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Design and Experimental Investigation of Thermal Performance of Different Heat Sink for High Power Led Lights

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Abstract- LEDs have been used in many products due to their longevity, more power saving, and higher lumens per watt. About 80% of the electrical power is wasted as heat or reductant heat, which increases the junction temperature of the LED's. This increase in the temperature in the LED'S decreases the longevity and color of LED'S. Proper thermal management is required to remove this heat effectively. The heat sink design and usage of proper thermal interface materials for increasing the heat removal is required. In this paper, temperature increase in a LED fixture during a time interval with and without thermal interface material is measured and tabulated to find the effectiveness of the thermal interface material in removing more heat is studied. In addition, a simulation using Solidworks thermal simulation is done to validate the analytical thermal-time study results. The entire study provides a guideline for the design of LED high bays in the future and demonstrates the importance of the thermal interface materials in the design studied.

Keywords- High power LED; thermal detection; heat sink; active and passive cooling; thermal resistance.

I. INTRODUCTION

Heavy construction machinery like excavators, haulers, loaders, bulldozers, harvesters, mining machinery etc. needs to be equipped with artificial light sources to make the work efficient and productive.

Most of today's work lights are often based on older technologies like halogen and xenon gas lamps. These traditional lamps draw a lot of current; produce a large amount of heat and break easily compared to LED lights. Re-placement of the lamps costs money in terms of parts, working time and downtime. LED technology offers enormous benefits for construction field applications. The long life, durability, and high efficiency of LED lights provide significant savings in service costs and power consumption. There are many LED work lights on the market nowadays; however, most of them are awkwardly bulky, low in quality and heavy.

Other issues are cold light colour temperatures, insufficient light, bad beam angle choices, bad water and dust protection. If an LED work light is supposed to last long, its cooling, among other things, needs to function properly in all possible conditions. The temperature of LED is carried out using analytical calculations where we find the junction temperature of LEDs, which helps us find the life of LED to a certain approximation. A general thermal resistance network is generally the common analytical technique used to predict the junction temperature considering a constant ambient temperature.

Manufacturers of high-power LED's have been exploring and using components with high thermal conductivity within the LED package to lower the thermal resistance from the p-n junction to the LED board so that the intersection will be at a lower temperature during operation.

In addition to long life, LED’s do not utilize filaments or gases to generate light. This enables the LED light fixture to have superior vibration resistance and lifetime compared with HID fixtures. This provides an industrial plant or mill site with a safer operating environment with more consistent light output, longer life, and reduced machinery downtime.

The optimization of the junction to ambient thermal resistance is very vital in designing a high bay fixture. This study will enumerate the architecture of the high bay led fixture with its thermal distribution and analytical study thermal components in various test modes to find the effectiveness of the thermal products for their temperature variance towards time.

Light-emitting diodes (LEDs) are semiconductor devices that generate light via electro- luminescence when an electric current passes across the junction of the semiconductor chip. Most semiconductors are made of a poor conductor material with impurities (atoms of another material) added to it. The process of adding impurities is called doping.

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LEDs are p-n junction devices constructed of gallium phosphate (GaP), gallium arsenide (GaAs) or gallium arsenide phosphate (GaAsP). For example, in pure GaAs, all of the atoms bond perfectly, leaving no free electrons to conduct electric current. Additional particles change the balance in doped material, either adding free electrons or creating holes for electrons to move. These alterations make the material more conductive.

A semiconductor with free electrons, which significantly increase the material's conductivity, is called N-type material. In N-type material, free electrons move from a negatively charged area to a positively charged area. A semiconductor that has deficiencies of valence electrons (holes) acting as a positive charge carrier is called P-type material; it has extra positively charged particles. Electrons can jump from hole to hole, moving from a negatively charged area to a positively charged area. As a result, the holes themselves appear to move from a positively charged area to a negatively charged area.

LEDs are the combination of p-type material, and -type material. When p- and n- type materials are placed in contact with each other, the electrons and holes combine at the junction so that a continuous current can be maintained, current flows in one direction (forward-biased), but not in the other, creating a basic diode. At the junction region the electrons diffuse across to combine with holes, creating a depletion zone.

When electrons cross the junction from n-type to p-type material, the electron-hole recombination process produce some photons in the infrared or visible light spectrum, this process is called electroluminescence, thus the semi-conductor surface emits light. This implies that the electron-hole pair drops into a more stable bound state, releasing energy by photon emission. The wavelength of the light emitted depends on the materials forming the P-N junction.

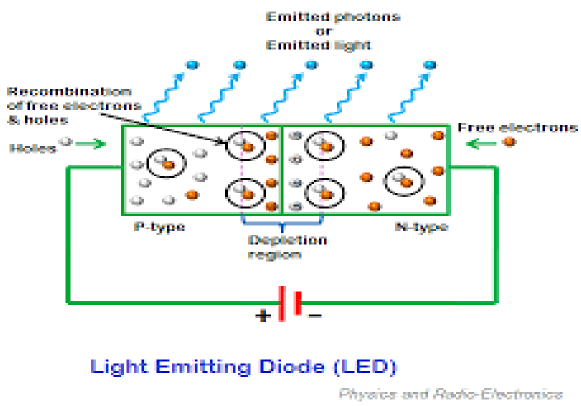

Fig 1. Light Emitting Diode(LED).

II. CONSTRUCTION OF HIGH POWER LED (HPLED)

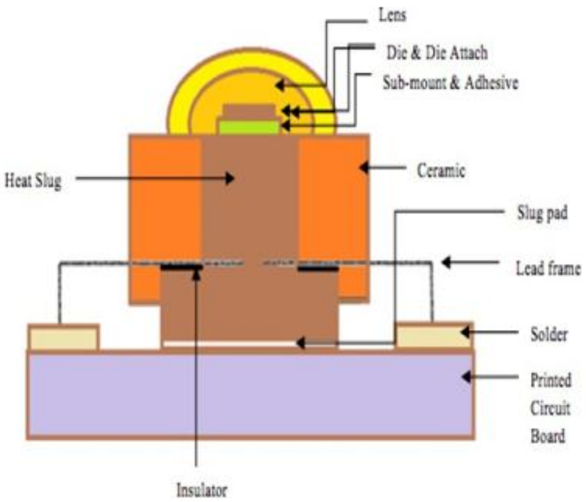

Fig 2. High Power (LED).

The construction of High Power LED is shown in Figure 3. The top surface of the submount in the LED chip die (also known as pn junction) with the support of die-attach is bonded. The die material varies for different illumination colors as given in Table 2. The sub-mount is bonded to a heat slug with the help of a sub-mount adhesive. The die and submount are protected by encapsulation and lens, which helps for better refraction.

The die and sub-mount and the encapsulation and lens are attached to the top of the ceramic package. The lead frames and heat slug are attached to the MCPCB (Metal core printed circuit board) through thermal slug pad and solder pads. The MCPCB is made up of FR- 4 (Fire retardant) material which acts as an insulator at top and bottom (base) and it is made of aluminum [61]. The insulator on both sides is used to avoid direct contact between the lead frames and the heat slug. The very thin and small size gold conductive wire is used to connect the lead frame and die.

In a LED, electrical energy is converted into light energy. Approximately 25 to 30% of the total energy supplied is used to illuminate, and about 75 to 80% of energy is dissipated as heat. The die is the major part of LED which is responsible for generating heat due to the supply of power. Dissipation of this heat plays a vital role for improving the life and efficiency and the LED. Even though heat slug helps to reduce heat on the package, it may not be sufficient to dissipate the heat generated.

The LED may require additional thermal management systems like an external forced cooling mechanism to dissipate heat to the atmosphere. The dimensions and material properties of typical LED components is shown in Table 2.

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Table 1. The dimensions and material properties of typical LED components.

Part	Material	Dimensions(mm)
Encapsulation	Silicone [62]	Diameter: 2
Lens	Polycarbonate[63]	Diameter: 3.5
Insulator	Thermal Interface material (TIM) [2]	Outer Diameter: 6 Inner Diameter : 2 Thickness : 2
MCPCB (top)	FR-4[64]	40x40x0.2
Ceramic Package	Ceramic5 [65]	9x9x3.2
Thermal slug [70]	Epoxy thermal conductive adhesive [66]	Diameter : 6 Thickness : 0.3
Die attach	Silver Epoxy [67]	1x1x0.2
Die	Gallium Nitride[68]	1x1x0.2
Solder	Lead Free SnAgCu	1.5x2.13
Submount Adhesive	Silver Epoxy [67]	1.5x1.5x0.05
Lead frames	Steel	1x0.15
Submount	Silicon	1.5x1.5x0.2
MCPCB (bottom)	Al6061 alloy[69]	40x40x1.3
Heat slug	Aluminium	Outer Diameter: 6 Thickness : 2.1 Inner Diameter: 3 Thickness: 1.33

III. THERMAL MANAGEMENT OF LEDS

1. Importance of proper thermal management:

High power LED generally refers to the LED module for which the single-chip size is not less than 1mmx1mm and the drive current is at least 350 mA.

Despite being one of the most efficient ways to generate light, LED photoelectric conversion efficiency is still relatively low, and much of the power running through the LED is output as heat. The efficiency of LEDs varies significantly from one manufacturer to another. For example, Cree® XLamp® XM-L LEDs expel nearly 80 % of the input electrical energy into heat, this means that 80 % of the power going to the LEDs the system must dissipate through conduction, convection and radiation.

The reliability and lifetime of any LED device is affected by the LED junction temperature. Improper thermal management resulting in exceeding the maximum operating temperature specification, typically a 150 °C junction temperature, causes failure or damage to the LEDs over time. Consequently, LED system designers must consider the heat dissipation challenges and their effects on LED performance, lifespan, and product reliability.

The performance characteristics of LEDs are presented in detailed product datasheets. Typically LED manufacturers to specify the operating conditions which shall be taken in account while designing a product. Light output, color, voltage and lifespan are those performance characteristics that are directly dependable on junction temperature.

High junction temperatures cause recoverable light output reduction, the relationship between the luminous flux and the junction temperature can be found in the LED datasheet. As the junction temperature increases, the light output of the LED decreases but recovers when the LED cools down. This can be observed in Figure 6 below. When approaching or exceeding maximum junction temperatures, the LED might fail to recover.

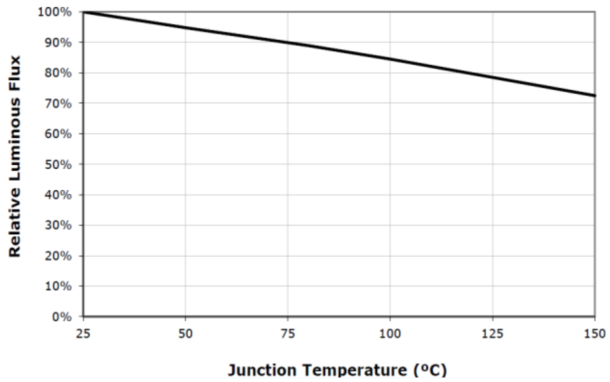

Fig 3. Relative Flux vs. Junction Temperature.

2. Thermal Resistance Model:

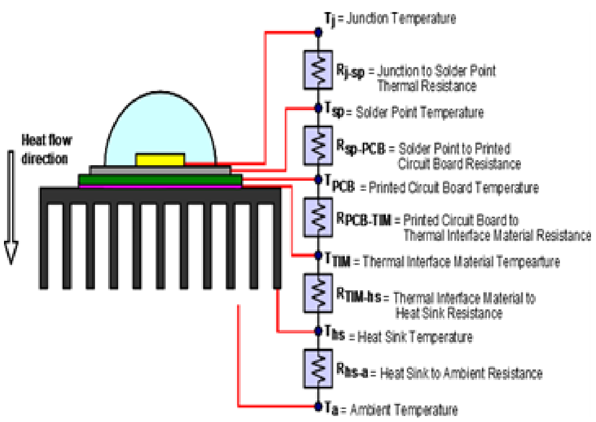

Fig 4. Thermal Resistance Model.

Thermal resistance is defined as the rate of temperature increase for the supplied power and is also known to dissipate heat.

Knowledge of the thermal resistance (Rth) of a LED helps to:

- Estimate the LED's junction temperature under operating conditions
- Calculate the highest allowable ambient temperature for a given power dissipation
- Determine the thermal management model and design appropriate heat sink

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A temperature difference is the driving force of the heat transfer. The thermal path of a LED system can be illustrated by a simple resistor network similar to an electrical circuit. Thermal resistances are represented by the resistors, the electrical current approximates the heat flow, and the corresponding temperatures within the system correspond to the electrical voltages.

In the Figure 7 above the heat path is illustrated; heat is conducted from the LED junctions through the LED components to the PCB, through the network of different resistances to the heat sink and then convected and radiated to the ambient air.

IV. HEAT SINKS: VARIOUS COOLING OPTIONS

The main aim of a heat sink is to provide a path for heat to be removed from the LED system. The heat in the sink must be continuously dissipated to achieve good air flow. If the heat remains trapped in the sink, the temperature will rise and LED chips will be overheated.

1. Heat Dissipation Options:
According to the way the heat is dissipated to the environment, the cooling systems can be divided into passive and active.

1.1 Passive Heat Dissipation:
A plate-fin heat sink is the most commonly used solution for LED cooling. A plate-fin heat sink has many advantages, such as low cost, simple structure, and high reliability. However, since based on natural convection, it has a relatively low cooling-to-volume ratio.

Newton's Law of Cooling (Equation 2.1) shows the relationship of coefficient h and heat exchange area A, they are the key factors affecting the heat transfer intensity of natural convection.

Heat transfer coefficient h can be improved by enlarging the area A of the heat sink. Material, number of fins, fin thickness, space between the fins, the fin height and heat sink base thickness, are critical factors directly affecting the performance of a heat sink and a LED product. Another solution for enhanced / slight cooling is heat pipes. Heat pipes do not dissipate heat; they move it to another location more efficiently than any ordinary material.

1.2 Active Heat Dissipation:
Free convection from the plate fin heat sink is limited and often insufficient to dissipate heat from high-power LED light sources. When the thermal load of a LED system is too high to be properly dissipated by passive means, active cooling is applied. There are many types of actively cooled systems; however, the reliability, noise, cost, added power consumption, and maintenance of these devices need to be compared against the benefits of an actively cooled system. Very few active cooling devices can equal the long lifetimes of LEDs, many thousands to hundreds of thousands of hours, thus making active cooling a weak link in a LED system.

Forced air convection is driven by artificial air force or power, such a pump, which ac- accelerates the rate of airflow, thus increasing the heat transfer coefficient h. Comparative- ly to natural convection, the heat exchange rate is significantly improved with forced convection. However, the reliability of the LED device might be reduced because of many moving parts such as fans or pumps, and extra noise is often an issue.

2. Heat Sink Design Considerations:
2.1 Heat Sink Type:
There are many varieties of heat sinks but generally, five main types are common in terms of manufacturing methods and their final shape: extruded, stamped, bonded fin, casted/metal injected and folded fin. The material most commonly used for heat sink construction is aluminum, although copper is also used.

Extruded heat sinks are by far the most common types, capable of dissipating large amounts of heat loads. Relatively simple manufacturing makes them a cheap and thus very attractive cooling solution (Figure). After being extruded, they may be cut, milled, machined etc. However, there are specific extrusion limits, such as the fin height-to-gap ratio and fin thickness, which usually prevent the flexibility in design options.

Fig 5.Typical extruded heat sink

Stamped heat sinks are manufactured from copper or aluminum sheets stamped and folded into desired shapes and mainly designed for low power thermal problems in cooling electronic components (Figure 12). They offer a low cost solution due to their simplicity and suitability for high volume production.

Fig 6. Typical stamped heat sink.

Most of natural convection heat sinks have limited heat transfer possibilities, the overall thermal performance of an air-cooled heat sink can often be improved significantly by enlarging surface area exposed to the air stream. Bonded fin heat sinks (Figure 13) use thermally conductive aluminum-filled epoxy to bond planar fins onto a grooved, ex- truded base plate. This process allows for a much greater fin height-to-gap aspect ratio to greatly increase the cooling capacity without increasing volume requirements.

Fig 7. Example of a bonded fin heat sink.

Casted metal injection molded heat sinks enables complex parts to be formed as easily as simple geometries, allowing a certain product design freedom (Figure 14). This technology is used in high density pin fin heat sinks which provide maximum per- formance when using forced air cooling. Metal injection molding can meet the tolerance requirements for heat sinks without the need for additional machining.

The disadvantages are: high cost of equipment investment, the molded/casted material thermal conductivity, and structural integrity are usually poorer than other heat sink manufacturing methods.

Fig 8. Example of high-pressure casted heat sink

In case of folded fins heat sink design, fins are pre-folded and then brazed or soldered to a plate base, thus surface area increases and, hence the volumetric performance (Figure 15). It is not suitable for high profile heat sinks, but it allows high performance heat sinks to be fabricated for specific applications.

Fig 9. Example of a folded fins heat sink

V. CONCLUSION

The entire study provides the results after numerical simulation and analytical approach using thermocouples, showing the maximum temperature in both cases. The study also provides the necessity of the thermal interface components in the architecture of the LED high bays which is evident from the results obtained at the test.

The study predicts that increasing usage of the thermal interface products outside the heat sink also is a valuable solution as we can reduce the area of the convection which in turn may reduce the weight of the total unit and ensuring longevity to LED's due to lower junction temperatures.

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