e-ISSN: 2146 - 9067

International Journal of Automotive Engineering and Technologies

journal homepage:

https://dergipark.org.tr/en/pub/ijaet

Original Research Article

hosted by Turkish JournalPark ACADEMIC

Thermal performance investigation of position function circuit board used in automotive exterior rear lighting

Birhat Sönmezay[1, *], Mehmet Aktaş[2]

[1, 2]Marelli Mako Turkey Electric Industry and Trade Incorporated Company, Bursa, Turkey.

ARTICLE INFO

Orcid Numbers
1. 0000-0002-8432-6192
2. 0000-0003-1552-9946

Doi: 10.18245/ijaet.830838

* Corresponding author
birhat@gmail.com

Received: Nov 25, 2021
Accepted: Jun 02, 2022

Published: 01 July 2022

Published by Editorial Board Members of IJAET

ABSTRACT

In this research, both numerically and experimentally, the thermal efficiency of a Printed Circuit Board (PCB) with two Light Emitting Diode (LED) chips was examined. The two LED lighting systems, which are single-cell LEDs, including PCB and copper plates, were manufactured, and tested under laboratory conditions to achieve this goal. The three-dimensional Computational Fluid Dynamics (CFD) model with natural convection effects prepared using the FloEFD software package to predict PCB surface temperature distributions. The goal was to perform comprehensive circuit board simulation and validate the numerical model built in this study using the experimental data during the studies. From the results, we can easily claim that higher temperature gradients are calculated and predicted near the LED chip because of heat generation. Data paths have played an essential role in the LED circuit board's temperature distribution. High-temperature variations are observed at short distances around the LED when the experimental and simulation results are compared. Temperature changes are minimized as they travel away from the LED chip. It is found that the error rate is below 5 percent overall between the experimental and simulation results. The numerical results were in proper alignment with numerical data obtained from the three-dimensional (3D) CFD model. Given thermal efficiency and using such models, this model can design and analyze Automotive Lighting Systems.

Keywords: Automotive lighting, CFD, LED, Heat transfer, Printed circuit board (PCB)

1. Introduction

LED systems based on electronic control boards and printed circuit boards (PCB), which include advanced technology in design and manufacturing, are used to provide light generation and lighting function. On the other hand, providing lighting function, the main reasons for preferring LED systems' usage are longer lamp life, low energy consumption, and short response times. Automotive manufacturers try to reduce fuel consumption with lower emissions. Besides, they try to decrease the high electrical consumption on an automobile due to the new generation electric car. In this development, the use of LEDs became more critical for the automotive industry.

In the available literature, there are many scientific kinds of research based on LED components or systems. For instance, Choi et al. studied the prediction of the junction temperature of a LED system with free convection. In addition, the temperature distribution of electronic boards was studied [1]. Tsai et al. studied thermal analysis and temperature measurement for LED packages and modules, which had high low cost and power [2]. Kikuchi investigated the LED system with aluminum fin heatsink where placed on the reflector. They calculate to LED system of junction temperature and with defined the thermal simulation methodology for an electric car produced by Nissan [3]. Yung et al. study on the thermal management of high-power LED package used on the printed circuit board material [4]. Mornet investigated the thermal performance of a LED system used signaling and lighting function [5]. Christensen investigated electronic board temperature distributions of a high brightness light emitting diode (LED) with numerical heat transfer models [6]. Keppens et al. try to determine the relationship between LED junction temperature and forward currents [7]. Kwok et al. studied on the thermal system of automotive LED systems [8]. They investigate the relationship between temperature and the current on the LED's luminous efficiency and calculate Junction temperature. Ceng et al. worked on thermal analysis and optimization of multiple LED packages based on general analytical solution [9]. Saati et al. studied on automotive LED exterior lighting for determined thermal characteristics with IR camera [10]. Sevilgen et al. Studied on PCB of automotive LED head lamp cooling. They examined LED PCB’s simulations and validations [11,12]. Keppens et al. Studied on determination of LED junction temperature with forward current. They developed models that can be used to simulate the junction temperature in practical applications [13]. Poelma et al. study on an ultra-thin multi-LED package. They were designed, manufactured to their own LED package, and investigated thermal performance. They were used high-resolution thermal camera and thermocouples in their research and measured the temperature distribution of the multi-LED package and the LED junction temperature for different powers. [14]. Tsai et al. studied on the thermal analysis of LED packages and modules which had high power and low cost. Also they validated their model with IR camera and thermocouple. They calculated LED junction temperature with analysis and compared with experimental results [15]. Chai et al. investigated the prediction of the LED junction temperature in free convection. The thermal management of power electronic modules was also studied. End of the research, authors were gave to predictable calculation for LED junction temperature [16]. Yung et al. were investigated to thermal performance of high-power LED package. They were performed PCB temperature distribution with CFD codes and compared with IR camera and thermocouple measurement results. Temperature distribution of PCB behavior and junction temperatures were obtained in their research [17]. Tamdogan et al. studied on LED junction temperature calculation with three different measurement methods. They were used coated and uncoated models to measure junction temperature. During the experimental studies, tests were performed with Raman Spectroscopy, micro-infrared (IR) Imaging, and forward voltage methods [18]. Arik et al. studied standard calculation way for LEDs. According to investigations, forward voltage change, peak wavelength shift and infrared thermal imaging methods were used for experimental and numerical calculation. They were obtained forward voltage method most accurate method (±3°C) than other methods [19].

In this study, a LED circuit board was investigated used in automotive exterior rear lighting, which was designed and performed position function on automobiles. Therefore, this paper difference to other literature models. Examined model will be produced 600K per year for automobiles. In addition, simulation and experimental results are important for customer quality problem. Simulations had been performed with designed printed circuit boards before the validation phase was achieved successfully. Detailed model of a LED circuit board was designed two single LED chip with double copper layer. After the simulation phase, the test was made with an IR camera and determined temperature distribution on circuit board. According to simulation results, LED junction temperature is calculated with a validated model. On the other hand, error rates are calculated with results of simulation and test measurement.

2. Materials and Methods

2.1 LED system design

In this analysis, the single-chip LEDs on the circuit board were developed and manufactured using advanced technology to test the thermal efficiency of the LED device. On the top copper plate, LEDs used in the automotive rear lighting products were mounted in this system. This method includes the interaction of the top and bottom copper plates with LEDs and PCBs between the copper plates (Figure 1).

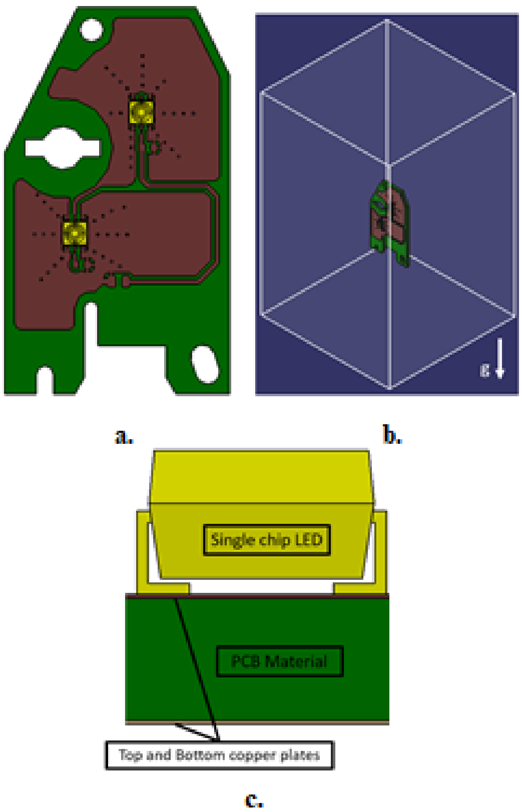

Figure 1: a. PCB with single-chip LEDs
b. Cross-sectional view of LED system
c. Computational domain with solid region

The size of the board was 48 x 28 x 1.62 mm, and the size of the single-chip LED was 3.3 x 3.2 x 1.9 mm. The printed circuit board was roughly rectangular in shape. The material for the printed circuit board was made of Glass-reinforced-epoxy laminate (FR4) material. With no thermal insulation, the thickness of the copper plates on both sides was 35 µm. Copper thickness can be increased by up to 50 percent by the process after the plating method of PCB. To prevent this, the PCB board cut and measured by an electronic microscope (Figure 2). The copper-covered top and bottom surface ratio was 55 percent and 60 percent, respectively.

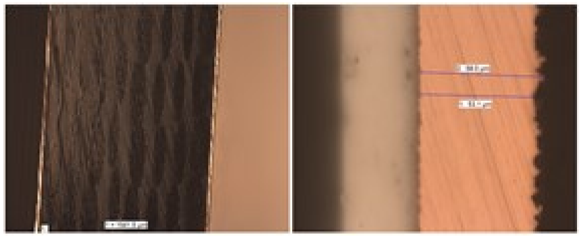

Figure 2: PCB measurements with an electronic microscope

Table 1. LED Characteristics

Parameter	Symbol	Unit	Values
Operating Temperature	T_{op}	°C	-40 125
Junction Temperature	T_j	°C	125
Forward Current	I_F	mA	70
Forward Voltage	V_F	V	2.15
Luminous Flux (I_F = 50 mA)	Φ_V	Lm	1.90 9
Real thermal resistance junction	$R_{thJS\ real}$	K/W	83

Table 1 was shown LED characteristics in this study. According to design requirement and cost issue, Osram LA-E67F LEDs were used on PCB. During the simulations, LED was performed with two resistor model and junction temperature calculated. There are two LED on PCB for position function and LEDs were driven with apart electronic control unit.

2.2 Numerical model of a single-chip LED lighting system

The numerical model of a single-chip LED lighting system was achieved by using the FloEFD software package, which includes 3D fluid flow and heat transfer analysis simulation tools coupled with CAD systems. The numerical simulation was performed under steady-state conditions, and the flow was assumed as laminar. The numerical solution includes all heat transfer nodes. The governing equations, including continuity, momentum, and energy equations for steady-state conditions of airflow with free convection effects can be written by using Equations 1-5. Due to the difficulties of modeling LED in details, we assumed that two resistor model for the single-chip LED with heat generation. The heat generation was selected considering the temperature increase in single-chip LED dependent on reducing lighting emittance. The governing equations and the boundary conditions used in the numerical calculations were described below.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (1)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\upsilon\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \quad (2)$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\upsilon\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \quad (3)$$

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\upsilon\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+g\beta(T-T_\infty) \quad (4)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \quad (5)$$

$$Q_{rad}=\varepsilon\cdot\sigma T^4$$

Where, u, v and w are the velocity components (m/s), α is the thermal diffusivity (m2/s), υ is the kinematic viscosity (m2/s), β is the volume expansion coefficient, g is the acceleration of gravity (m/s2), T is the temperature (°C), ρ is the density(kg/m3) of fluid in the computational domain and k and S are the thermal conductivity (W/mK) of the LED material and the source term (K/s) in LED chip, respectively. No slip boundary condition was used for solid-fluid boundaries. ε is the surface emissivity coefficient, σ Stefan-Boltzmann constant. The thickness of the copper plates in the top and bottom sides was 53 µm without thermal insulation. Also LED material was assumed copper and LED circuit board material was used FR4 material. In the simulation, LED power was assumed the two-resistor heat generation rate. Test and simulation were performed with 13.5V, 140mA. The electrical power was calculated 0.3W. The surface contact resistance between the board and the single-chip LED were neglected. The maximum junction temperature for the LED used in experimental and numerical studies is 125c°C given by the manufacturer.

2.3. Mesh structure and boundary conditions

In the numerical study, the thermal analysis of the circuit board which was achieved by using a software package that was capable of numerical simulation in the CAD environment. All heat transfer modes were considered during numerical simulations. Monte-Carlo radiation heat transfer model was used in radiation heat transfer calculations. Quadro mesh structure was used for the circuit board during the analysis.

Figure 5 shows the mesh structure, and approximately 850 000 elements were used in the simulations. About 350 000 elements were used for the fluid zone, about 500 000 elements were used in the solid region. Due to the difficulties for the detailed design of the single-chip LED, two resistor model is selected. The heat generation was selected considering the temperature increase in LED. In all numerical calculations, the circuit board was analyzed under 23 °C ambient conditions.

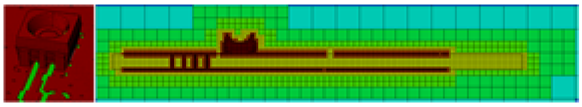

Figure 3: Mesh structure

Table 3 shows the bottom temperatures on the LED, depending on the total mesh number. The mesh structure used on the model was created with the FloEFD software. While creating the mesh structure, solid and liquid volumes are separated automatically; a mesh structure with various node numbers has been created. When the temperature changes due to the node number are examined, the change in the bottom temperatures decreased parallel with the decrease in the number of cells.

Table 2 Number of mesh and LED bottom temperature

Total Cell Count	Numerical Results (°C)
1 800 000	44.75
850 000	44.71
620 000	44.69
360 000	44.69
135 000	44.65

The air temperature was assumed as a constant value of 23°C (T∞) considering experimental conditions. Emissivity was set to 0.93 both in the thermal camera and the simulation conditions.

Table 3 Boundary Conditions and materials

Surface or Domains	Boundary Condition
Two resistor model selected for LED Solid surface emissivity was assumed 0.93	The air temperature was assumed 23°C Steady-state conditions, and the flow was assumed as laminar

Part	Material	Thermal Conductivity (W/mK)
Plates	Copper	395
FR4	Epoxy	0.35

2.4. Experimental set-up

The temperature measurements were performed (Figure 3) by using a FLIR SC620 thermal camera (Figure 4) with an 18mm lens, which had 40 mK at 30°C thermal sensitivity. Thermal cameras other specifications given below Table 1.

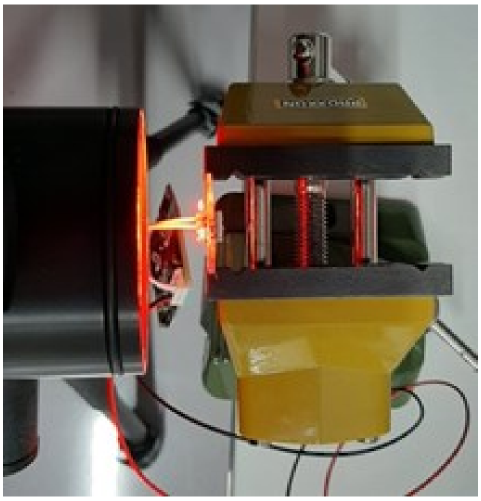

Figure 4: Experimental test setup

Figure 5: FLIR SC620 thermal camera

Table 1 FLIR SC620 Specifications

Descriptions	Determinations
Field of View (FOV) / minimum focus distance	24° x 18° / 0.3m - 45° x 34° / 0.2m as an option
Spatial resolution	0.65 mrad for 24°lens – 1.3 mrad for 45° lens
Measurement Accuracy	± 2 °C or ± 2% of reading
Temperature range	-40°C to +500°C (optional up to +2000°C)

All measurement was performed at 23°C ambient temperature condition in laboratory with controlled air conditions. Temperature data was measured with thermal camera. To find out the experimental error, an uncertainty analysis was performed according to the method proposed by Moffat [11]. The highest uncertainty in experimental data was calculated to be within ± 2%.

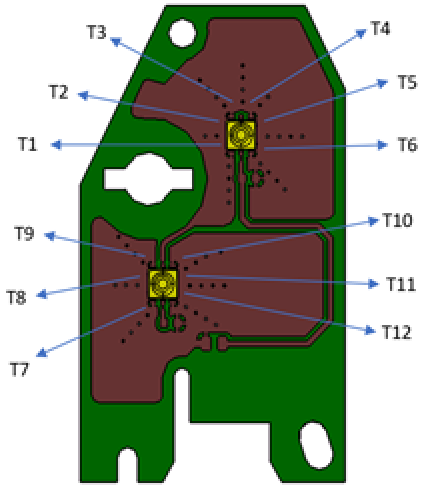

Figure 6. Measurement Points

Figure 6 shown that measurement points on PCB surface. During the experimental studies, K-type thermo-couples were used on different locations. The reasons for the different measurement locations are the obtain temperature distribution on circuit board and the effects of PCB layout design on the temperature distribution.

3. Results and Discussion

The results of the numerical solutions for the top surface of the printed circuit board were shown in Figure 6. The maximum temperature for the top surface of the circuit board was predicted as a value of 44.7 °C on the LED bottom surface. Additionally, in this figure, the temperature predictions for the locations of the top LED T1 to T6 are 43.3°C, 43.1°C, 42.8°C, 42.8°C, 43.1°C, 43.1°C, and for the bottom LED T7 to T12 are 41.0°C, 41.1°C, 41.1°C, 41.1°C, 40.8°C, 40.8°C, respectively. From the numerical results, we can easily say that the data paths had great effects on the temperature distribution of the LED circuit board.

The experimental results were shown in Figure 7. The experiments were performed in a test room in temperature was set to 23°C. The single-chip LED system was fixed in an air domain and the maximum temperature was achieved for the T1 location in both experimental and numerical studies.

The temperature difference between the numerical result and experimental data was calculated as 4%. The temperature predictions were in good agreement with the experimental data used in this study. The numerical and experimental results were given below Table 2.

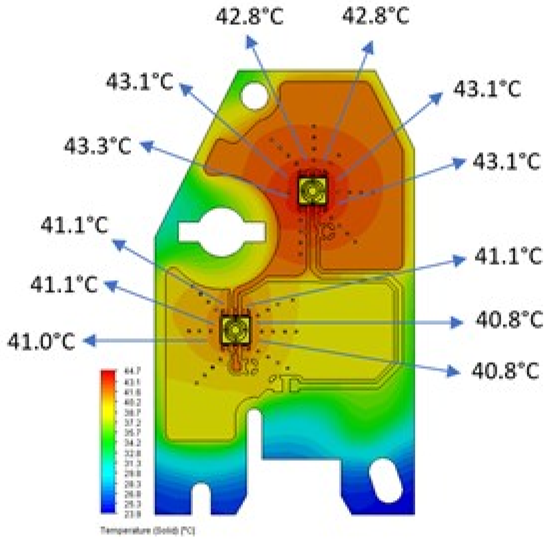

Figure 7: Top surface thermal results

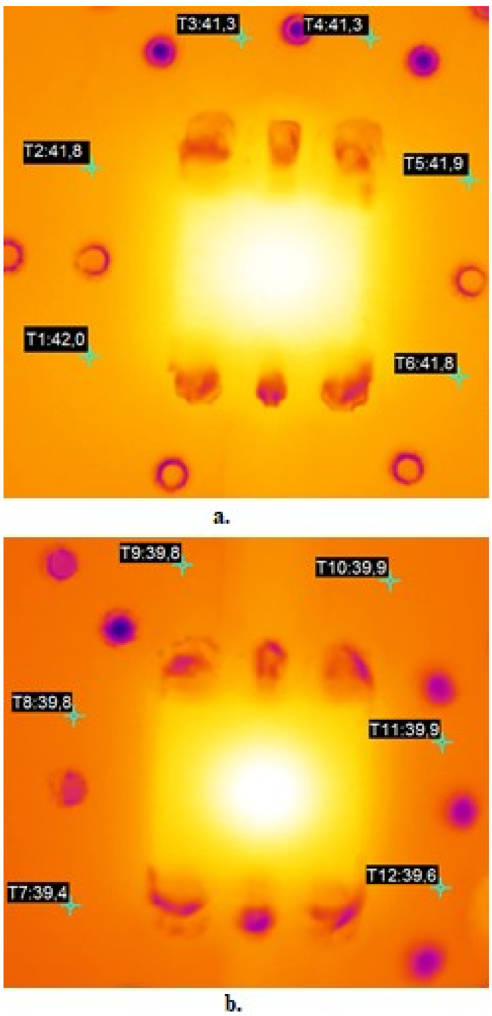

Figure 7: a) Top LED thermal results
b) Bottom LED thermal results

4. Conclusion

In this study, the thermal performance of a PCB with a single chip LED (Light Emitting Diode) chip was investigated numerically and experimentally. The results were achieved for single-chip LED during emitting light in an air domain. The thermal camera temperature measurements were performed for different locations to allow to evaluate the temperature differences on the PCB and near the LED chip.

Table 2 The numerical and experimental results comparison

Pos	Numerical Results (°C)	Experimental Data (°C)	Difference (%)
T1	43.3	42.0	3
T2	43.1	41.8	3
T3	42.8	41.3	4
T4	42.8	41.3	4
T5	43.1	41.9	3
T6	43.1	41.8	3
T7	41.0	39.4	4
T8	41.1	39.8	3
T9	41.1	39.8	3
T10	41.1	39.9	3
T11	40.8	39.9	2
T12	40.8	39.6	3

The maximum temperature measured for the top surface of the circuit board was predicted as a value of 44.75°C on the LED bottom surface. PCB's temperature distribution depends on the covered ratio of the top and bottom copper plates. The maximum temperature was achieved for the T1 location which was very close to the LED chip in both experimental and numerical studies. The temperature difference between the numerical result and experimental data was calculated as 3% in percentage for the T1 location. In general, the difference of the numerical results and experimental data were below 5% in percentage and when the results of studies examined, the validation of the numerical results were achieved for the three dimensional (3D) numerical model.
When simulation result was examined, copper area and top copper layer design had an important role on LED circuit board for temperature distribution. In addition, temperature distribution of the LED circuit board depends on the covered ratio of the top and bottom copper layer design.
In further investigations, the design parameters of electronic card will investigate. In addition, ambient condition and environmental automotive parts effect will search.

Credit Authorship Contribution Statement

Birhat Sönmezay: Writing - original draft, Investigation, Validation, Visualization, Supervision, Methodology, Software, Formal

analysis.
Mehmet Aktaş: Investigation, Visualization, Supervision, Methodology, Software, Review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors wish to thank Marelli Mako Tukey Elektrik Sanayi Ticaret A.Ş for supporting this research.

5. References

1. Choi, S., Kim, Y., Byun S., Choi K. "A Study on Predictable Program of LED Junction Temperature in Natural Convection", 9th International Symposium on Automotive Lighting, 27-28 September 2011.
2. Tsai, M., Chen, C., Kang, C., "Thermal measurements and analyses of low-cost high-power LED packages and their modules", Microelectronics Reliability, Volume 52, 845 – 854, December 2012.
3. Kikuchi, K. "Thermal simulation of LED unit for Headlamp and Rear lamp", 9th International Symposium on Automotive Lighting, 27-28 September 2011.
4. Yung, K., Liem, H., Choy, H., Lun W., "Thermal performance of high brightness LED array package on PCB", International Communications in Heat and Mass Transfer, Volume 37, Issue 9, 1266 – 1272, November 2010.
5. Mornet E., "Thermal management of LED for signaling and lighting functions", 8th International Symposium on Automotive Lighting, 28-30 September.
6. Christensen A., Graham S., "Thermal effects in packaging high power light emitting diode arrays" Applied Thermal Engineering, Volume 29,364–371, October 2009.
7. Keppens A., Chen h., Lu Y., Chen Z., Gao Y., Deconinck G., Hanselaer P., "Light-emitting diode junction temperature and power Determination from forward current", Light & Engineering, Volume 19, Issue 1, 34-44, January 2011.
8. Kwok K.F., Divakar B.P., Cheng K.W.E., "Design of an LED Thermal System for Automotive Systems", 3rd International Conference on Power Electronics Systems and Applications, 20-22 May 2009.
9. Cheng T., Luo X., Huang S., Liu S., "Thermal analysis and optimization of multiple LED packaging based on a general analytical solution", International Journal of Thermal sciences, Volume 49, 196 – 201, January 2010.
10. Saati K. F., Tufekci, C.S., Arik M. A., "Computational and Experimental Study on a Harsh Environment LED System for Vehicle Exterior Lighting Applications", 4th Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), 27-30 May 2014.
11. Sevilgen G., Kiliç M., Aktas M., "Dual-separated cooling channel performance evaluation for high-power LED PCB in automotive headlight", Case Studies in Thermal Engineering, Volume 25, June 2021.
12. Kilic M., Aktas M., Sevilgen G., "Thermal Assessment of Laminar Flow Liquid Cooling Blocks for LED Circuit Boards Used in Automotive Headlight Assemblies", Energies, Volume 13, Issue 5, March 2020.
13. Keppens, H.L. Chen, Z. Chen, Y. Gao, G. Deconinck, P. Hanselaer, "Light-Emitting diode junction temperature and power determination from forward current", Light Eng., Volume 19, 34–44, January 2011
14. R.H. Poelma, S. Tarashioon, H.W. van Zeijl, S. Goldbach, J.L.J. Zijl, G.Q. Zhang, "Multi-LED package design fabrication and thermal-analysis", J. Semiconductors, Volume 34, Issue 5, May 2013.
15. Tsai, M.; Chen, C.; Kang, C., "Thermal measurements, and analyses of low-cost high-power LED packages and their modules". Microelectronics Reliability, Volume 52, Issue 5, 845–854, May 2012.
16. Choi, S., Kim, Y., Byun S., Choi K., "A Study on Predictable Program of LED Junction Temperature in Natural Convection", 9th International Symposium on Automotive Lighting, 27-28 September 2011.
17. Yung, K., Liem, H., Choy, H., Lun W., "Thermal performance of high brightness LED array package on PCB", International Communications in Heat and Mass Transfer, Volume 37, Issue 9, 1266 – 1272, November 2011.

18. Tamdogan E.; Pavlidis G.; Graham S.; Arik M. A., “Comparative Study on the Junction Temperature Measurements of LEDs with Raman Spectroscopy, Microinfrared (IR) Imaging, and Forward Voltage Methods”, IEEE Transactions on Components, Packaging and Manufacturing Technology, Volume 8, Issue 11, 1914-1922, November 2018.
19. M. Arik, K. S. Kulkarni, C. Royce and S. Weaver, "Developing a standard measurement and calculation procedure for high brightness LED junction temperature," Fourteenth Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), 2014, pp. 170-177, doi: 10.1109/ITHERM.2014.6892277.
20. R.J. Moffat, “Describing the uncertainties in experimental results”, Experimental Thermal and Fluid Science, Volume 1, Issue1, 3–17, January 1988.