„POLITEHNICA" UNIVERSITY OF BUCHAREST
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EXTENDED SUMMARY

THERMAL MANAGEMENT FOR POWER ELECTRONIC MODULES

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BUCHAREST 2020

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Abbreviation list

LED – Light-Emitting Diode
COB – Chip-on-Board
TEC – Thermo-Electric Cooler
SSL – Solid-state lighting
CRI – Colour Rendering Index
PWM – Pulse Width Modulation
FR4 – Flame Retardant 4
PCB – Printed Circuit Board
EMI – Electro – Magnetic Interference

Chapter 1

Introduction

1.1 The field of the doctoral thesis

During operation any electronic component will dissipate heat (with the exception of Peltier modules). If the amount of disipated heat is high enough the temperature of the elements of the component may increase.

Every designer of electronic equipment including components that dissipate heat will try to find the cooling solution that best combines the three methods of heat transfer without affecting the functionality of the system, without increasing energy consumption, or the size of the equipment or its price.

The main problem designers face is not the amount of heat produced during operation, but the fact that it is not removed at the same speed as it is produced. Particular attention must also be paid to the materials used; they should be chemically compatible so that no constriction occurs on the heat removal path.

1.2 The purpose of the doctoral thesis

This thesis attempts to answer the following questions:

- How do we power a power LED?
- How, where and with what do we measure the temperature on an LED?
- How can we estimate the temperature at the junction of the LED and how does knowing it help us?

- How do we ensure adequate thermal management for a COB LED and how can we improve existing cooling methods?
- How can the boundary conditions, the material parameters and the constructive structure influence the performance parameters of an LED?
- When do we use LED lighting fixtures?
- What does the thermal model of an LED look like and what information should it include?
- How important is the transient operating mode of an LED?
- How can we improve the types of heat sinks on the market in order to improve the heat distribution capacity?

To answer these questions the active cooling solutions used in lighting fixtures that employ high-power LEDs were analyzed, evaluated and further developed. Geometric and thermal models were be created for some of the fixtures used in the measurements. A constructive solution was proposed to improve an existing active cooling method. At the same time, a solution was proposed to improve the heat dissipation for an existing heat sink. A constructive solution was proposed for a traffic light that works in extreme thermal conditions. We analysed the best way to supply power LEDs and how to estimate the junction temperature.

1.3 The content of the doctoral thesis

The thes is structured in 8 chapters as follows:

- Chapter 1 includes the presentation of the field of the doctoral thesis, its purpose and content.

- Chapter 2 contains a brief theoretical introduction on the methods of heat transfer, the quantities and units of measurement used for LEDs, methods of obtaining white light, life time and causes of LED failure.

- Chapter 3 examines how the thermal, electrical and optical parameters of an LED are affected if it is supplied with direct current and direct current pulses. Thus, a case study is presented regarding the DC supply, respectively pulses of different values, frequencies and filling factors. The comparison between the two power supply methods is made from a thermal, electrical and optical point of view.

- In Chapter 4 theoretical concepts regarding the stationary and transient modeling of LEDs and are presented as well as 2 case studies regarding the estimation of the junction temperature. The first case study starts from the premise that the static operating junction temperature can be estimated based on a known relationship and the appropriate instrument for measuring the temperature is identified to obtain an accurate value of the temperature on the LED package. The second case study presents a simple and inexpensive method of estimating the junction temperature of an LED without removing it from the lighting fixture. The power supply used is different from the one employed in the forward voltage method in terms of duration and amplitude.

- In Chapter 5 theoretical aspects regarding active and passive cooling methods are summarized and four lighting fittings using active cooling methods are analyzed, compared and evaluated. Their analysis is done from thermal, electrical, price and consumption points of view.

- Chapter 6 studies the effect of boundary conditions and material parameters on the results of measurements and simulations. A geometric model is developed and thermal simulations are performed for the lighting fitting that uses cooling based on the air jet devices presented in Chapter 5.

Also in this chapter a thermal model for a lighting assembly that contains two different ambient temperatures, one at the heat sink and one at the LED lens is proposed.

A solution to lower the temperature on the fitting by using holes in the compact core of the heat sink is proposed.

A solution is also proposed to improve one of the active cooling methods presented in Chapter 5.

- Chapter 7 presents a LabView communication interface between a PC and a multimeter. The interface was based on examples already existing in LabView that were improved in order to obtain as many measurements per second as possible without using an acquisition board. The measurements obtained using this interface were necessary for the second case study presented in Chapter 4.

- Chapter 8 proposes a constructive solution for a traffic light that operates in extreme weather conditions of frost and snow.

- The last chapter contains the conclusions, the list of published works as well as perspectives for further development.

Chapter 2

Theoretical notions

2.1 Heat transfer methods

There are three methods of heat transfer: conduction, convection and radiation.
Fig.2.1 illustrates the three heat transfer methods for an LED using a passive cooling method.

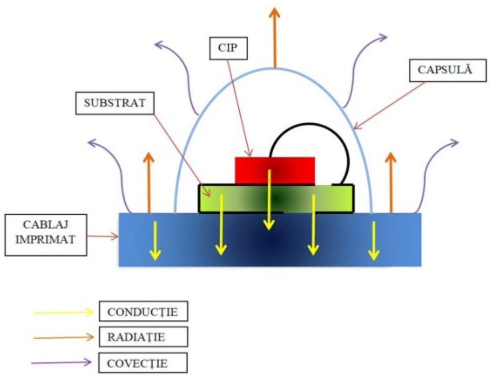


Fig. 2.1 Heat transfer from an LED mounted on a printed circuit board to the environment by conduction, convection and radiation.

In the thesis theoretical notions regarding the methods of heat transmission are presented.

2.2 Measurement units

In this subchapter the main parameters and units of measurement encountered in photometry are presented: light efficiency, color rendering index, color temperature, light flux, illumination, luminance, light intensity.

2.3 Methods to obtain white light

The method used to obtain white light influences the structure as well as the thermal and electrical behavior of the LED. According to [3] there are four methods of obtaining white light: by mixing the light from three LED chips: blue, green, red; blue LED chip mixed with yellow LED chip; blue LED chip with a layer of yellow phosphorus powder; ultraviolet chip that excites three types of phosphorus: red, blue and green.

2.4 LED lifespan and causes of failure

We can consider that the LED has failed if:

- The value of the illumination has dropped below 70% of its initial value
- The value of the direct voltage has decreased by 10% of its initial value
- There was a shift of the chromatic coordinates by 0.01 of their initial value

Failure of an LED is a progressive process [8] caused generally by one of the following:

- defects due to the chip manufacturer: the presence of defects in the crystal, electrode degradation, non-transparent epoxy or silicone gel
- defects due to the user of the chip: inadequate thermal management - heat removal solutions are not adapted to the real system, defects in soldering, reverse polarization, corrosion, thermal packaging.

The thesis presents the formulas for light degradation as well as how Arrhenius' law helps us in determining the rate of degradation of light flux and in estimating the lifespan of a material at different temperatures.

Chapter 3

Pulse power supply and DC power supply for power LEDs

In this chapter a comparison between two power supply methods, direct current and pulses, is made. This was done based on LED temperature (the temperature at the LED junction cannot be measured directly), dissipated heat, lighting and energy consumption. The frequencies of 100Hz and 1KHz were chosen and the filling factor was 25%, 50%, 75%. The LED was powered at I_{LED} = 500mA. The measurement results are centralized in Tab. 3.1.

Tab. 3.1. Maximum temperature value for the six situations studied

	Maximum temperature (˚C)		
Signal frequency	Signal filling factor of 25%	Signal filling factor of 50%	Signal filling factor of 75%
100Hz	34.4	52.2	66.1
1kHz	48.4	63.2	67.5

3.1 Conclusions

A comparison was made between an LED powered by constant current and the same LED powered by current pulses. The results obtained show a low temperature on the LED and a lower power consumption if we use current pulses but the lighting will also be reduced.

Chapter 4

Methods for estimating the junction temperature for steady state and transient state LEDs

4.1 The need to estimate the junction temperature of LEDs

In this subchapter, in the thesis, theoretical notions regarding the influence of the junction temperature on the light flux, direct voltage and chromatic coordinates are presented.

4.2 Modeling the thermal regime by electro-thermal analogies

When modeling thermal phenomena, an analogy between the propagation of electric current and the propagation of heat through conduction is used. This subchapter presents the thermal-electrical correspondences that will be used to equate the thermal model with an electrical circuit.

4.3 Steady state modelling of LEDs

The thermal model of a stationary LED will only contain thermal resistors because the dissipated power is constant (for multichip LEDs it will be assumed that all chips dissipate the same amount of power) and the temperature does not vary over time and the thermal capacity is not taken into account.

4.4 Transient state modelling of LEDs

4.4.1 Single pulse

In the case of the dynamic, pulse or in the micro-millisecond region, all the thermal capacities of the constituent parts of the component must be taken into account.

4.4.2 Continuous pulses

In the case of continuous pulses, from a thermal point of view, the temperature peaks due to the pulses overlap over the average temperatures due to the continuous operation.

4.5 Measuring instruments used to estimate the junction temperature of power LEDs in steady state

In this subchapter an experiment was performed that aims to determine the appropriate instrument for measuring the solder-point temperature used in estimating the junction temperature in steady state. To achieve this, thermal measurements were performed on a high-power LED using four instruments: thermal imaging camera, Velleman DVM4200 multimeter with K-type thermocouple, Raynger ST contactless thermometer and a temperature measurement system with a DS1821 sensor connected to the PC (Fig.4.9).

The measurement points in the present case study were the power supply pads of the LED and its lens.

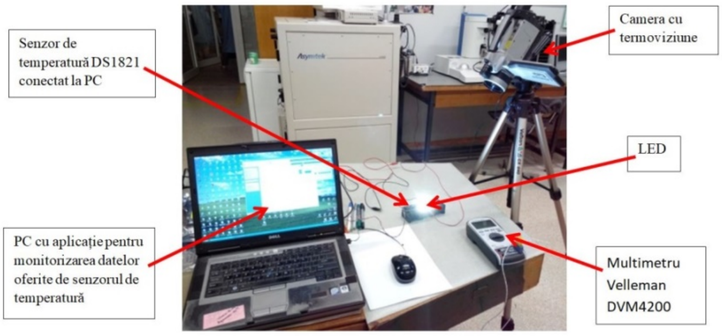


Fig. 4.9 Measurement stand

4.5.1 Conclusions

In order to be able to use the thermocouple to measure the temperature on the lens, it should be shielded. In order to obtain the most accurate information, I recommend that the measurements be made initially with both the thermocouple and the thermal imaging camera to ensure that its parameters have been set correctly.

4.6 Method for estimating the junction temperature of power LEDs as a function of direct voltage under certain operating conditions directly in the light fitting

The method presented in this chapter is based on a linear dependence between the junction temperature and the voltage drop across the P-N junction under certain operating conditions directly in the lighting assembly. The constituent parts of the measuring stand are presented in Fig.4.15.

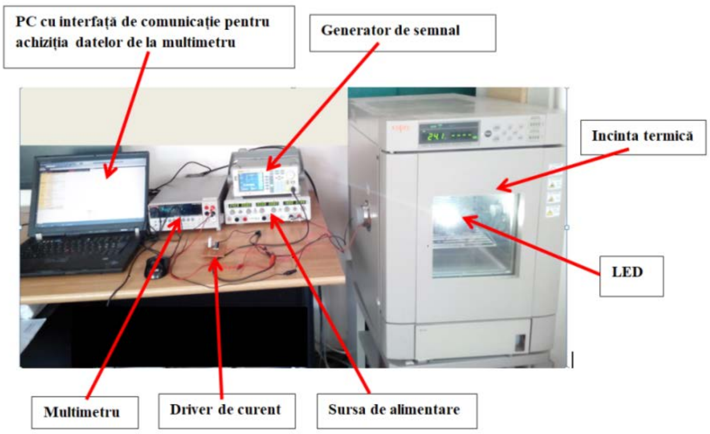


Fig. 4.15 Measurement stand

The method is presented in the thesis.

4.6.1 18W LED with heat sink

Measurements were made for the 18W LED equipped with a heat sink, the value of the LED current was 500mA and 1A, respectively, the signal frequency was 20Hz and the filling factor was 50%. The results of the measurements are presented in the thesis. For both situations it is found that with the increase of the operating temperature the direct voltage decreases but not by a constant value. For 500mA it takes values between 4-7mV/˚C and for 1000mA it takes values between 4-10mV/˚C.

4.6.2 1W LED

Measurements were made for the 1W LED. 20Hz frequency pulses with a filling factor of 50% and an amplitude of 350mA were applied. The ambient temperature inside the enclosure was varied between -20˚C and + 65˚C. The results of the measurements are presented in the thesis. $K_{T, UF}$ is in the range 4-6mV / ˚C.

4.6.3 Osram Golden Dragon LED

Measurements were made for another power LED: the Golden Dragon from Osram. 20Hz frequency pulses with a filling factor of 50% and an amplitude of 350mA and 100mA, respectively, were applied. The ambient temperature inside the enclosure was varied between -10˚C and + 90˚C. The results of the measurements are presented in the thesis. $K_{T, UF}$ is in the range is 1-2mV/˚C for 350mA and 1-2 mV/˚C for 100mA.

4.6.4 Conclusions

The method presented differs from the "forward voltage" method in that the LED was supplied at a normal working voltage, the supply period was 5s, the first 5 results were extracted, the average was calculated and the interval between two measurements was 2ms. Also another novelty is the fact that a COB LED is used and the temperature range also includes temperatures lower than 25˚C. This method allows the estimation of the LED junction temperature without the need for expensive equipment and customized results for each LED can be obtained.

Chapter 5

Cooling methods for power LEDs

5.1 Active cooling methods

5.1.1 Peltier module

This chapter presents theoretical notions regarding Peltier modules.

5.1.2 SynJet

This chapter presents theoretical notions regarding the device that produces synthetic air jets.

5.1.3 Ventilators

This chapter presents theoretical notions regarding fans.

5.2 Passive methods

5.2.1 Heat pipe

This chapter presents theoretical notions regarding heat pipe.

5.2.2 Heat sink

This chapter presents theoretical notions regarding heat sinks.

5.3 Thermal and electrical measurements on Led light fittings using various active cooling solutions

Four lighting fittings were made (Fig.5.21, Fig.5.22, Fig.5.23, Fig.5.24). They used the same LED as the light source and the same thermal interface material. Each active cooling solution was compared with the passive one obtained by not powering the active device or by removing it because various shapes, sizes and materials were used for the heat sink.

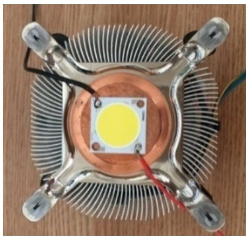


Fig. 5.21 Light fitting with ventilator

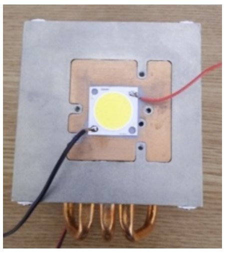


Fig. 5.22 Light fitting with ventilator and heat sink with heat pipe

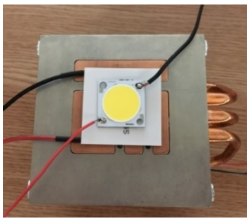


Fig. 5.23 Light fitting with Peltier module and heat sink with heat pipe

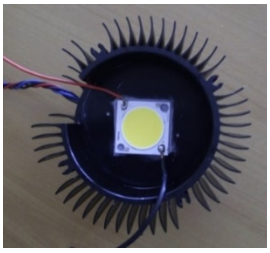


Fig. 5.24 Light fitting with SynJet

A comparison is presented in Tab. 5.1.

Tab.5.1 Comparison of cooling methods in terms of costs (20.07.2017), additional power consumption and noise introduced

Nr. Crt.	Cooling solution	Additional power consumption (W)	Noise (dB)	Total price (lei)
1.	SynJet	0.84	15	190
2.	Heat sink and Intel ventilator	0.96	20	94
3.	Heat sink with heat pipe and Sunon ventilator	0.34	17.8	120
4.	Peltier module and heat sink with heat pipe	10	0	150

5.3.1 Light fitting 1

The results of the assessment of the first light fixture for two situations when the fan is switched on or off are presented

5.3.2 Light fitting 2

The results of the assessment of the second light fixture for two situations when the fan is switched on and off are presented.

5.3.3 Light fitting 3

The results of the evaluation of the third light fixture for two situations are presented when the Peltier module is present and absent.

5.3.4 Light fitting 4

The results of the evaluation of the fourth light fixture are presented for two situations when the device for producing air jets is turned on and off.

5.3.5 Conclusions

It has been found that one of the quietest and most efficient methods from a thermal and electrical point of view is the one in which we use devices to generate synthetic air jets.

Chapter 6

Thermal modelling using equivalent thermal circuits and geometric models of power LEDs

6.1 LED package level modelling

A model of the LED was developed and simplified from the point of view of the array (the LED is COB type) in the sense that a compact silicon zone was used and the influence of the thermal interface materials between the COB component parts was neglected. This subchapter is based on the article [52] published by the author. The component parts of the COB LED are presented in Fig.6.1.

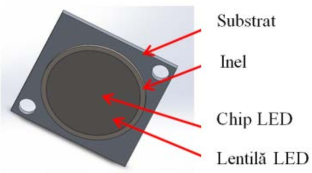


Fig. 6.1 Components of the COB LED

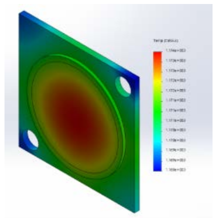


Fig. 6.2 Simulation results for the COB LED without heat sink for P_d=12.8W, h=7W/m^{2}K, T_a=20ºC.

The properties of the materials of the components of the light fixture used in the simulation are presented in the thesis. The simulation results are presented in Fig.6.2. We notice that the value obtained from the simulations is very high (1174 ° C).

6.2 System level modelling

The model of a light fixture was developed (Fig.6.4) consisting of a COB type module of very high power placed on a metal substrate (aluminum) and an aluminium heat sink (Fig. 6.4).

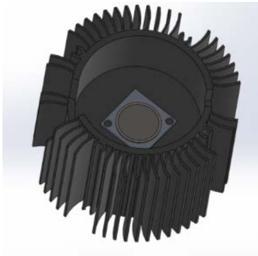


Fig. 6.4 LED light fitting model

Measurements were made on the fitting. Measurement results after 90min. when the fitting has reached thermal equilibrium are shown in Fig.6.6.

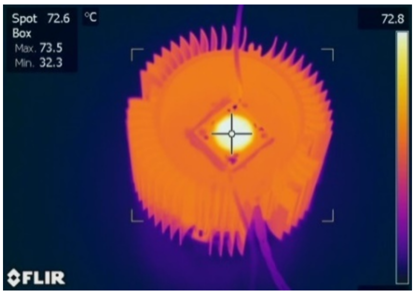


Fig. 6.6 Measurement results after 90min.

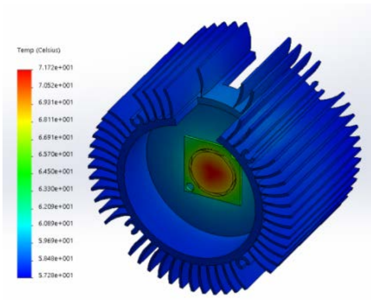


Fig. 6.7Simulation results for aluminium substrate, aluminium heat sink and h=7W/m²K, P_d=12.8W, T_a=20°C

Simulation results are presented in Fig.6.27 For the contact between the LED module and the heat sink, a thermal resistance of 0.2˚C/W was estimated. The simulation results are presented in Fig.6.7.

6.3 Model validation

The validation of the model was done by comparing the results of the simulations with those resulting from the measurements (Fig.6.8.)

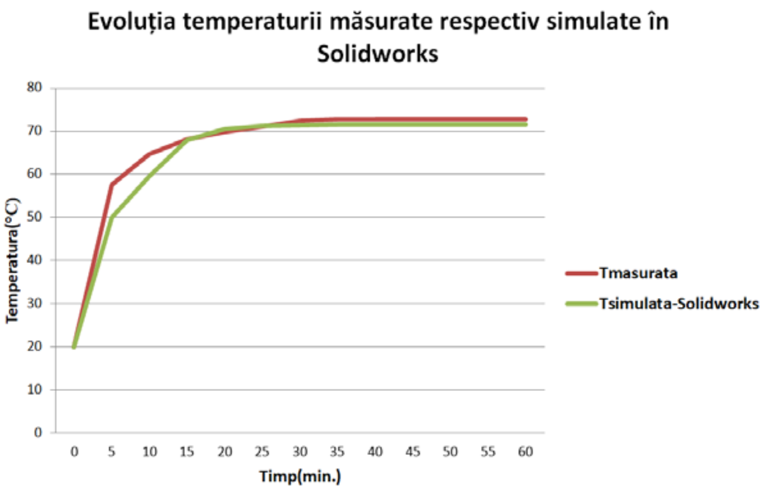


Fig. 6.8 Temperature evolution resulting form the measurements ande from Solidworks simulation respectively

The difference between the results provided by the simulations and the measurements is less than 2ºC. Therefore, the proposed model and the settings used have been validated.

6.4 Ambient condition and material parameters influence on simulation results

6.4.1 Ambient temperature influence

Thermal simulation of the light fitting was performed for 5 values of the ambient temperatures -20ºC, 0ºC, 20ºC, 40ºC and 60ºC respectively. The value of the dissipated power respectively of the convection coefficient remained the same: P_d=12.8W, h=7W/m^2K. In the thesis the results of the simulations are presented.

6.4.2 Convection heat transfer coefficient influence

The convection heat transfer coefficient is a parameter that is very difficult to measure. In general its value is estimated. The simulation for the light fitting was performed for 3 values of the convection heat transfer coefficient: h=5W/m^2K, h=7W/m^2K, h=10W/m^2K (Fig.6.17) The value of dissipated power and ambient temperature were the same: P_d=12.8W, T_a=20°C.

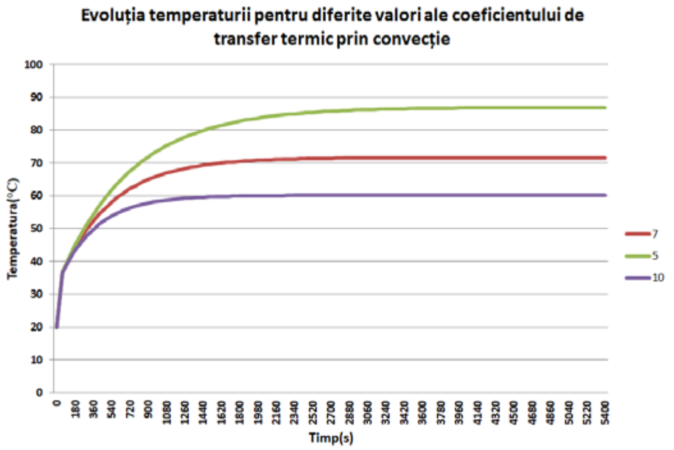


Fig. 6.17 Evolution of the maximum temperature for different values of the convection heat transfer coefficient

6.4.3 Substrate material

The substrate used for power LEDs has an important role in its thermal characterization. There are three types of materials predominantly used as substrate: metallic, ceramic or organic. Simulations were performed for 3 materials: aluminum, alumina and FR4 (Fig. 6.8).

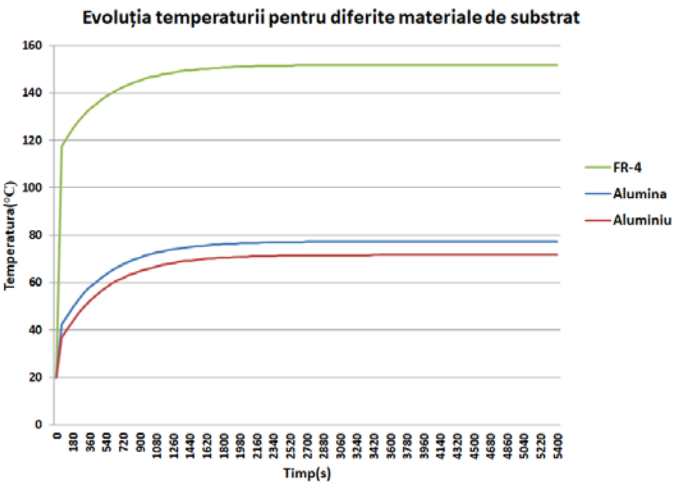


Fig. 6.8 Evolution of the maximum temperature over time for different substrate materials

6.4.4 Heat sink material influence

The shape, dimensions, material and processing of the heat sink impact its thermal performance. Simulations were performed for three types of material: aluminum, copper and graphite, the rest of the settings remaining the same (Tab.6.1).

Tab. 6.1 Simulation results for different materials

Nr. crt.	Material	Maximum temperature (°C)
1	Aluminium	71.72
2	Copper	69.69
3	Heat sink with copper core and aluminium fins	70.11
4	Graphite	69.38

The length of the heat sink was doubled (Fig.6.24).

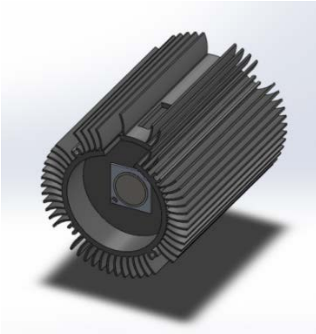


Fig. 6.24 Resized virtual model

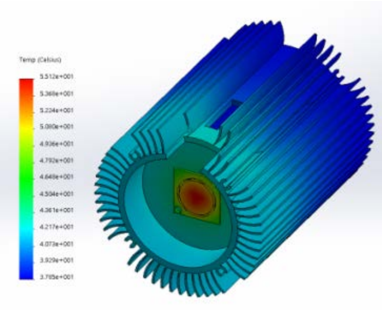


Fig. 6.25 Simulation results for an LED on an aluminium substrate, aluminium heat sink with doubled length, $h=7W/m^2K$, $P_d=12.8W$, $T_a=20°C$

The simulation results are presented in Fig.6.25. Note that the maximum temperature is 55.12°C. This is the value obtained if we use the active cooling method with synthetic air jets.

6.4.5 Signal frequency influence on simulation results

A signal with a frequency of 5Hz, 25Hz, 50Hz and 100Hz respectively and with a 50% fill factor was applied. The values obtained one second after connecting the power supply are centralized in Tab.6.2.

Tab. 6.2 Simulation results

Power supply type	Temperature on the chip after 1s(°C)
Direct current	29.63
Pulses with 100Hz frequency and 50% filling factor	24.569
Pulses with 50Hz frequency and 50% filling factor	24.526
Pulses with 25Hz frequency and 50% filling factor	24.426
Pulses with 5Hz frequency and 50% filling factor	24.161

6.4.6 Conclusions

It was determined that an increase of the ambient temperature will lead to an increase with the same value of the maximum temperature on the simulated assembly. Regarding the convection coefficient, although it has values in the field of natural convection, an increase of $1W/m^2K$ can lead to a change in temperature by up to 5°C. The best thermal performance was obtained for the metal substrate material and it would not be recommended to use an FR4 substrate for a very high power LED. The differences between the results obtained for copper compared to aluminum are not significant enough to justify its use. Pulse supply leads to a lower temperature on the chip than in the case of direct current supply but the value of illumination is greatly reduced.

6.5 Steady state and transient thermal modelling using equivalent thermal diagrams and geometric models for power LEDs

In creating the thermal model both as an equivalent Spice schematic and at the level of thermal simulation, Solidworks starts from the premise that there will be two ambient temperatures: one at the heat sink level and the other above the primary lens of the LED. This difference is due to the fact that the LED is part of a fitting that has a lens/light diffuser that prevents the exchange of fluids between the primary lens of the LED and the outside of the fitting.

6.5.1Steady state modelling for two ambient temperatures

In Fig.6.29 the results of the simulation at the same ambient temperature for different convection coefficients are presented. In Fig.6.30 the measurements are resumed for two values of the ambient temperature T_a=293K outside and T_{a1}=296K inside the enclosure created between the chip mounted on the heat sink and the lens.

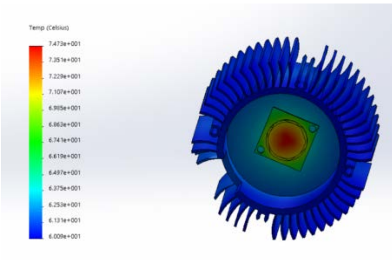


Fig. 6.29 Simulation results for P_d=12.8W, T_a=T_{a1}=293K, h=7W/m^{2}K outside and h_2=3W/m^{2}K inside the light fitting (T_{max}=74.73ºC)

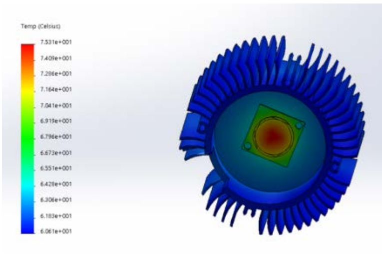


Fig. 6.30 Simulation results for P_d=12.8W, T_a=293K, h=7W/m^{2}K outside and h_1=3W/m^{2}K, T_{a1}=296K inside the light fitting (T_{max}=75.31ºC)

The equivalent electrical diagram in steady state is presented in Fig.6.31.

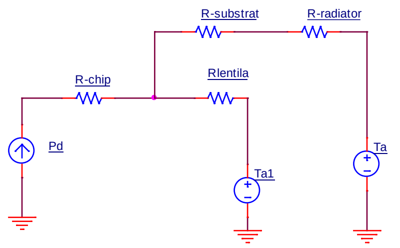


Fig. 6.31 Equivalent schematic in steady state

This schematic takes into account the thermal resistance of the lens. The result of the simulation in steady state with temperatures equal to 20°C led to a maximum temperature of 76.109°C, and with two ambient temperatures of 20°C, respectively 23°C led to a maximum temperature of 77.417°C.

6.5.2 Transient state modelling

The structure of the Spice subcircuit with Cauer networks for thermal modeling in transient regime is presented in Fig.6.36:

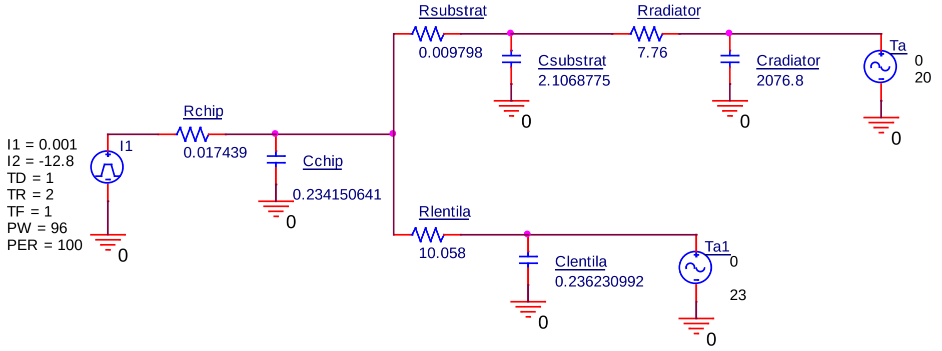


Fig. 6.36 Spice subcircuit structure with Cauer networks for transient thermal modeling

In Tab. 6.4 the values of the temperature obtained following the measurements respectively the Solidworks and Spice simulations in transient regime are presented.

Tab. 6.4 The value of the measured and simulated temperature obtained under certain conditions

	Ambient temperature (°C)				
				T_a	T_{a1}
	20	0	40	20	23
Measured (°C)	72.6	-	-	-	
Solidworks simulation (°C)	71.72	51.72	91.72	75.31	
Spice simulation (°C)	76.082	56.082	96.082	77.389	

6.5.3 Conclusions

It was determined that in order to obtain the most realistic models, it is recommended to take into account the difference between the values of the fluid parameters above the primary lens and the heat sink.

6.6 Solution to improve the thermal capability of a solid core heat sink

Starting from the premise that the maximum temperature on a fitting is affected not only by the volume but also by the air contact surface we performed simulations for the fitting studied in 6.1 but we modified the heat sink core in the sense of drilling it in the area where it is not is in contact with the LED base. The simulation results are centralized in Tab. 6.5.

Tab. 6.5 Synthesis of simulation results

	Distance between holes (mm)	T_{max}(°C)
Without holes		71.72
3mm holes	8	70.97
	4	68.97
2mm holes	8	71.09
	4	68.66

6.6.1 Conclusions

It was determiend that the best thermal performance is obtained when the number of holes was the highest.

6.7 Improved active cooling solution

The package of the device for the production of synthetic air jets was added to the Solidworks model developed in 6.1 (Fig.6.49) to obtain the model of the lighting fitting with synthetic air jets studied in 4.4. This material was published by the author in [59].

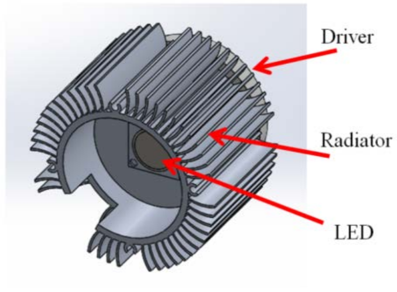
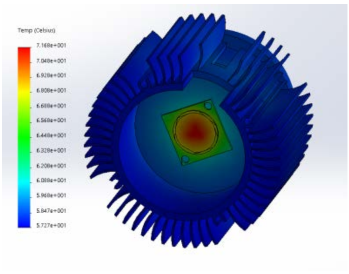


Fig. 6.49 Light fitting model

The simulation was performed with the following initial conditions: P_D=12.8W and the natural convection coefficient h=7W/m^{2}K.



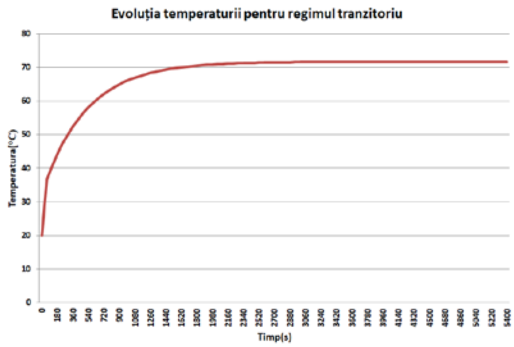


Fig. 6.50 Simulation results for P_D=12.8W and natural convection coefficient h=7W/m^{2}K.

Fig. 6.51 Temperature evolution in transient state

Transient analysis was performed (Fig.6.51).

The value of the heat transfer coefficient on the heat sink fins was changed to 14W/m^{2}K (among them the air is moved due to the synthetic jet generator), otherwise it remained at the value of 7W/m^{2}K. In Fig.6.53 the measurement and simulation results are compared.

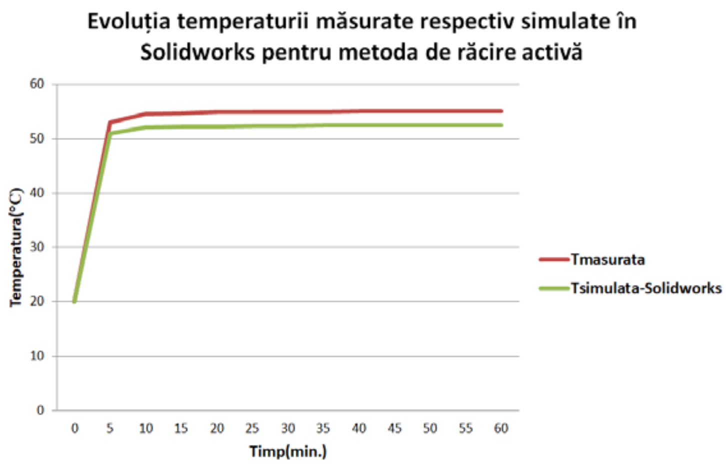


Fig. 6.53 The evolution of the measured and simulated temperature if the active cooling method is used.

To reduce the temperature on the LED module, the heat sink geometry has been changed. Three fins were removed (Fig.6.56) and in their place a structure to guide the air coming out of the nozzles to the LED lens was placed, to create a forced convection above the lens (Fig.6.60).

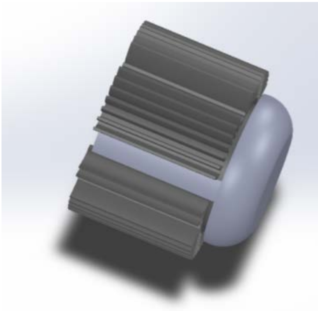


Fig. 6.56 Light fitting without three fins and with air jet redirection channel (side view)

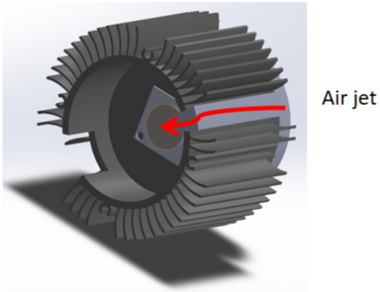


Fig. 6.26 Air flow to the LED lens

The simulation was resumed but in this case the value of the heat transfer coefficient by convection was set at 14W/m^{2}K on the entire surface of the fitting(Fig.6.61).

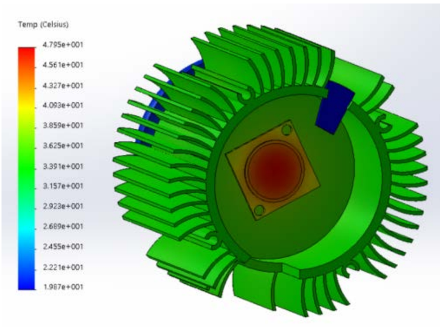


Fig. 6.61 Simulation results for P_D=12.8W and convection coefficient h=14W/m^{2}K.

6.7.3 Conclusions

A method for improving an existing active cooling method has been proposed. This method of improvement consists in redirecting synthetically generated air jets from the device that generates them, along the heat sink and to the LED lens. The fact that the LED can also be cooled from the side through which it emits light has been taken into account. The modified fitting was simulated and the results were compared with those obtained from the measurements and simulations of the unmodified LED assembly, the temperature obtained on the LED for the modified assembly being lower by 4.53°C than in the case of the unmodified lighting assembly.

Chapter 7

Developed software tools

7.1 PC- Keithley 2700 multimeter communication interface

In order to obtain a large number of measurements per second, an interface was created, using LabView, allowing communication between a PC and a Keithley multimeter via GPIB. It was based on examples already existing in LabView that were adapted to obtain as many measurements per second as possible without using an acquisition board. The minimum interval between two measurements was 2ms. The interface and its program are presented in the thesis.

7.2 Labview interface for pentru computing junction temperature

An interface was developed using Labview to allow computing the junction temperature using the measurement results in both steady and transient operation mode. The interface allows choosing the mode of operation as well as entering from the keyboard the parameters obtained from the measurements. This interface and program are presented in the thesis.

Chapter 8

Power LEDs application

8.1 Constructive solution for traffic lights operating in extreme weather conditions

This chapter presents a traffic light model published by the author in [60] that uses a Peltier module for heating the external lens of a traffic light based on a RGBW type LED power module. A Peltier module was used to cool the LED. The LED was mounted on its cold side and the package of the fiting was mounted on the warm/hot side. The heat is transferred thorugh the package to the external lens. Thin wires made of a good conductive metal will be inserted in the externl lens to allow it to heat as evenly as possible, but without affecting its transparency. Simulations were performed for various ambient temperatures and various values of current through the Peltier module.

8.2 Conclusions

Traffic lights using Peltier modules can be used for areas where extreme weather events are encountered.

Chapter 9

Conclusions

9.1 Results

In this subchapter, in the thesis, the results obtained are presented.

9.2 Original contributions

- Development of a solution to improve the cooling system with SynJet presented in Chapter 6 and published in [11].
- Development of a method for estimating the junction temperature of the LED directly in the lighting fitting described in Chapter 4 and published in [6].
- Development of a method of increasing the thermal capacity of a heat sink with an aluminum core and side fins by using via-type through-holes presented in Chapter 6 and not yet published.
- Development of an equivalent thermo-electric model that takes into account the temperature difference between the ambient and above the lens described in Chapter 6 and published in [13].
- Development of a constructive traffic light solution that works in extreme weather conditions described in Chapter 8 and published in [4].

- Analysis through simulations of the effect of boundary conditions, material parameters as well as supply type on the results of the simulations described in Chapter 6 and published in [7, 12,14].
- Comparative analysis from the thermal and electrical points of view of direct current supply, respectively direct current pulses presented in Chapter 3 and based on the article published in [2].
- Comparative analysis of temperature measuring instruments at component and overall fitting level described in Chapter 4 and published in [5].
- Carrying out thermal, electrical and optical measurements on LED light fittings on a ceramic or metal substrate using active cooling methods with Peltier module [1, 12], fan [9,10,12], or SynJet type devices [8, 12] presented in Chapter 5.
- Development of Solidworks models for the LEDs used in measurements with various forms of heat sinks and thermal simulation of the assembly [7, 11, 12].
- Development of Solidworks models for the the LED with metal substrate used in measurements and various forms of heat sinks and thermal simulation of the assembly formed by them with modified physical parameters (substrate material or radiator material), or with the resized heat sink [12].
- Development of a communication interface between the PC and a Keithley multimeter in order to increase the measurement and acquisition speed without using an acquisition board presented in Chapter 7.
- Development of a program that allows the graphical representation of the estimated life time if useful life times are known for three different values.
- Comparative analysis in terms of acquisition costs, noise introduced by cooling devices but also the dimensions of the four fittings using active cooling methods performed in Chapter 5.

9.3 List of original works

[1]. **N. Bădălan**, P. Svasta, *Peltier elements vs. heat sink in cooling of high power LEDs*, 38th International Spring Seminar on Electronics Technology (ISSE), 2015, pp: 124-128 , DOI: 10.1109/ISSE.2015.7247975, WOS:000374113000026.

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[3]. **N. Bădălan**, P. Svasta, *Analysis of LEDs thermal properties*, 2016 IEEE 22nd International Symposium for Design and Technology in Electronic Packaging (SIITME), Oradea, 2016, pp. 155-158, DOI: 10.1109/SIITME.2016.7777267, WOS:000390557400032.

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[10]. **N. Bădălan((Drăghici)**, P. Svasta, *Fan vs. passive heat sink with heat pipe in cooling of high power LED*, 2017 IEEE 23rd International Symposium for Design and Technology in Electronic Packaging (SIITME), Constanta, 2017, pp. 296-299. DOI: 10.1109/SIITME.2017.8259911, WOS:000428032300062.

[11]. **N. Bădălan((Drăghici)**, P. Svasta and C. Marghesu, *A Method for Improving an Active Cooling Solution for LEDs*, 2018 IEEE 24th International Symposium for Design and Technology in Electronic Packaging (SIITME**)**, Iași, 2018, pp. 5-8, DOI: 10.1109/SIITME.2018.8599197, WOS:000466960400001.

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[13]. **N.Bădălan(Drăghici)**, P.Svasta , C. Marghescu, *Thermal Model for LED Luminaire,* 2019 IEEE 25th International Symposium for Design and Technology in Electronic Packaging (SIITME)**,** *Cluj-Napoca,* 2019, pp: 335-358, DOI: 10.1109/SIITME47687.2019.8990735

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9.4 Further developments

One future direction of development could be to check the improved active cooling method with SynJet in practical applications, to correct design and implementation errors and to improve its efficiency.

The drilling of the radiator could be performed in order to practically realize the method of improving the thermal parameters of the radiator with a compact, homogeneous core.

Another direction of further development could be conducting measurements with the integrative sphere for the revalidation of the proposed models.

Also regarding the use of Peltier modules in cooling the power LEDs in future research we will try to recover some of the electrical voltage and reduce the consumption of the Peltier module.

Regarding the equivalent thermal model with two ambient temperatures, a solution could be found so that the convection coefficient can be included in the diagram.

Regarding the proposal for a constructive solution of a traffic light that works in extreme conditions, the respective light fitting could be practically realized.

10 Annexes

10.1 Matlab script for graphical representation of LEDs lifespan

The Matlab program used to make the graph of the lifetime and the useful lifetime for an LED is presented.

10.2 Mesurement interface with sensor

The thesis shows the PC-sensor interface.

10.3 Thermal simulations at 0°C and 50°C ambient temperature

The results of the simulations are presented for the proposed traffic light model but for the ambient temperature equal to 0° C and 50° C respectively.

10.4 Thermal modelling of a power LED mounted on a rectangular heat sink

The model of the LED fitting from chapter 4 was made. Simulations are made for different heat sink materials, dissipated power and convection heat transfer coefficient.

10.5 Thermal modelling of a LED light fitting with heat sink and ventilator

The model of the lighting fixture with fan was made, on which we made the measurements in Chapter 3. In the thesis, simulations are presented for different substrate materials and for different convection heat transfer coefficient.

10.6 Active cooling method with Peltier module

The results of the measurements for an experiment similar to the one in which we use the active cooling method with Peltier modules but for an LED with a ceramic substrate and the heat sinkradiator used is the one from the air jet device are presented in the thesis.

10.7 Measurements on a LED light fitting with ceramic substrate and active cooling method with ventilator

This material was published by the author in [64]. The results of the measurements for the experiment similar to the one presented in 5.3.1 but for an LED with a ceramic substrate are presented in the thesis.

10.8 Measurements on a LED light fitting with ceramic substrate and active cooling method with ventilator and heat pipe

Acest material a fost publicat de autoare în [65]. In teză sunt prezentate rezultatele măsurătorilor pentru experiment asemanator celui prezentat în 5.3.2 însă LED-ul folosit are substrat ceramic. This material was published by the author in [65]. The results of the measurements for the experiment similar to the one presented in 5.3.2 but for an LED on a ceramic substrate are presented in the thesis.

10.9 Constant current driver with buck converter

In order to supply the high power LED, a constant current driver with buck converter was designed and built. The thesis presents the electrical diagram and its operation.

10.10 Temperature evolution over time for different substrate materials

A table with the evolution of temperature over time for different substrate materials is included in the thesis.

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