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DIRECT DRIVEN AC LED MODULE TEMPERATURE MEASUREMENT, SIMULATION AND THEIR CORRELATION

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DIRECT DRIVEN AC LED MODULE TEMPERATURE MEASUREMENT, SIMULATION AND THEIR CORRELATION

This thesis studies thermal management of the LED module through simulation and testing in a laboratory. The simulator used is HyperLynx Thermal included in Mentor PADS PCB design. Before the thermal simulation and measurement, heat transfer methods and circuit board thermal behaviour are studied. Studying heat transfer methods including convection, conduction and radiation helped to understand how the heat is transferred away from the components. LED module components lifetime and heat management are also considered.

The goal was to study the thermal simulation software and to determine if it is useful and could be used in a development of a LED module. There was also a need for a user guide to the software, therefore stages of the simulation and the setup of the software are explained.

The temperature of the LED module was first measured in a temperature chamber and then the results were compared to the simulated ones. There are different test cases with variable environment for testing the simulation software and to determine the temperature chamber characteristics.

Results from the simulation software matched the temperature measurements with few degrees Celsius difference. Simulator gives a good general view of the module, which can be useful in the product design. Nevertheless, many specific or important thermal properties of the simulated module, aren't precise enough, don't work or aren't available.

From the comparison of the measurements to the simulation results, an instruction of use was made with information what the software is capable of and what are its limitations.

KEYWORDS:

LED, temperature, thermal, simulation, electronics, PCB

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SÄHKÖVERKKOON KYTKETTÄVÄN AC LED-MODUULIN LÄMPÖTILAMITTAUKSET, SIMULAATIO JA NIIDEN KORRELAATIO

Opinnäytetyössä tutkittiin LED-moduulin lämpötilahallintaa simulaation ja laboratoriotestien avulla. Työssä käytetty simulaattori on HyperLynx Thermal ohjelma, joka on osana Mentorin PADS-piirilevysuunnittelu ohjelmaa. Ennen LED-moduulin lämpötilamittauksia tutkittiin lämmön siirtymisen teoriaa, ja piirilevyn lämmönsiirto-ominaisuuksia. Lämmön siirron tutkiminen, johon kuuluu johtuminen, konvektio ja säteily auttoi ymmärtämään lämmön siirtymistä komponenteista ympäröivään ilmaan ja valaisimen runkoon. Komponenttien elinikä ja lämmönhallinnan vaikutus elinikään otettiin myös huomioon.

Päämääränä oli tutkia lämpösimulointiohjelmistoa ja sen hyödyllisyyttä LED-moduulin kehitysprosessissa. Ohjelmalle pyydettiin myös tekemään käyttöohjeet, joten testien ohella tehdyt säädöt ja asetukset kirjattiin ylös.

LED-moduulin lämpötilat mitattiin ensin lämpötilakaapissa, minkä jälkeen mitattuja tuloksia verrattiin simuloituihin tuloksiin. Testejä tehtiin eri kokoonpanoilla ja ympäristöissä, jotta simulaattorin ominaisuuksia saatiin testattua ja simulaattorin ympäristöasetukset saatiin vastaamaan lämpötilakaapin ympäristöä.

Simulaatio-ohjelman tulokset vastasivat muutamien asteiden tarkkuudella mitattuja tuloksia. Simulaattorin alkuperäisiä ympäristöasetuksia täytyi kuitenkin säätää, jotta tulokset saatiin täsmäämään. Simulaattori antoi moduulin lämpokäyttäytymisestä kokonaiskuvan, jonka hyödyntäminen on mahdollista tuotekehityksessä. Kuitenkin monet tärkeät ominaisuudet, joista kaipasi lisää tietoa, eivät toimineet, olleet tarpeeksi tarkkoja tai eivät olleet saatavilla.

Ohjelmalle suoritetuista testeistä ja vertailusta lämpökaapin mittaustuloksiin tehtiin ohjeet. Käyttöohjeiden ohella selvitettiin, mihin ohjelma kykenee ja käydään läpi osa-alueita, joissa esiintyi ongelmia.

ASIASANAT:

LED, lämpötila, simulointi, piirilevy

SYMBOLS AND ABBREVIATIONS

°C	Degree Celsius
AC	Alternating current
ActivePAQ	AC direct driven LED module by Tepcomp oy
ε	Emissivity
FET	Field effect transistor
L	Lifetime
LED	Light emitting diode
Mosfet	Metal-oxide-semiconductor field-effect transistor
PADS	Mentor's PCB design software (Personal Automated Design Solutions)
PCB	Printed circuit board
$\dot{Q}$	Heat flow, heat transfer rate
R	Resistance
$R\theta_{a\text{-}b}$	Thermal resistance between points (°C/W)
RGB	Red, green, blue
T	Temperature
TC point	Temperature measurement point of the circuit board
K	Kelvin
W	Watt
λ	Thermal conductivity

CONTENTS

1 INTRODUCTION

The goal of the thesis was to study the possibilities of thermal simulation software as one of the designing tools for LED modules. The software for simulation was HyperLynx Thermal simulation software. The LED module studied in the thesis is an AC direct driven ActivePAQ from Tepcomp Ltd. After testing the capabilities of the software, an instruction of use was requested, therefore simulation test settings are documented.

The simulation software had not been used before for designing LED modules, therefore, it was necessary to determine what it could simulate and how. The temperature simulation of the module could reduce the prototyping steps by giving more information about the thermal behaviour of the module beforehand. Lessening the prototyping steps lowers costs and reduces time needed for development.

Heat management of LEDs and LED modules are studied well in the thesis [1]. LED manufacturers have good information about heat management and LED reliability [2] [3]. Studies of LED module thermal simulation have not been so widely documented and information of HyperLynx Thermal is scarce.

When designing LED modules one of the key factors is temperature management. Proper thermal management enables greater efficiency with more light for less power. LED modules with a driver integrated on the board have many other components along LEDs on the circuit board whose temperatures must be also considered. Heat must be properly spread out on the board and away from heat sensitive components. Excessive heat reduces component lifetimes, lumen output and can cause an early failure, resulting in module breakage or a fire risk due to the component overheating.

2 ACTIVE-PAQ LED MODULE

The LED module simulated and measured in this thesis is ActivePAQ from Tepcomp Ltd. ActivePAQ is a linear LED module with an integrated driver that can be connected straight to 230V mains. The module is 560mm long with 100 LEDs onboard that outputs 4000 lumen light output. The dimensions of the ActivePAQ can be seen in Figure 1. ActivePAQ is designed for luminaire manufacturers' lightning applications. The current source for ActivePAQs LEDs is integrated on board and no external power supply is needed [4].

ActivePAQs integrated power supply on the module makes heat management more challenging. The mosfets on board generate much more heat compared to the only passive modules with external power supplies. To manage the board temperature, heat must be spread out and conducted away from the other components, therefore, an important part in thermal management is the casing of the luminaire where ActivePAQ is attached to.

Temperature management in ActivePAQ is currently measured with four TC points. These points include: TC1 point: mosfet temperature, TC2 & TC4 points: electrolytic capacitors and TC3 point: LED temperature.

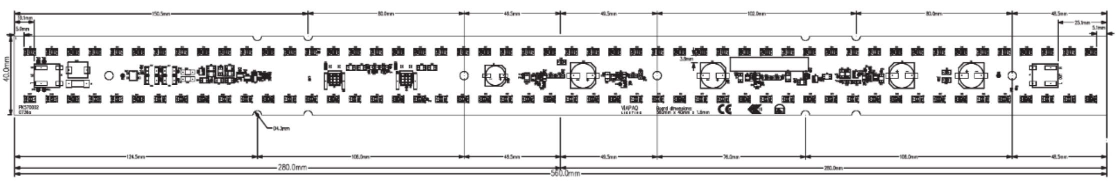


Figure 1. ActivePAQ dimensions picture [4]

3 LEDS

LED stands for light emitting diode. LEDs are semiconductors that emit optical radiation when current is applied. LEDs have a P-N junction that consists of n-type and p-type materials. Like normal diodes, LEDs work similarly by allowing the current to flow only one direction [5].

When a current is applied from the cathode to anode, the diode's electrons from the N side start to move towards the P-N junction. At the same time, the electron holes on the P side start to move also towards the P-N junction [6]. When contacting with electron holes at the junction, electrons filling the empty holes release energy in the form of electroluminescence and produce light, which can be seen in Figure 2. Part of the energy produced by the combination is heat energy produced by nearby atoms vibrating [7].

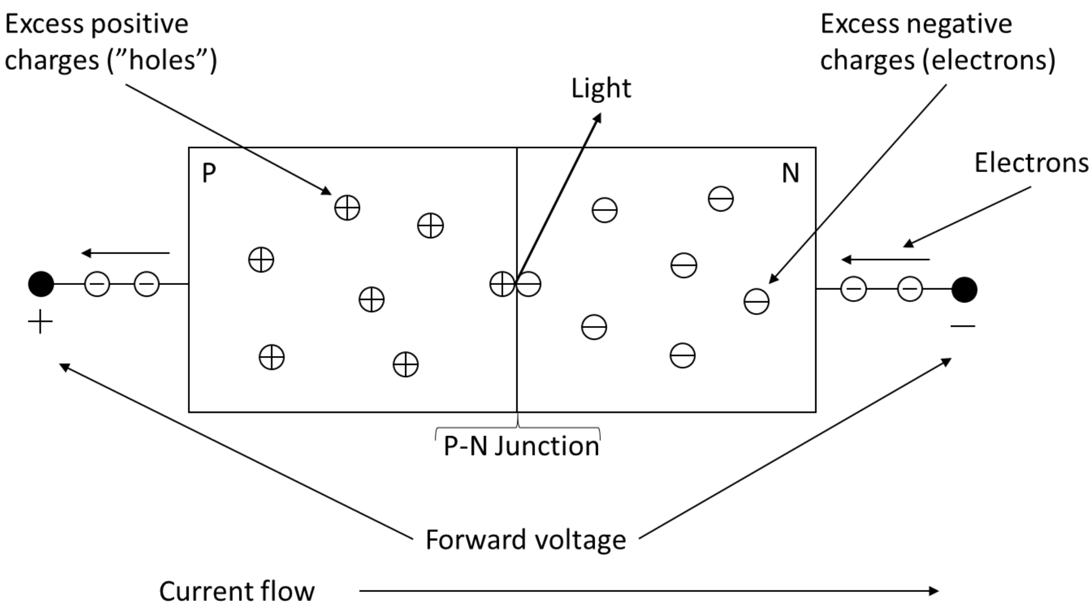


Figure 2. Functionality of LED [6].

Materials used in the semiconductor alter the wavelength of the produced light, thus allowing different colour and LED type variations. Different semiconductor materials change the energy difference between junction bands. The higher the energy difference between the bands, the shorter wavelength light is produced.

Figure 3 demonstrates how the material used changes the energy between bands resulting in different wavelengths. Different wavelengths can be achieved by using different ratios in the semiconductor material, in example: aluminium gallium arsenic (AlGaAs) or indium gallium nitride (InGaN). InGaN can be tuned to produce longer or shorter wavelengths as seen in Figure 3. Red light has the longest wavelength due the lesser energy difference between the bands.

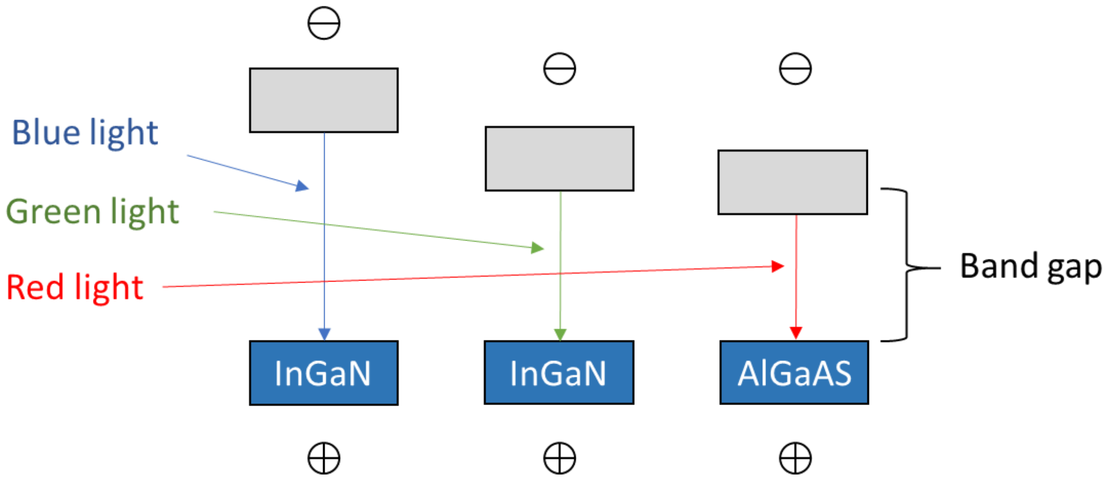


Figure 3. Producing different wavelengths [6].

White light can be produced from LED by using phosphor in front of blue LED which mixes the yellow from phosphor with emitted blue light from LED. White light can also be produced mixing RGB LEDs together where red, green and blue produce white light together. Ultraviolet light can be used by emitting it through RGB phosphor [6].

3.1 Temperature management of LEDs

Most of the power applied to LED is converted to heat. Heat is then dissipated through conduction, convection and radiation. Heat management is important for the LED so a maximum lifetime for LED can be achieved and the risks of light or colour degradation can be avoided. Excess heat can cause colour, or colour temperature change, especially noticeable with white LEDs. Another issue is lumen degradation that decreases lumen output as the component ages depending on junction temperature, as seen in Figure 4 [7] [8].

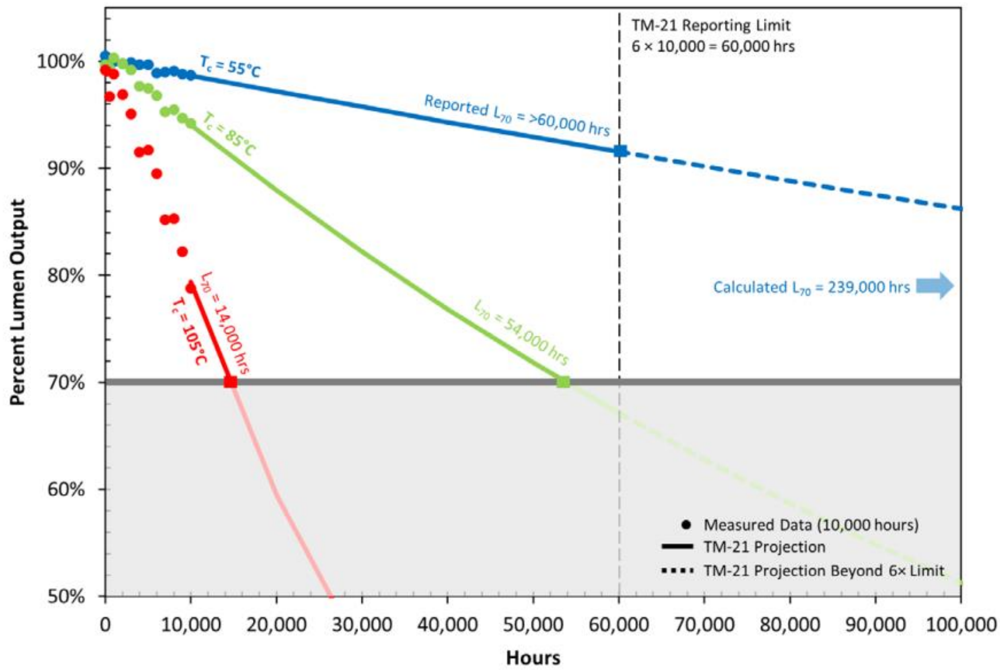


Figure 4. Lumen output degradation example [8].

The heating of the LED component reduces the forward voltage of the component thus reducing the current. Lower current decreases the relative luminous flux and less light is produced. Higher temperatures cause lumen output degradation, which makes good temperature management as important as a constant current for LED module. With good thermal management, less current can be used and therefore less power is used which is more economic. Figure 5 shows how Samsung LED component characteristics are affected by heat [9].

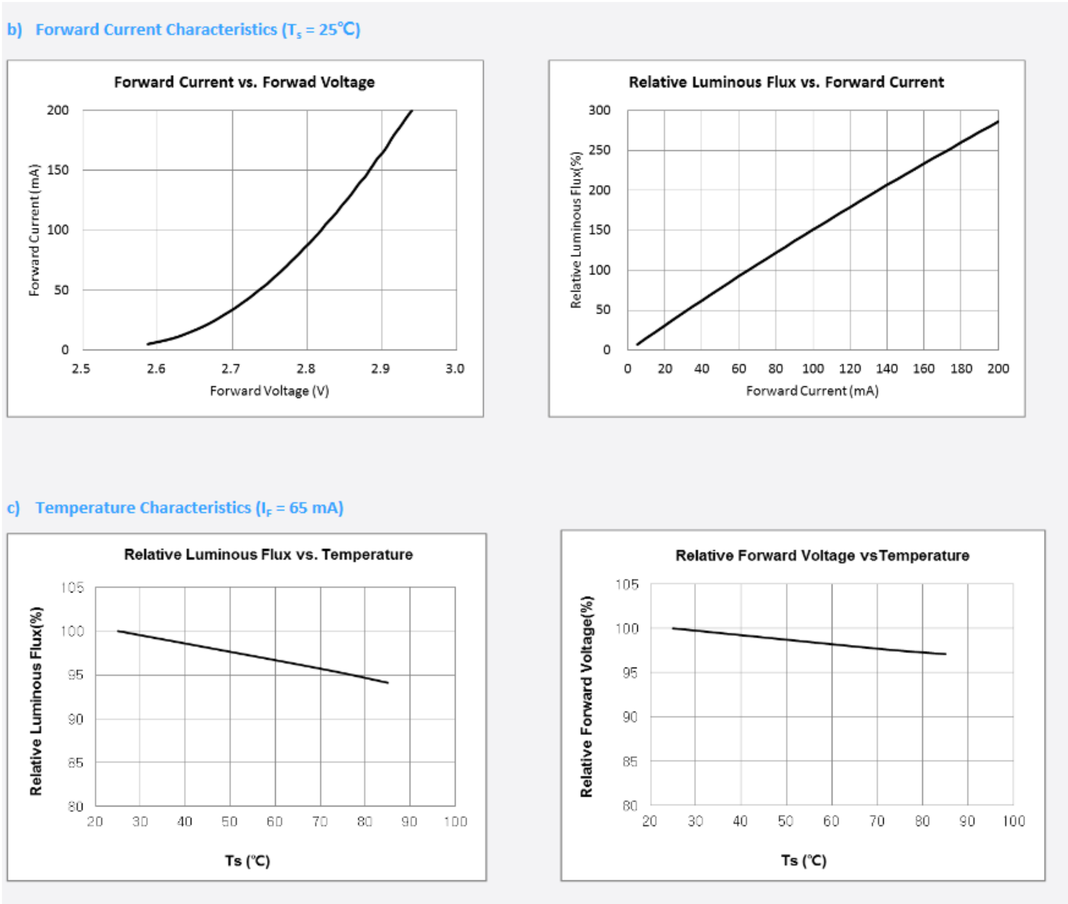


Figure 5. Samsung LED current and temperature characteristics example [9].

4 MODES OF HEAT TRANSFER

4.1 Conduction

Convection plays an important role in cooling LED modules when LED module is physically connected with the luminaire casing. Connection with the PCB and luminaire casing allows heat to transfer away from LED module components through PCB to luminaire casing. A bad connection between the luminaire parts or use of materials with low thermal conductivity can lessen the cooling properties of luminaire significantly.

Heat transfer by conduction occurs inside of material or between connected materials due to the temperature gradient between points. When part of an object is hotter and contains more energy than the other part attached to it, energy flows from hotter to colder and results in a heat flow. Heat flow occurs because the higher energy including molecules of the hotter parts move faster than ones in colder and less energy containing parts. Faster moving molecules collide with slower ones increasing their speed resulting in energy flow [10].

Metals are usually good conductors of thermal energy because their high concentration of free electrons that can transfer the energy well. That's why they are used in cooling or conductors between heating elements.

When calculating heat flux $Q\,(W/m^2)$ objects thermal conductivity λ must be known. When calculating heat flow in electronic circuits important thermal conductivity values are in example: copper and PCB. The thermal conductivity SI unit is watts per meter-kelvin ($W/(m \cdot K)$) [9]. Table 1 has conductivity examples of materials used in electronics.

Table 1. Thermal conductivity examples [11].

Thermal conductivity examples of materials in electronics	
Material	Thermal conductivity [$W/(m \cdot K)$]
Air	0.026
Copper	384
Aluminium	200
PCB material FR4	0.3

PCB material CEM-3	1.0
Silicon	120
Thermal adhesive	6

Because direction of heat flow is known, Fourier's law can be written in simple form:

$$\dot{Q} = \lambda \cdot A \frac{(T_1 - T_2)}{L}$$

Where:

L = length

λ = thermal conductivity

A = area

$\dot{Q} = \frac{dQ}{dt}$ (heat flow, heat transfer rate) [W] = $[Js^{-1}]$

T= temperature

4.2 Thermal resistance

Understanding the thermal resistance model is important when choosing the materials for the designed LED module. Because the budget limitations or required physical properties, in example rigidity or thermal performance, there is lot to be considered. Different PCB materials have various thermal conductivities and physical properties.

When calculating thermal resistance, it is easy to get an understanding of the thermal properties of the module elements and it can help to define good and bad layers of a thermal resistance model. It is also easy to experiment how the model should be adjusted for desired performance by changing the layer conductivity values. The thermal resistance model gives a good and simple image of how heat flows from a LED components junction to ambient.

Thermal resistance is a one-dimensional steady state model, so it is not completely accurate. In reality heat distribution is 3-dimensional. Nevertheless, a heat resistance model is a good tool in thermal engineering.

A thermal resistance model is illustrated by a simple resistor model. Two different temperatures can be thought as voltages in a simple resistor model. Resistors in the model indicate thermal resistances. Heat flow is calculated to be the current running through the resistors [2].

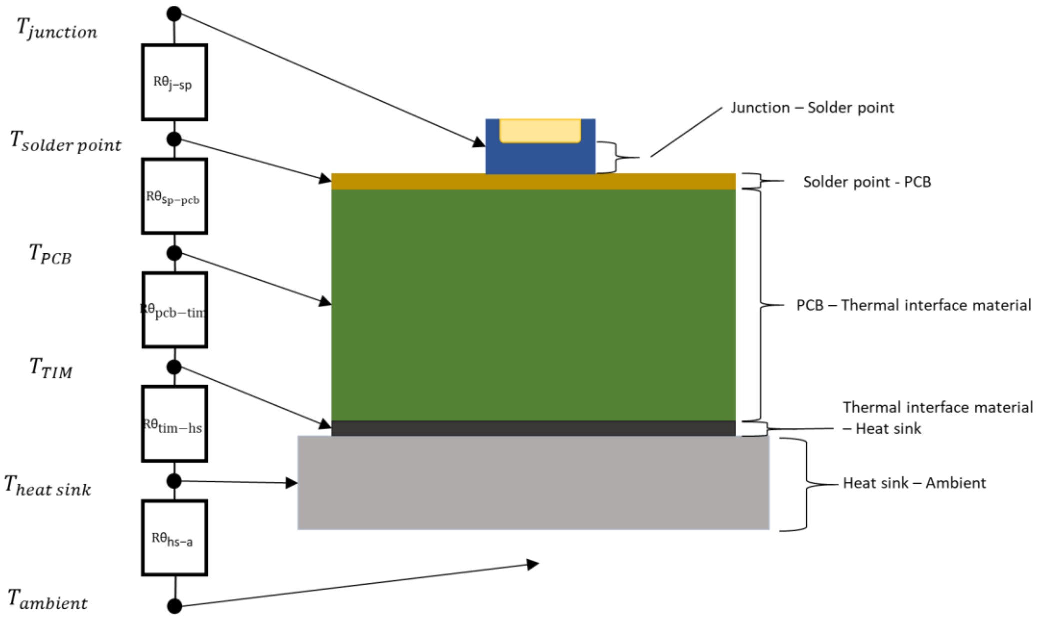


Figure 6. ActivePAQ example thermal resistance model [2].

Figure 6 is an example of thermal resistance model of ActivePAQ, where [2]:

T points indicate each location temperature (°C)

$R\theta_{a\text{-}b}$ indicate thermal resistances between points (°C/W)

Ohm's law

$$I = \frac{\rho \cdot A}{L}(V_1 - V_2) = \frac{1}{R}(V_1 - V_2)$$

Fourier's law

$$Q = \frac{\lambda \cdot A}{L}(T_1 - T_2) = \frac{1}{R_{thermal}}(T_1 - T_2)$$

Definition of thermal resistance

$$R_{th} = \frac{L}{\lambda \cdot A} = \frac{(T_1 - T_2)}{Q}$$

Where:

L = length

λ = thermal conductivity

A = area

$\dot{Q} = \frac{dQ}{dt}$ (heat flow, heat transfer rate) [W] $=$ $[Js^{-1}]$

T = Temperature

LED manufacturers usually give a derating curve to the LED components depending on a junction – ambient thermal resistance. The derating curve on Figure 7 shows how important the conductivity of the material is for efficient LED usage [12].

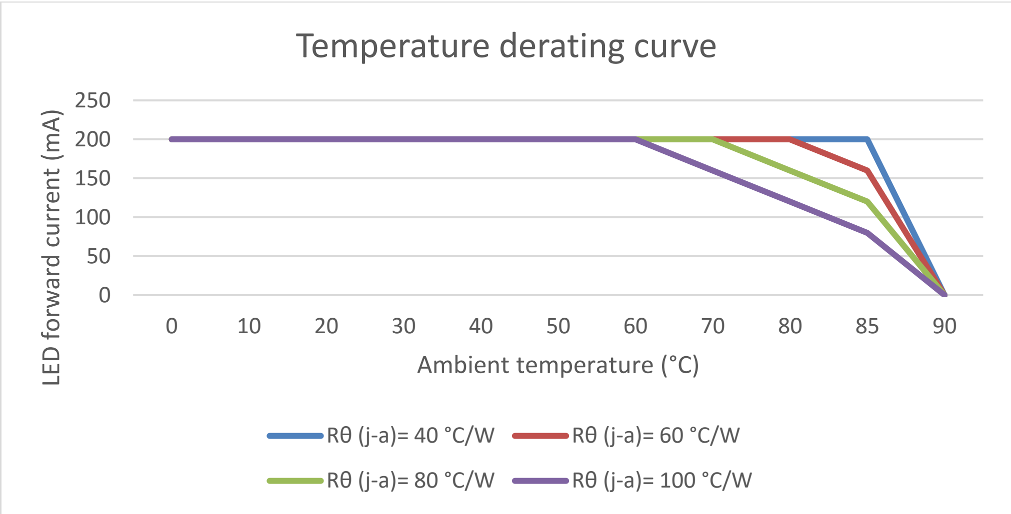


Figure 7. Temperature derating curve [12].

4.3 Convection

Convection occurs when LED module body is hotter than surrounding air which results in the warming of surrounding air. When surrounding air warms up it rises and results in airflow and natural convection occurs. Airflow carries new colder air which again warms up and rises again. Convection is heat energy transferred between a moving fluid and an object that are different temperatures.

Convection can be split in two categories, forced convection and natural convection. Natural convection occurs when the object warms up the adjacent gas or liquid which creates flow and therefore convection.

Natural convection is the main type of convection of LED components and modules for tests made in this study because no external cooling methods, in example fans are used. Natural convection also occurs between luminaire body and surrounding air with some forced convection due to the air conditioning as seen on Figure 8 [2].

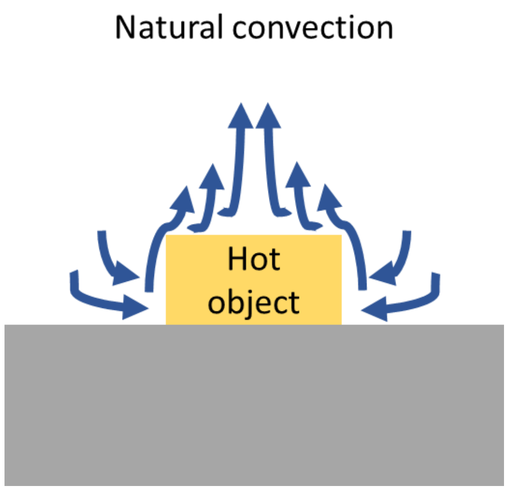


Figure 8. Natural convection example [13].

Forced convection is achieved when a gas or a liquid flow is created by an external force, in example a fan in Figure 9 demonstrating an air-cooling system or a radiator in a liquid temperature management system [2].

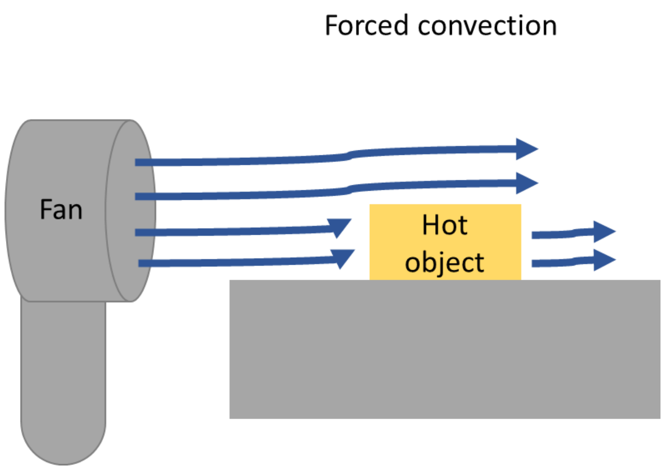


Figure 9. Forced convection example [13].

Rate of heat transfer can be calculated by using the steady-state form of Newton's law of cooling equation [2]:

$$\dot{Q} = \alpha \cdot A(T_{body} - T_F)$$

Where:

α = heat transfer coefficient

A = area

$\dot{Q} = \frac{dQ}{dt}$ (heat flow, heat transfer rate) [W] = $[Wm^{-2}K^{-1}]$

T= temperature of body and flowing fluid

The Unit of heat transfer coefficient is $W/(m^2 \cdot K)$ and it represents the heat transfer between fluid and the surface. Value of a heat transfer coefficient can change from usual estimation $5 - 20\ W/(m^2 \cdot K)$ in natural convection as seen in Figure 10 up to $100\ W/(m^2 \cdot K)$ with forced convection according to component manufacturer CREE [12] [14]. Table 2 has few convective heat transfer coefficient examples.

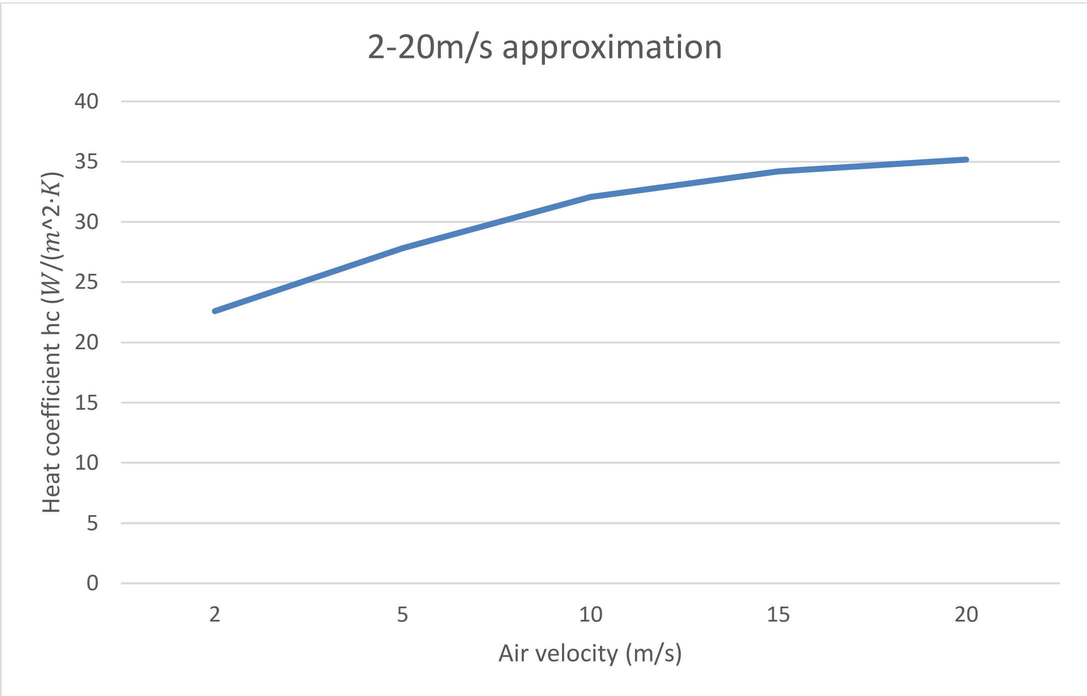


Figure 10. Air velocity example [14].

Table 2. Convective heat transfer coefficients [14].

Flow type	$\alpha(W/m^2K)$
Forced convection; low speed flow of air over a surface	10
Forced convection; moderate speed flow of air over a surface	100
Forced convection; moderate speed cross- flow of air over a cylinder	200
Forced convection; moderate flow of water in a pipe	3000
Forced convection; boiling water in a pipe	50,000
Free convection; vertical plate in air with 30°C temperature difference	5

4.4 Radiation

Unlike conduction and convection, thermal radiation can transfer heat between two surfaces without a need of a medium. Thermal radiation is electromagnetic radiation between two bodies. Thermal radiation depends on temperature difference and emissivity of bodies. All bodies over 0 kelvin emit radiation.

An object's ability to transmit energy through radiation depends on the shape and physical properties of the object. An ideal object "black body" is an object that absorbs and emits all electromagnetic radiation that has the emissivity of ε= 1. When the emissivity of material is given it is always compared to the ideal heat emitter "black body".

Inside luminaire casing with only natural convection cooling by thermal radiation can be significant. Most of the surface area of ActivePAQ is solder resist, therefore emissivity is around ε= 0,9 [2]. Table 3 has examples of PCB emissivity values.

Table 3. Emission examples of PCB materials from OSRAM application note [2].

Surface	Temperature (°C)	ε
Aluminium Polished: Heavily oxidized:	 20 20	 0.4 0.25
Lacquers	100	0.9-0.97
Plastics	20	0.9

Solder stop mask	20	0.9

Heat energy transferred by radiation can be calculated by [2]:

$$\dot{Q} = \varepsilon \cdot A \cdot \sigma(T_{body}^4 - T_{fluid}^4),$$

where

ε = is the emissivity coefficient

σ = Stefan-Boltzmann constant

A = area

T = temperature

5 THERMAL MANAGEMENT AND LIFETIME OF COMPONENTS

5.1 LED lifetime

LED failures can be divided into three categories: early failures, random or spontaneous failures and wear-out period. Failure rates can be presented with Figure 11 "bathtub curve". The bathtub curve starts at early failures that occur already at the manufacturing process by bad materials or process faults in example bad soldering. At the start failure rate is high due to the manufacturing process. Random or spontaneous failures are also usually caused by manufacturing process faults or faulty materials used [3].

Wear-out period includes the aging and wearing of the component. Most noticeable degradation is usually brightness or colour changes. Lumen output decreases over time depending on an operating current and the temperature. High temperature and current accelerate the wear out of the module, but also module with a specified temperature and current suffers from lumen degradation.

Lifetime values are given to components with a percentage of light output in example L70, 10 000h products have 70% of the lumen output at 10 000h. The Mortality of a component can be described by B value, in example B50 describes the point in time where 50% of the components have failed [3].

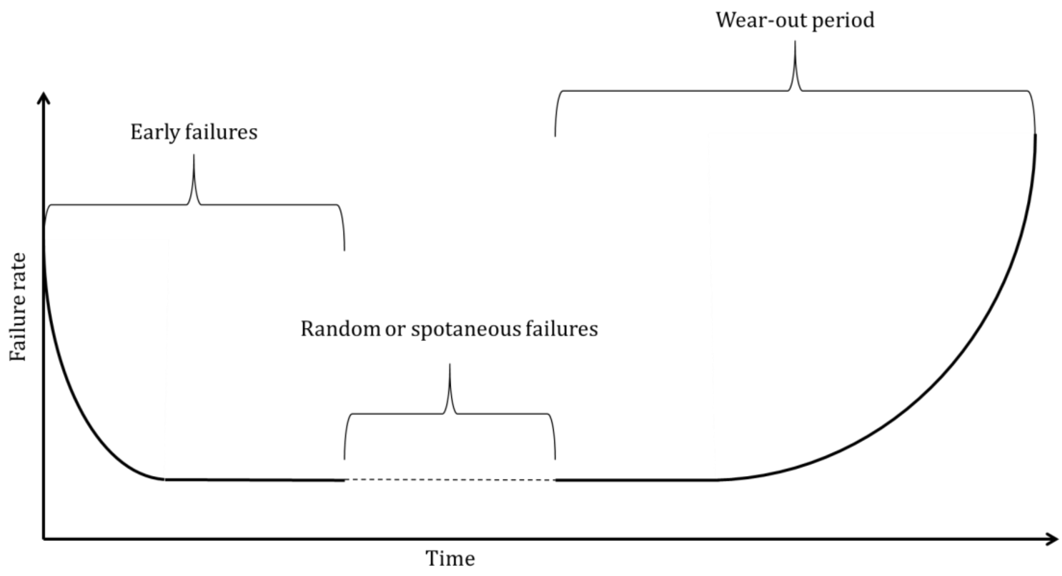


Figure 11. Failure rate over time "bathtub curve" [3].

LED's lifetime and reliability are affected by many factors: temperature, humidity, current, voltage, mechanical forces, chemicals and light radiation. These factors must be considered to minimize the risk of early failures, random or spontaneous failures and to achieve a maximum lifetime in wear-out period [3].

5.2 Aluminium electrolytic capacitor lifetime

One of the ActivePAQ's TC point is for measuring aluminium electrolytic capacitors temperature. Capacitor manufacturers usually give the lifetime expectation from the maximum rated temperature, in example 105°C. Aluminium electrolytic capacitor lifetime is calculation is based on Arrhenius's law. For every 10°C rise in temperature the lifetime (Hr) value halves, whereas 10°C decrease in temperature doubles the lifetime expectancy [1].

Ripple current is another factor in electrolytic capacitor lifetime. When ripple current is applied to the electrolytic capacitor, it generates Joule's heat and must be considered when calculating lifetime values [15].

Estimated lifetime is calculated by: $L = L_0 \times 2^{\frac{T_{max} - T_a}{10}}$ [15], where:

L = Estimated lifetime (Hr)

L_0= Life at rated temperature (Hr)

T_{max}= Rated temperature (°C)

T_a= Ambient temperature (°C)

5.3 Mosfet lifetime calculation

The Mosfet (metal–oxide–semiconductor field-effect transistor) handles the currents for all the LEDs in the module. Because the high power of mosfets, they generate lots of heat in the module. The heat management for the mosfets is done by using larger copper pads below the mosfet heatsink, so that the heat spreads more efficiently to the PCB and from there through luminaire casing to the ambient. Without copper PADS the heat would be in one spot on the mosfet and could cause breakdown of the component or change the current and voltage characteristics of the component. Maximum operating and storage temperature range for mosfets are given in their respective datasheet [17].

Figures 12 and 13 display the correlation between temperature and mosfet performance characteristics.

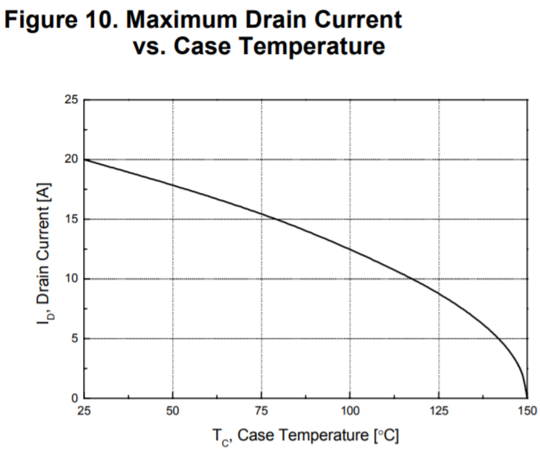


Figure 12.Mosfet drain current vs case temperature [17]

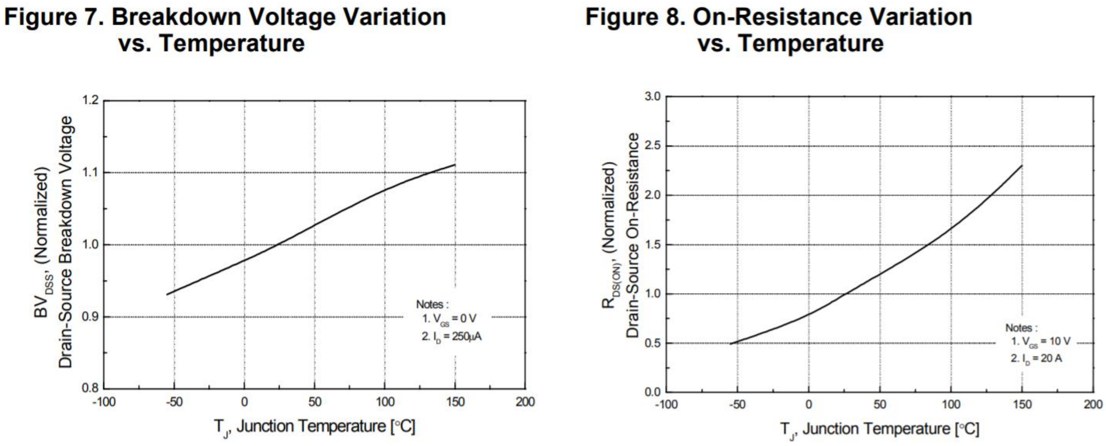


Figure 13. Mosfet breakdown voltage & on-resistance variation vs. temperature [17].

6 SIMULATIONS AND MEASUREMENTS, INCLUDING USER INSTRUCTIONS

6.1 HyperLynx Thermal simulator

HyperLynx Thermal simulation software is included in PADS layout software. HyperLynx Thermal simulation environment simulates the board on a test "rack". The version used in these tests has only the basic simulation controls available, in example the incoming air temperature is locked to 20 degrees Celsius. Simulation of higher temperatures can still be done with closed casing simulation.

There are multiple settings and material properties that must be checked before starting simulation. First procedure is to move the simulated module to a vertical position. This is due to the calculation method used by the simulator. Horizontal long and thin modules can cause false results from the simulation. Rotating the module can be done in PADS by right clicking the background > *Select Anything* > drag the whole module with left click > *CTRL + R (rotate)* > and click the background. The board outline usually must be redone for the vertical module after rotating the components, routes and areas.

Layer settings of the module can already be inputted in the PADS layout definitions menu from: *Setup > Layer Definitions > Layer Thickness* as seen in Figure 14. From the layer definitions, the thickness of each layer must be checked. Thickness and the layer material can also be altered later in the simulation menu, but it saves time if multiple simulations are required. Thickness of the material influences thermal resistivity of the layer.

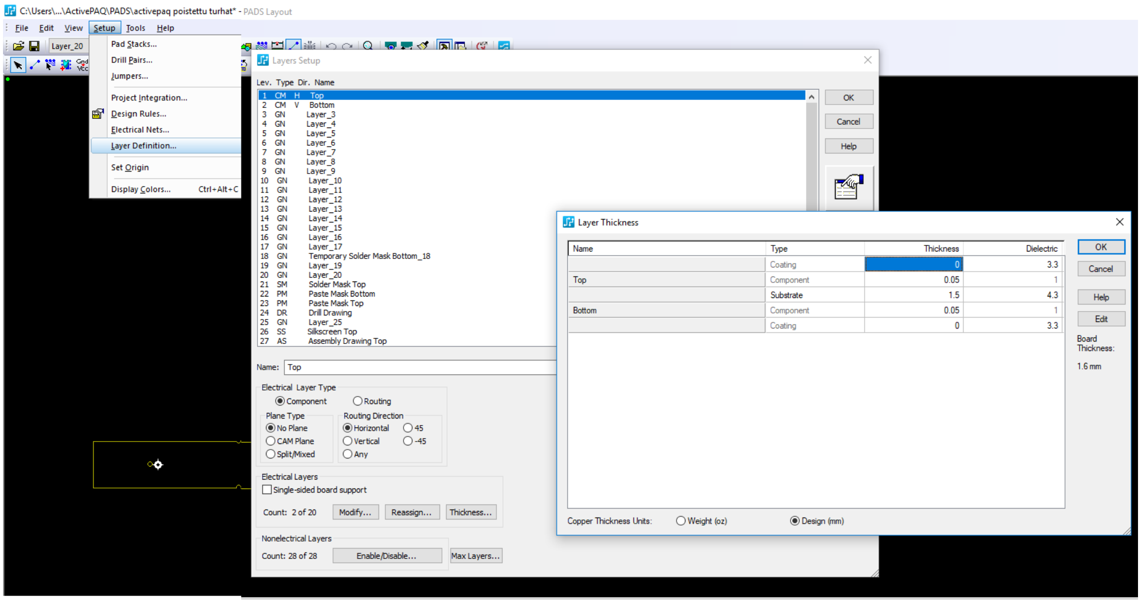


Figure 14. PADS *Layer Setup > Layer Thickness.*

Figure 15 shows the menu options of the HyperLynx thermal simulator. Thermal simulation can be started from the PADS menu: *Tools > Analysis > Thermal Analysis*. Selecting the *Thermal Analysis*, opens the thermal simulation window and BoardSim window. Before going into thermal simulation, PCB layers, materials and layer thicknesses should be checked from the BoardSim stackup editor menu.

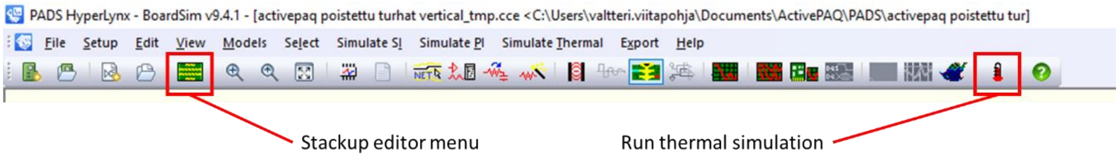
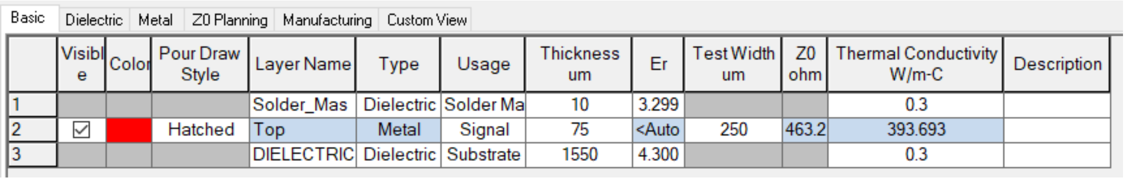


Figure 15. BoardSim stackup editor and run simulation buttons.

On the Figure 16 stackup editor menu, the thickness of the layers can be altered, and any unwanted layers can be removed. Here it is possible to change the dielectric substance thermal conductivity depending on the material therefore different PCB materials can be tested easily. Stackup editor also gives an image of the stackup so it is easy to see the whole PCB construct.



Basic | Dielectric | Metal | Z0 Planning | Manufacturing | Custom View

	Visible	Color	Pour Draw Style	Layer Name	Type	Usage	Thickness um	Er	Test Width um	Z0 ohm	Thermal Conductivity W/m-C	Description
1				Solder_Mas	Dielectric	Solder Ma	10	3.299			0.3	
2	☑		Hatched	Top	Metal	Signal	75	<Auto	250	463.2	393.693	
3				DIELECTRIC	Dielectric	Substrate	1550	4.300			0.3	

Figure 16. Stackup editor settings.

After the PCB characteristics setup, thermal simulation window should be closed and reopened for the settings to update. When the ThermalSim window is reopened, the power dissipation of the module components must be checked. Each component can be adjusted individually by double clicking the component. Changing one component changes all the similar components, in example changing one LED properties changes all other same model LEDs. The junction to casing thermal resistance should also be entered with the power dissipation. After inputting the power dissipation values and the junction to casing thermal resistances, the power dissipation of the components can be verified by clicking the *Run Thermal Simulation* button. When the simulation is done, the component temperatures and power dissipation values are show on a list where it’s easy to scroll the components and check if there is any unnecessary power dissipation or something is missing.

From the top menu: *View component power* selection shows each components power by a colour gradient. From the image in Figure 17 it is easy to see there is no unnecessary power dissipation. Dark areas have 0 power dissipation, whereas the brighter colourful areas including mosfet 1.2W (red) and the LEDs 0.105W (lighter blue) have more power dissipation.

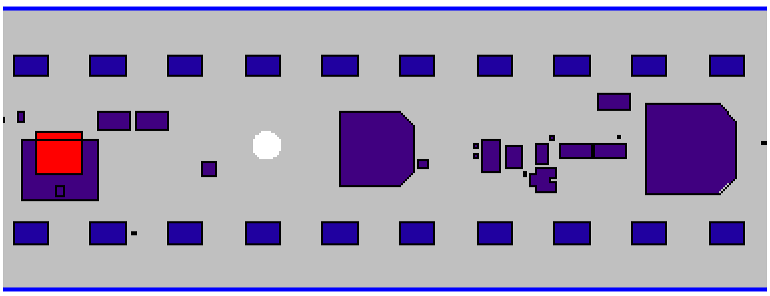


Figure 17. Component power dissipation visualized with colour gradient.

The Environmental condition definition menu in Figure 18 has the simulation properties. Software allows the incoming air velocity to be directed according to Y+- and Z+-. Incoming air can be applied to the front or to the back of the module.

Casing setup has options:

Incoming air velocity

- This is used when there is forced airflow in example a fan. In the ActivePAQ's case there usually aren't any cooling fans or good airflow in the luminaire bodies, however there is some airflow in the temperature chamber so it might be necessary to set some airflow for the correct simulation results.
- When there is only natural convection present in the closed casing the value is 0.0.
- When casing sides at Casing/System/front and back side are set to "closed", the incoming air velocity does not affect the temperature of the module

Figure 19 demonstrates the air flow direction (+y, -y, +x or -x) that must also be considered because heat spreads differently on the surface of the PCB depending on the airflow direction.

Board location menu gives options for board positioning:

- In a rack with boards on both sides of the module
- A single board with casing walls

System:

- The board is in a case that is open and has an air flow or is in a closed case with no external airflow.

Board spacing is the distance between the board and the casing wall or other board. The board spacing was set to maximum 10cm in the simulation comparsion with the measured results. Adjecent board power was 0W.

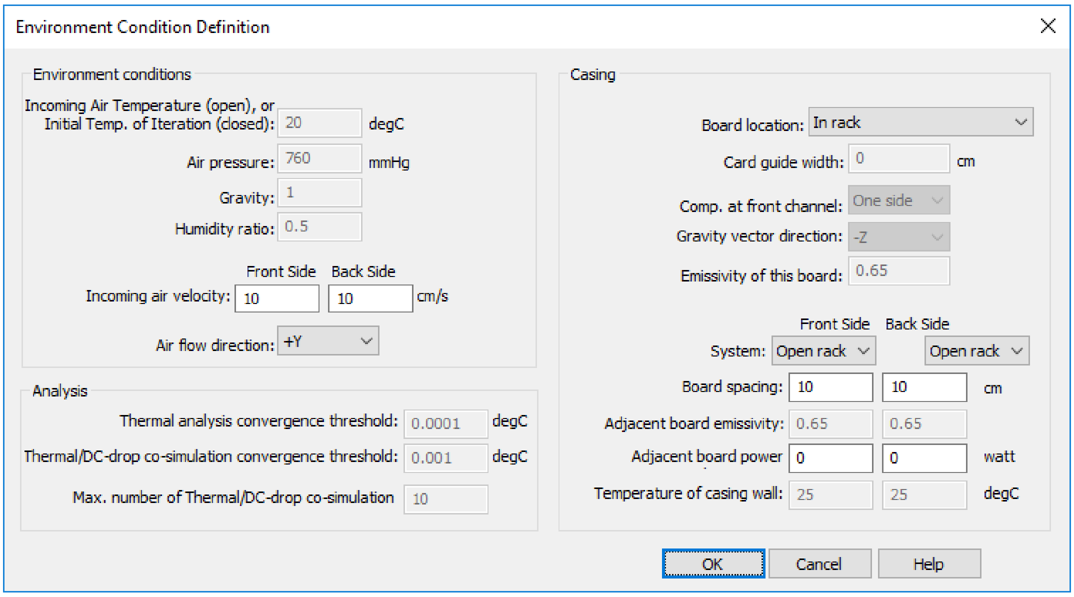


Figure 18. Environment condition definitions menu.

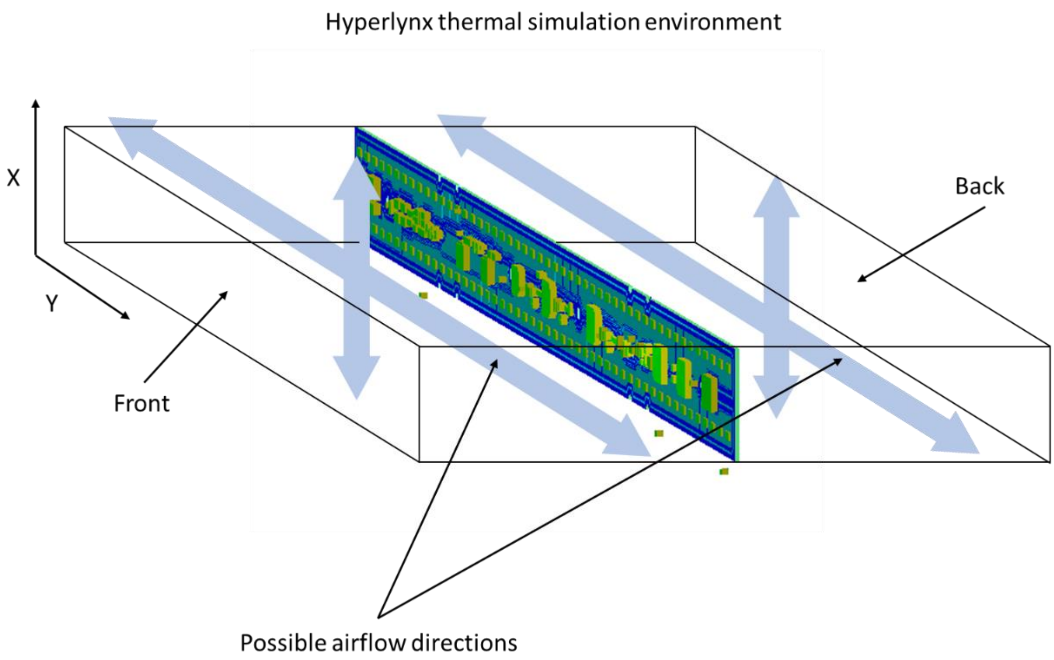


Figure 19. Airflow direction in the simulation software.

In most installations ActivePAQ is attached to the luminaire casing so that the back of the module is connected to the luminaire casing. Hence representative thermal simulation of the module would only have airflow on the front side of the module. If the aluminium backplate simulating the luminaire casing is part of the simulated module, then airflow could be applied also to the back of the module.

ActivePAQ(s) are usually mounted inside enclosed luminaire casing with small or no airflow at all. Luminaire casing has the most important role in heat management of the module. An aluminium luminaire body can cool the module well, whereas plastic casing can't transfer the heat from the module to ambient air. Connection between the ActivePAQs PCB and the metal of the luminaire casing is essential for good convection resulting in efficient heat transfer.

Simulating ActivePAQ's usage temperature is hard because the manufacturer of the module does not know the luminaire body where the module is eventually attached to and the luminaire body can't be simulated in the software. These test cases have been chosen for easy comparison between simulated and measured results.

6.2 Temperature measurement devices

ActivePAQ temperatures are measured from 4 temperature points (TC points) listed in Table 4. Measurements are done with K type thermocouples soldered to the copper pads of TC points. Temperatures are logged with TES 1384, 4 input thermometer/datalogger.

Table 4. ActivePAQ temperature point locations.

Temperature point location	
Mosfet	Mosfet large drain pin
Capacitor 1	Smallest electrolytic capacitor
LED	LED near the mosfet
Capacitor 2	Larger electrolytic capacitor

The LED module temperatures are also captured with a Fluke Ti32 thermal imaging IR camera. A thermal image shows the temperature of both, the components and the TC points and the spread of the heat can be seen clearly.

6.3 Temperature measurement comparison to the simulation results

6.3.1 First simulation test in an open rack

First test was done with the module on top of a steel cage in the temperature chamber, which is presented in Figure 20. The module had good airflow on both sides but no attached cooling elements. The temperature was set to 20°C and the module had around 2 hours to warm up. This test was done to determine how close the simulation results will be to measured values and how much airflow is in the temperature chamber according to simulator. First test would also help to give some idea what the simulation environment settings should be.

Figure 20. ActivePAQ in a temperature chamber.

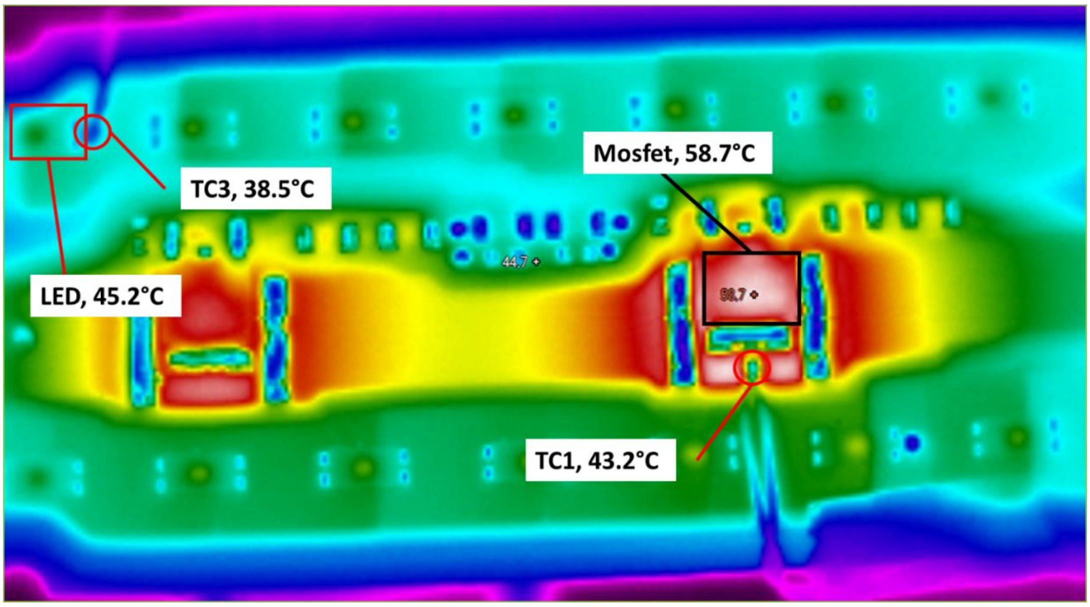
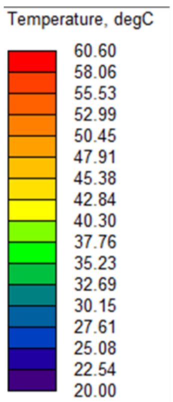


Figure 21. LED and mosfet temperatures thermal image.



	Component temperatures (°C)			
	TC1 (Mosfet)	TC2 (Capacitor 1)	TC3 (LED)	TC4 (Capacitor 2)
Thermocouple measurement	43.46	27.07	31.71	28.03
Thermal image TC point	43.2		38.5	
Thermal image compoinent	58.7		45.2	
Simulation TC point	48.5	35.1	46.4	32.2
Simulation component	60.7	35.04	44	32.01

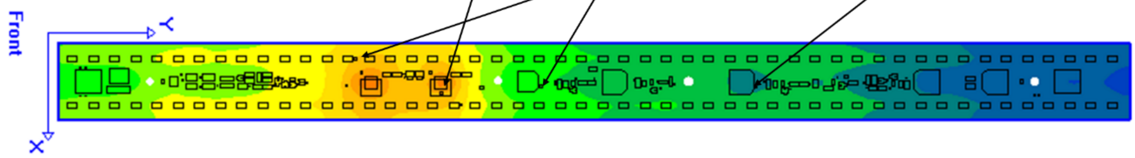


Figure 22. Temperature of the TC points from the measurement with thermocouples.

Adjusting the simulator by taking both thermal image of Figure 21 and thermocouple measurements in Figure 22 into account, the proper temperatures are achieved when airflow is set to 100cm/s both front and back side. Simulated component values are very close to thermal image component temperatures. TC points 1 and 3 are around 10 degrees hotter on the simulation than in the thermocouple measurements. Capacitor component temperatures aren't exactly right and maybe hotter than in reality because the simulated ActivePAQ does not have the correct cylindrical capacitor shapes which cool off the capaitors signifigantly.

6.3.2 Second simulation test with closed backside

The second test displayed in Figure 23 was done with ActivePAQ on top of a plastic sheet, which removes the airflow from the backside. The backside was set to closed from the simulator, whereas the front was open with good airflow. The temperature chamber was set to 20°C. Figure 24 is the thermal image of the module and Figure 25 has the thermocouple measurements.

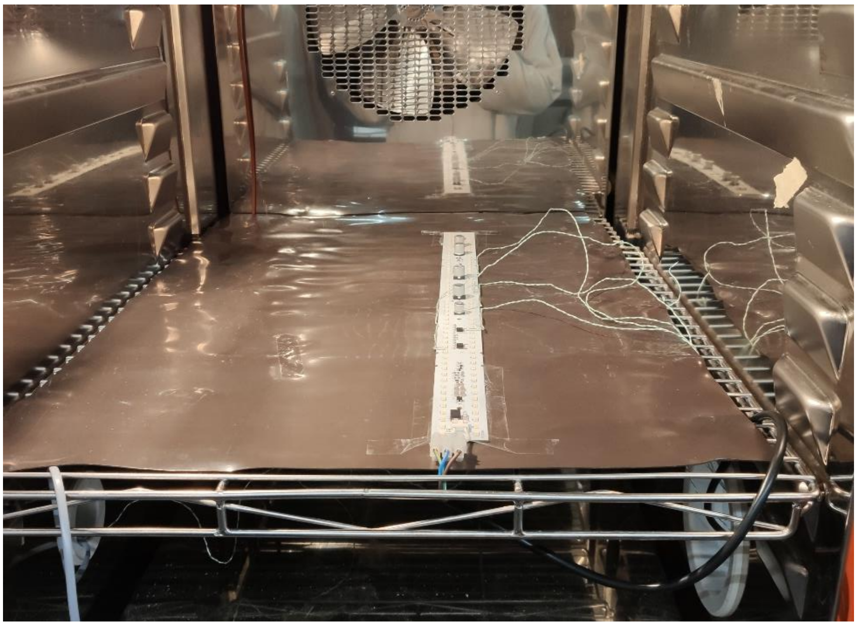


Figure 23. Second simulation test with closed backside.

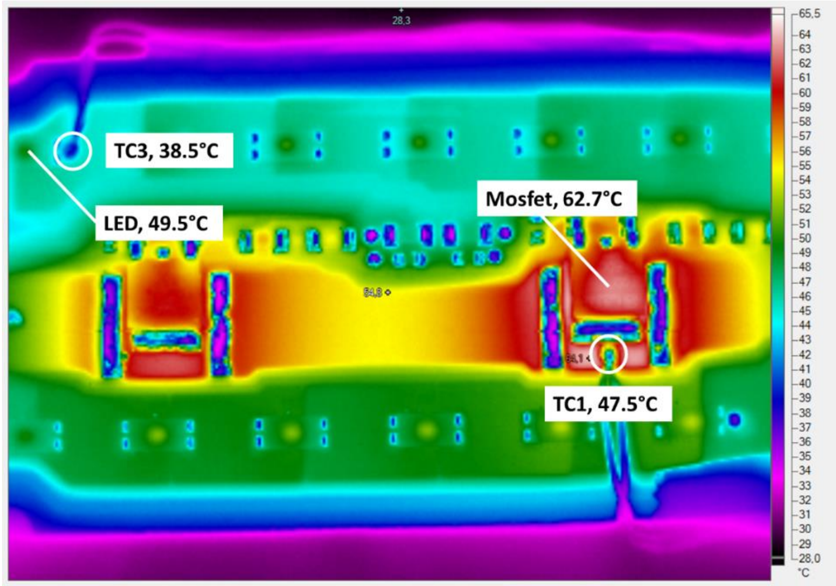
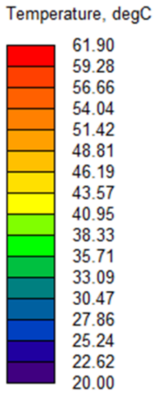


Figure 24. Thermal image from the second simulation test with closed backside.



	Component temperatures (°C)			
	TC1 (Mosfet)	TC2 (Capacitor 1)	TC3 (LED)	TC4 (Capacitor 2)
Thermocouple measurement	47.32	26.22	34.11	28.26
Thermal image TC point	47.5		38.5	
Thermal image component	62.7		49.5	
Simulation TC point	49.60	35.1	46.2	33.0
Simulation component	61.9	35.41	47.78	32.6

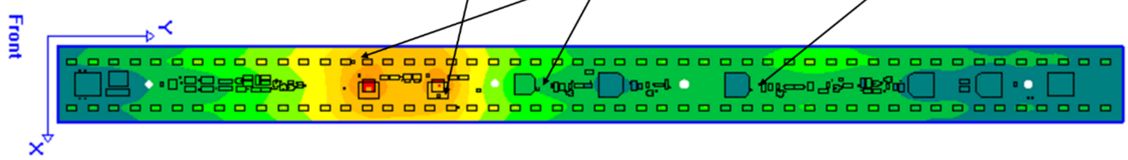
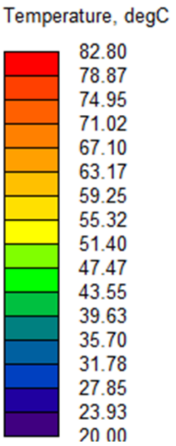


Figure 25. Simulation second test with closed back side.

Testing few different air velocities values to the front side to match the measured results lead to 150cm/s air velocity. The simulation settings for second test was set up by considering both, the thermal image and the thermocouple measurements. The airflow direction was set to -Y for most accurate results.

6.3.3 Third simulation test with enclosure

Third test goal was to lessen the airflow in the temperature chamber, thus reducing the forced convection. The test was done in 20°C in the temperature chamber and the module was in a cardboard box (40cm x 30cm x 60cm). Box reduced the airflow from the temperature chamber fans.



	Component temperatures (°C)			
	TC1 (Mosfet)	TC2 (Capacitor 1)	TC3 (LED)	TC4 (Capacitor 2)
TC point	TC1	TC2	TC3	TC4
Thermocouple measurement	70.67	43.15	60.80	45.32
Simulation TC point	70.5	46.8	62.9	41.3
Simulation component	80	47.9	64.1	40.15

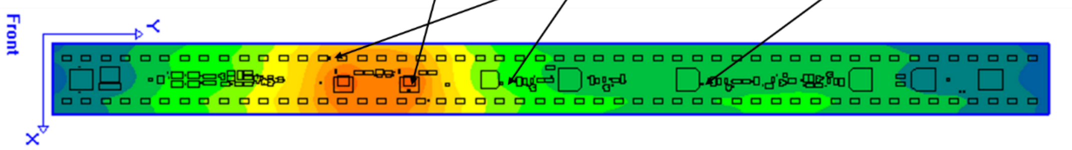


Figure 26. Measurement results from the third test of simulation.

After testing the different values of air velocities in the simulator, the closest results in Figure 26 were achieved with 20cm/s both back and front of the module, which was reasonable due cardboard box lessening the airflow. The airflow direction was set to +X. Simulation TC point values were close to the measured values. With lower air velocities the temperature simulation results seem more accurate than in other tests with higher velocities

6.3.4 Different PCB material comparison

One important thing to consider while designing LED modules is the PCB material. Simulation with different thermal conductivity values show how much a difference can be. Figure 27 example is comparing a PCB material with 0.3W/(m·K) to 1.0W/(m·K). Heat is more spread out through the module and the hottest temperatures are 10°C lower. Air velocity on the test was set to 100cm/s to the front- and backside of the module.

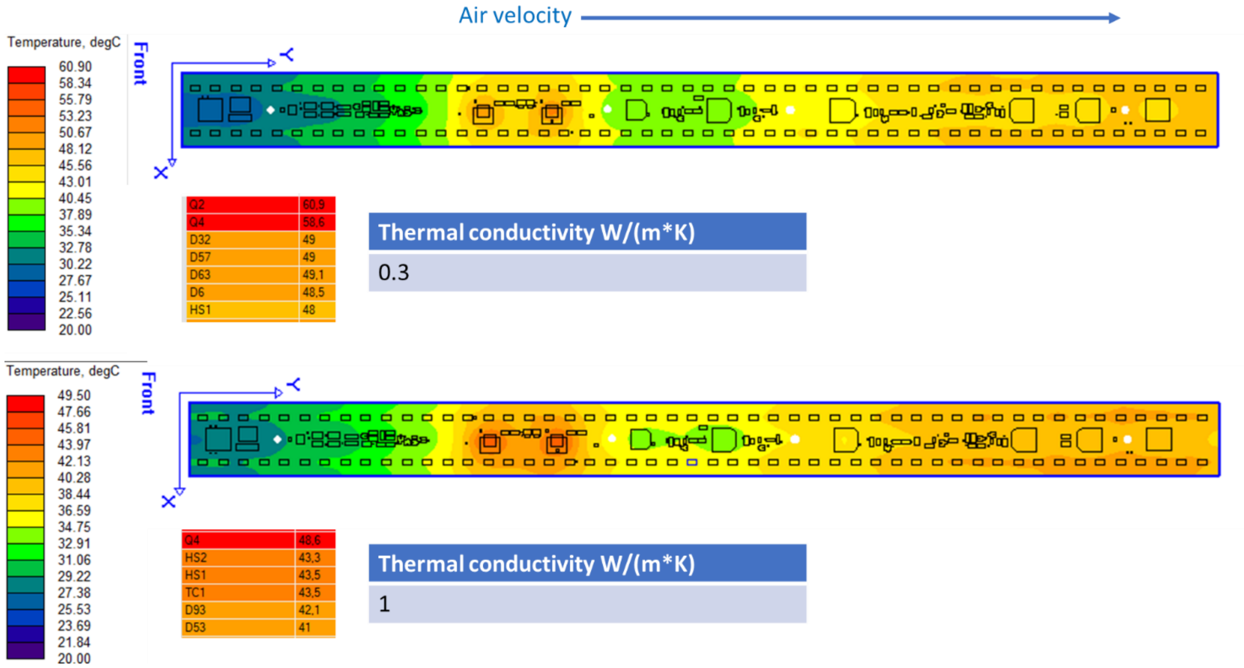


Figure 27. Simulation with different PCB materials.

6.4 Correlation of temperature measurements and simulations

Figure 28 has all the simulated and measured values from three tests in the same graph. Third simulation and measurement with enclosed environment has the most similar temperature results due to the lower air velocity used in simulation. Simulation setup 1 & 2 have more difference in temperature. Temperatures closer to each other in simulation setup 1 & 2 are mosfet temperatures measured from the TC points.

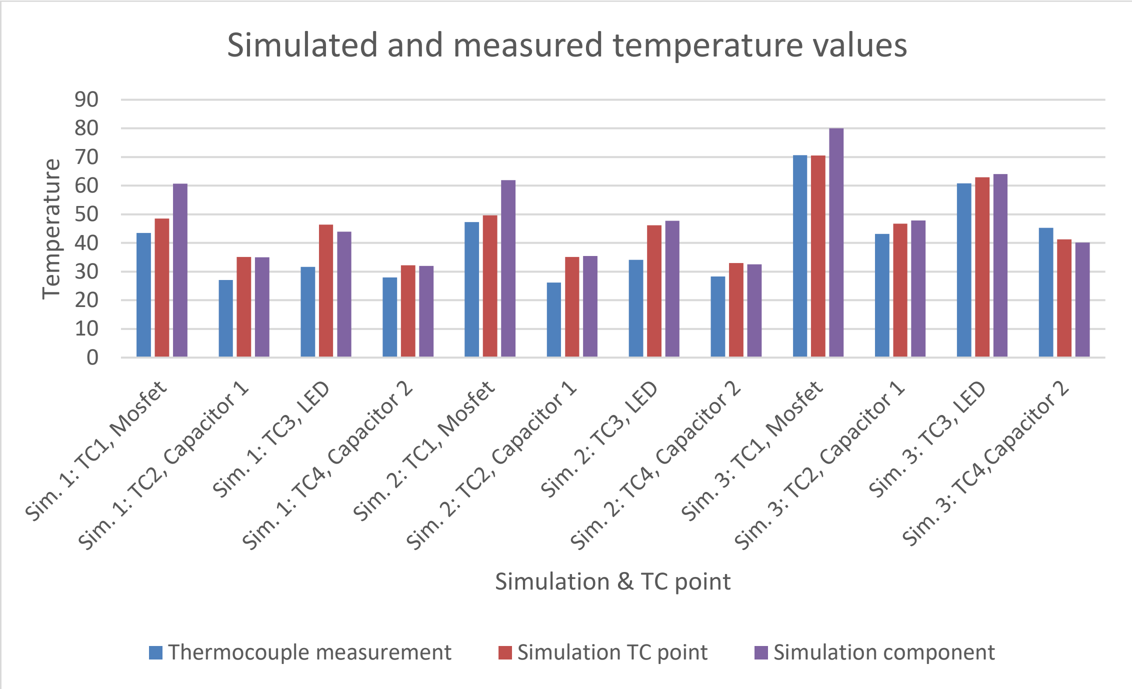


Figure 28. Simulated and measured temperature values comparison.

6.5 Simulator issues

There were some issues during the thermal simulation of long and narrow LED modules. Simulator showed the thermal gradient view wrong. When simulating 40mm x 560mm LED module in Figure 29 the thermal gradient image just showed flat narrow heat areas, whereas 80mm x 560mm LED module simulation in Figure 30 is more reasonable. The simulator still shows reasonable results for board temperature but the thermal gradient (degrees C per mm) is displayed incorrectly.

Increasing the board size does not alone solve the problem, also the components must be more spread out.

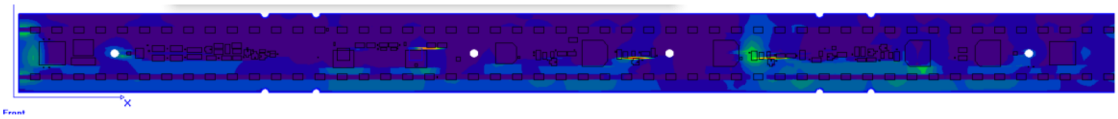


Figure 29. Error in the thermal gradient image in the simulator.

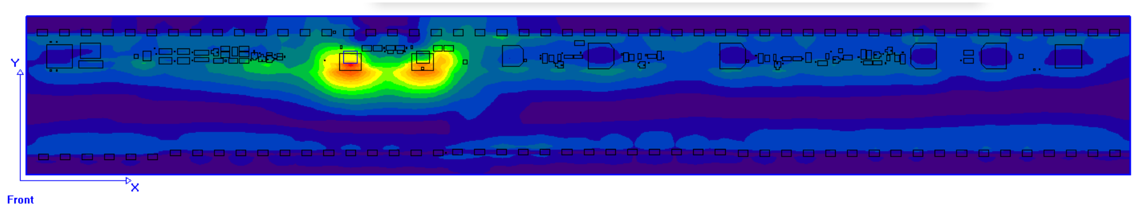


Figure 30. Thermal gradient error fixed with spreading out components.

There was also an issue with copper areas in simulation with narrow modules. Figure 31 is from a passive 30mm x 280mm LED module. In the pictures below copper areas are shown as black on a grey surface. The copper areas spread the temperature better on the PCB and from there to environment, yet the right side is displayed hotter in Figure 32.

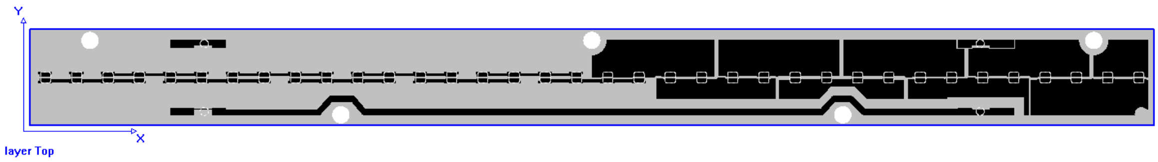


Figure 31. The copper areas of a faulty simulation test.

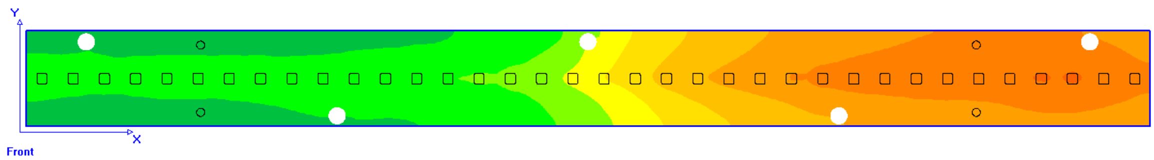


Figure 32. Simulation temperature error example.

Because of the problems in the copper area simulation, Mentor graphics software retailer was emailed, and they got in contact to the HyperLynx Thermal simulation engineer. Feedback was that the unique dimensions of the board (long and narrow) pose a problem for the HyperLynx Thermal convection model. Solution to see correct results from these long and narrow modules would only be to use more advanced software.

After a lot of testing one solution was found by simply rotating the module from a horizontal position in Figure 33 where the x axis was the longest side to the vertical position in Figure 34 where the y side is the longest. Rotating the module fixed the thermal gradient view but still had some simulation issues with copper area temperatures. From the conversation with

HyperLynx Thermal engineer, he also implied that the airflow model can choke on certain occasions and simulating the module in the horizontal position was one of them.

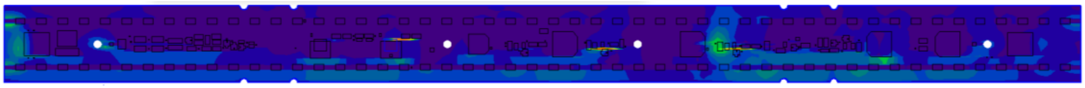


Figure 33. Example image of the horizontally simulated board with false thermal gradient.

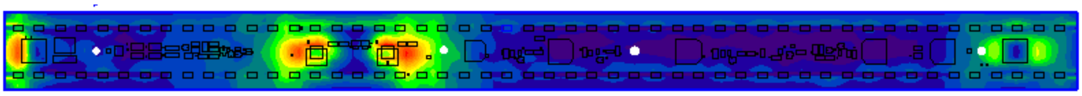


Figure 34. Figure 27. Example image of the vertically rotated board with proper thermal gradient.

One of the problems in the simulator was that the airflow direction could only be set to one direction. In the temperature chamber and in real use the airflow direction might not be constant. Environment temperature control would also be good tool in thermal simulator.

There was also an option for adding cooling fins to the module but adding cooling element as big as a luminaire casing or aluminium strip attached to the bottom of the module cause the LED module to cool way too efficiently. Cooling elements in the software are designed for a much smaller scale than to cool the whole LED module, in example cool one component.

7 CONCLUSION

The goal of this thesis was to study the possibilities of the HyperLynx Thermal simulator in a LED module thermal simulation. The testing of the simulation software was implemented by measuring the LED module first in a temperature chamber and setting up the simulator to match closely as possible to the measured temperatures. User instructions were requested for the software by Tepcomp Ltd, therefore thermal simulation stages and the simulation environmental settings were documented. Before measurements and simulations, the thermal management of a LED module was studied with thermal behaviour and lifetime calculation for components.

The HyperLynx Thermal simulator simulates the component and TC point temperatures compared to the measured temperatures well, therefore it could be used for testing the general LED module temperature or a component temperature. An accurate simulation of heat spreading through the PCB layers and the impact of copper areas used in a LED module is where the program struggles.

The Tepcomp Ltd development team has comprehensive knowledge and a long history with LED module thermal management, hence the HyperLynx Thermal temperature and heat spread information might not give any new or accurate enough information. More inexperienced user could find the temperature results more useful. The product development could find the most use for the simulator from comparing different modules.

The precise information of heat transfer through the layers of the PCB to the LED module casing could be useful for designing smaller or multilayer PCBs. The HyperLynx Thermal simulation software is not designed for narrow led strips used in these tests, which resulted in some simulation errors. Software simulation options are also limited; therefore, some simulation setups cannot be implemented. A LED module is typically attached to a luminaire casing that cools off the module significantly, which cannot be simulated with HyperLynx Thermal simulator.

Accurate temperature values for a LED module can be hard to achieve with HyperLynx Thermal simulation without any previous knowledge about the simulated module thermal behaviour. The simulation environment setting documented in this thesis can be used as a future reference for testing other products.

The greatest advantage of the HyperLynx Thermal software in LED module design comes from testing different possible components or materials, in example, power dissipation values or PCB materials. Changing the power dissipation or PCB material gives a good indication of what the difference between materials can make in temperature and should help product developers to choose between materials, components or other versions of module.

In the future, more specific tests could be carried out for the simulator. For example, more accurate and smaller copper area tests could be conducted to determine how well the software can simulate copper areas used for heat spreading and transfer. For more accurate simulation results and better usability, more advanced software could be used.

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