Consequently, forced convection air cooling, particularly the combination of heat sink and fan continues to be the main and most preferred approach to deal with crucial challenge of high thermal dissipation.

1.3 Problem statement

Although high power LED is believed to revolutionize an entire new generation of lighting application, thermal management has been the biggest challenge that slows its penetration. Apparently, heat is generated at p-n junction of the semiconductor when electrical input power is supplied to LED. Exceeding 10 °C above the specific operating junction temperature would result in approximately 50% reduction of average time to failure for most high power LED applications (Zou et al., 2007). Furthermore, a single LED light output is still insufficient when compared to the old type incandescent and the newer compact fluorescent light bulb. Therefore, in application for general illumination systems, multiple number of LED's, if not large array is essential. Thermal behavior of LED's in an array is significantly affected by environment temperature and side effect from multiple chips. As the LED performance and reliability are strong function of its temperature, successful thermal management is crucial to ensure the efficiency, reliability and life time of LED. The ability to prevent LED from overheating is the most challenging task.

Previous researchers focused on thermal management and thermal characteristics of a single package LED, while LEDs in array, which have important practical applications, is not widely studied. Even though LEDs in array are being applied in most of lighting solutions, researchers however focused their attention to the LED placement in array in order to get uniform illumination and tried to contain the thermal issues using alternative complicated active cooling techniques. Investigation on the cooling performance of heat sink with air flow to force the heat convection for various types of LED arrangement in array with a constant number of LEDs is lacking.

1.4 Objectives of the study

The present study is aimed to achieve the following objectives:

1. To study the cooling performance of high power LED arrays by using heat sink at different Re.
2. To examine the thermal behavior of different arrangement of LED array.
3. To perform 3D numerical simulation to predict the flow behavior and temperature distribution for different arrangement of LED array at various Re.
4. To compare the results obtained from experimental and numerical studies.

1.5 Scope of research work

This research investigates the impact of Re and LED arrangement on cooling performance of high power LED array system using experiment and 3D simulation. The focus of this investigation is to understand the system level thermal management. Heat transfer by radiation is assumed to be negligible in this study as it is typically responsible for less than 5% of the heat transfer. The LED package level thermal management is beyond the scope of this study. Therefore, the resistances from thermal interfaces and within the LED constitute will not be discussed in detail.

1.6 Thesis outline

This thesis is organized in five main chapters consisting of introduction, literature review, methodology, results and discussion and finally conclusion. Chapter One elaborates the introduction and thermal characterization of high power

LED. This chapter also presents the problem statement, objectives and scope of research. In Chapter Two, the literature review discusses the impact of high junction temperature on the performance and reliability of LED as well as the studies on thermal management for high power LED, in particular the studies related to LED array arrangement at board level and system level. The experimental methodology details and approach in mathematical modelling and numerical method are highlighted in Chapter Three. The fourth chapter extensively reports the experimental results and numerical results. The effect of Re and LED arrangement on the system cooling performance are presented in this chapter. Chapter Five states the final conclusions and proposes future work to further the development of the thermal management of high power LED.

CHAPTER TWO
LITERATURE REVIEW

2.1 Overview

The purpose of this chapter is to discuss the thermal management for high power LED, particularly LED in the form of array which has been investigated by different researchers all around the world. Firstly, the advantages of high power LED over conventional light sources are reviewed. A review on the effect of high junction temperature on LED performance and reliability is presented next. Then the works on thermal management in application to high power LED lighting systems, which help to provide the background for the present study is reviewed. The review starts with a brief review of thermal management at package level followed by board level. The studies on spacing and placement design of LED array are also presented in this sub-chapter. A summary of thermal solutions for high power LED lighting systems is presented next. Subsequently, a survey of the published works on the optimizations and application of heat sink in high power LED array are provided before concluding with the general remarks.

2.2 Advantages of LED

One of the key benefits of LED is that it has high luminous efficacy. Energy efficiency of a light source is typically measured in lumen per Watt (lm/W) known as luminous efficacy. Luminous efficacy is a measure of the amount of luminous flux produced for each unit of input electrical energy. Figure 2.1 shows the efficiency of various light sources. The efficiency of LED has already surpassed that of incandescent light sources and is even comparable to that of high-pressure sodium vapor lamp. Currently the efficiency of LED is up to 140 lm/W and higher efficiency are expected to be achieved in the next few years which could lead to a large energy saving. This value is far greater than an incandescent white light and fluorescent light in which the maximum efficiency is around 15 lm/W and 70 lm/W respectively (Steigerwald et al., 2002).

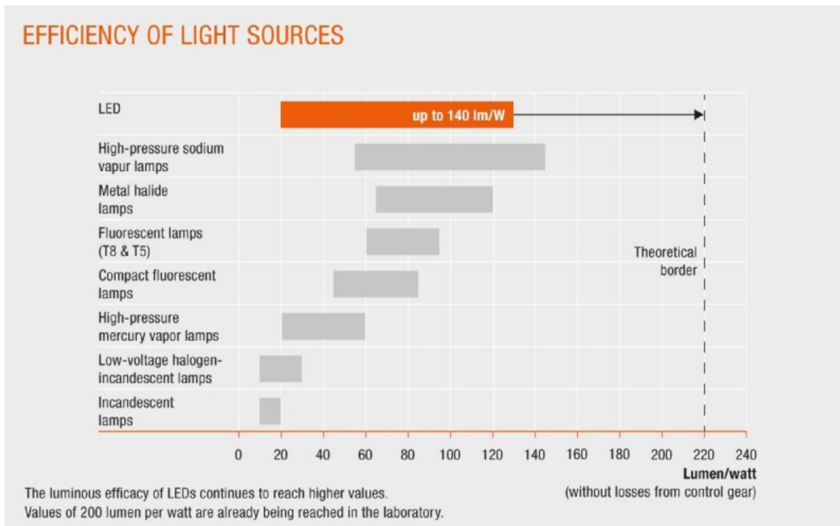

Figure 2.1 The efficiency of various light sources (OSRAM, 2012).

Another major feature of LED that attracts the lighting industry is its long lifetime. As can be seen in Table 2.1, LED life time is far longer than the other conventional light sources. Most manufacturers of high power white LEDs estimate a lifetime of around 50,000-100,000 hours before the LED light output decreased. Catastrophic failures which commonly occur in incandescent lamps are very rare for LED. The most common way for LED to fail is the gradual lowering of light output and loss of efficiency. LED end of life is defined to be when the light output decreases to 70% of its initial value. Meanwhile, life time for incandescent lamp is 1,000 hours, 20,000 hours for fluorescent lamp, and 24,000 hours for HID lamp. This means that LED lamp lifetime is more than 10 times longer compared to traditional lamps which could significantly reduce life-cycle cost and maintenance cost.

Table 2.1 Life time of various light sources (Ha, 2009).

Light Source	Range of Typical Rated Life (hours)
Incandescent	750-2,000
Halogen incandescent	3,000-4,000
Compact fluorescent	8,000-10,000
Metal halide	7,500-20,000
Linear fluorescent	20,000-30,000
High-Power White LED (estimated useful life by L_{70})	35,000-50,000

The small form-factor allows the designers to make the cost-effective product, compact and simple with minimal external components. Significantly, there are numerous other advantages of LED. These include low energy usage, no hazardous materials and very easily be dimmed. An intensive discussion of such important factors is not the objective of the present investigation as the advantages of LED over conventional light are already acknowledged.

2.3 Junction temperature and its impact on LED performance

Like a normal diode, the LED is made of p-type coupled with n-type semiconductor elements constructing a p-n junction. Upon application of electrical power, the luminescence reaction strikes at p-n junction, followed by emission of energy by means of light which is also called luminous flux. Basically, some percentage of energy becomes luminous flux during the reaction while the rest becomes the form of heat. Through this heat generation, the p-n junction carries the highest temperature in the device which is known as junction temperature. The junction temperature is a critical parameter that determines LED performance.

As shown in Table 2.2, all light sources transform electrical energy into radiant energy as well as thermal energy in different percentages. The amount of heat generated that need to be dissipated by conduction and convection in LED is significantly more compared to other light sources. Hence, the junction temperature increases excessively without appropriate thermal management.

Table 2.2 Power conversion of various light sources (Ha, 2009).

	Incandescent (60W)	Fluorescent (Typical)	Metal Halide	LED
Visible Light	8%	21%	27%	15-25%
IR	73%	37%	17%	0%
UV	0%	0%	19%	0%
Total Radiant Energy	81%	58%	63%	15-25%
Heat (Conduction+Convection)	19%	42%	37%	75-85%
Total	100%	100%	100%	100%

Operating LED with excessive junction temperature leads to color shift, shortened life, light output depreciation and decreased efficacy (Arik et al., 2004). Figure 2.2 illustrates the light output and color shift dependency on junction temperature.

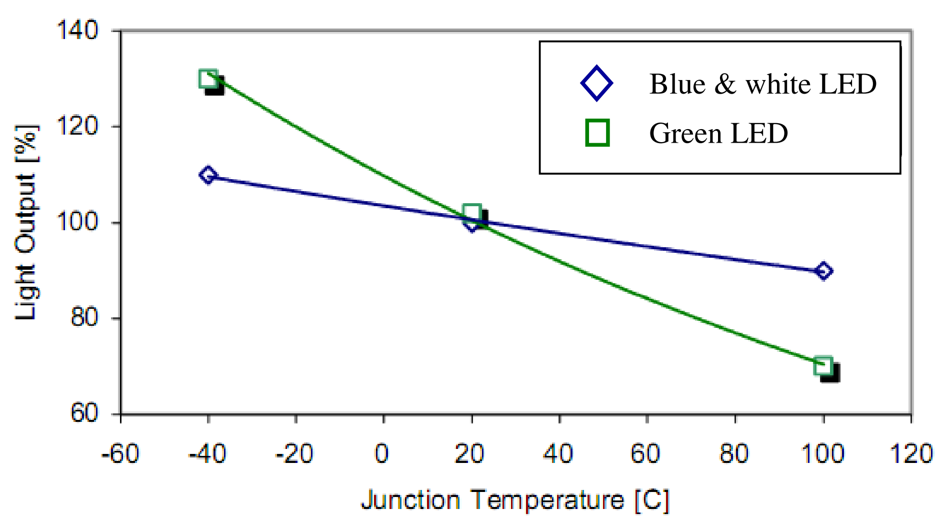

Figure 2.2 Light output variation of different colored LED responding to junction temperature changes (Arik et al., 2004).

Another impact of excessive junction temperature is early light output degradation. Figure 2.3 shows the light output depreciation of phosphor-converted white LEDs over time at different junction temperatures. Obviously, the rate of depreciation increases with junction temperature. Most LED manufacturers use the term L70 (for the lighting industry approach) and L50 (for the display industry approach) as a standard to quantitatively classify the lifetime of LED, which is the time a given LED needs to maintain 70% and 50% of initial light output value at room temperature, respectively (Paisnik et al., 2011). By the definition of L70, increase of 10°C in junction temperature shortens LED life by 50% reduction.

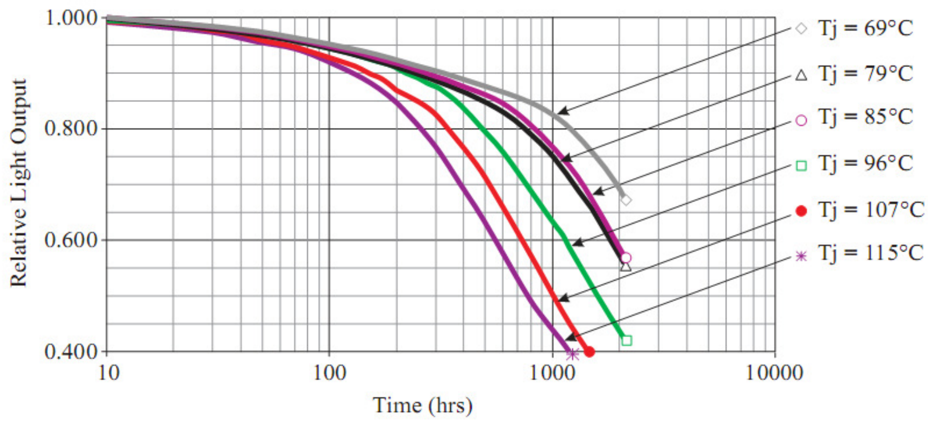

Figure 2.3 Light output depreciation of phosphor-converted white LEDs with time at different junction temperatures (Narendran et al., 2004).

As shown in Figure 2.4, light output degradation might be characterized in terms of lifetime as a function of junction temperature or solder point temperature (dashed line). High junction temperatures were found to significantly reduce the expected lifetime. Narendran and Gu (2005) experimentally demonstrated that the life of LED decreases exponentially with increasing junction temperature. On top of that, majority of the LED manufacturers fixed the maximum junction temperature, generally between 130-185°C which can be obtained with high power input. Driving LED over the maximum junction temperature might result in instant damage and even failure in devices.

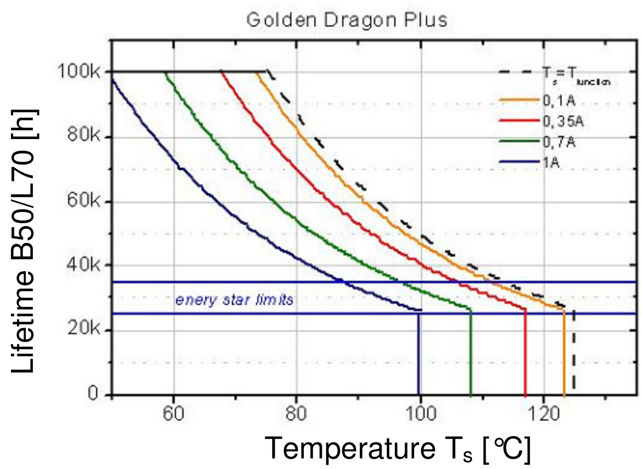

Figure 2.4 Lifetimes of Golden Dragon Plus with respect to solder point temperature (T_s) and junction temperature (T_j) (Semiconductors, 2011).

2.4 Thermal management of high power LED lighting systems

Previous sub-chapters have highlighted how junction temperature influences the performance and reliability of high power LED. As an important parameter, keeping the LED junction temperature as low as possible is essential. Compared to other light sources, high power LED has a serious heat problem due to the thermal energy (approximately 90% or more) being directly dissipated away by conduction instead of radiation (Petroski, 2004). Table 2.3 compares the modes of heat transfer in various lighting sources. By examining this table, one can see that LED radiates only little heat as LED produces no electromagnetic radiation in the infrared. Furthermore, LED package is unable to dissipate heat through convection effectively without additional cooling means due to the small size. Thus, conduction now becomes the primary mode of heat transfer near the heat source (LED). Therefore, an excellent thermal path to extract the heat from the chip to the ambient through the device must be designed properly (Ken, 2007). Although there are many approaches and possible solutions from package level, board level to system level thermal management, a typical high power LED lighting system must deal with the availability of the orientation independent and cost-effective thermal solutions (Arik et al., 2004). Thus, thermal management of high power LED is a crucial area of research and will remain an active area of development in near future.

Table 2.3 Light source efficiencies and the mode of heat removal (Arik et al., 2007).

Light source	Luminous efficacy (lm/w)	Heat lost by radiation (%)	Heat lost by convection (%)	Heat lost by conduction (%)	Cost efficiency ($/lm)
Incandescent	10–20	>90	<5	<5	0.001
Fluorescent (LFL)	75–90	40	40	20	0.0005
Cold cathode fluorescent (CCFL)	55–65	40	40	20	0.01
High intensity discharge	100–120	>90	<5	<5	0.002
LED	40–50	<5	<5	>90	0.04

2.4.1 Thermal management at package level

In general, typical high power LED packaging consists of chip, die attach, heat sink and encapsulation. The whole package is designed to maximize the optical output and back to remove heat from the LED chip. As one of the dominant factors of LED chip heat dissipation, many researchers are focusing on high performance material selection and optimized device package structure designed to improve the performance of the thermal conduction (Jiang et al., 2010, Mingsheng et al., 2011). The correct thermal management by choosing the suitable packaging materials and packaging structure leads to a minimum package thermal resistance. Figure 2.5 illustrates the development history of LED packaging and the improvement of package thermal resistance.

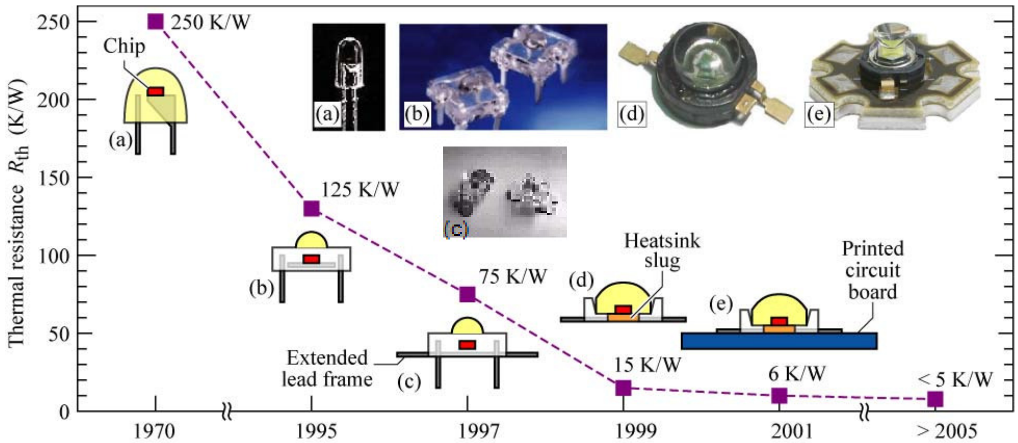

Figure 2.5 LED packaging history (Arik et al., 2002).

Numerous research works have been done in order to enhance heat dissipation in LED package. However, as the thermal management at package level is beyond the scope of the present work, it will not be discussed further.

2.4.2 Thermal management at board level

Package design with low thermal resistance helps to move the heat away from the LED junction inside the package. However, the thermal design in package level alone is insufficient to dissipate the electrical power that is converted to heat and light during operation. As LED packages are usually bonded to a printed circuit board (PCB) substrate, the direct solution is to use a high conductivity substrate material to conduct the heat generated away from the LED package (Huaiyu et al., 2011). The thermal conductivity for a traditional FR4 PCB with thermal vias (0.23 W/m·K) is considered low in application to an array of high power LED. Alternative boards with high thermal conductivity such as metal core PCB (MCPCB) and ceramic based board have been developed and employed in application of high power LED (Tsai et al., 2011, Long et al., 2009). Table 2.3 shows the thermal conductivity of several materials and substrates. Despite many material choices with excellent thermal conductivity, MCPCB has the best optimal performance to cost ratio (Tsai et al., 2011, Huaiyu et al., 2011).

Table 2.4 Coefficient of thermal expansion and thermal conductivity of several materials and substrates (Lafont et al., 2012).

	CTE (ppm K^{-1})	Thermal conductivity ($W\,m^{-1}\,K^{-1}$)
Materials		
Si	4	150
SiC	4	120
GaAs	6.5	54
GaN	6	130
Al_2O_3	6.7	20
AlN	3.5–5.7	170–230
Al	23	150–230
Cu	16.5	398
AlSiC	8.4	200
Substrates		
PCB (FR4)	13–17	0.36
MC-PCB	4.8–8	24–170
Ceramic (Al_2O_3/AlN)	3.5–6.7	20–230
Cu–Mo–Cu	7	184
SiC/Al	8.75–11.5	170–220
Carbon fiber/Al	3.2–11	218–800
Carbon fiber/Cu	4.2–6.8	300–800
Graphite flake/Al	6–7	400–420
Diamond/Al	3.4	400–600
Diamond/Cu	5.8	600–1200
CVD diamond	1–2	1100–1800

Yu et al. (2005) investigated the thermal behavior of MCPCB in application for high power LED. They simulated a 38 x 15 mm MCPCB with 1 mm^2 power area of LED using ANSYS simulation tool. The convective and radiation boundary condition on the top and side walls of the board were neglected. Their results showed that the thermal resistance for a 35 µm of copper, 127 µm of dielectric layer and 1.5 mm aluminium MCPCB was 2.75 K/W. MCPCB will absorb the heat released by LED due to the low thermal resistance and dissipate it to the ambient.

Nicolics et al. (2010) compared the thermal performance of three different types of PCB demonstrator boards assembled with three different types of high-power LEDs. The investigation of the thermal performance of the respective combination was done experimentally using thermocouple and thermal image camera. They found that conventional glass fiber epoxy based PCB technology with advanced thermal design (improved heat-spreading capability by thermal pads and thermal vias) could satisfy the thermal management of a power loss range of a few Watts. Higher rates of power loss need the superior thermal performance of the insulated metal substrate (IMS) to fulfil cooler or heat spreader function.

Yin et al. (2010) used the finite element method (FEM) and the electrical test method to evaluate the thermal performance of multi-chip LED modules with three different heat slugs (Al, AlN and Al_2O_3). The simulation and experimental results showed that the AlN heat slug exhibits better thermal performances compared to the two others because the AlN substrate has better heat conductivity without a dielectric layer. Moreover, LED module with AlN-based substrate showed the best optical performances.

Long et al. (2011) proposed a simple and efficient packaging technique with aluminium-core printed circuit board component embedded copper reflectors for fabricating high power LED arrays. The optical and thermal performance of 3 x 3 LED array were investigated by a thermal-electrical analysis based on finite element COMSOL 3.4 code modelling, and thermal imaging infrared cameras. The results demonstrate that the proposed structure have obtained a luminous efficiency of 126 lm/W and thermal resistance of 3.4 K/W. It is feasible to package multiple-chip white LED arrays for SSL with low cost, and high performance.

Sim et al. (2012) proposed low temperature co-fired ceramic-chip on board (LTCC-COB) package with improved thermal characteristics. In the proposed structure, LED devices are mounted directly on the metal substrate without insulation layer between the LED chip and metal base. This leads to a good thermal path from the LED chip to PCB. The experiment and simulation results showed that the proposed LED lamp structure has excellent thermal properties, compared with SMD type LED mounted on MCPCB package lamp. The thermal resistance between packing area and air for the proposed structure was 0.6 K/W lower than the SMD-MCPCB packing type.

2.4.3 LED array spacing and placement design

The continuous effort by researchers to enhance the luminous output and efficiency of LED resulted in the achievement of high power white LED with 106 lm/W at 350 mA with single packages producing luminous flux of 92 lm in 2006 (Narukawa et al., 2006). According to Narukawa et al. (2007), it is further increased to 134 lm/W at 350 mA producing 145 lm of luminous flux in the following year. However, light output for application in general illumination required hundreds and thousands of lumens. This requires a number of LEDs if not large arrays (Yung et al., 2011). LED array consist of multiple LEDs mounted on PCB. Thus, the placement of LEDs on PCB becomes crucial. Placing LEDs close to each other is always desirable in order to make a compact lighting system. As a result, the LED will be in other thermal zone which could elevate LED junction temperatures. The LED array can be made by locating level 1 packages next to each other or locating COB LEDs next to one another (Petroski, 2004).

Petroski (2004) studied the spacing issue in LED array. The investigation on 3 x 3 LED array was done using ANSYS. As shown in Table 2.4, the analyzed parameters were the LED spacing, the boundary temperature and dielectric layer thickness, copper layer thickness and solder layer thickness of the MCPCB. The upper bound of LED spacing represents the closest one can space some typical power packages (dies packaged with lead frames and plastic). The other spacing configurations were for COB type of packaging. He found that for a widely spaced LED array, boundary condition temperature was the primary driving force of the maximum LED temperature. However, the spacing term became dominant for the spacing of 2.825 mm and below. Thermal zone for 1 W LED was approximately 4-5 mm in diameter for a typical MCPCB. The dielectric, copper and solder layers of the MCPCB only gave secondary effects on the temperature gradients produced in the system.

Table 2.5 Parameters listing and ranges (Petroski, 2004).

Parameter	Units	Lower Bound	Upper Bound
LED Spacing	mm	1.7	6.2
Dielectric Thickness	mm	0.1016 (0.004in)	0.2032 (0.008in)
Copper Thickness	mm	0.01778 (1/2 oz)	0.07112 (2 oz)
Solder Thickness	mm	0.0762 (.003 in)	0.254 (.010 in)
Temperature BC	°C	20	40

Christensen et al. (2007), Christensen and Graham (2009) investigated the effect of LED chip gap on the overall heat dissipation of a light source consisting of 25 high power LEDs arranged in square array on an aluminium heat sink. The 5 x 5 square array of high power LEDs separation distance are 10 mm, 5 mm and 1 mm. Numerical heat flow models and thermal resistance network models were used to predict junction temperature values. The results showed that the tightly packed devices had a higher junction temperature when the devices were driven by the same power consumption.

Cheng et al. (2010) used general analytical solution for optimizing a uniform LED thermal distribution. Their temperature distribution analysis revealed that LED chip distribution strongly influenced the spreading thermal resistance.

Yung et al. (2011) proposed an algorithm for the thermal placement of LED arrays on PCB substrates in order to produce uniform illuminance. They discussed the effect of fundamental components to thermal management of a LED array using a practical model that involved a thermal simulation. In the experiments, the temperatures were measured by infrared camera and thermocouples. SOLIDWORKS FLOW SIMULATION was used for simulation analysis. The analysis parameters are shown in Figure 2.6. Their investigations were focused on how the temperature of the surface of LEDs changed in accordance with different placement methods. They found that the good heat dissipation in MCPCB leads to an improvement in optical performance. Triangular and arithmetic spacing placement methods gave a significant drop in the surface temperature of the LEDs. The overall heat dissipating capability of the LED array to the PCB was improved by optimizing the placement design.

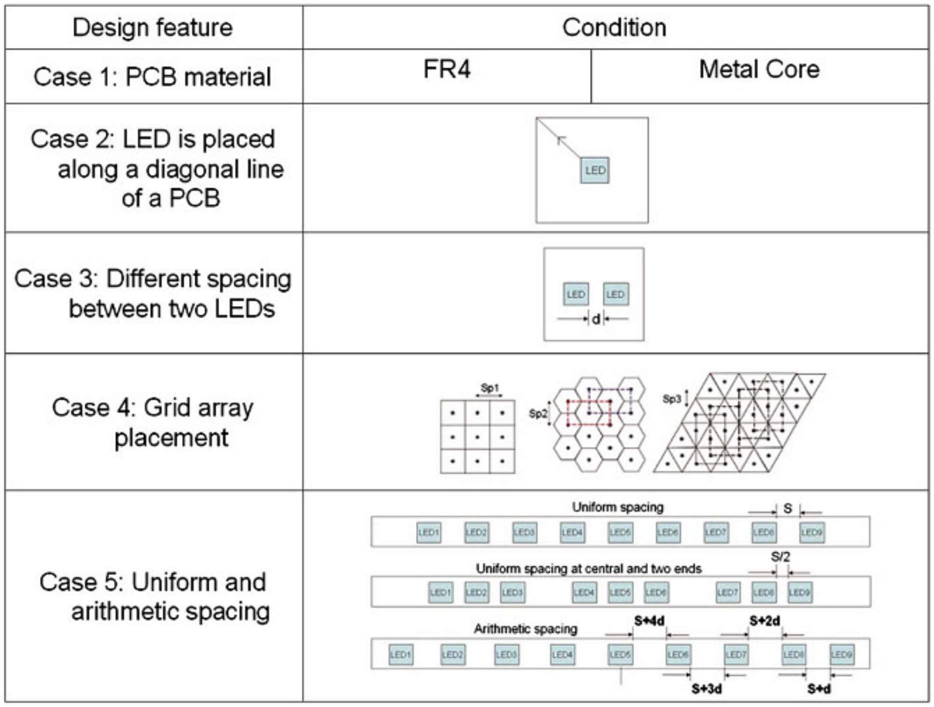

Figure 2.6 Study case for PCB (Yung et al., 2011).

Wu et al. (2012) investigated the effect of chip gap on heat dissipation efficiencies of high power multi-chip COB LEDs. Five different chip gaps ranging from 0.5 to 2.0 mm were considered and the results were compared by assessing their junction temperature and thermal resistance. Infrared thermal image camera was used to measure the junction temperature and simulation analysis was done using CFdesign version 10.0. Their investigation indicated that the structure with the smallest gap cannot dissipate heat generated by the LED chip to the air which results in high junction temperature. CFD software simulations showed that significant heat concentration occurs in the center of the structure and can be reduced by a larger chip gap. They also compared the effect of different material and thickness of heat slug. Copper heat slug has the lowest junction temperature and increasing the thickness of the heat sink can effectively reduce the LED chip junction temperature. Lumen measurement results indicate that luminous efficiency of high power LEDs is strongly affected by the heat generated in the LED chip.

2.4.4 Thermal solutions for high power LED lighting systems

An array of multiple LED packages with a board is the typical current structure of the LED module. In the application of numerous LEDs within a refined spaced, the amount of heat dissipated is limited and PCB alone cannot efficiently dissipate enough heat. In this case, the structure need to be mounted to an additional means of cooling for heat dissipation (Huaiyu et al., 2011).

With the advantages of a simple structure and low cost, passive thermal solution is the desired method of heat rejection in most systems (Arik et al., 2007). Passive cooling method has no moving parts and requires no energy input include the use of thermal vias, heat sinks, heat pipes, heat spreading mechanism, phase change materials and material with high thermal conductivity (Gleva, 2009). Currently, the most common passive cooling solutions are heat sinks and phase change recirculation systems (Huaiyu et al., 2011).

For high-performance LED lighting systems, the limited heat transfer ability of passive cooling may not be enough to maintain the LED junction temperature within acceptable limits. This leads to various types of active cooling solutions, although the disadvantages of active cooling must be countered. Active cooling method has excellent performance in dissipating heat away from devices. However, active cooling solutions need external energy, expensive and usually involve higher volume and noise than passive cooling methods (Gleva, 2009). These include forced convection, cold plates, liquid loops, thermosyphons, spray cooling, thermoelectric cooling and many others. Table 2.5 summarizes a variety of cooling solutions for high power LED module systems.

Table 2.6 Various cooling solutions for high power LED module systems.

Type	Author
Heat pipe	(Kim et al., 2007)
Loop heat pipe	(Lu et al., 2009)
Flat plate heat pipe	(Hsieh et al., 2011)
Vapor chamber	(Luo et al., 2010), (Wang et al., 2010), (Wang, 2011)
Porous micro heat sink	(Wan et al., 2011)
Phase change heat sink	(Xiang et al., 2011)
Thermosyphon heat sink	(Kai et al., 2011a)
Liquid metal cooling	(Deng and Liu, 2010)
Microchannel	(Zetao et al., 2005), (Yuan et al., 2006)
Microjet	(Sheng et al., 2006), (Xiaobing and Sheng, 2007), (Liu et al., 2008)
Piezoelectric fan	(Acikalin et al., 2004), (Ma et al., 2009), (Kai et al., 2011b)
Thermoelectric cooler	(Li et al., 2011)

As shown in Table 2.6, many researchers are interested in investigating liquid cooling as high power LED thermal solutions. Accordingly, as described in Table 2.7, the convective heat transfer coefficients for liquid are higher compared to air which makes it possible for greater heat dissipation (Veken, 2005). Consequently liquid cooling is much more efficient than air cooling and becomes even more efficient when fluid is forced to move through channels with very small dimensions (Tuckerman and Pease, 1981). Unfortunately liquid cooling also has some disadvantages such as the occurrence of dry-out phenomena, the risk of leakage, corrosion and an increase of weight in comparison with air cooled systems (Cheng et al., 2011). Therefore, air cooling has always been preferred above liquid cooling in real application of electronics. In fact, heat sink coupled with a fan is the most used cooling technique in current applications.

Table 2.7 Convective heat transfer coefficients of liquids and gases (Veken, 2005).

Cooling technique	h [W/m^2·K]
Natural convection	
Gases 2-25	2-25
Liquids 50-1000	50-1000
Forced convection	
Gases	25-250
Liquids	50-20000
Boiling and condensation	2500-100000

2.5 Heat sink application in high power LED lighting systems

Cheng et al. (2011) studied the heat dissipation in an enclosed channel with 10 high power LED array stage on MCPCB, a longitudinal multi-fin heat sink with different heat transfer coefficients. They explored fin geometry design and heat transfer coefficient in order to reduce the LED junction temperature on MCPCB applied to LED flat panel displays. A 3D FEM was used by utilizing ANSYS 11. Experiments were also conducted as comparison to simulation results. From the results, they concluded that the heat dissipation improvement is limited for a heat sink without forced convection. A fan at the side wall of the heat sink channel increased the convective heat transfer coefficient, resulting in low LED junction temperature which could prolong LED lifetime.

Shyu et al. (2011) experimentally investigated a LED backlight panel consisting of 270 1 W LEDs on 558 mm x 348 mm MCPCB and a plate-fin heat sink in an acrylic housing. They examined the overall thermal performance of a large

LED array in a confined space under natural convection and the effects of shroud clearance, obstructions at entrance, exit or above the heat sink. The results showed that the rise of shroud clearance from 0 mm to 5 mm slightly reduced the heat transfer coefficient but a notable increase in heat transfer coefficient was observed by further increasing the shroud clearance with its peak between 10 mm and 20 mm. The minimum local Nu is found near the exit of LED panel.

Kaikai et al. (2011) studied the structure optimizations of a heat sink for 196W high power LED street lamp. In order to get the optimized length, 1/7, 2/7 and 3/7 length diminution of the heat sink were studied by them. Simulation results showed that with 3/7 bulk and weight reduction, temperature of plate surface is increased by 16 °C. Cross sectional shape optimization of fin is also studied. The result showed that by replacing the fins of the heat sink to triangular shape, the bulk and weight of fins are reduced over 50% with only 0.42 °C rise in temperature. They successfully optimized the heat sink without affecting the cooling demand of high power LED street lamp.

Xiangjun et al. (2011) investigated the thermal characteristic of four chips high-power LED downlight with heat sink by FEM. The effects of the height of the heat sink were studied based on the consistency of the LED lamp by experimental and simulation results. They found that by increasing the height of the heat sink from 65 mm to 75 mm, the junction temperature decreases about 5 °C. However, the decline rate of temperature becomes slower with further increase in the height.

Fengze et al. (2011) investigated the thermal behavior of 3 x 3 LED array with the total power of 9 W mounted on MCPCB. Thermal analyses of the LED lighting system with plate fin, staggered and in-line pin fin heat sinks as cooling means were done using a 3D one-fourth finite element model. Three kinds of heat sinks were compared under the same conditions. The LED chip junction was found to be 48.978 ° C when the fins of heat sink are aligned alternately. Under the same condition, the heat sink with alternately aligned pin fin was found to produce lowest junction temperature with the best heat dissipation capability.

2.6 Concluding remarks

An extensive review on the effect of high junction temperature on the performance and reliability of high power LED and also the thermal management from package level to system level has been presented. Package level is the closest to the heat source. Thus, past research has focused on improving heat dissipation in package level. There are numerous studies on the thermal behavior of single package of high power LED in board level and also with external cooling means, while multiple packages of LED in array which has important practical applications has not been widely studied. Moreover, significant research on the thermal analysis of LED array with cooling solution is currently quite rare. Since LED array with multiple heat sources has increased the volumetric heat generation, researchers have introduced many active cooling solutions using liquid. However, so far, there have been very few applications of liquid cooling in thermal management practically using LED lighting system. Current application demands simpler cooling system satisfying the criteria such as cost effectiveness, power consumption, reliability, etc. As a matter of fact, heat sink is the best candidate.

It is clear from literature that although LED has a lot of advantages compare to conventional light sources, there is still a lot to do to overcome the thermal barrier that prevents extensive adoption and long-term success of LED technology for general illumination. Accordingly, the present research performs detailed