Thermal management and design optimization for a high power LED work light

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Abstract:

This thesis work deals with the optimization project of the heat sink and explains in details the design path of the thermal aspect of a long-life, high quality LED work light, as well as some general fundamentals of product design and manufacturing to consider. Although the path from an idea to the finished product is described mainly from the thermal aspect; the entire process of electronics development and casing mechanical design is not included in this thesis work.

The study was done for Five Watts Oy, a company based in Finland designing, developing and manufacturing LED work light solutions for heavy duty equipment. The first prototypes of LED work light were made without proper cooling simulations and thus did not provide sufficient cooling of the LEDs; in a space with no external airflow the prototypes always reached overheat protection temperatures. A proper Computational Fluid Dynamics simulation was made to optimize the most crucial part of the cooling fins, the spacing. The results of the simulation were integrated into overall work light design; nowadays the product is on the market and functioning successfully.

Keywords:	LED, heat sink, COMSOL, work light, product design, heat resistance model, heat transfer, LED junction temperature
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CONTENTS

FIGURES

TABLES

1 INTRODUCTION

1.1 Project Background

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 large amount of heat and break easily compared to LED lights. Replacement 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 is a big variety of LED work lights on the market nowadays; however, most of them are awkwardly bulky, low in quality and heavy. Other issues are cold light color temperatures, insufficient light, insufficient beam angle choices, bad water and dust protection.

The proposed thesis topic aims to be written for Five Watts Oy, Finnish designer and manufacturer of durable work lights. Company's first product, designed for demanding use, the rugged floodlight Zaurac 4-30, was released in the second quarter of 2013 after extensive development, rigorous prototyping and testing.

The project of optimizing the cooling system of a LED work light was started when the development of the first version of regulating electronics of the light was nearing completion. It was already known that the LEDs need cooling, but the extent of the cooling requirements were unknown. A few prototypes were made, that worked well in a well-ventilated environment, but not in still air.

If an LED work light is supposed to last long, its cooling, among other things, needs to function properly in all possible conditions.

1.2 Research objectives

The main objective with this research project is to produce a functional and durable cooling profile by understanding how the LED chip’s maximum junction temperature is influenced by the geometry of cooling fins.

The aim of this thesis study is to simulate a case of passive cooling where also the viscosity of air is taken into account; The amount of energy that needs to be dissipated is known, and thus the aim of research is to find out at what temperature the armature will saturate at given ambient temperature. In other words the results of FEM analysis would give dimensions of cooling fins and spacing between them in mm. These findings have to be integrated into overall look of a lamp as a ready product.

The cooling profile is supposed to be used as such by Five Watts OY, and/or be the basis of further cooling systems for LED lighting and other devices that need cooling.

2 KEY FACTORS IN LONG-LIFE LED SYSTEM DESIGN

Many factors are crucial for the longevity of a product, and any of those, mentioned below points, if not done correctly might cause premature light device failure. There is a large number of different LED based lighting systems available on the market nowadays. As the number of manufacturers offering LED lights continues to grow, it appears that many are not taking full benefit of the potentially very long lifetime of the LEDs. The following details cited below just give an overview of basic ideas that are good to consider in a LED product development process.

2.1 Efficient thermal management

Without a good sink design junction temperature of a LED rises causing its performance characteristics to change. This will be discussed later in details, but in short, the temperature the heat sink is allowed to reach greatly affects the lifespan of the product.

Very often the cooling fins of a heat sink are too short or positioned too closely together to produce an effective convection to remove the heat from the lamp's enclosure. This in turn will keep the LEDs running at close to, or even over, their maximum junction temperatures, rapidly degrading the quality of the LED chip, resulting in reduced output and light discoloration. Very small gaps between the cooling fins are also easily filled with dirt, making the cooling even less efficient.

2.2 LED current regulation electronics design

LEDs are very sensitive to overheating, overvoltage, reverse voltage, overcurrent and static electricity, and thus, should be well protected from all of the above, for the whole life expectancy stated in LED data sheet (50 000 + hours). The electronics need to be carefully designed, keeping in mind the estimated lifetimes of each component in the conditions where it will be used. The electronics design should also take into account numerous problems, such as long drive cycles in high temperatures, vibrations, thermal shocks, input voltage spikes, reverse connections, static discharges etc. For example, many switching power supplies, commonly used as current regulators for LEDs due to high efficiency, have heavy components such as inductors and capacitors that cannot withstand vibrations very well.

In some cases LED lights are equipped with electronics that do not match the LEDs long life, as an example many cheaper electrolytic capacitors, often used in switching regulators such as computer power supplies and LED drivers, are rated to last 2000 - 8000 hours in normal operating conditions. Typical example of a cheap low ESR electrolytic capacitor (most common in switching power systems); the data sheet promises to maintain ± 20% of its original capacitance after 2 000 hours of use, and due to the composition of the electrolytic capacitor, the characteristics will degrade rapidly when they start. [1]

Compared to 50 000 – 150 000 hours of the LEDs themselves, it is obvious that the LEDs are not the weak link. There are also other possibilities of failure, such as badly optimized switching transitions which can destroy transistors and capacitors much faster than intended.

2.3 Enclosure design, casing ingress protection

The electronics involved in LED lights often have components or signal conduits that are sensitive to moisture and other electrically conductive substances and particles. Great care should be taken for a long-life product to stay appropriately well isolated from its environment. The casing must also be resistant to impacts, shocks, vibrations, temperature changes and other events that might occur within such a long life span. Moisture also should not enter the casing through the electrical power input, or any other way.

There are many LED work lights, in which a cable is pulled directly into the casing from outside. This design, although simpler and sometimes cheaper, is a direct way for moisture to enter the casing, especially in outdoor conditions. If there is any way for water or moist air to enter the cable itself, such as the connector or a crack in the cable sleeve, capillary forces combined with the thermal expansion and shrinkage of the air inside the casing, is very likely to pull in moisture which eventually causes the electronics to fail.

Also the choice of production method is usually based on price, which typically leads to pressure casted aluminum, iron or magnesium. However these methods have the common problem that most pressure casting alloys have restrictions to their surface treatment, especially when aesthetics design plays significant role for the product marketing. The lights are often desired to have a specific casing color, and this is mostly possible in pressure casting only by different methods of painting, which usually do not bond chemically with the material, and/or can allow corrosion from inside when damaged, meaning that if scratched, the oxidation will spread under the paint.

Another important design consideration for a LED system is the size and weight. Often LED work lights, constructed for heavy use, weigh up to 2.9 kg and can be up to 160 mm high, which causes vibration on the mounting point in dynamic applications, such as excavator parts which can very suddenly change speed or direction. [2]

2.4 Light color temperature and lumen output

LED chip will deteriorate whenever used, but the rate of it depends on the operating conditions. The closer to its maximum rated current the LED is run, the faster the light efficiency decreases which can even lead to the product failure. Cree, LED manufacturer, provides XM-L white LEDs test data where the diodes are tested in different ambient temperatures at the same drive current resulting in percentual decrease of average lumen maintenance at 6000 hours with the increase of temperature. [3] It is a matter of product price, expected lifetime and size, how many LEDs of what power are chosen to produce the desired light output.

A cooler white LED will, for the same amount of electrical energy, produce more radiant energy, simply due to the fact that the phosphor layer used to convert the blue light to white has a certain power loss in itself, and a thicker layer will have slightly lower efficiency than a thin one.

With this in mind, it seems logical to use as cool white LEDs as possible, since there is a higher light output to input energy ratio, and thus the same amount of power gives more lumens. However, the cooler the light, the less “warm” colors reflect back in the light beam, for example a red object is barely visible and looks brown. This in turn stresses the human eye a lot making it uncomfortable for usage.

3 LEDS TECHNOLOGIES

In order to successfully engineer a high quality LED solution, it is advisable to understand the principles of operation of the LED technology.

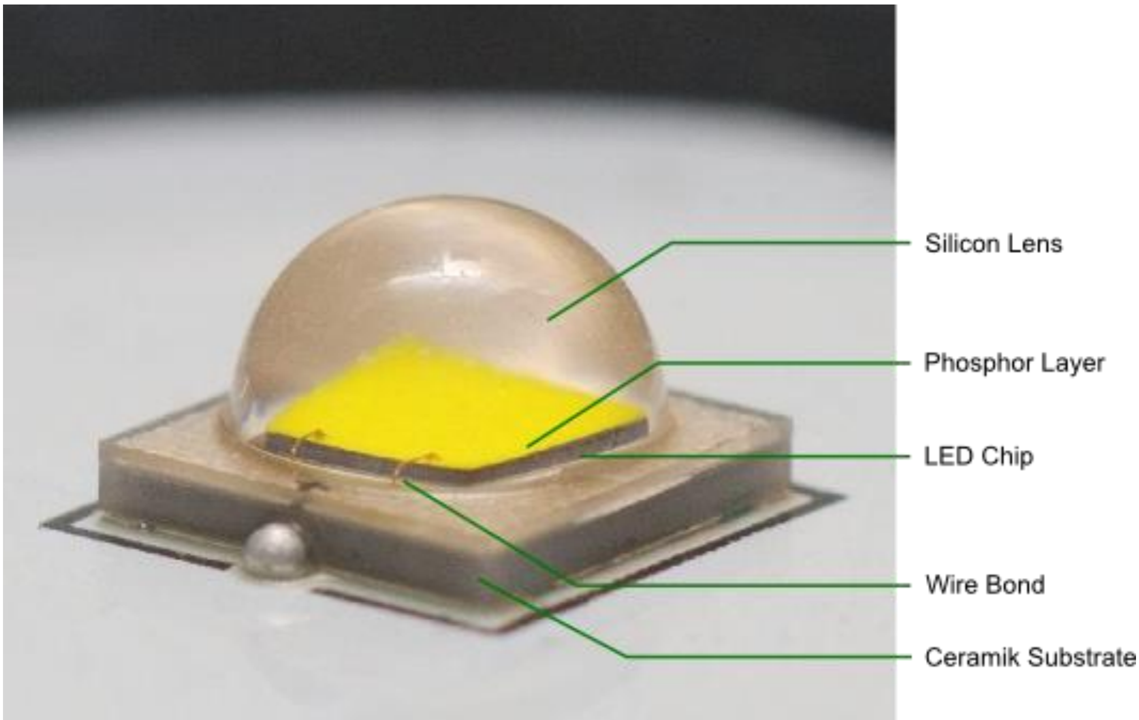

Figure 1. Structure of a Cree XM-L LED (Compiled by author)

Light-emitting diodes (LEDs) are semiconductor devices that generate light via electroluminescence when electric current passes across the junction of the semiconductor chip. Most semiconductors are made of a poor conductor material that has impurities (atoms of another material) added to it. The process of adding impurities is called doping. [4]

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. In doped material, additional atoms change the balance, either adding free electrons or creating holes for electrons to move. These alterations make the material more conductive.

A semiconductor with free electrons, which greatly increase the conductivity of the material, is called N-type material. In a N-type material, free electrons move from a negatively charged area to a positively charged area. A semiconductor which has deficiencies of valence electrons (holes) acting like 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 combination of p-type material, and n-type material. When p- and n- type materials are placed in contact with each other, at the junction the electrons and holes combine 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 semiconductor surface emits light. This implies that the electron-hole pair drops into more stable bound state, releasing energy by the emission of a photon. The wavelength of the light emitted depends on the materials forming the P-N junction. [5]

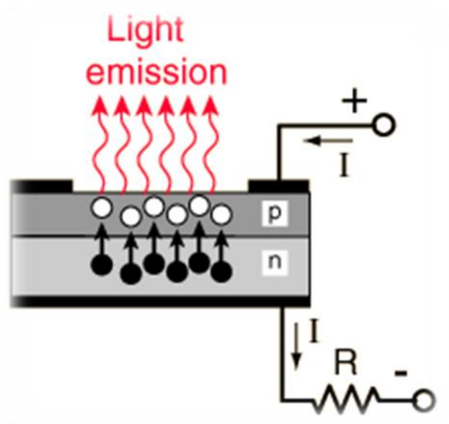

Figure 2. Light emission process in a LED chip (www.hyperphysics.phy . LED structure, 2013)

LEDs have been available as electronic components since 1960. When first developed, LEDs were limited to low-power applications like, for example, indicator lights. Then, higher-powered LEDs were developed and used in applications like traffic lights. It is only recently; however, LED lights have attracted the attention of the illumination industry on big scale and have begun to become a practical light source. Nowadays LEDs are used in a variety of applications, such as strip lighting, conventional residential space lighting, outdoor and commercial lighting. [4]

The LED lighting market is one of the world's fastest growing at the moment. Old light technologies, such as incandescent filament and compact fluorescent lights (CFLs) are being overrun by the high efficiency, mechanical ruggedness, safety (due to low voltages and temperatures) and long lifespan of LEDs.

Over the last 50 years LED development has been improving at logarithmic rates, while the cost of light from LEDs has been decreasing. This phenomenon is known as Haitz's Law. Haitz's Law states that every 10 years the price of LEDs decreases by a factor of 10, while the performance, measured in lumen output per unit, increases by a factor of 20. Since 1960s this rate is illustrated in Figure 3 below. [6] Such a fast development might be explained by increased competition in the LED component market. The latest revolutionary news on LED market is the development of LED which delivers up to 303 lumens-per-watt, enabling lighting manufacturers to create the next generation of high power, high efficiency lamps. [7]

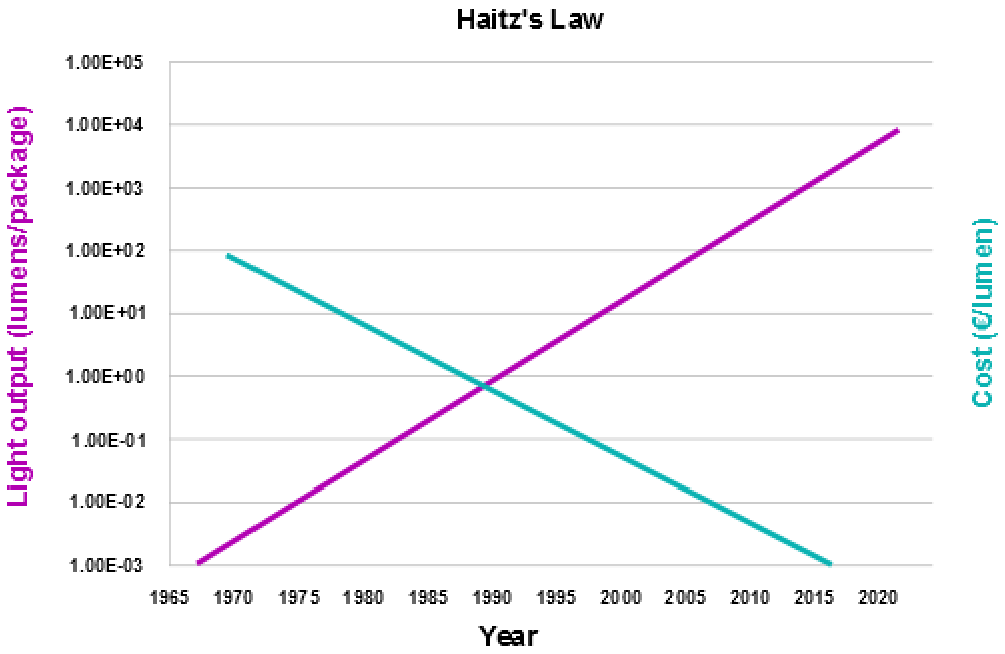

Figure 3. Haitz's Law(www.sitelightting.com,2013)

LEDs are more and more often used to replace conventional light sources such as incandescent, compact fluorescent and halogen. LEDs use about 40% less power than CFLs and last six to seven times longer. [4] The main advantage of the LEDs is the efficiency. Conventional incandescent bulbs, for example, can generate up to 95 % heat. LEDs produce relatively little heat. A much higher percentage (20-30%) of the electrical power is going directly to light.

LEDs have more lumen output than conventional light sources. For example, Osram's LED bulb PARATHOM CL A 60 10 W/827 E27 produces 81 lm/W compared to a CLASSIC A 40 W 230 V E27 incandescent bulb's 10,3 lm/W [8]

Up until recently, LEDs were expensive for most lighting applications due to the use of advanced semiconductor materials and rather complicated product designs. Rare earth metals used in LEDs are subject to price control monopolies by certain nations. The price of LEDs can be compensated by their longer lifespan, up to 150000 hours compared to 1200 hours of a regular commercial incandescent light bulb and 8 000 of compact fluorescents. [9]

LEDs have the possibility to a very stable light output and their small size and compact structure makes them a lot more durable. They also fit more easily into modern electronic circuits.

4 BASIC CONCEPTS OF HEAT TRANSFER

Heat transfer can be briefly described as energy movement due to differences in thermal energy potential. Energy always strives to migrate from higher to lower concentrations, and the laws of thermodynamics set of energy conservation indicates that the total energy in a closed system is always constant. [10]

For proper LED performance and product design it is important to understand the physical mechanisms which determine the heat transfer and the amount of energy being transferred. The heat originates in the LED junction, and is conducted through the LED package and circuit board to a heat sink, which then dissipates it. Three basic modes of heat transfer are conduction, convection and radiation. In a LED system all three forms of heat transfer play a role in maintaining the temperature of a LED chip, generating a good thermal path from the LED to the environment is critical in keeping the LED within specified temperatures.

The three modes are briefly described below.

4.1 Conduction

Conduction is the transfer of heat through a material by direct contact due to the temperature gradient. The physical mechanism of conduction can be viewed as a flow of energy from the more energetic to less energetic particles due to interactions between them. An object's temperature depends on the atoms' and molecules' movements. The more energy the particles have the greater their movements. When the movement of the atoms increases with warming, they will collide with neighboring atoms and increase their energy.

The rate of heat energy transferred through a given surface, per unit area is called heat flux. The process of conduction is described in Fourier's law. In 1822 Fourier concluded that "the heat flux resulting from thermal conduction is proportional to the magnitude of the temperature gradient and opposite to it in sign" [11]

For a unidirectional conduction process this observation may be expressed as:

$$q''_x = -k\frac{dT}{dx} \qquad (4.1)$$

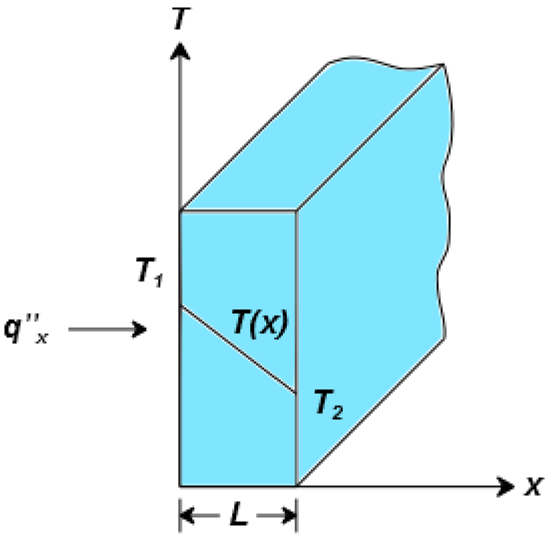

Figure 4. One-dimensional heat transfer by conduction (diffusion of energy) (Incropera, 2006 p.5)

The heat flux equation gives the general heat transfer rate per area. If one wants to know the heat output q in Watts, one must count with area also. [12] The equation then becomes:

$$q = A \cdot q'' \qquad (4.2)$$

Thermal conductivity is a unique property of a material; it is measured in watts per meter Kelvin.

The table below shows some example of the thermal conductivity of typical materials used in electronic industry. [13]

Table 1. Thermal conductivity of typical materials used in electronic industry (Compiled by author)

Material	k (W/mK) at 25 °C
Aluminum	205
Lead	35

Copper	401
Polyurethane resin	0,65
Air	0,024
Poly carbonate	0,19
Epoxy	0,35
Fiber glass	0,04

4.2 Convection

Convection is the transfer of heat which occurs between the fluid or gas in motion and a bounding surface when the two are at different temperatures. Convection consists of both conductive heat transfer and heat transfer resulting from the bulk motion of a fluid or gas. The energy on the surface of the solid body moves via diffusion to the layers of liquid or gas that is in direct contact with the surface in the same manner as in conduction.

The heated liquid is then led away by the current and replaced by cooler liquid. Convection can also occur in the other direction that energy moves from the liquid or gas to the solid body, such as in liquid filled radiators for indoor heating. Convection can be classified to two sub-categories according to the nature of the flow: natural and forced. Natural convection is induced by buoyancy forces, arising from the density differences caused by temperature variations in the fluid or gas. Heat flow in forced convection is caused by external means such as a fan, pump, and atmospheric winds or may result from propulsion of a solid through the fluid. As an example, for cooling electrical devices, fans are often used to provide forced air flow. The difference between forced and natural convection is illustrated in the Figure 4 below.

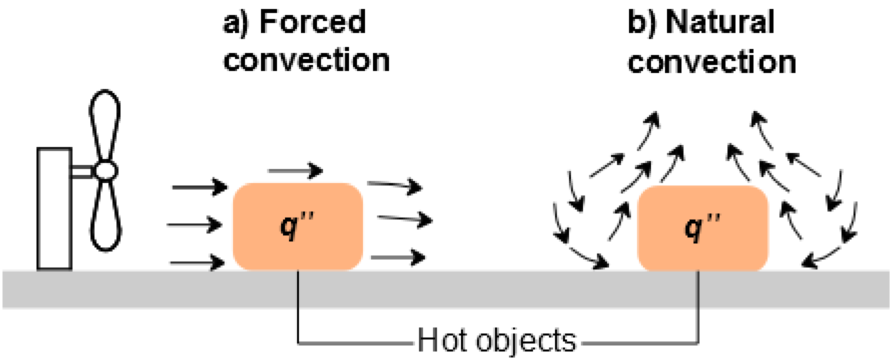

Figure 4. Convection heat transfer process (a) Forced convection (b) Natural convection (Compiled by author)

Regardless of the nature of the convection the quantity of heat transferred can be calculated, the appropriate rate equation is of the form:

$$q'' = h(T_s - T_\infty) \qquad (4.3)$$

Convection heat transfer coefficient h denotes the ability of the fluid or gas to convey thermal energy to or from the material's surface. Convection is the main mode of heat transfer to remove the generated heat from the LED system through heat sink to the ambient air. The determination and calculation of heat transfer coefficient (h) can be a real challenge. Values for h can vary significantly and depend on many factors, like boundary conditions (how close the objects that interfere with the air flow are), geometry, surface roughness, velocity of the fluid or gas over the solid surface and many others. [13]

One of the biggest LED manufacturers recommends using the following values for initial rough calculations: forced convection h values can be as high as 100 W /m^2K for air and up to 10,000 W/m^2K for water, for natural convection in air, values can be in the range of 5-20 W /m^2K. 10 W/m^2K for natural convection coefficient is a good assumption for preliminary calculations. [14]

4.3 Radiation

Radiation occurs when radiant energy leaves the surface via electromagnetic waves and travels until it meets another surface. The emission happens due to the changes in electronic configuration in atoms or molecules, the energy produced is transported by electromagnetic waves, and thus the transfer of energy does not require the presence of material. Radiation transfer is most efficient in vacuum, if the aim is to heat up another object.

Radiant energy is emitted by any piece of matter which is at any temperature above absolute zero. The intensity of such energy depends on the temperature and surface emissivity of the object and its material, which is viewed as the ratio of how closely the surface resembles an ideal radiator.

If a surface receives more radiative energy than it emits, its temperature increases. Very often in a LED system values of radiant heat transfer are so small that they can be neglected in comparison with convection and conduction.

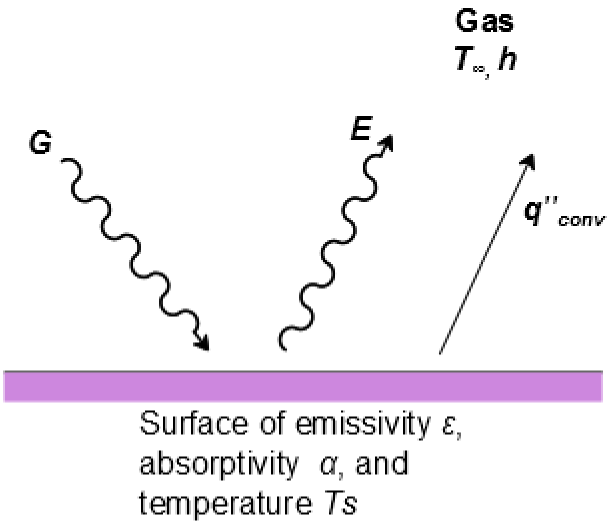

Figure 5. Radiation heat exchange (Incropera, 2006 p.7)

Equation that describes how to calculate the amount of heat transferred via radiation is:

$$q''_{rad} = \varepsilon\sigma(T_s^4 - T_{sur}^4) \qquad (4.4)$$

Where:

σ is the Stefan-Boltzmann constant (5.67x10-8 W/m^2K^4). Surface with such constant is called an ideal radiator. [13]

5 THERMAL MANAGEMENT OF LEDS

5.1 Importance of proper thermal management

> High power LED generally refers to the LED module for which the single chip size is not less that 1mmx1mm and the drive current is at least 350 mA. [15]

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. [16]

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, which is typically a 150 °C junction temperature, causes failure or damage to the LEDs over time. [16]

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 data sheets. Typically LED manufacturers specify the operating conditions which shall be taken in account while designing a product. Light output, color, voltage and lifespan are those performance characteristics which 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 data sheet. As the junction temperature increases, the light output of the LED decreases, but recovers when the LED cools down. This can be observed in the Figure 6 below. [16]
When approaching or exceeding maximum junction temperatures, the LED might fail to recover.

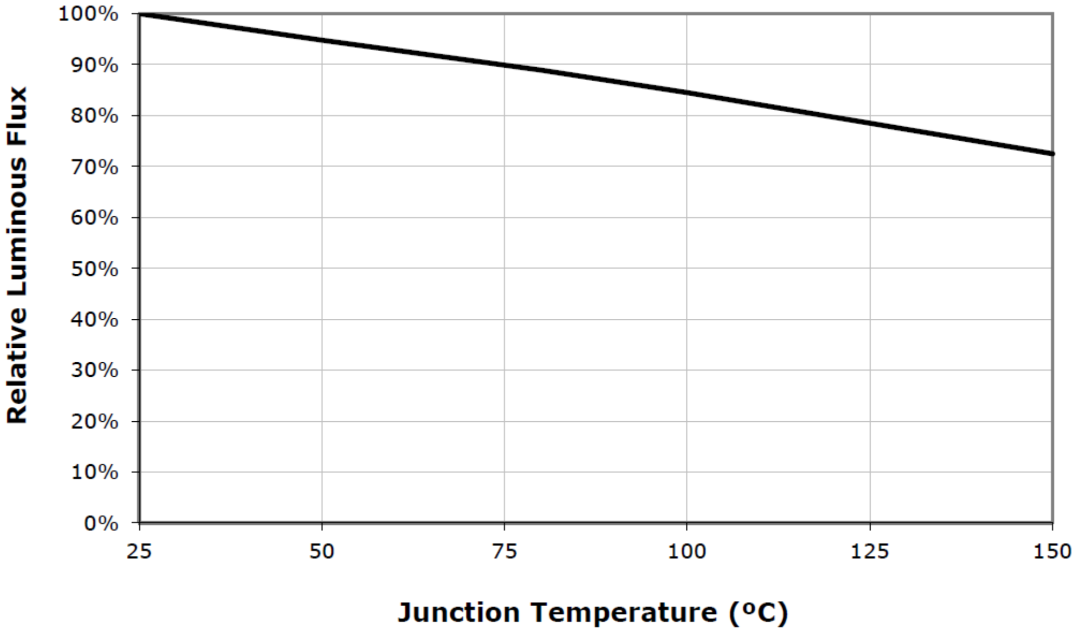

Figure 6. Relative Flux vs. Junction Temperature (CREE XLamp XM-L LED Datasheet, 2013)

With increasing junction temperatures, the color of LEDs shifts slightly. This needs to be considered in more color sensitive designs, such as stage lighting. For some specific applications like, for example, LED modules used in digital displays this phenomenon might be unfavorable. If LEDs aren't matched properly, they might produce a rainbow effect of different shades. It can be determined from the datasheet that the chromaticity coordinate will shift as the ambient temperature increases. The chromaticity coordinate also shifts as the forward current increases. An increase in current also results in slightly lowered efficiency and thus proportionally higher heat generation. One way to solve this is to actively regulate the LED junction temperature by keeping the circuit board under thermal control, and adjusting the temperature according to how much power the LEDs are run with. [16]

Thermal resistance between the LED junction and ambient also determines maximum continuous forward current. It is crucial for the end product to be designed in a manner that minimizes the thermal resistance from the solder point to ambient in order to optimize lamp life and optical characteristics. Forward voltage decreases as the junction temperature of an LED increases. This is shown on each of Cree's XLamp data sheets as the temperature coefficient of voltage, and varies slightly depending on the color and package type.

5.2 Thermal resistance model

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

Knowledge of the thermal resistance (R_{th}) 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

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 heat flow is approximated by the electrical current, and the corresponding temperatures within the system correspond to the electrical voltages. [17]

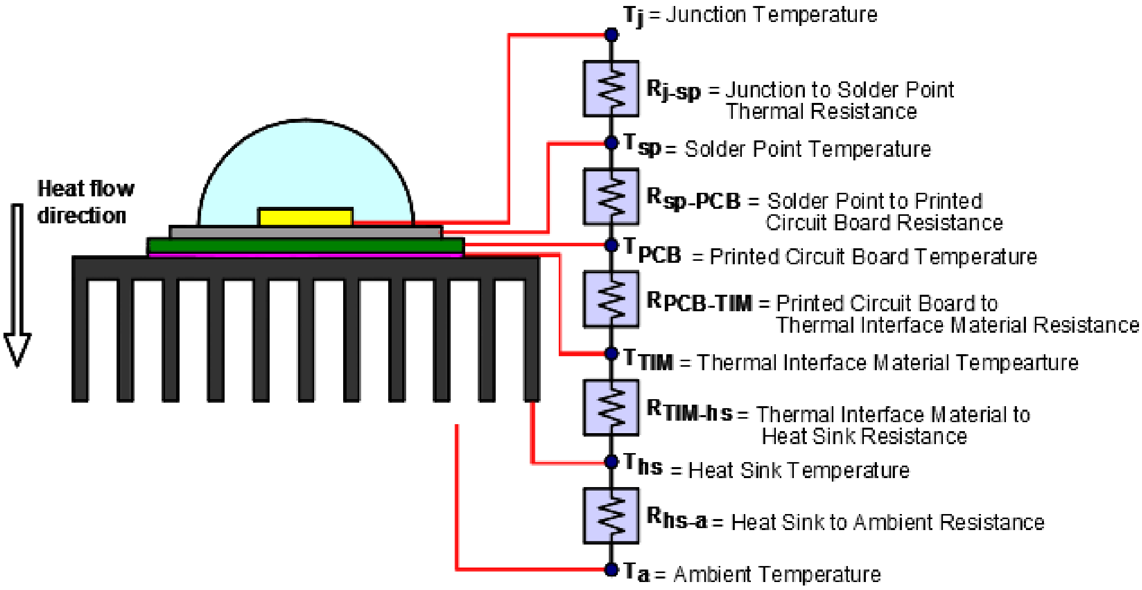

Figure 7.Detailed thermal resistance circuit of a LED (Compiled by author)

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. [14]

The nodes in the circuit represent the individual sections where temperatures may be measured. The individual thermal resistances described above can be calculated from Equation (5.1) below. General formula for thermal resistance is:

$$R_{a-b} = (T_a - T_b)/P_{th} \qquad (5.1)$$

Where:

$R_{(a-b)}$ is the thermal resistance from point “a” to point “b” (°C/W)

T_a is the temperature at point “a” (°C)

T_b is the temperature at point “b” (°C)

P_{th} is the thermal power

The equation (5.1) above represents the thermal resistance for a single LED. Usually power LEDs are mounted on metal-core printed circuit boards (MCPCB), which are attached to a heat sink. Heat flows from the LED junction through the PCB to the heat sink by conduction. The heat sink releases heat to the ambient surroundings by convection. In most LED applications, thermal resistances from solder point to PCB (R_{sp-PCB}) and from PCB to thermal interface material ($R_{pcb-tim}$) are small with respect to the thermal resistance between the junction and thermal pad, thermal pad and heat sink and heat sink to ambient, thus they can be omitted in calculations.

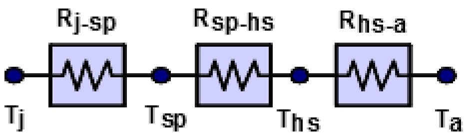

Figure 8. Thermal resistance model including three main resistances (Compiled by author)

The formula for the total thermal resistance is the series resistances from the junction to the solder point, from the solder point to the heat sink and from the heat sink to ambient:

$$R_{j-a} = R_{j-sp} + R_{sp-hs} + R_{hs-a} \qquad (5.2)$$

Where:

R_{j-a} is the thermal resistance from LED junction to ambient (°C/W)

R_{j-sp} is the thermal resistance from LED junction to solder point (°C/W)

$R_{sp\text{-}hs}$ is the thermal resistance from solder point to heat sink

$R_{hs\text{-}a}$ is the thermal resistance from heat sink to ambient (°C/W).

For multiple LEDs, their thermal resistances act in parallel. The thermal resistance from junction to solder point shall be divided by the number of LEDs (n). [18]
Equation 5.3 and Figure 9 below demonstrate that:

$$R_{j-a} = R_{j-sp}/n + R_{sp-hs} + R_{hs-a} \qquad (5.3)$$

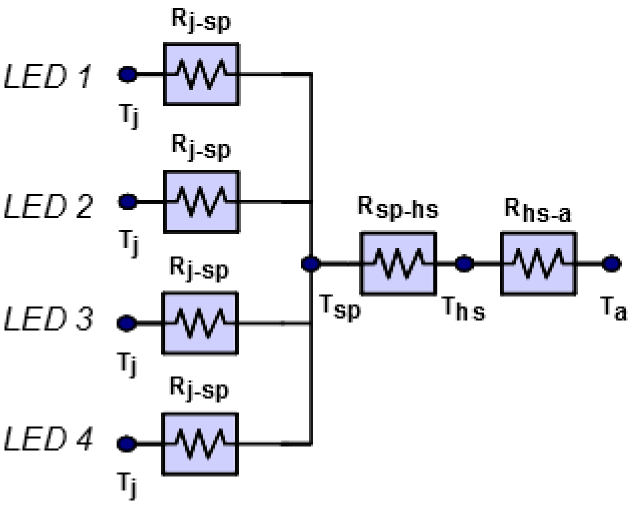

Figure 9.Thermal resistance model for four LEDs (Compiled by author)

For thermal power (P_{th}) calculations, it is important to realize that total heat dissipation is lower than total electrical power input to the system as a certain amount of electrical power is converted to the emission of photons (both visible and non-visible) , and that the driver causes additional heat in the form of conversion power-loss.

Approximately 70-80 % of the input power consumed by the LEDs themselves, after the power losses from the LED driver, is transformed into heat. Assuming LEDs convert 25 % of the input power to light and output 75 % of the input power as heat. This estimate varies depending on current density, brightness and LED model, but is a good estimate for thermal design.

The efficiency of a LED driver also varies from case to case, good drivers can be up to 95 % efficient, this means that 5 % of the initial input power of the system is converted to heat before reaching the LEDs.[14]

Equation (5.4) below shows how to calculate the thermal power.

$$P_{th} = P_{input} - P_{light} \qquad (5.4)$$

Where:
P_{th} is the thermal power (W)
P_{input} is the input electrical power (W)
P_{light} is the power emitted from the LEDs in the form of light (W)
P_{input} is the product of the forward voltage (V_f) and the forward current (I_f) of the LED

$$P_{input} = V_f \cdot I_f \qquad (5.5)$$

The V_f and I_f can be measured directly or calculated, so the thermal power can easily be determined.
In order to know how much power is converted to light the following formula can be used:

$$P_{light} = \left(P_{input} \cdot \eta_{driver}\right) \cdot \eta_{LED} \qquad (5.6)$$

Where:
P_{light} is the power used for light emission (W)
P_{input} is the input power (W)
η_{driver} is the efficiency of driver, running the LEDs (%)
η_{LED} is the optical efficiency of LEDs , approximately 20-30 %

One of the most important factors of successful LED product design is a good thermal management of the lamp or luminaire. When the LED junction temperature (T_j) increases, the performance of the LED decreases, thus, is resulting in lower light output from the system. Increased junction temperatures have also proven to shorten the lifetimes of LEDs. [3]

The LED junction temperature cannot be measured directly; however it can be calculated if the solder point temperature (T_{sp}) is known.

For solder point thermal measurements thermocouples can be used. A thermocouple is made of two thin metal wires of two different types of metal (nickel chromium and nickel aluminum, for example). The ends of the wires are welded together, and the leads are separated with insulation, so that only the welded end is in contact with the device under test. When the welded end is heated or cooled, a DC voltage differential is created between the two metals. The DC voltage is interpreted by a thermometer to provide a temperature reading; the voltage generated is proportional to the temperature of the device under test. [19]

LED manufacturers provide data characterizing LED performance versus T_j (Figure 6). Junction temperature can be calculated using Equation 5.7 below, based on the measured T_{sp}, the total power input to the LED and the thermal resistance of the LED as stated on its data sheet.

Power consumption can be monitored by the power supply's measurements which have been tested for adequate accuracy.

$$T_j = T_{sp} + R_{th} \cdot P_{th} \qquad (5.7)$$

Where:

T_j is the junction temperature (°C)

T_{sp} is the measured solder point temperature (°C)

R_{th} is the thermal resistance of the LED (°C/W) (LED's thermal resistance can be found in its data sheet)

P_{th} is the thermal power input to the LED (W) [14]

5.3 The practical implementations of heat resistance model

5.3.1 Junction temperature calculations

LEDs must not exceed their maximum junction temperature specified on the data sheet. First, assume the driver circuitry is positioned away from the LED so its heat output doesn't affect the LED chip. This is a best practice recommended by LED manufacturers.

In this example a work light with 4 Cree XM-L LEDs is taken for calculations. [7] The LEDs are driven with forward voltage of 3.2 V at a forward current of 2500 mA.
According to the product data sheet, the thermal resistance from the junction to the solder point ($R_{j\text{-}sp}$) is given as 2.5 °C/W.

The total system power dissipation is the product of number of LEDs, forward voltage and forward current.

$$P_{input} = n_{LED} \cdot V_f \cdot I_f = (4) \times (3.2\ \text{V}) \times (2.5\ \text{A}) = 32\ \text{W}$$

Total thermal power is calculated using equations 5.4 and 5.6

$$P_{th} = P_{input} - P_{light} = ((P_{input} \cdot \eta_{driver}) \cdot \eta_{LED}) = (32\ \text{W}) - (((32\text{W}) \times (0.95) \times (0.25)) = \\ = 24.4\ \text{W}$$

In order to calculate junction temperature *(T_j)*, the temperature of the solder point *(T_{sp})* has to be measured, for example by using a thermocouple mounted close to the LED's thermal pad to measure temperature there.

The set up using a thermocouple was made and T_{sp} was measured to be 66 °C.
The T_j of an LED cannot be measured directly; it is possible to calculate using equation 5.7, based on the measured T_{sp}, the total power input to the LED and the thermal resistance of the LED as stated on its data sheet.

$$T_j = T_{sp} + \frac{R_{j-sp}}{4} \cdot P_{th} = (66\ °C) + ((2.5\ °C/W))/4 \times (24.4\ W) = 81.25\ °C$$

81.25 °C is lower than the specified in the datasheet 150 °C maximum junction temperature, consequently the system is not overheated. With a known junction temperature, it is possible to predict theoretical luminous flux produced by the light system using the graph from LED datasheet (Figure 6).

5.3.1 Thermal resistance of the heat sink calculations

The example above is based on an existing product model, when temperature Tsp can be measured.

More challenging task is to predict a proper thermal management for a LED product. Assumptions and approximations need to be done in order to succeed. The following calculations will show how to determine the thermal resistance of the heat sink, later on these values can be used for the heat sink design or selection of a ready one.

In this example the same product with 4 Cree XM-L LEDs is used. Max junction temperature $T_{j\,max}$ is 150 °C, the thermal resistance from the junction to the solder point *Rj-sp* is 2.5 °C/W, and ambient temperature T_a is 25 °C. Therefore:

$$T_j = T_a + P_{th}\left(\frac{R_{j-sp}}{4} + R_{sp-hs} + R_{hs-a}\right)$$

The thermal resistance between the solder point and heat sink depends on the surface quality, material type, thickness of the heat sink base and area of the contact between LED and heat sink. Good design *Rsp-hs* values may be minimized down to 1 °C/W.
The maximum thermal resistance from the heat sink to ambient R_{hs-a} can be calculated. Using the previous equation and solving for R_{hs-a}:

$$R_{hs-a} = \frac{(T_j - T_a - R_{j-sp} \cdot \frac{P_{th}}{4} \cdot P_{th})}{P_{th}} = 3.49\ °C/W$$

As it was written before, it is recommended to keep the junction temperature lower than 150 °C for longer lifetime and higher LED efficiency. In order to keep the junction temperature below 150°C in worst-case conditions, a heat sink with thermal resistance from heat sink to air R_{hs-a} less than 3.49 °C/W must be chosen. A heat sink with the required characteristics may be selected using data provided by heat sink manufacturers or through modeling and testing.

6 HEAT SINKS: VARIOUS COOLING OPTIONS

A heat sink is designed to maximize the surface area in contact with the cooling medium surrounding it, such as the air. Air velocity, choice of material, fin design and surface treatment are factors that affect the performance of a heat sink. Heat sink attachment methods and thermal interface materials also directly affect the thermal resistance, and thereby the LED junction temperature. Thermal adhesive or thermal paste improves the heat sink's performance by filling air gaps between the heat sink and the device.
The design considerations are different for every LED application. The essence of LED system design is transferring the heat efficiently from the LED chip through enclosure or an external heat sink to its surroundings.

Transmission of heat from a heat source (e.g. the junction of a LED) via the heat sink into the surrounding medium takes place in four major steps:

- Transfer from heat source to the heat sink
- Conduction from within the heat sink to its surface
- Transfer from surface into the surrounding medium by convection
- Radiation depending on the temperature and nature of the heat sink’s surface [14]

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. [20]

6.1 Heat dissipation options

According to the way the heat is dissipated to the environment, the cooling systems can be divided into passive and active.

Passive cooling is based on free convection heat transfer process and occurs without any applied effort. On the contrary the active cooling requires external active heat removal, which can be forced air, liquid cooling, semiconductor refrigeration etc. [15]

6.1.1 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 / remote cooling is heat pipes. Heat pipes do not dissipate heat; they move it to another location more efficiently than any common material.

> The heat pipe is filled with a small quantity of fluid. Inside a heat pipe, at the hot interface a fluid in contact with thermally conductive solid surface turns to vapor by absorbing heat from that surface. The gas naturally flows along the heat pipe and condenses at the cold interface. The liquid forms and moves back by capillary action, centrifugal force, or gravity to the hot interface to evaporate again, thus the cycle repeats. This effective high thermal conductance helps maintain near constant temperatures along the entire length of the pipe. [21]

Heat pipes are often also used as parts of a flat fin heat sink, to distribute the heat more effectively to the entire cooling assembly, such as a computer processor cooling element. This makes thinner cooling fins possible and thus makes the cooling unit lighter and more efficient. Heat pipes can also be used in tight spaces to transfer heat to a remote heat sink for both active and passive cooling.

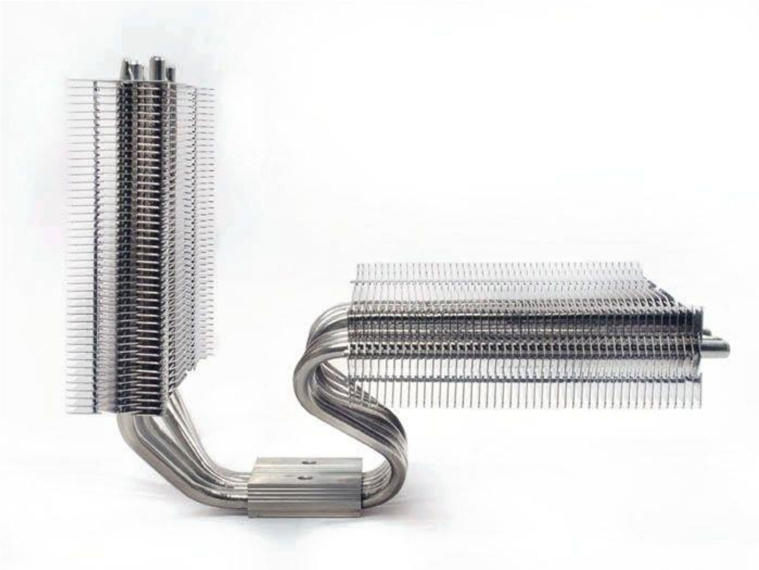

Figure 10. Example of a heat pipe sink (www.jimms.fi, 2014)

6.1.2 Active heat dissipation

Free convection from the plate fin heat sink is limited and quite often is not enough to dissipate heat from high-power LED light source. 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 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 accelerates the rate of airflow, thus increasing the heat transfer coefficient h. Comparatively to the 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 a pumps, and extra noise is often an issue.

Another active solution is a thermoelectric cooling which provides such advantages like high cooling density, compact construction, no moving part, long life time. Thermoelectric cooling uses the Peltier effect to create a heat flux between the junction of two different types of materials-electrical conductors and semiconductors. A thermoelectric cooling system typically consists of a matrix of semiconductor pellets sandwiched in between two large electrodes. When current is applied, the negatively-charged side becomes cooler while the positively-charged side becomes warmer. The negative electrode is placed in contact with the element to be cooled, while the positive electrode is connected to a heat sink that radiates or dissipates thermal energy into the external environment. Main disadvantages of this solution are high cost and low electrothermal efficiency. [15]

The element's "cooling power" is the amount of power (in the form of heat) that is actively removed from the cooled side, approximately 10-15% of the total electrical power requirement for the element. As an example, a 10W LED circuit board is kept at ambient temperature by a Peltier element by 10 % cooling efficiency. The element requires 100 W of power to do this, of which 90W of "moved" energy needs to be dissipated. This phenomenon makes thermoelectric cooling rare in LED solutions where power saving is one of the key goals [22]

One more type of active heat dissipation is liquid cooling, which is based on a pump-driven fluid flow to remove heat from the system. A liquid cooling system usually includes pump, heat exchanger and cooling plate as main components. The flow of liquid absorbs the heat through the cooling plate and transfers it to the heat exchanger which dissipates it to the environment. The main advantage of the liquid cooling is the high cooling density; it can be used in high heat flux applications. On the other hand, the high cost and reduced reliability due to many required parts and the requirement of water/airtight cooling fluid transportation make liquid cooling rare in LED applications. [15]

6.2 Heat sink design considerations

6.2.1 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 11). 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.

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

Most of natural convection heat sinks have limited heat transfer possibilities, 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, extruded base plate. This process allows for a much greater fin height-to-gap aspect ratio, with the intent of greatly increasing the cooling capacity without increasing volume requirements.

Casted metal injection molded heat sinks enables complex parts to be formed as easily as simple geometries, thereby allowing a certain product design freedom (Figure 14). This technology is used in high density pin fin heat sinks which provide maximum performance 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 is usually poorer in comparison with other heat sink manufacturing methods.

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. [23]

Figure 11.Typical extruded heat sink (for TO-220 transistor package) (www.farnell.com, 2014)

Figure 12. Typical stamped heat sink for TO-220 transistor package (www.farnell.com, 2014)

Figure 13. Example of a bonded fin heat sink (www.catalog.chtechnology.com, 2014)

Figure 14. Example of high-pressure casted heat sink (for TO-3 transistor package) (www.farnell.com, 2014)

Figure 15. Example of a folded fins heat sink (www.enertron-inc.com, 2014)

Heat sink models can be very complicated and have restrictions such as dimension constraints, cost, weight, manufacturability, etc. Each application has its unique approach and requirements to heat sink design, this work is concentrated on optimization of extruded horizontally-located plate fin heat sink (Figure 16). The picture below depicts the most important optimization parameters, such as height of the fin (*H*), thickness of the base (t_b), width (*W*), length (*L*), fin thickness (*t*), and spacing between the fins (*s*).

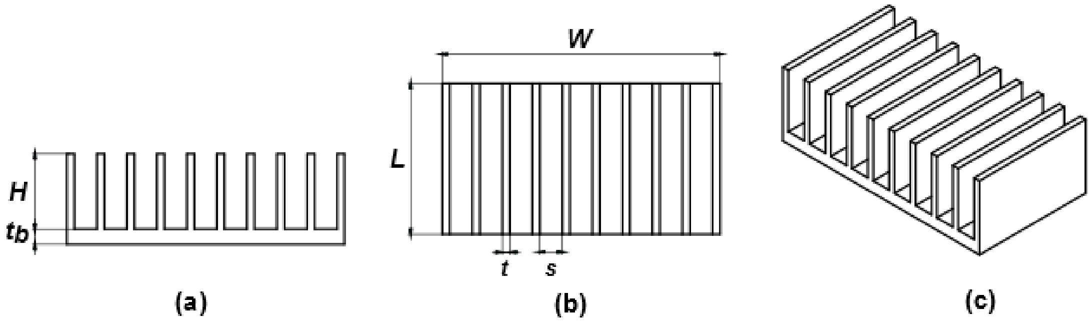

Figure 16. Horizontally extruded plate fin heat sink, (a) front view; (b) top view; (c) isometric configuration.

(Compiled by author)

The use of thermal modeling can eliminate repetitive prototyping, indicate design deficiencies and potential areas which can be improved early in the design process.

Heat sink thermal radiation is a function of surface finish, especially when the heat sink is at higher temperatures. A painted surface will have a greater emissivity than a bright, unpainted one. The effect is most noticeable with flat plate heat sinks, where about one-third of the heat is dissipated by radiation. The color of the paint used is relatively unimportant. The thermal resistance of a flat plate heat sink painted gloss white will be only about 3% higher than that of the same heat sink painted matte black. With finned heat sinks, painting is less effective since heat radiated from most fins will fall on adjacent fins, but it is still worthwhile. Both anodizing and etching will decrease the thermal resistance. [14]

6.2.2 Surface area of the heat sink

Thermal transfer takes place at the surface of the heat sink. Therefore, heat sinks should be designed to have a large surface area. This goal can be reached by using a large number of fine fins or by increasing the size of the heat sink itself.

6.2.3 Air flow rate

Heat sinks must be designed in a way that air can flow through easily, considering its viscosity. Heat sinks with a large number of fine fins with short distances between the fins may not allow good air flow. A compromise between high surface area (many fins with small gaps between them) and good aerodynamics must be found. One should also consider "choking points" such as ejector placements in high-pressure molded cooling systems, which might prevent rather weak natural convection airflow. Heat sink orientation is also crucial, if a heat sink is designed to be mounted horizontally, it will not be as efficient if mounted vertically.

6.2.4 Thermal transfer within the heat sink

Large cooling fins are ineffective if the heat can't reach them. The heat sink must be designed to allow adequate thermal transfer from the heat source to the fins. Thicker fins have better thermal conductivity; so again, a compromise between large surface area (many thin fins) and good thermal transfer (thicker fins) must be found. The material used has a major influence on thermal transfer within the heat sink.

6.2.5 Surface quality of the contact area

The portion of the heat sink that is in contact with the LED or MCPCB must be perfectly flat. A flat contact area allows the use of a thinner layer of thermal compound, which will reduce the thermal resistance between the heat sink and LED source.

6.2.6 Mounting method

To achieve a good thermal transfer, the pressure between the heat sink and the heat source must be high. Heat sink clamping systems must be designed to provide high pressure, while still being reasonably easy to install. Heat-sink mountings with screws or springs are often better than regular clips. Thermal conductive glue or sticky tape should only be used in situations where mounting with clips or screws is not possible. [18]

7 THERMAL SIMULATIONS

The performance of any heat sink is measured by the temperature difference between its base and the ambient air. The geometry of the heat sink quite often follows the product design idea and might have complicated shape making it impossible to estimate the cooling power with standard heat sink calculations. This is where Computational Fluid Dynamics (CFD) becomes a handy tool for engineers. CFD provides a visual and numerical description of the flow field and temperature distribution in and around the heat sink. CFD can help with the selection and/or design of a heat sink for electronics cooling applications. With CFD the real world performance of a product can be predicted, helping to save time and money by eliminating the need to build multiple physical prototypes.

CFD is used to perform heat transfer and fluid simulation analyses in order to study the thermal characteristics of design models and simulate the detailed fluid flow behavior.
Heat sinks might seem quite simple in function but their interaction with the components to be cooled and the air flow is complex. The heat is carried away from the system by an air flow which in turn greatly depends on the geometry. Important areas to model are the fluid flow area near the heat sink surfaces, between the fins, the entry and exit areas.

In the heat sinks design, heat transfer coefficient (h) is an important factor. The value of h is associated with the fin dimensions, and is the subject for optimization. Additionally, due to the overall geometry of the heat sink, it is very difficult to calculate the heat transfer coefficient in order to identify and resolve thermal issues in the early stages of the product design.

CFD modeling tools help study the initial design intent and accurately predict product performance. This allows validating and optimizing design before manufacturing, increasing efficiency, minimizing physical prototypes, reducing costs and decreasing errors. Thus, high performance of heat sinks can be acquired through the design optimization which maximizes heat transfer and minimizes pressure drop. [24]

After simulating a system and optimizing a design it is recommended to build a final prototype to accurately measure its performance. Experimental validations provide valuable feedback on modeling. The chosen design can be verified experimentally by measuring the base temperature relative to the ambient air temperature or by using heat camera. Quite often the numerical results do not exactly match the measurements. After all, the CFD model gives only an average result, whereas an experimental measurement shows the real situation. Even if there is not a perfect agreement between physical and numerical models, model performance trends are presented well enough to shorten the total design cycle. In the final analysis, the goal of the CFD work is to make a good design approach, and as long as the physics of the model was presented correctly, the trends will be correct.

7.1 CFD simulations and thermal analysis of three suggested heat sink models

CFD simulation was done using Comsol Multiphysics, in 2D environment taken into account the air around the heat sink. The most important factor of the cooling unit, the fin spacing, was iterated to produce the lowest heat sink base temperature with a fixed input power evenly distributed on the entire surface, while keeping the height and length of the cooling fin array fixed. The size of the lamp itself was defined by the internal electronics, which were made as small as possible, since the compact size was one of the main goals of the product design. The width of the fin in all models is 3 mm.
Three different cooling fin arrangements were tested, with different fin spacing and fin amounts.

The following 3 arrangements are:

1. 10 fins with 11 mm spacing between the fins
2. 12 fins with 9 mm spacing between the fins
3. 14 fins with 7 mm spacing between the fins

The cooling system with 12 fins and 9 mm spacing was chosen as the best of the three, since its air channels to surface area ratio delivered the most effective cooling. CDF model provides two types of results: air velocity and temperature distribution. Both results of simulation are shown below for each type of heat sink design.

7.1.1 10 fins with 11 mm spacing design

The pictures below depict the cooling arrangement allowed for quite effective volumetric airflow through the cooling fins. The temperature of the air between the cooling fins in a saturated state of natural convection is low. When comparing the three different models, the model below, has less cooling surface area and thus cannot dissipate as much heat with the same power input as the 12 fin version.

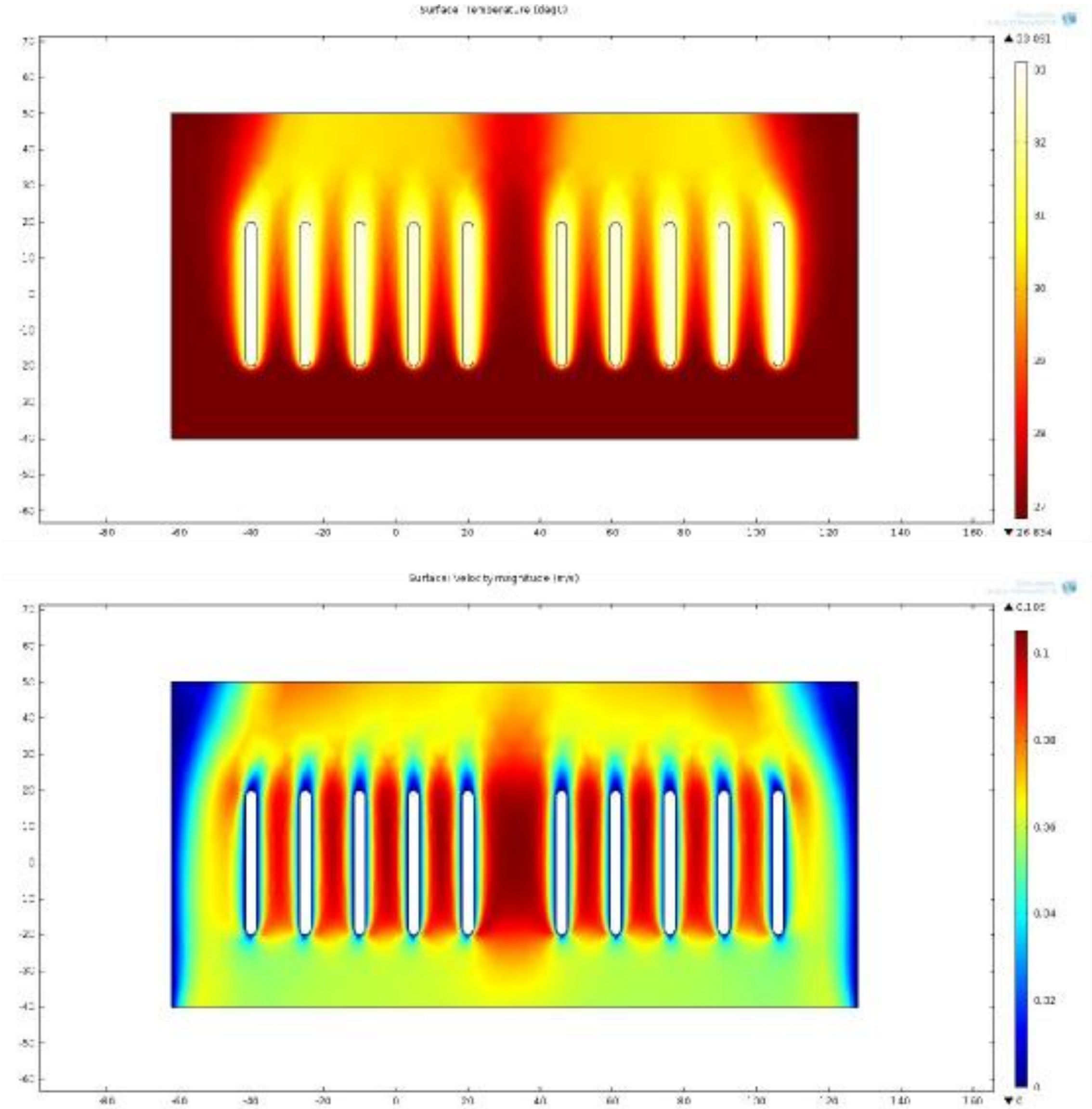

Figure 17. CFD analyses results for 10 fins heat sink design (Compiled by author)

7.1.2 12 fins with 9 mm spacing design

The 12 fin version, despite the smaller fin spacing, still allows enough air to be pulled through. This can be seen from the airspeed analyses results between the fins, and from the fact that the air between and above the cooling fins is still not very warm. Since it has a combination of more cooling fins and adequate spacing between them to allow the air to move through relatively fast, it has better cooling power than the 10 fin version.

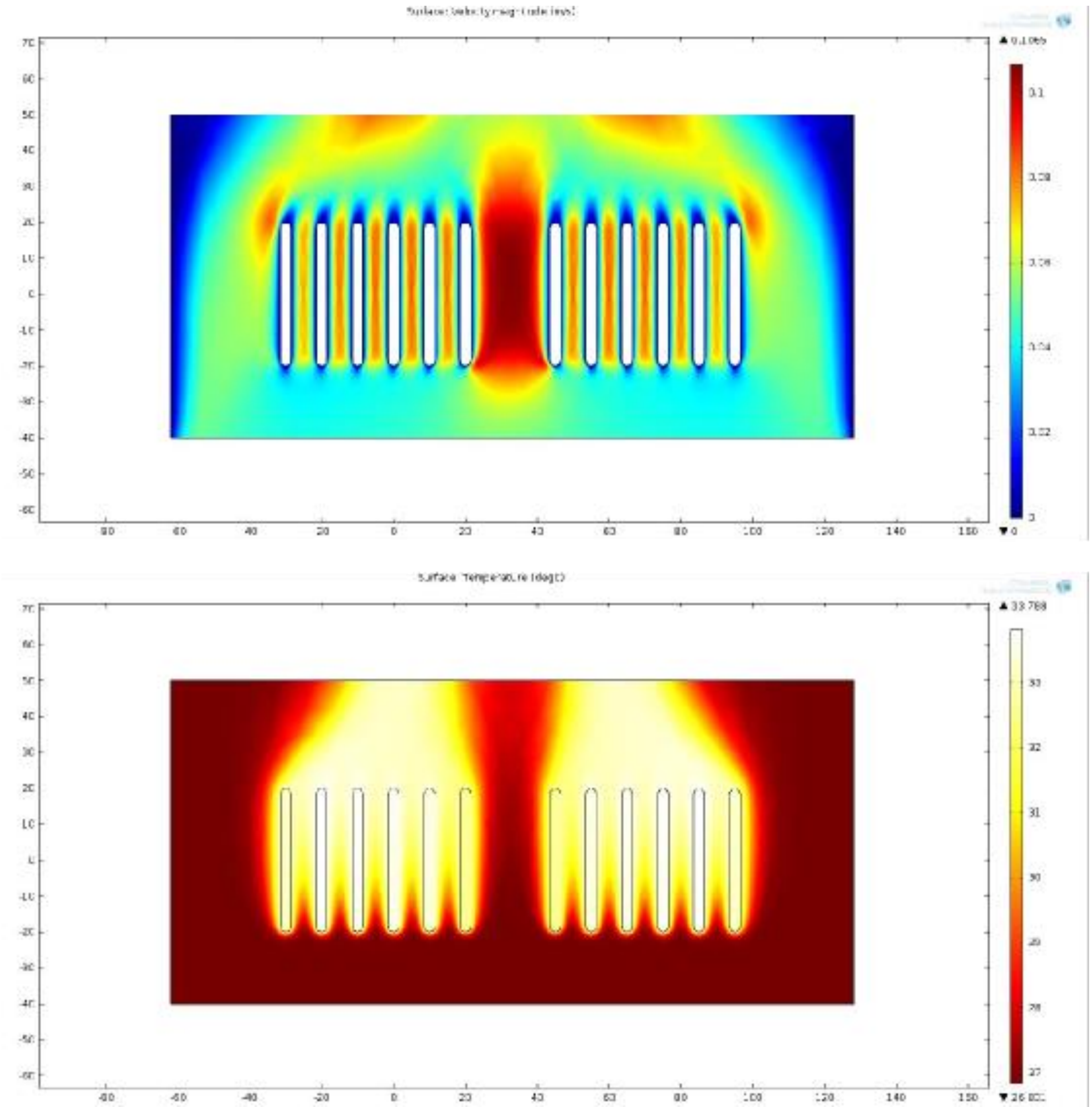

Figure 18. CFD analyses results for 12 fins heat sink design (Compiled by author)

7.1.3 14 fins with 7 mm spacing design

The 14 fin version, as can be seen, has less volumetric flow between the cooling fins than the other two heat sink models, due to the lower airflow and narrower gaps between the fins. This causes less heat to be dissipated into the air because the air heats up relatively fast, as can be seen on the thermal map image, the air has close to cooling fin temperature very early in the cooling unit, rendering the rest of the cooling surface very inefficient. Despite the added cooling surface area, the fact that this model has insufficient air gaps between cooling fins makes it worse in comparison to the 12 fin model.

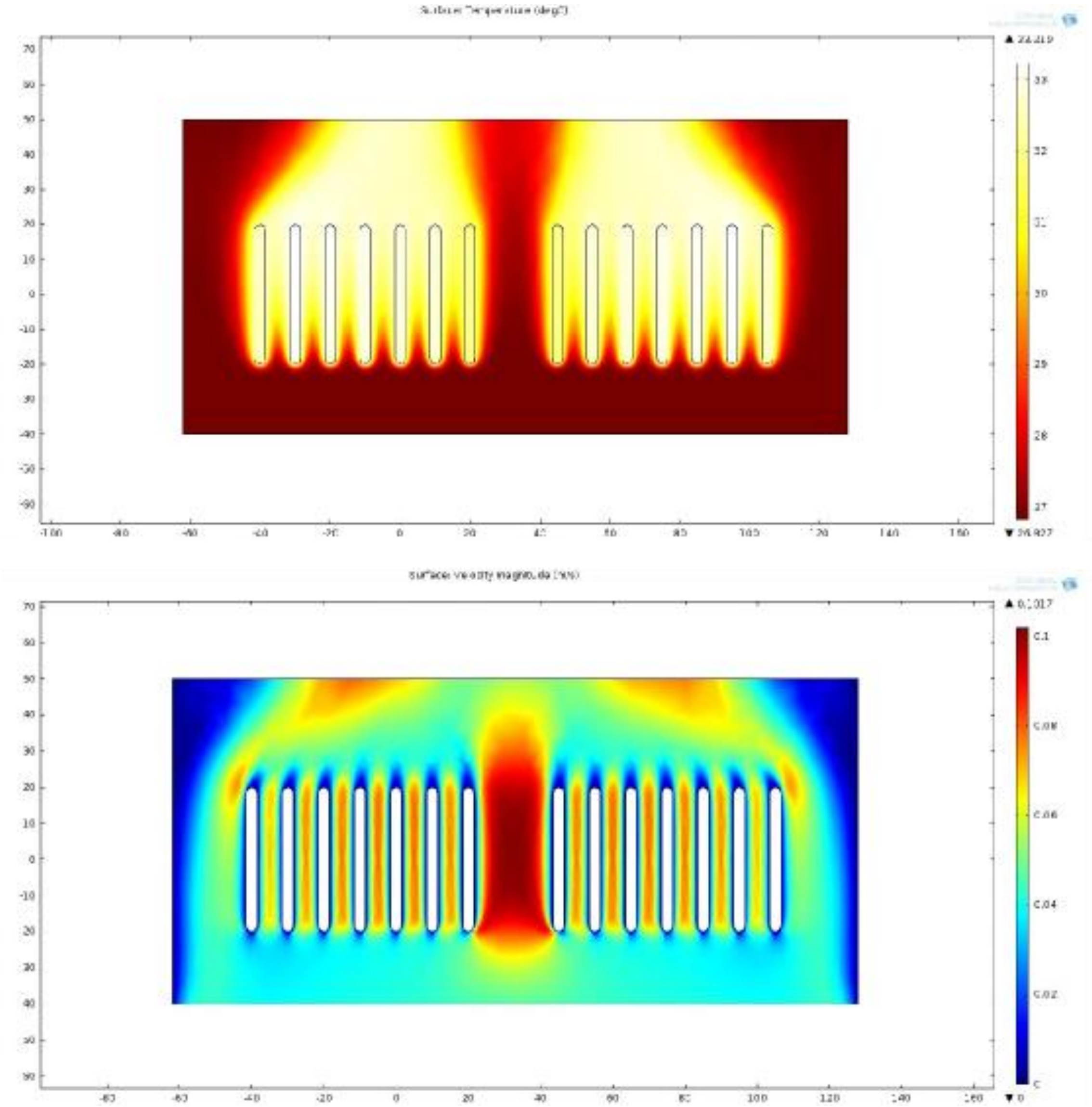

Figure 19. CFD analyses results for 14 fins heat sink design (Compiled by author)

8 DESIGN OF THE WORKLIGHT

The origin of the product that became Zaurac 4-30 was a demand for a better work light which came from construction industry.

The key requirements were:

1. Durable
2. Compact size
3. High light output
4. At least IP 68 rating

The first 2 prototypes had the LED current regulating electronics outside of the LED casing, due to the fact that it was developed quickly and there had been no chance to optimize the size.

The biggest problem with the first 2 prototype models was the cooling. It was not a fatal one, since all the prototypes had overheat protection but further heat sink performance optimizations were required.

Then a prototype with integrated electronics was designed and built, shaped optimally for high-pressure aluminum casting. Also that model had problems with cooling, so the decision was made to properly optimize the cooling based on natural convection, the most demanding type of cooling environment. The model was redesigned to use the optimized cooling fin profile, and also the production method was changed to extrusion and milling, thus the overall design was adjusted to the new manufacturing method and mass production.

The main reasons for the change in production plans were the following:

1. Startup costs. The high pressure aluminum mold price was high.
2. Surface treatment possibilities. The pressure molding alloy does not allow colorized anodization, but has to be painted if a specific color is desired, and paint easily peels off in certain conditions. Extruded alloys are very easy to anodize.

3. Structural integrity. The pressure casted aluminum is slightly harder than extruded, but much more brittle and thus more likely to crack from impacts.
4. Freedom of shaping. If a flaw is detected in the shape, or there is a desire for different versions, the extruded parts can be milled differently with very low extra cost but a pressure mold is what it is and is very expensive to change.
5. Aesthetics and functionality. The high pressure molding sets strict requirements to the shape of the parts, whereas extruding and milling gives relatively free hands to decide the shape according to looks and practical needs.

Figure 20 below shows various proposed product design which represent product development process on different stages.

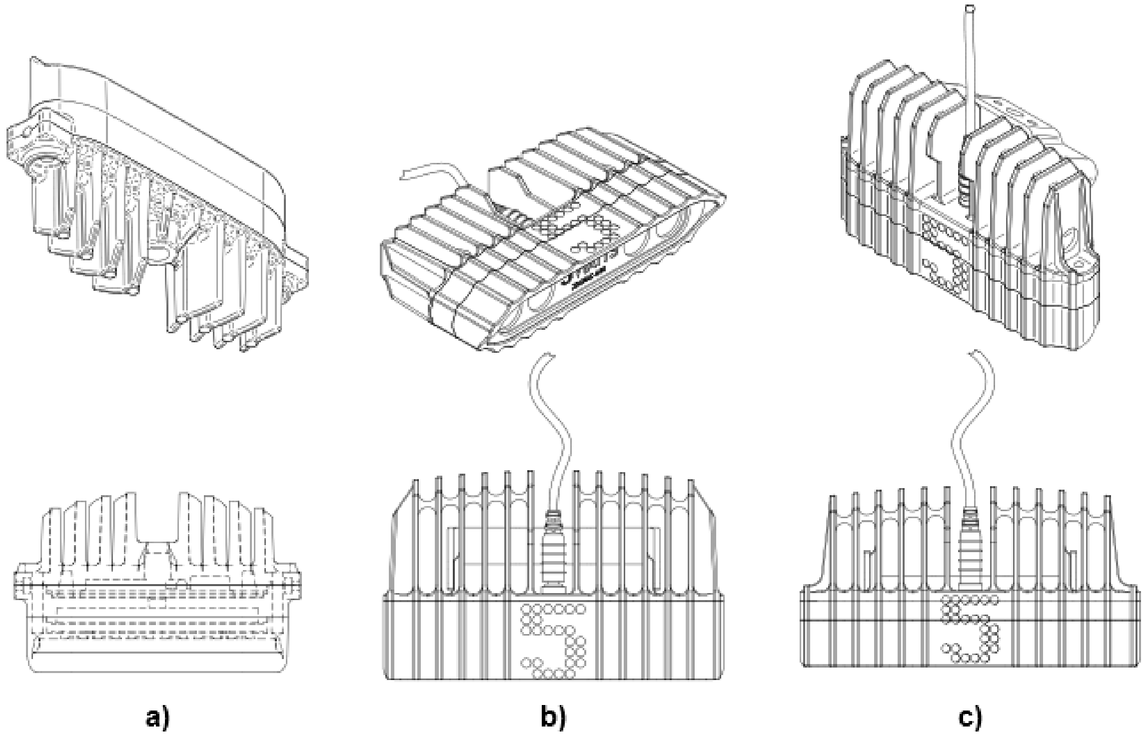

Figure 20. Different LED work light designs during optimization of heat sink geometry. (Compiled by author)

Model a) was the first design with integrated electronics, as well as the last prototype before cooling system optimization. This model had V-shaped cooling fins, to provide extra support against mechanical damage, due to the brittleness of high-pressure casted aluminum. This model had overheating issues (75 °C casing temperature) due to the insufficient heat sink when used for a long time in a windless environment. Tests performed outside lab conditions in different weathers showed, however, that casing temperature was quite low and the LEDs were not overheated.

Model b) had the cooling fin dimensions implemented from CFD analyses results, but still had small structural impracticalities. Some support structures, not possible for high-pressure casting but possible to include in an extruded shape, were added to the end of the heat sink to support the cooling fins. It was designed to be extruded in 2 profiles, and milled to the final shape, one part per extruded profile. Tests of the heat sink performance were very promising, after saturation in room temperature (25°C) the highest temperature measurable from the lamp was 53°C, the base between the 2nd and 3rd outer cooling fins. This design also gave the lamp a very rigid structure, but had the flaws of bad cooling reliability of the LEDs (the LED board was pressed down by the lenses, which could shatter at the slightest impact directly on the front of the lamp), and excessive waste material; 1.5 kg of extruded material was required to produce the 0.85 kg casing (0.65 kg waste).Also the length of the cooling fins was changed after testing, to get the size as compact as possible.

The current production model Zaurac 4-30 (model c)), released in December 2013, is milled from extruded aluminum and then either anodized or nickel-plated.

The current production version of the lamp (Figure 21) consists of 4 aluminum parts, of which the casing itself consists of parts made from 2 different extrusion profiles, and a “front shield”, an aluminum sheet part protecting the polycarbonate spacer underneath.
In the final version, the LED board is pressed down onto the heat sink by its edges, and material losses were reduced to 0.15 kg.

Figure 21. Zaurac 4-30 LED work light (www.5watts.fi, 2014)

9 THERMAL CAMERA MEASURMENTS

The heat sink designed as a result of this project was tested in completely windless conditions, where the optimization is most crucial. At the moment, at 25°C ambient temperature, running at 32 W, the hottest point on the outside of the casing (heat sink base between 2nd and 3rd cooling fin) saturates at around 50°C.

In summer 2013 the product successfully passed official environmental testing for machine accessories which was performed in VTT labs in Finland, Helsinki.

Before the official testing, the lamp’s performance was examined in different temperatures by measuring the heat sink temperature at the base of it. Also heat camera was used to get more detailed visual representation of the heat spreading through the system to see potential hot spots and maximum temperature of the casing.

In the pictures below the differences in temperature throughout the casing can be seen. The warmest region is at the base of the cooling fins where the LEDs are located; the heat sink cools down further away as the thermal resistivity of the material limits the heat transfer. The pictures are taken with the lamp in a saturated cooling state, meaning that the input energy is equal to the cooling capability. It is visible on the thermal camera that the temperature difference between cooling fins’ base and tips and the different saturation temperatures when mounted vertically and horizontally.

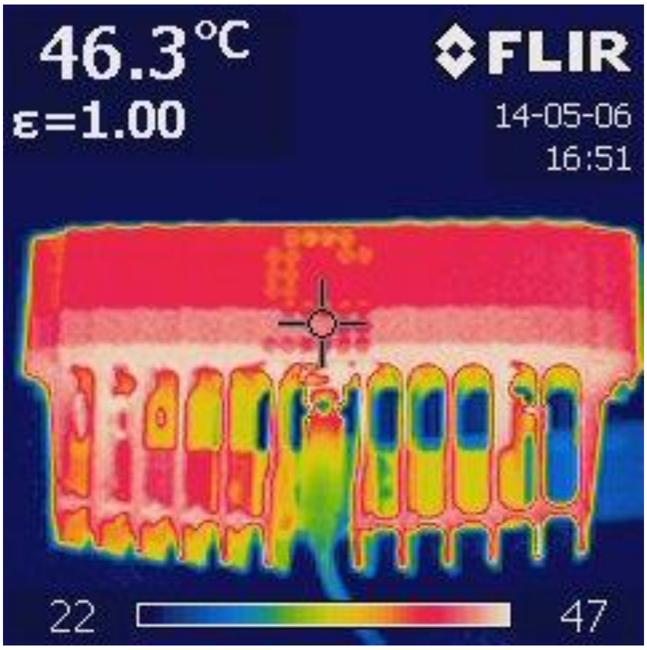

Figure 22. Thermal camera image, lamp's top view (Compiled by author)

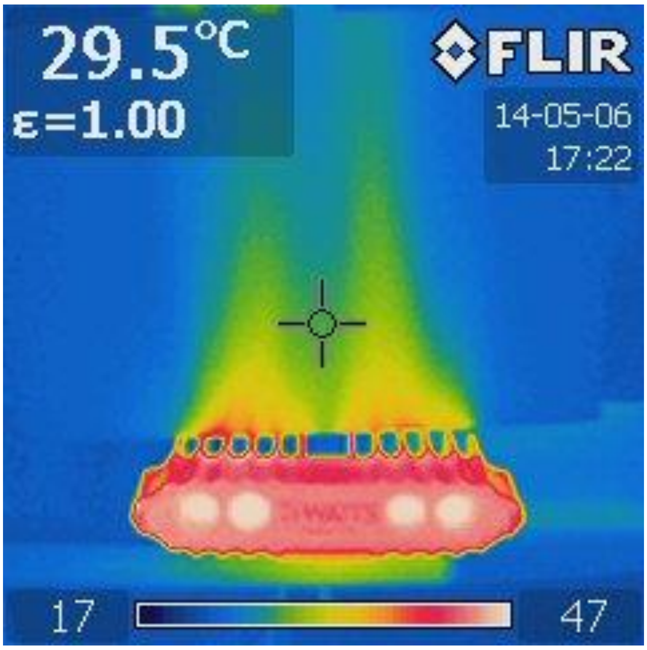

Figure 23. Infra-red camera image, air flow at the heat sink, airflow at the heat sink demonstrated with a piece of paper hanging above it (Compiled by author)

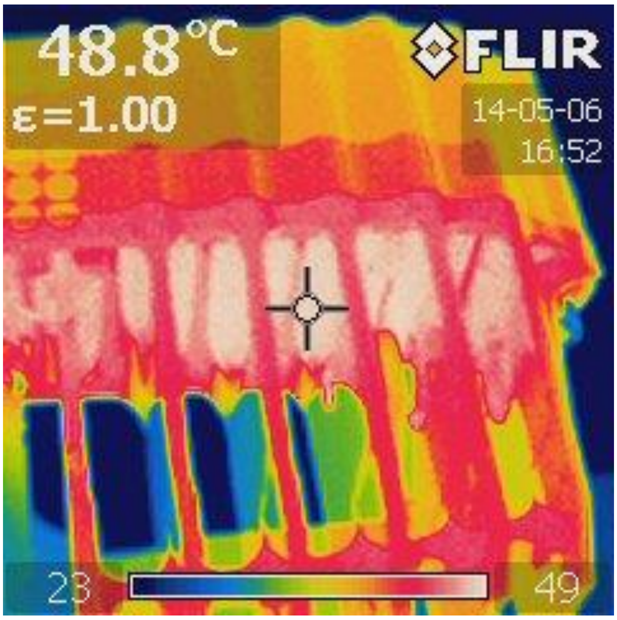

Figure 24. Hottest point of the casing when mounted horizontally (Compiled by author)

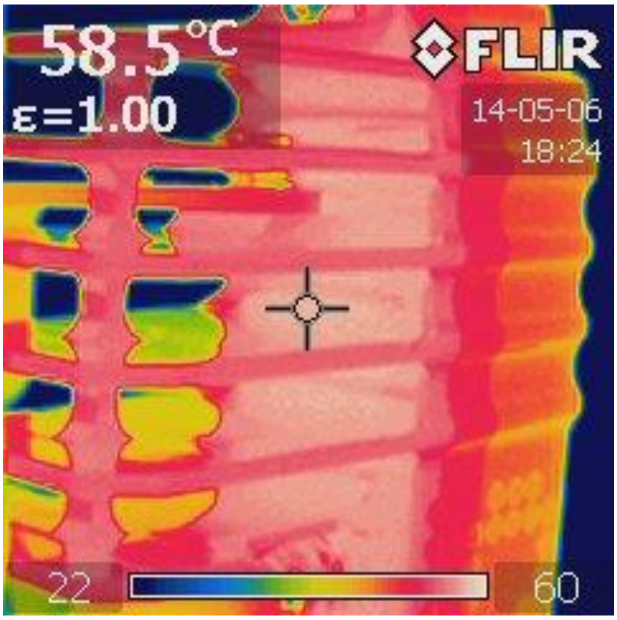

Figure 25. Hottest spot of the casing when mounted vertically (Compiled by author)

10 DISCUSSIONS

This thesis study focuses on a problem very common in today’s world; cooling of a LED light. The thesis work was requested by Five Watts Oy, as a part of the project to create a reliable LED work light in all respects, including cooling.

The company had already decided upon passive cooling, due to the superior mechanical ruggedness of such a system, but other methods were looked into for good measure, and for possible later use in other projects.

Passive cooling by convection is as such rather ineffective, so in order to provide the best cooling for the lamp at all times, different heat sink configurations were simulated with CFD (Computational Fluid Dynamics) to get a more accurate cooling fin placement. Since the physical dimensions of the lamp had already been set, what remained was to optimize the spacing between cooling fins and test if the set outer dimensions could be used. A lot of thought was put into the cooling design, since overheating directly reduces the lifetime of electronics components, including the LEDs themselves.

It is important to be aware of how heat travels inside the casing, and how much the thermal path from LED junction to the casing can be affected by the internal design, so this was also looked into.

It turned out that great care must be taken when designing LED light cooling systems, if not using a ready made heat sink with easily accessible convection cooling values. And even with the values, one might get a poor result if the heat sink isn't oriented as intended.

During this thesis study the heat sink design got improved. A functional and durable cooling profile was suggested, CFD simulations were made for different test models out of which the model with the best results in terms of air velocity and temperature was chosen. These were the main goals to the work which were achieved within this thesis study.

In this work, thermal management of high power LED system were discussed. This topic is extremely critical and understanding it is essential when designing and developing LED systems. Basic information about LEDs, concepts of heat transfer were briefly introduced, covering facts about LEDs, convection, conduction and radiation processes as well as thermal resistance model. Different types of heat dissipation to the environment were discussed. Based on the theoretical studies, a model of the heat sink was created, it was further optimized with the help of CFD analyses. The results from simulation were implemented to the CAD model of the product which led to the manufacturing of prototypes, their testing and finally to the product release.

The knowledge of thermal management of the LEDs helps to design efficient and reliable LED systems. The study done for this thesis has proven very valuable for Five Watts Oy, by delivering a working, optimized cooling solution for a LED work light.

As a result of this thesis work, Five Watts Oy now has a finished product, the Zaurac 4-30, currently with market leading quality-to-price ratio considering size, weight, light output, light quality (smoothness of beam and color temperature), internal electrical protection and cooling.

In today's world, where resource conservation is crucial, it seems only right to try to maximize the lifespan of tools and products, and with the recent emergence of more and more LED lights promising 100 000 of hours of lifetime, the importance of a long-term design (including effective cooling) that actually delivers those hours should be emphasized instead of low prices.

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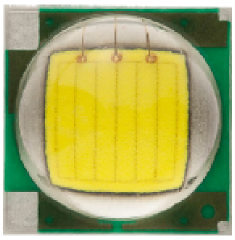
APPENDIX 1

CREE

PRODUCT FAMILY DATA SHEET

CLD-DS33 REV 9A

Cree® XLamp® XM-L LEDs



PRODUCT DESCRIPTION

The XLamp XM-L LED is the industry's highest performance, single-die white lighting-class LED. The XLamp XM-L is 20% more efficient than the XLamp XP-G at the same current, and can deliver 1000 lumens with 100 lumens per watt efficacy. The XLamp XM-L LED offers Cree's industry-leading features: wide viewing angle, symmetrical package, unlimited floor life and electrically neutral thermal path.

XLamp XM-L LEDs can enable LED light into new applications that require tens of thousands of lumens, such as high bay and high-output area lighting. The XM-L is also the ideal choice for lighting applications where high light output and maximum efficacy are required, such as LED light bulbs, outdoor lighting, portable lighting, indoor lighting and solar-powered lighting.

FEATURES

- Maximum drive current: 3000 mA
- Low thermal resistance: 2.5 °C/W
- Maximum junction temperature: 150 °C
- Viewing angle: 125°
- Available in cool white, 80-CRI minimum neutral white and 80-CRI, 85-CRI and 90-CRI warm white
- ANSI-compatible chromaticity bins
- Unlimited floor life at ≤ 30 ºC/85% RH
- Reflow solderable - JEDEC J-STD-020C
- Electrically neutral thermal path
- RoHS- and REACh-compliant
- UL-recognized component (E349212)

TABLE OF CONTENTS

WWW.CREE.COM/XLAMP

Cree, Inc.
4600 Silicon Drive
Durham, NC 27703
USA Tel: +1.919.313.5300

CHARACTERISTICS

Characteristics	Unit	Minimum	Typical	Maximum
Thermal resistance, junction to solder point	°C/W		2.5	
Viewing angle (FWHM)	degrees		125	
Temperature coefficient of voltage	mV/°C		-2.1	
ESD withstand voltage (HBM per Mil-Std-883D)	V			8000
DC forward current	mA			3000
Reverse voltage	V			5
Forward voltage (@ 700 mA)	V		2.9	3.5
Forward voltage (@ 1500 mA)	V		3.1	
Forward voltage (@ 3000 mA)	V		3.35	
LED junction temperature	°C			150

FLUX CHARACTERISTICS (T_J = 25 °C)

The following table provides several base order codes for XLamp XM-L LEDs. It is important to note that the base order codes listed here are a subset of the total available order codes for the product family. For more order codes, as well as a complete description of the order-code nomenclature, please consult the XLamp XM-L Binning and Labeling document.

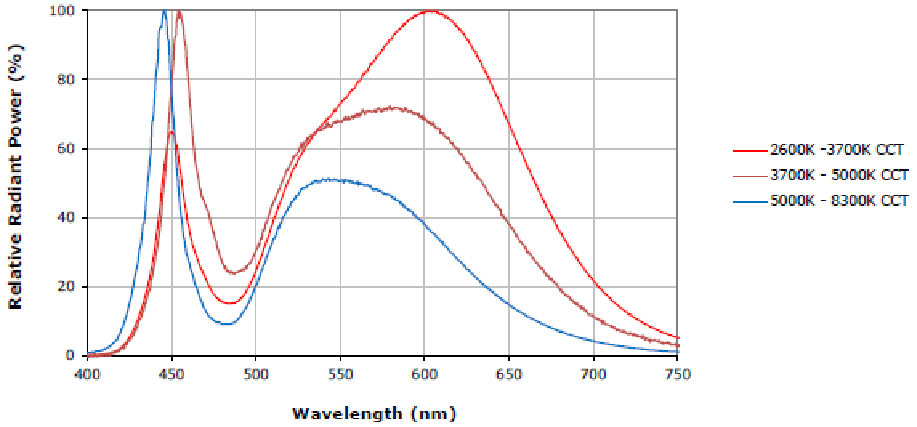
Color	CCT Range		Base Order Codes Min. Luminous Flux @ 700 mA		Calculated Minimum Luminous Flux (lm)*			Order Code
	Min.	Max.	Group	Flux (lm)	1000 mA	1500 mA	2000 mA	
Cool White	5000 K	8300 K	T5	260	360	511	643	XMLAWT-00-0000-0000T5051
			T6	280	388	551	692	XMLAWT-00-0000-0000T6051
			U2	300	416	590	742	XMLAWT-00-0000-0000U2051
Neutral White	3700 K	5000 K	T4	240	332	472	593	XMLAWT-00-0000-000LT40E4
			T5	260	360	511	643	XMLAWT-00-0000-000LT50E4
80-CRI White	2600 K	4300 K	T2	200	277	393	494	XMLAWT-00-0000-000HT20E7
			T3	220	305	433	544	XMLAWT-00-0000-000HT30F7
Warm White	2600 K	3700 K	T2	200	277	393	494	XMLAWT-00-0000-000LT20E7
			T3	220	305	433	544	XMLAWT-00-0000-000LT30F7
85-CRI White	2600 K	3200 K	S4	164	227	323	406	XMLAWT-00-0000-000PS40E7
			S5	172	238	338	425	XMLAWT-00-0000-000PS50E7
			S6	182	252	358	450	XMLAWT-00-0000-000PS60E7
90-CRI White	2600 K	3200 K	S4	164	227	323	406	XMLAWT-00-0000-000US40E7
			S5	172	238	338	425	XMLAWT-00-0000-000US50E7
			S6	182	252	358	450	XMLAWT-00-0000-000US60E7

Notes:

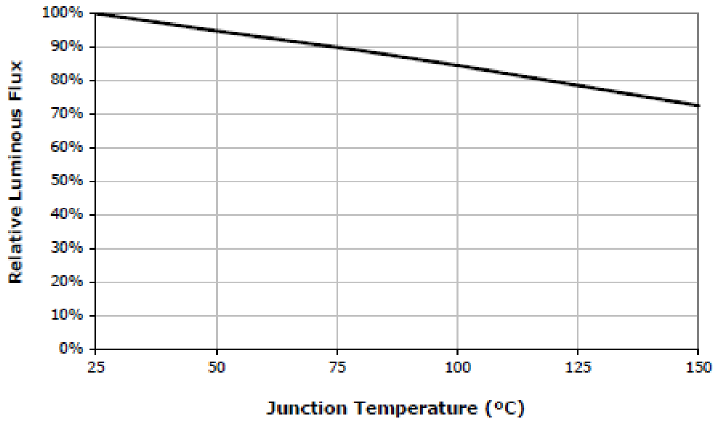
- Cree maintains a tolerance of ± 7% on flux and power measurements, ±0.005 on chromaticity (CCx, CCy) measurements and ± 2 on CRI measurements.
- Typical CRI for Cool White (5000 K – 8300 K CCT) is 65.
- Typical CRI for Neutral White (3700 K – 5000 K CCT) is 75.
- Typical CRI for Warm White (2600 K – 3700 K CCT) is 80.
- Minimum CRI for 80-CRI White is 80.
- Minimum CRI for 85-CRI White is 85.
- Minimum CRI for 90-CRI White is 90

* Calculated flux values are for reference only.

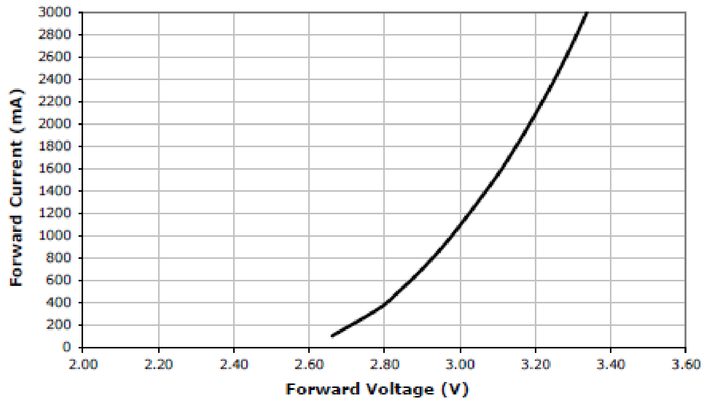
RELATIVE SPECTRAL POWER DISTRIBUTION



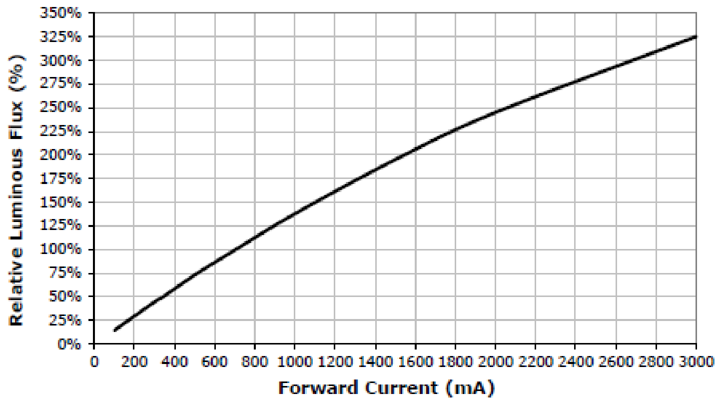
RELATIVE FLUX VS. JUNCTION TEMPERATURE (I_F = 700 mA)



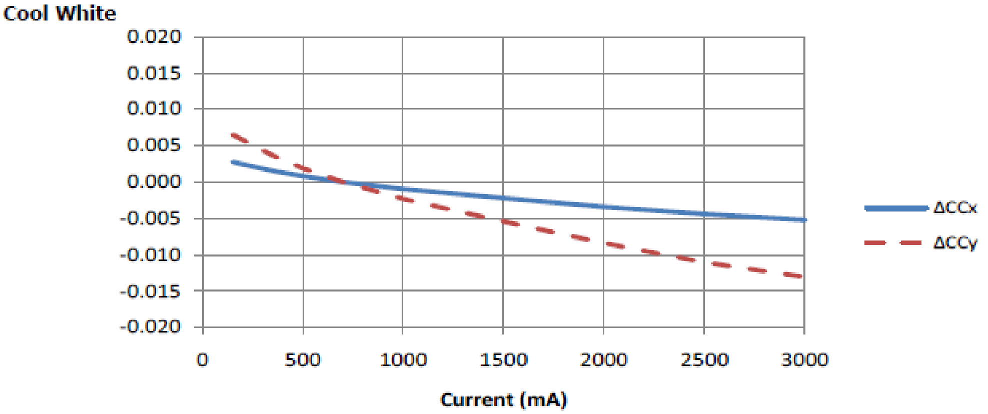
ELECTRICAL CHARACTERISTICS (T_J = 25 °C)



RELATIVE FLUX VS. CURRENT (T_J = 25 °C)



RELATIVE CHROMATICITY VS. CURRENT (COOL WHITE)



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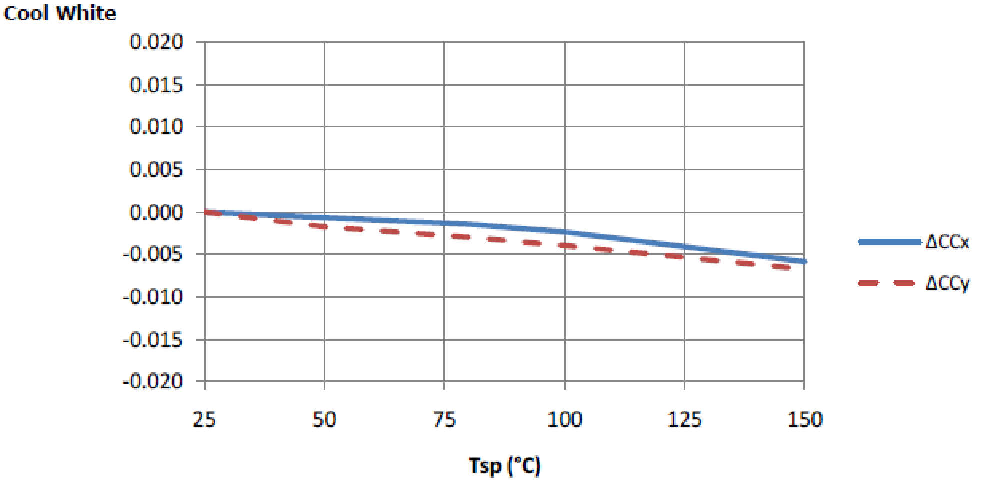
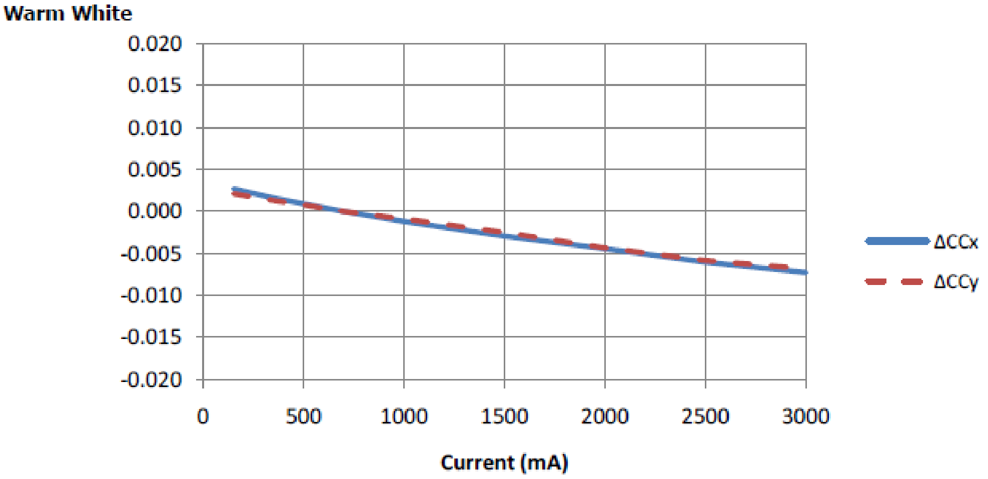
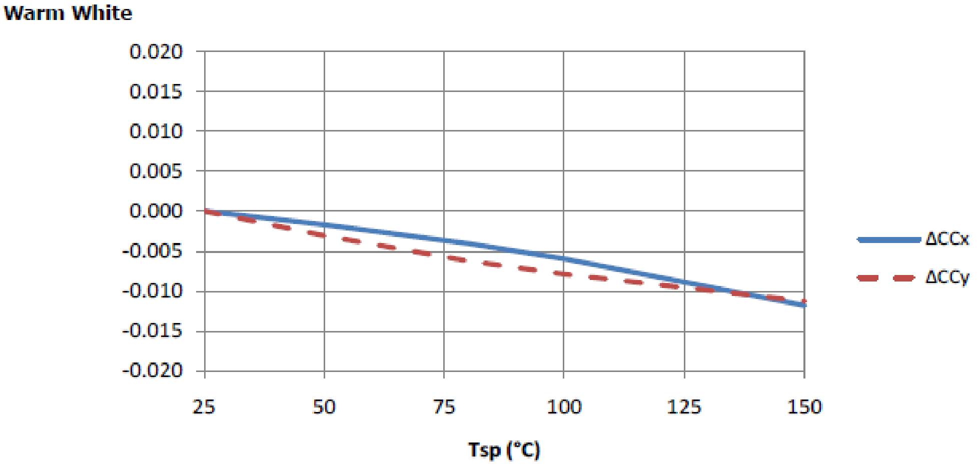


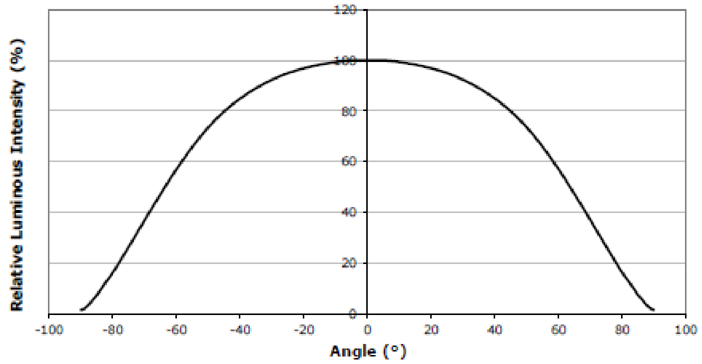
RELATIVE CHROMATICITY VS. CURRENT (WARM WHITE)



RELATIVE CHROMATICITY VS. TEMPERATURE (WARM WHITE)

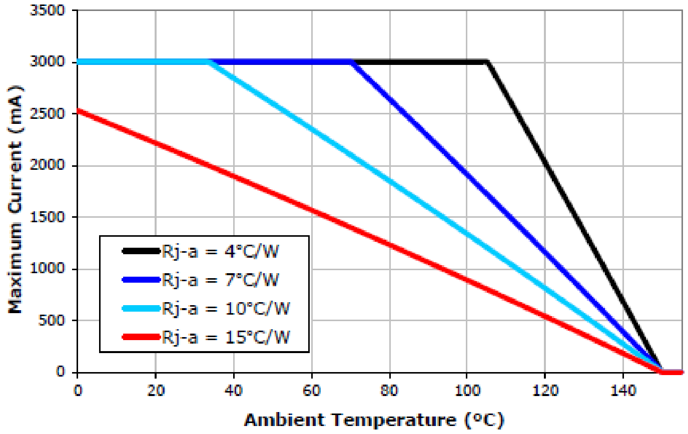


TYPICAL SPATIAL DISTRIBUTION



THERMAL DESIGN

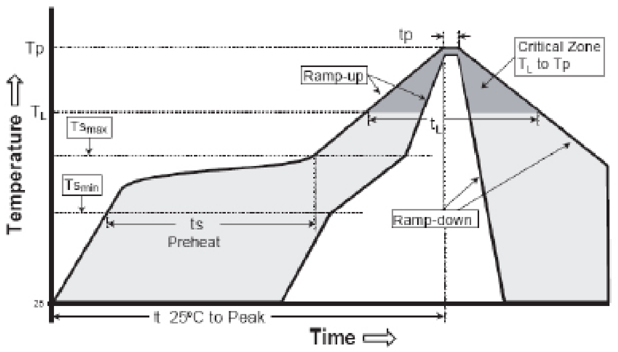
The maximum forward current is determined by the thermal resistance between the LED junction and ambient. It is crucial for the end product to be designed in a manner that minimizes the thermal resistance from the solder point to ambient in order to optimize lamp life and optical characteristics.



REFLOW SOLDERING CHARACTERISTICS

In testing, Cree has found XLamp XM-L LEDs to be compatible with JEDEC J-STD-020C, using the parameters listed below. As a general guideline, Cree recommends that users follow the recommended soldering profile provided by the manufacturer of solder paste used.

Note that this general guideline may not apply to all PCB designs and configurations of reflow soldering equipment.



IPC/JEDEC J-STD-020C

Profile Feature	Lead-Based Solder	Lead-Free Solder
Average Ramp-Up Rate (Ts_{max} to Tp)	3 °C/second max.	3 °C/second max.
Preheat: Temperature Min (Ts_{min})	100 °C	150 °C
Preheat: Temperature Max (Ts_{max})	150 °C	200 °C
Preheat: Time (ts_{min} to ts_{max})	60-120 seconds	60-180 seconds
Time Maintained Above: Temperature (T_L)	183 °C	217 °C
Time Maintained Above: Time (t_L)	60-150 seconds	60-150 seconds
Peak/Classification Temperature (Tp)	215 °C	260 °C
Time Within 5 °C of Actual Peak Temperature (tp)	10-30 seconds	20-40 seconds
Ramp-Down Rate	6 °C/second max.	6 °C/second max.
Time 25 °C to Peak Temperature	6 minutes max.	8 minutes max.

Note: All temperatures refer to the topside of the package, measured on the package body surface.

NOTES

Lumen Maintenance Projections

Cree now uses standardized IES LM-80-08 and TM-21-11 methods for collecting long-term data and extrapolating LED lumen maintenance. For information on the specific LM-80 data sets available for this LED, refer to the public LM-80 results document at www.cree.com/xlamp_app_notes/LM80_results.

Please read the XLamp Long-Term Lumen Maintenance application note at www.cree.com/xlamp_app_notes/lumen_maintenance for more details on Cree's lumen maintenance testing and forecasting. Please read the XLamp Thermal Management application note at www.cree.com/xlamp_app_notes/thermal_management for details on how thermal design, ambient temperature, and drive current affect the LED junction temperature.

Moisture Sensitivity

In testing, Cree has found XLamp XM-L LEDs to have unlimited floor life in conditions ≤30 ºC/85% relative humidity (RH). Moisture testing included a 168-hour soak at 85 ºC/85% RH followed by 3 reflow cycles, with visual and electrical inspections at each stage.

Cree recommends keeping XLamp LEDs in their sealed moisture-barrier packaging until immediately prior to use. Cree also recommends returning any unused LEDs to the resealable moisture-barrier bag and closing the bag immediately after use.

RoHS Compliance

The levels of RoHS restricted materials in this product are below the maximum concentration values (also referred to as the threshold limits) permitted for such substances, or are used in an exempted application, in accordance with EU Directive 2011/65/EC (RoHS2), as implemented January 2, 2013. RoHS Declarations for this product can be obtained from your Cree representative or from the Product Ecology section of www.cree.com.

REACh Compliance

REACh substances of high concern (SVHCs) information is available for this product. Since the European Chemical Agency (ECHA) has published notices of their intent to frequently revise the SVHC listing for the foreseeable future, please contact a Cree representative to insure you get the most up-to-date REACh Declaration. Historical REACh banned substance information (substances restricted or banned in the EU prior to 2010) is also available upon request.

UL Recognized Component

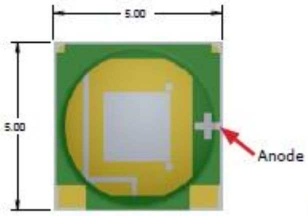
Level 4 enclosure consideration. The LED package or a portion thereof has been investigated as a fire and electrical enclosure per ANSI/UL 8750.

Vision Advisory Claim

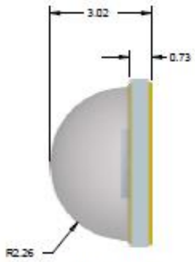
WARNING: Do not look at exposed lamp in operation. Eye injury can result. See the LED Eye Safety aplication note at www.cree.com/xlamp_app_notes/led_eye_safety.

MECHANICAL DIMENSIONS

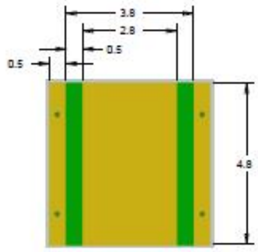
All measurements are ±.13 mm unless otherwise indicated.



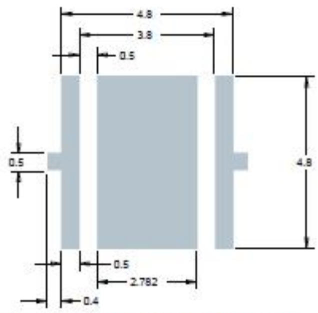
Top View



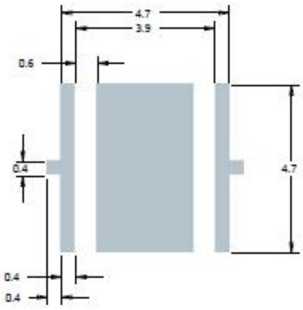
Side View



Bottom View



Recommended PCB Solder Pad

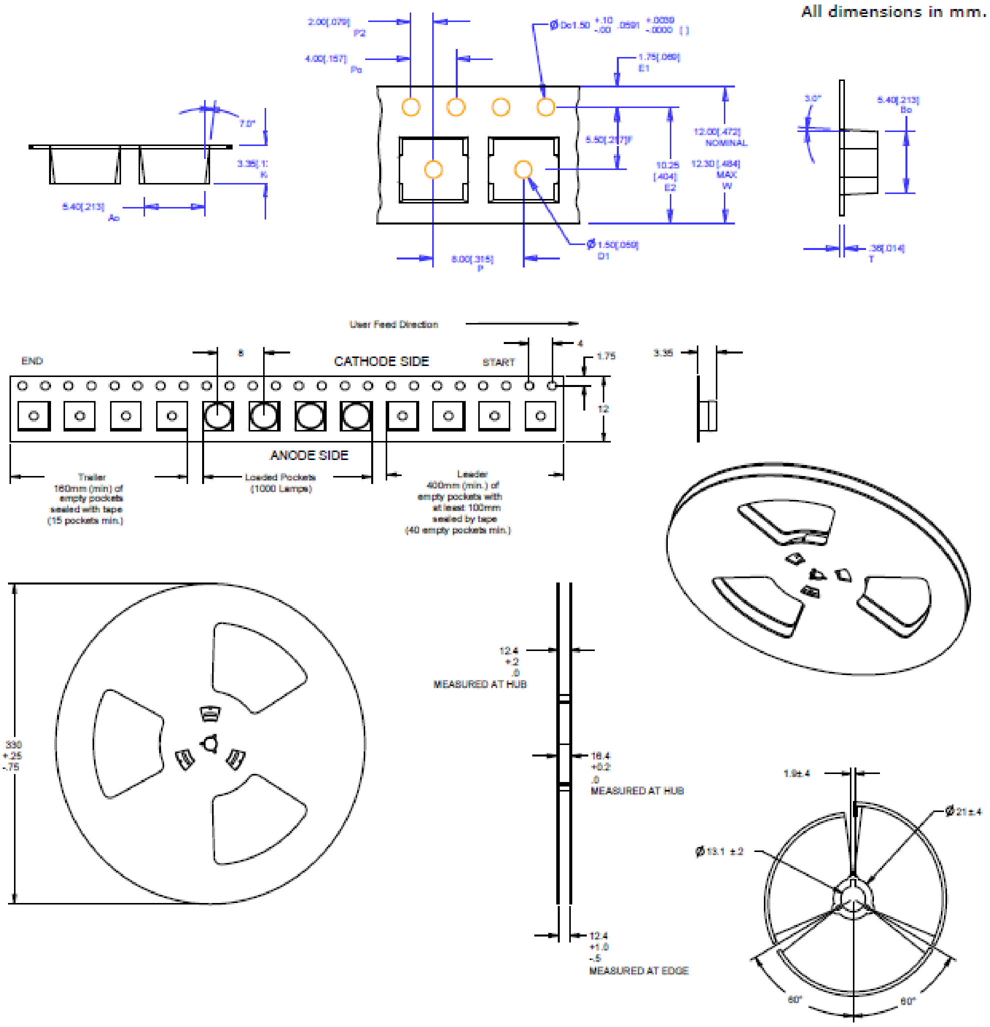


Recommended Stencil Pattern
(Shaded Area Is Open)

TAPE AND REEL

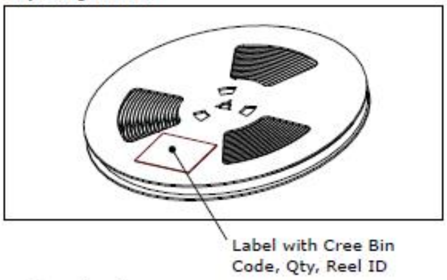
All Cree carrier tapes conform to EIA-481D, Automated Component Handling Systems Standard.

All dimensions in mm.

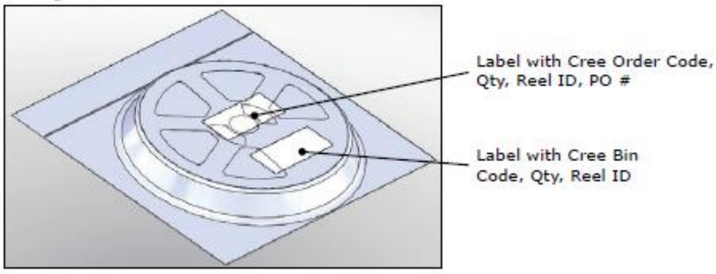


PACKAGING

Unpackaged Reel



Packaged Reel



Boxed Reel