3. LED THERMAL

3.1. Introduction

An LED is an electronic device that lights up when electricity is passed through. They are used as indicators in many devices and increasingly used for other lighting purposes such as indoor and outdoor lightings. LEDs have much higher efficacy than other traditional light sources such as incandescent, and unlike fluorescents, efficacy of LED isn’t affected by its shape and size. However, LEDs like all electronic devices are temperature dependent. LED performance strongly depends on the ambient temperature. Operating LED-based luminaires at high ambient temperatures without proper thermal design may overheat LED packages, eventually lead to short lifespan or device failure in the worst case. Well-designed cooling system is required to maintain long lifetime and high efficacy of the luminaire (Figure 3.1.1). Therefore thermal management is the most critical part within LED-based luminaire design.

3.2. Heat transfer introduction

Heat transfer is a discipline of thermal engineering that concerns the exchange of thermal energy and heat between physical systems. It is classified into three main mechanisms (Figure 3.2.1):

- Conduction
- Convection
- Thermal Radiation
Conduction
When a temperature gradient exists in a body, there is an energy transfer from the higher temperature to the lower temperature region. Conduction is the most significant medium of heat transfer within solids or between solid objects in mechanical contact.

Convection
Convective heat transfer (or convection) is the heat transfer from one place to another by the movement of fluids. It is usually the dominant form of heat transfer in liquids and gases. Natural convection is a type of heat transport in which the fluid motion is not generated by external source such as pump, fan, suction device, etc. Forced convection is when the fluid is forced to flow over the surface by external means, such as stirrers, and pumps for creating an artificially induced convection current.

Thermal radiation
Thermal radiation is electromagnetic radiation emitted by a body as a result of its temperature and it propagates without the presence of matter. The characteristics of thermal radiation depend on various properties of the surface. If the radiating body and its surface are in thermodynamic equilibrium and the surface has perfect absorption at all wavelengths, it is characterized as a black body. Lighter colors such as white or metallic substances absorb less illuminating light, and thus heat up less. Shiny metal surfaces have low emissivity both in the visible wavelengths and in the far infrared. Such surfaces would reduce heat transfer by thermal radiation.

3.3. Power conversion
All light sources convert electric power into light and heat in various proportions. Incandescent bulbs emit mainly in infrared (IR) region with only approx. 8% of light emitted. Fluorescents emit higher portion of light (21%) but also emit IR, UV, and heat. LEDs generate little IR and convert up to 40% of the electrical power into the light (see Figure 3.3.1). The rest is converted to heat that must be conducted from the LED active area to the underlying printed circuit board, cooling system, housing, and atmosphere.

![Figure 3.3.1: Power conversion rates for "White" Light Sources.](image)

In case of LED light source, there is no heat removal by thermal radiation, thus dissipative heat has to be withdrawn only by conduction and convection. However LED has the best efficacy, thermal management of this light source is the most challenging and proper design of cooling system is crucial for LED-based luminaire.

Wall-Plug efficiency
To calculate more accurate thermal power (i.e. how much power is converted to heat within the lighting source) for better structure design, wall-plug efficiency (WPE) is required to count on. It is the ratio of the input electrical power and the emitted optical power (i.e. how much power converts to visible light) of the LED. The wall-plug efficiency of LED is typically between around 40%. It means about 60% of the input power which is dissipated as heat. In OMS, conservative 20% of WPE is assumed as emitted optical power.

If the input electrical power for all these light sources is 20W, the heat dissipated by conduction and convection for each light source is shown below:

Case 1: Incandescent light source
20W x (1-WPE) x 19% = 20W x 80% x 19% = 3.04 W

Case 2: Fluorescent light source
20W x (1-WPE) x 42% = 20W x 80% x 42% = 6.72 W

Case 3: LED light source
20W x (1-WPE) x 75% = 20W x 80% x 60% = 9.6 W

About 60% of power will convert to heat within LED die and it is mainly removed by conduction and convention. Without efficient thermal management and cooling system, this will overheat the LED and cause the change of LED characteristics. This change would directly affect both short-term and long-term LED performance. The short-term effects are color shift and reduced light output while the long-term effect is accelerated lumen depreciation and thus shortened useful life.
3.4. LED performance

The use of LEDs has been increasing dramatically over the last few years. At the beginning, heat dissipation from LED junction was not a problem because low-power LEDs were used. However, modern high-power LEDs dissipate much higher portion of heat which has to be removed from the junction in order to maintain high efficacy, reliability and lifetime of LED-based light source.

Basic parameters to evaluate LED performance are (Figure 3.4.1):

- Junction temperature – $T_j$
- Thermal resistance – $R_{j-a}$

**Thermal resistance**

Thermal resistance is the ratio between the temperature difference and the power. It shows how good the heat transfer between the materials/components is. The equation is defined below.

$$R = \frac{\Delta T}{P}$$

- $R$ – Thermal resistance between two points;
- $\Delta T$ – Temperature difference between two points;
- $P$ – Heat transfer rate between two points.

**Junction temperature**

When switching-on the LEDs, by-product of the emitted light production is heat. It is important to maintain junction temperature of LED at lowest possible value. The word “junction” refers to the p-n junction inside the semiconductor die. You can find the maximum recommended value for each LED product in the data sheet.

As junction temperature is the highest temperature within the LED, it represents figure-of-merit when predicting LED lifetime. From the thermal point of view, junction temperature is affected by many factors such as cooling system, environment, interface material, etc.

The equation for calculating junction temperature is expressed by:

$$T_j = R_{JC} \times P + T_c$$

Where $R_{JC}$ – thermal resistance from junction to case which is supplied by the manufacturer, the thermal power, $P$ – usually calculated by electrical power and WPE, and $T_c$ – the case temperature. If $T_j$ is higher than the maximum allowable junction temperature which is specified by the manufacturer, the luminaire has to be redesigned.

**LED performance degradation**

High junction temperature degrades LED performance, particularly useful life, color quality and lumen output. Beyond the maximum rated junction temperature, the LED will experience from 30% to 50% decreases in its useful life for every 10 °C increase.

Increase in junction temperature also creates a noticeable color shift toward the higher end of the spectrum. This is important with “white” light LED sources that typically use blue wavelengths coupled with a phosphor. With heat casing a shift towards red wavelengths, the interaction with the phosphors is altered, resulting in a different hue of white light.

The last major factor impacted by LED thermal management system is lumen output. Increases in electrical current generally product increases in lumen output. However, higher current also increases thermal buildup within the LED. Because of this, the current has to be adjusted in order to optimize system performance and useful life.
3.5. Thermal design of LED-based luminaire

From the thermal design point of view, typical LED-based luminaire consists of an LED light source, a printed circuit board (PCB) and a cooling system. The LED light source incorporates semiconductor die (active part), optics, casing, and heat slug which is used to withdraw the heat away from the die. Heat slug is soldered to the PCB (mostly metal core PCB – MCPCB). Prediction of the thermal performance of LED light source within the lighting fixture is becoming a necessity while reducing time of products under development to market. However, with increasing installed lumen package, heat dissipation from LEDs starts to be a challenge. Therefore, the thermal design of luminaires is essential for proper design of LED-based luminaires. Thermal simulation based on finite element method is a widely used software tool in early design stages. Figure 3.5.1 shows simplified setup of typical LED luminaire being simulated with basic input/output parameters.

Thermal modeling

Three things affect the junction temperature of LED. They are: drive current, thermal path, and ambient temperature. In general, the higher the drive current is the greater the heat is generated at the die. Heat must be moved away from the die in order to maintain expected light output, lifetime and color. The amount of heat that can be removed depends upon the ambient temperature and the design of the thermal path from the die to the surroundings.

Model description

A 3D model of the LED luminaire is shown in Figure 3.5.2. In this model, different materials of housing are in use to find out which one is the best for the heat dissipation. There is no heat sink in use and the housing will act as a heat sink to transfer the heat from LED to the ambient. In this case, the material and the shape of the housing would be critical.

Boundary conditions

For Computational fluid dynamics (CFD) analysis, the following properties are assumed:

- 32W of electrical power
- Steady state.
- Ambient temperature 35°C.
- Heat is dissipated through natural convection and conduction.
- Radiation effect is set to 0.8 for all parts.
- The orientation of luminaire is in horizontal position (the worst position).
- Computational domain is (800 x 800 x 800) mm³
**Material properties**

Figure 3.5.3 shows the various properties of material used for the thermal simulation.

<table>
<thead>
<tr>
<th>No.</th>
<th>Component</th>
<th>Material</th>
<th>Thermal conductivity (W/m.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Chip</td>
<td>Gallium Nitride GaN</td>
<td>230</td>
</tr>
<tr>
<td>2</td>
<td>Dielectric layer</td>
<td>Alumina 96%</td>
<td>24.7</td>
</tr>
<tr>
<td>3</td>
<td>Circuit</td>
<td>Copper</td>
<td>400</td>
</tr>
<tr>
<td>4</td>
<td>Solder</td>
<td>Solder point: Solder (Sn96.5%/Ag 3.5%)</td>
<td>78.4</td>
</tr>
<tr>
<td>5</td>
<td>Reflector</td>
<td>PMMA</td>
<td>0.3</td>
</tr>
<tr>
<td>6</td>
<td>Case 1: Housing</td>
<td>ADC 12</td>
<td>92</td>
</tr>
<tr>
<td>7</td>
<td>Case 2: Housing</td>
<td>Al 6082</td>
<td>167</td>
</tr>
<tr>
<td>8</td>
<td>Diffuser</td>
<td>PMMA</td>
<td>0.3</td>
</tr>
<tr>
<td>9</td>
<td>Others</td>
<td>Aluminum 6061</td>
<td>150</td>
</tr>
</tbody>
</table>

**Results**

There are two different materials for the housing, ADC 12 and Al 6082. ADC 12 material is good for die casting and Al 6082 is used for machining. From the numerical study, the model with Al 6082 is about 6% better than the one using ADC 12. The maximum allowable case temperature of the LED chip is 78°C. Both cases pass the requirement. However, Case 1 is close to the border. The best choice will be use of Al 6082 for this luminaire. Figure 3.5.4 shows simulation results.

**3.6. Cooling system**

Excess heat affects directly short-term and long-term LED light source performance.

- Short-term: color shift and light output reduction
- Long-term: accelerated lumen depreciation and shortened lifetime

Natural (passive) and forced (active) cooling systems are commonly used for heat dissipation (Figure 3.6.1).

**Passive cooling**

The term “passive” implies that energy-consuming mechanical components like pumps, jets, and fans are not used. Heat sinks are the most commonly used for LED luminaires. Generally, heat sink has finned metal encasements that conduct accumulated heat away from the LED light source. Since heat sink does not consume any additional energy, it is the most energy-efficient cooling system. However, LED light source with high power consumption requires large cooling area, i.e. complexly shaped heat sink, which adversely influences luminaire design.

**Active cooling**

The term “active” implies that cooling system contains energy consuming mechanical components like pumps, jets, and fans. Active cooling system is necessary for high lumen packages within small luminaires since it makes smaller structural shapes possible.
3.7. Thermal design of passive cooling

Passive cooling is the most preferable cooling system for LED luminaires. During such a thermal design it is necessary to take into account several factors such as spacing of LED light sources, material properties of materials used for luminaire construction, shape and surface finish of heat sink being designed, and several others which are described in following text.

LED spacing

Majority of the electrical power in the LED is dissipated as heat. Tighter LED spacing provides a less area for heat dissipation, resulting to higher junction temperatures. The LEDs should be spaced as far apart as packaging and optical constraints will allow (Figure 3.7.1).

Material properties

Thermal conductivity is the property of a material which relates the ability to transfer heat by conduction. Some materials better heat conductors than others and thermal conductivity is used to measure the effectiveness of thermal conduction (Figure 3.7.2). For example, pure copper has a thermal conductivity of about 400W/m.K while air is of about 0.025W/m.K.

Aluminum is a common material for heat sinks. Besides it is a cost-effective material, Aluminum can be easily staped by using machining, casting, and extrusion processes. Another critical characteristic of heat sink is geometry and the ease of converting aluminum into a shape conducive to thermal design needs adds to its suitability. Other factors that come into play such as weight, corrosion-resistance, dimensional stability, etc. make Aluminum an excellent choice for heat sink material.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity (W/m·K)</th>
<th>Material</th>
<th>Thermal conductivity (W/m·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.025</td>
<td>Concrete, stone</td>
<td>1.7</td>
</tr>
<tr>
<td>Wood</td>
<td>0.04 - 0.4</td>
<td>Stainless steel</td>
<td>12.11 – 45.0</td>
</tr>
<tr>
<td>Thermal grease</td>
<td>0.7 - 3</td>
<td>Aluminum</td>
<td>237</td>
</tr>
<tr>
<td>Glass</td>
<td>1.1</td>
<td>Copper</td>
<td>401</td>
</tr>
</tbody>
</table>

Shape

Convection is the fluid process whether in air or liquid, in which heat-energy is transferred from the surface to the ambient. The greater the surface area is, the more convection occurs. One of the examples is heat sink. Aim of the geometry design is to maximize convection surface area. The fins effectively increase surface area while remaining confined to a given footprint (Figure 3.7.3).

Surface finish

The emissivity of a material (usually written $\varepsilon$ or $e$) is the relative ability of its surface to emit energy by radiation. It is the ratio of energy radiated by a particular material and energy radiated by a black body at the same temperature. An ideal black body radiator has $\varepsilon = 1$ while any real object would have $\varepsilon < 1$. 
High-emissive coatings are used to increase heat-transfer rate to surroundings. In general, the duller and blacker a material is, the closer its emissivity is to 1. The more reflective a material is, its emissivity is closer to 0.

**Printed circuit board**

The LEDs are mounted on multi-layer FR4 or on metal core printed circuit board (MCPCB). To ensure optimal operation, the thermal resistance of PCB should be kept as low as possible.

**FR4-based PCB**

FR4 is standard material for PCBs. Number of LEDs per each PCB depends on the LED input power, boundary conditions, etc. Thermal vias are the method to transfer the heat from the PCB to the cooling system. These thermal vias are plated through holes (PTH) that can be open, plugged, filled or filled and capped. The final thermal resistance is determined by the number and the density of thermal vias, the copper plating thickness and PTH plating thickness.

**MCPCB**

Figure 3.7.4 shows structure of MCPCB. A MCPCB consists of Copper layer, dielectric layer and heat spreader, Aluminum or Copper plate. Increasing the copper thickness and using a thinner dielectric with higher thermal conductivity would lower the thermal resistance dramatically. Figure 3.7.5 exemplifies actual FR4- and metal core-based PCBs.

**Roughness**

Attaching a heat sink to a semiconductor package requires that two solid surfaces be brought together into contact. Unfortunately, no matter how well-prepared, solid surfaces are never really flat or smooth enough to permit intimate contact. All surfaces have a certain roughness due to microscopic hills and valleys. Superimposed on this surface roughness is a macroscopic non-planarity in the form of a concave, convex or twisted shape. As two such surfaces are brought into the contact, only the hills of the surfaces come into physical contact. The valleys are separated and form air-filled gaps.

**Thermal interface material**

Thermal interfacial materials (TIMs) are thermally conductive materials, which are applied to increase thermal conductance across joined solid surfaces, such as between the PCB and heat sink in order to increase thermal transfer efficiency. The gaps between surfaces which are in mechanical contact are filled with the air which is a very poor conductor (see Figure 3.7.6).
The most common is the white-colored paste or thermal grease, typically silicone oil filled with aluminum oxide, zinc oxide, or boron nitride. Some brands of thermal interfaces use micronized or pulverized silver. Another type of TIM is the phase-change materials. These are solid at room temperature but liquefy and behave like grease at operating temperatures.

**Manufacturing methods**

The most common technique to take advantage of natural convection is to put holes in the top and bottom side of the housing to allow for vertical air flow over the LED. Comparing an Aluminum die casting to an aluminum extrusion, the extrusion process inherently creates a product with greater density (less air voids inside the heat sink) than the die casting process (Figure 3.7.7). Assuming insulating properties of air and the conductive properties of aluminum, even the small amounts of the air in the Aluminum die cast renders a significant reduction in thermal conductivity. Die-casted heatsinks are 20-30% less thermally conductive than extruded ones of the same shape and size.

**Housing design and mounting method**

LED housings should be designed to provide a conductive path from the backside of PCB to the housing. This is typically accomplished by mounting the backside of the PCB directly to the LED housing such that they are contacting one another across the entire rear surface of the PCB (Figure 3.7.8).

This mounting scheme can be improved by applying a thermal conductive pad between the PCB and the housing. Thermally conductive pad conforms to the features on the backside of the PCB and provides a larger contact area for conduction.

Also, the most common technique to take advantage of natural convection is to put holes in the top and bottom side of the housing to allow for vertical air flow over the LED light source (Figure 3.7.8).