Thermal Simulations of an LED Light Using Comsol Multiphysics

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Abstract

An experimental LED light composed of a multi-chip LED module, a LED driver and an efficient heatsink, was investigated using Comsol Multiphysics software and the Heat Transfer Module. In an LED light heat is mainly generated in the LEDs but some amount of heat is generated also in the LED driver. The main target of the simulations was to resolve the junction temperatures of LEDs, the most important information related to the light production and operational life time of the LEDs. The simulations provided temperatures in various parts of the LED light structure in steady-state conditions. An approximate thermal model was constructed based on the results. Time dependent simulations resolved the main time constant of the structure. Combining photometric measurements to the thermal measurements, luminous flux versus the junction temperature was resolved. The simulation results were validated using temperature measurements made with thermocouples and IR-imaging.

Keywords: LED light, thermal simulation

1. Introduction

Solid-state lighting (SSL) based on LEDs is replacing traditional lighting technologies like incandescent and compact fluorescent (CFL) lighting. The benefits of an LED light compared with the traditional lights are significantly higher light production and a longer lifetime. The typical light production of present-day high brightness white LED is between 30-130 lm/W. Lifetime can be even 25 000 - 50 000 hours. The benefits of LED technology can easily be lost if thermal management is not made properly. Both the light production and the lifetime will be reduced if the temperature of an LED will be increased. The most important parameter is the junction temperature of the LED. Often the junction temperature is well below 100 °C, sometimes even higher but clearly below 150 °C . In case the junction temperature rises up to or near 150 °C the total destruction of the LED is liable to happen. The thermal design of an LED light can be based on thermal simulations made with FEM software. In this work Comsol Multiphysics and the Heat Transfer Module have been used to simulate an experimental LED light composed of an effective LED module and an heatsink. Comsol Multiphysics has been widely used in studies of LED light thermal issues [1-2].

2. CAD model for the LED light

3D thermal model building for an LED light will be started by using a CAD tool to draw the geometry. This will be done using the CAD tool of the Comsol Multiphysics.

A high power white LEDs are most often based on GaN LEDs which have a phosphor layer covering them. GaN LED generates blue light which spectral width is rather narrow. The function of the phosphor layer is to convert this light to a white light which spectrum would cover large part of visible light. In order to reduce thermal resistance from a LED to package of it multichip structure is widely used.

In this work, the used LED module includes 140 LEDs. LEDs are mounted on aluminum substrate using a fixture of high thermal conductivity. LEDs are enclosed with flat silicon package. There are no lenses or other optical elements included. The LED module can be used as part of spot light if a reflector is included. The wide radiation angle (120 degrees) makes it possible to use it as a part of a powerful spot or down light.

The internal structure of the LED packages in the module is largely unknown. There are basically three possible configurations for an LED chip:

face-up, flip chip and vertical chip [3]. From the thermal point of view the flip chip and vertical chip do not differ much. The following study assumes the face-up chip configuration is in use. Figure 1 illustrates that configuration. The measures in the figure are typical values. The bonding wires (not shown in the Fig 1.) show minor role in heat transfer and they are not included in the simulation model.

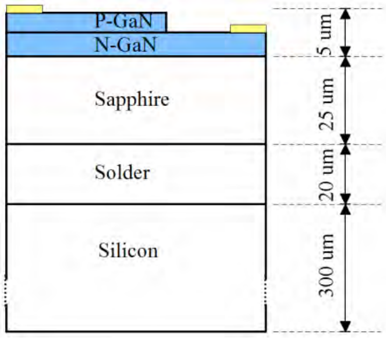

Figure 1. A cross-section of a single LED package with the face-up chip configuration.

Two stainless steel screws are used to fasten the LED module firmly on the heatsink. Small amount of thermal grease is normally used between the LED module and the heatsink. Unless otherwise mentioned, 100 µm layer of thermal grease is included in the simulation model.

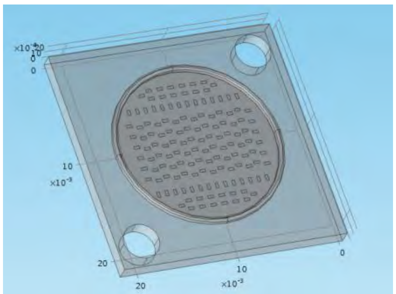

Figure 2. The geometry of the LED module.

The aluminum heatsink is a rather efficient model able to dissipate the maximum heat power of the LED module in external natural convection. The heatsink has a large number of fins. There are practically two choices for the LED module mounting. In case of a spotlight, the LED module would be on the inner side of the heatsink. In this case, a roof light is constructed and the LED module is mounted on the outer side. This leaves the inner side empty or as a place to locate the LED-driver. A plastic bulb is mounted on the LED module. The material of the dim bulb is assumed to be polycarbonate. In this experimental construction, the bulb is fixed using epoxy glue. The sealing is not air tight. There will be normal constant air pressure inside the bulb. A CAD model for this volume will also be created. All the models will be created with separate projects and their geometry will be included in the main project using the model import feature of Multiphysics.

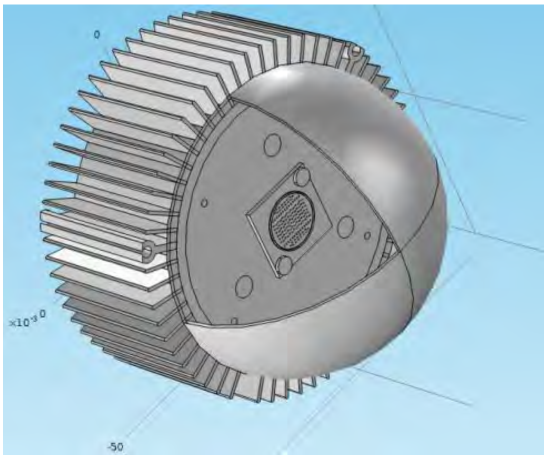

Figure 3. The geometry of the LED light model.

Multiphysics calculates volume or surface integrals. The volume of the heatsink model is calculated and mass of is resolved using the known density. This ensures the uniformity of heatsink and its model. Some of the other calculated measures are listed in the Table 1.

Table 1. Some dimensions of the heatsink model.

Volume	100.7 cm^3
Surface	847.2 cm^2
Convection heat surface	807.4 cm^2
Conduction heat surface	39.8 cm^2

3. Thermal model and simulations

For completing the simulation model, material characteristics must be included in the model. Some of the materials can be found in the standard material library of Multiphysics. Table 2 lists some of the characteristics of the used materials.

Using symmetries is an effective way to reduce the size of the model. In 3D-model, a symmetry boundary will be defined. In this case one half of the geometry is used. The model still includes some small details which could be removed to make the model even more efficient for computing.

Multiphysics has “Joule Heating interface” which is applicable and adequate for this study. In the “Joule Heating interface” several models are included to cover different heat transfer mechanisms. “Heat Transfer in Solids” models heat transfer in all solid domains of the model. “Heat Transfer in Fluids” models heat transfer in the air domain inside the bulb. “Convective Cooling” models heat convection to ambient and all the outer surfaces which participate in heat convection to ambient will be selected for this model. Heat radiation is modeled by including “Surface-to-Ambient Radiation” and “Surface-to-Surface Radiation” models. The dimensions of the LED packages (as shown in fig.1) are very small in comparison with other dimensions of the LED light. The LED package is therefore defined using “Thin Thermally Resistive Layer” model where the multiple layer feature can be used. The thermal grease layer will be defined similarly.

There are some methods thermal sources can be added into the model. The total electrical power which is dissipated in the LEDs can be entered by the user. The heat sources can be domains or boundaries. The latter is the simplest and as the LED chips are rather thin, it is possible to model them as heat generating surfaces. The electro-optical efficiency of the LEDs must be known as part, normally max 20 % of the electrical power is transformed to optical light and the rest of the power will be dissipated as heat.

Table 2. Typical characteristics for the materials used in the model.

Material	Density ρ, kg/m^3	Thermal Conductivity k, W/(m·K)	Specific Heat C_p, J/(kg·K)
Air [1]	1.127	0.0271	1005
Aluminum	2700	160	900
Aluminum 6063	2700	201	900
GaN	6150	130	483
Polycarbonate	1150	0.2	1250
Sapphire	3980	41.9	875
Silicon	2329	130	700
Silicon package	1060	2	700
Solder SnAg	7290	78	221
Structural steel	7850	44.5	475
Thermal grease	2800	1	705

[1] at 20 °C. Multiphysics uses exact equations for air in different conditions.

Mesh is generated automatically using the element size “finer”. Thermal simulation for the stationary case requires (desktop computer, Core 2 Duo, 2.33 GHz, 8 GB memory) approximately 22-27 minutes of computing time when the surface-to-surface radiation model is included in the model. When the model is not included, simulation requires approximately 4-5 minutes to be completed.

Time dependent thermal simulation resolves the time constants of the LED light. The main time constant is defined by the thermal resistance and the heat capacity related to the heatsink. The temperature of the LED chip rises fast but it takes relatively long time until the heatsink has reached its stationary temperature. The measured surface point is in the middle of the heatsink on the inner side of the heatsink. Figure 5 shows both the measured and the simulated temperature. They match well together with the exception of 2°C difference in the stationary conditions.

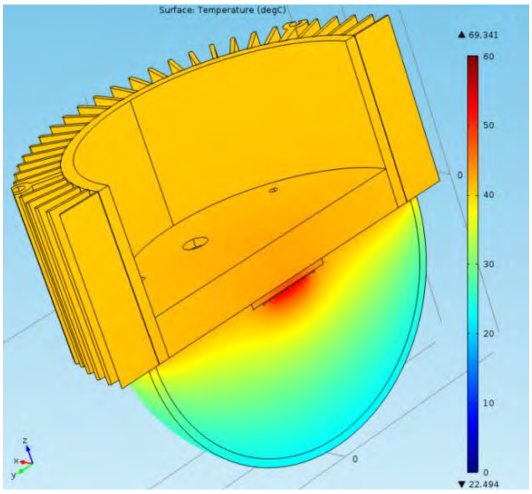

Figure 4. Surface temperature in stationary conditions in case P_{LED} = 14.46 W, I_{LED} = 350 mA and natural external convection conditions.

Multiphysics software allows simulation data to be post processed. Domain or boundary probes can be defined for calculating the average or integral values of selected parameters. The average temperature of the heatsink, the LED module, the bulb and the air domain were calculated by this way. Total normal heat fluxes which flow through the selected surfaces were calculated in order to resolve the thermal resistances.

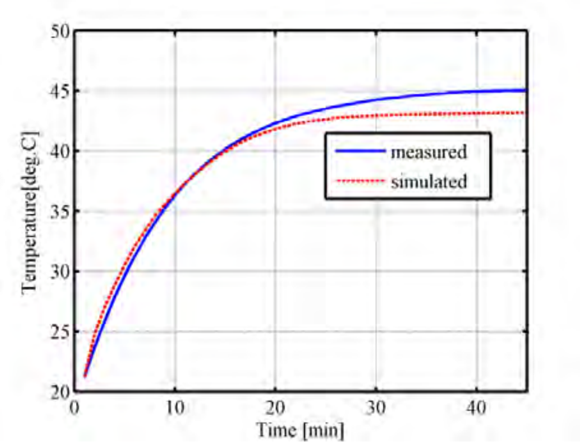

Figure 5. Time dependent thermal simulation. P_{LED} = 14.46 W, I_{LED} = 350 mA. The surface point is in the middle of the heatsink.

4. Photometric measurements

The luminous flux and spectrum of the LED light are measured using an integrating sphere and a photometer & spectrometer attached to it. Light generation per used electrical power, the efficacy, will be defined. The measured spectral radiant power (W/nm) will be integrated over the visible range of light. This results in total light power. The electro-optical efficiency can be defined by dividing the light power by the input electric power. Measurements were done in stationary conditions when temperatures were already stabilized.

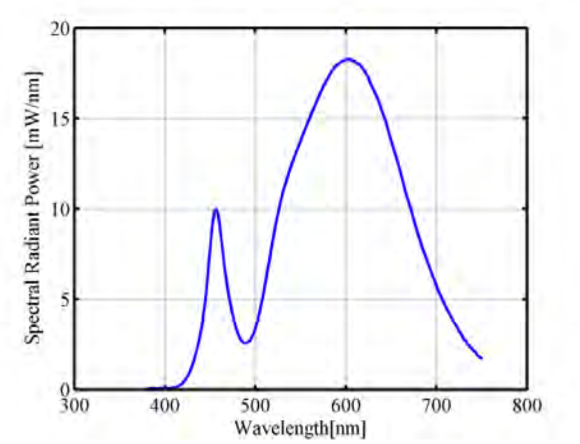

Figure 6. Measured spectral radiant power of the LED light. P_{LED} = 14.46 W, I_{LED} = 350 mA.

Table 3. Luminous flux [lm], efficacy [lm/W], electro-optical efficiency [%].P_{LED} = 14.46 W, I_{LED} = 350 mA.

Configuration	[lm]	[lm/W]	[%]
without the bulb	1072	72.1	22.7
with the bulb	986	66.3	21.8

5. Heat convection coefficient and thermal resistance

A large number of empirical equations for the heat convection coefficient of structures can be found in the text books of heat transmission. The following equation presented by W. McAdams already 1950's is valid for the case of laminar gas or fluid flow in natural heat convection [4]. The heat convection coefficient will be calculated for a heatsink which can be approximated to be a vertical or horizontal cylinder or plate. Dimensionless number C will be set according to the geometrical form and the value of the Rayleigh number (Ra). The Rayleigh number is the product of the Prandtl number (Pr) and the Grashof number (Gr). The Nusselt number (Nu) can be calculated by using the values of Gr and Pr. Lch is the characteristic length of the heatsink. Exponent n depends on the geometry and fluid conditions. For laminar flow n is typically 1/4, for turbulent flow n is increased to 1/3.

$$h_c = \frac{N_u \cdot k}{L} \quad (1)$$

$$N_u = C \cdot (G_r P_r)^n \quad (2)$$

$$G_r = \frac{L^3 \rho^2 g \beta \Delta T}{\mu^2} \quad (3)$$

$$P_r = \frac{\mu C_p}{k} \quad (4)$$

The other parameters are:

k = thermal conductivity of air [W/m·K]
L = characteristic length [m]
ρ = density [kg/m^3]
g = gravity [m/s^2] = 9.80665 m/s^s
β = coefficient of volumetric expansion [1/K]
ΔT = temperature difference between the surface and ambient
μ = viscosity of the fluid [kg/m^2·s] = [Pa·s]
C_p = specific heat of the fluid [J/kg·K]

The equations of McAdams are often referenced in studies of LED light thermal control [5]. Improved equations for vertical heatsink of multiple parallel fins is presented by R.E. Simons [6].

Table 4. Parameters used in the McAdams' model for natural heat convection and laminar air flow.

Geometry	L_{ch}	C	n
Vertical cylinder	H	0.59	0.25
Horizontal cylinder	D	0.53	0.25
Sphere	R	0.59	0.25
Vertical plate	H	0.59	0.25
Horizontal plate upper surface	0.5·WL/(W+L)	0.54	0.25
Horizontal plate bottom surface	0.5·WL/(W+L)	0.27	0.25

For a heatsink which has a large number of fins mounted on a flat plate, there is an equation presented by Churchill and Chu [7]. While using the model of McAdams the used heatsink is approximated to be a vertical cylinder or a vertical plate. Table 5 lists the calculated values and the simulated value for the h_c. The experimental equations overrate the h_c. This is understandable as the convection surface is some amount reduced by the bulb.

Table 5. The calculated and simulated heat convection coefficient of the heatsink.

Model	h_c [W/m²·K]
McAdams	7.08
Churchil & Chu	6.56
Simulated	5.39

The thermal resistance of heatsink is related to the heat convection coefficient.

$$R_{th} = \frac{1}{h_c A_c} \quad (5)$$

Where A_c is the surface area of heat convection.

Table 6. Simulated average temperatures. P_{LED} = 14.46 W, I_{LED} = 350 mA.

Domain	Avg. Temperature [°C]
Ambient	21.0
Heatsink	41.8
LED module	46.0
LED chip	64.4
LED junction	86.5 [1]

[1] Junction temperature is calculated using data given by the manufacture.

As a part of the heatsink surface is covered by the bulb the surface area for heat convection is reduced. This causes h_c to decrease. Some amount of heat is conducted from the heatsink to the air inside the bulb. Part of this heat flow will be absorbed inside the bulb and part will be removed via convection to ambient via the surface of the bulb. This is a minor thermal path for the heat as most of the heat (> 90 %) flows from the LED module to ambient via the heatsink. The main thermal resistances of the LED light has been resolved from the simulations and are shown in the table below.

Table 7. The main thermal resistances.

Thermal Resistance	R_{th} [°C/W]
LED chip to module $R_{th, j-m}$	3.55
LED module to heatsink $R_{th,m-h}$	0.36
Heatsink to ambient $R_{th,h-a}$	2.30

The thermal resistance from junction to ambient is 5.66 °C/W. As there are other thermal paths than LED/chip -> LED module –> heatsink –> ambient, the total thermal resistance is not the sum of resistances in Table 7 but somewhat less.

6. Validation of the simulations results

For the validation of the simulation results both thermocouples and IR-imaging are used to measure the surface temperatures of the LED light. The thermocouples are the most reliable ones. In the IR-imaging, the measured values depend on the emission coefficients of surface materials. Unless the IR-image is not corrected by the right emission coefficient it shows somewhat lower value than the thermocouple.

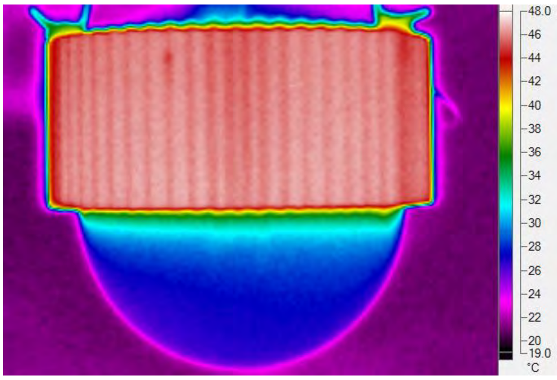

Figure 7. IR-image of the LED light. P_{LED} = 14.46 W, I_{LED} = 350 mA.

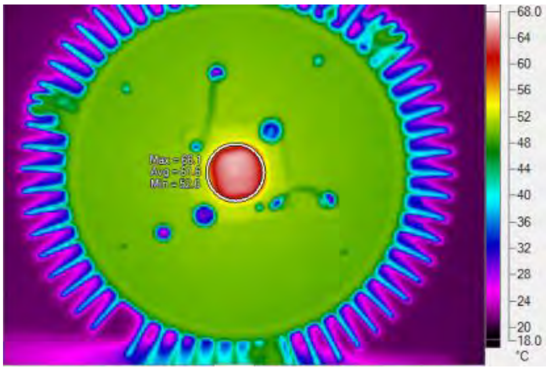

Figure 8. IR-image of the LED module and the heatsink. The bulb is removed. P_{LED} = 14.46 W, I_{LED} = 350 mA.

Figure 8 shows IR-image of the top of the LED module. The highest temperature is 66.1 °C and average 61.9 °C inside the area of the LED package surface. The bulb is removed in this photo.

7. Conclusions

Thermal simulations have been made for the experimental LED light. The created thermal model included a quite accurate geometrical model with correct material data. Photometric measurements resulted in the visible spectrum of the LEDs. The electro-optical efficiency of the LEDs was resolved from the spectrum. The electro-optical efficiency was used to define the thermal heat source equivalent to the heat dissipation of the LEDs. Temperatures of the LED light were simulated for the stationary case and the time dependent simulation resolved the time constant related to the model. Thermal grease used between the LED module and the heatsink was modeled as a thin thermally resistive layer. The main thermal resistances were resolved from the simulation results. Simulation results were validated with thermocouple and IR measurements. The simulations resulted in slightly lower values than the measurements. The difference was 2 °C for the surface of the heatsink and 3.5 °C for the surface of the LED module.

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Acknowledgements

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