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RESEARCH INTO THE JUNCTION TEMPERATURE AND POWER OF NEW LED MODULES GENERATION IN DEPENDENCE ON VARIABLE PARAMETERS

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ABSTRACT

In this research, the change in the junction temperature and luminous flux of a new generation LED module depending on variables such as radiation, lens piece, ambient temperatures, currents, and quantity of elements had been studied. Commercial software *FloEFD2019* was used in the finite volume analysis made during the study. The analyses were verified by experiments. On basis of the analysis, a solution was obtained that does not depend on the number of elements. The force of gravity was taken into account. While the ambient temperatures were taken as Ta = 23 °C and 40 °C, and the radiation value as 1009 W/m^2, currents as 140 mA, 160 mA, 180 mA, 200 mA, 220 mA and 240 mA, meanwhile, samples numbers on PCB were taken as 101 and 202. In order to determine the effect of the lens piece located on the LED module, the analysis was repeated with and without using the lens. As a result of the study, it was found that the increase in ambient temperature and radiation has an adverse effect on the temperature T_j and luminous flux. It has been observed that changing samples number has a negligible effect on luminous flux and temperature Tj. It was found that the use of radiation and lenses are the most important factors affecting the luminous flux of the module.

Keywords: LED automotive lamp, laminar natural convection, Monte Carlo method of radiation, computational fluid dynamics (CFD), junction temperature

1. INTRODUCTION

LED (Light Emitting Diode) systems have recently become widely used in lighting systems. The LED provides a lifetime of up to 100 000 hours depending on usage. The temperature below 110 °C helps the energy distribute more efficiently at 3000 °C in halogen bulbs, and 700 °C in xenon bulbs. The basic studies of the thermal management of LEDs were carried out by Karim et.al. [1]. Another study on the thermal behaviours of LEDs was carried out by Poppe and Lasance [2]. Besides, in other studies [3] regarding the determination of the junction temperature (Tj), an attempt was made to determine both the optical features and the lifetime of the thermal conductivity resistances of LEDs [4]. Some technical articles regarding the calculation and formulation of Tj have been published by LED manufacturers [5–7]. In 2009, Bider investigated the effect of ambient temperature on LEDs and their lifetime [8]. Another basic study was conducted by Bielecki and et.al.in 2007 [9]. While the study by Kikuchi et.al aimed to determine the values of Tj using a three-dimensional model, Monte Carlo random radiation method was used for the radiation model [3]. Rubenstein and Kroese also studied the Monte Carlo method for the simulation [10]. The increase in thermal conductivity and a decrease in Tj temperature to 20 °C due to increase of copper plating on the printed circuit were reported in another study by Vora and Vijaykumar on LED [11]. Sheu et.al. [12] conducted a study of thermal conductiv-

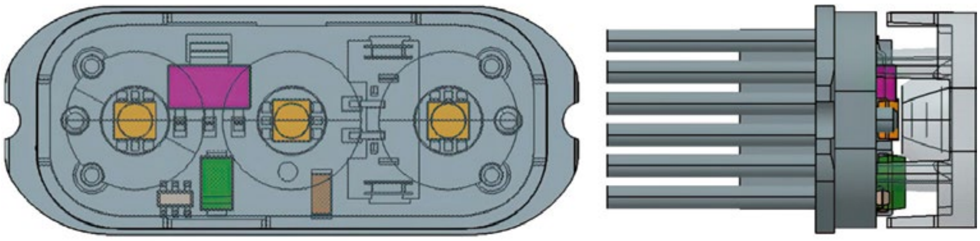


Fig. 1. Geometry and location of LEDs and electronic devices

ity and thermal resistance based on the determination of the temperature *Tj*.

LEDs that consume a large amount of power in the direction of increasing demands are intended for use in smaller volumes, which makes the thermal design of LEDs more difficult [13]. Arık et al. investigated the effects of local thermal points available on LEDs using finite elements method in order to define the thermal problems arising in LEDs [14]. Petroski et al. developed a spot module with LED equipped with heat distributor. In this study, where cooling is provided by natural convection, the positioning problem of LED was resolved using a heat distributor with vertical wings located throughout a cylindrical pipe [15]. Yung et al. investigated the effect of printed circuit board (PCB) positioning at different angles on heat transfer in a system with LED, where cooling is provided with natural convection. Yung et al. investigated how the availability of PCB at different angles affects heat transfer in a system with LED, where cooling is provided by natural convection [16]. Some researchers have investigated the design of led cooling systems using a thermoelectric cooler. Zhong et al. compared the system with thermoelectric cooler, with cooling system with heat distributor and fun. As a result of the comparison, it was found that a system with a thermoelectric cooler is more efficient than that with heat distributor and fun, in the case that when the air speed is 3.6 m/s and the LED power is less than 35 W [17]. Computational fluid dynamics method is often used in thermal designing of the system with LED. Cheng et al. in their study, done using the finite element method, investigated the change in heat distribution at different heat convection coefficients in the system, where there are 10 LEDs, a closed volume existing behind PCB, and vertical winglets are available. It was seen that LED temperature could be decreased using a fan to increase heat convection coefficient [18]. In another study, which used the finite elements method, the effect of the number, widths and lengths of winglets available in a heat distributor on thermal design was investigated. Weng investigated the thermal performances of the systems with LED using the finite elements method [19]. There are also various studies in the literature, which describe the use liquid instead of air in the cooling system. Lai et al. developed a liquid cooling system in their study. They showed that air cooling could be insufficient compared to a liquid cooling system [20].

This study, which differs from other studies, took into account variables such as thermal analysis of LED module, ambient temperature, radiation, current, and samples number. The study analysed the interaction of the junction temperature and luminous flux of LED module.

2. MATERIAL AND METHOD

2.1. Geometry and Model

The new generation LED module used in this study is shown in Fig. 1. 3 LEDs are used in the module. These produced LED modules are mounted to any intended design.

Each LED consumes power of 0.1 W in response to a current of 0.4 A. One of the drivers operates

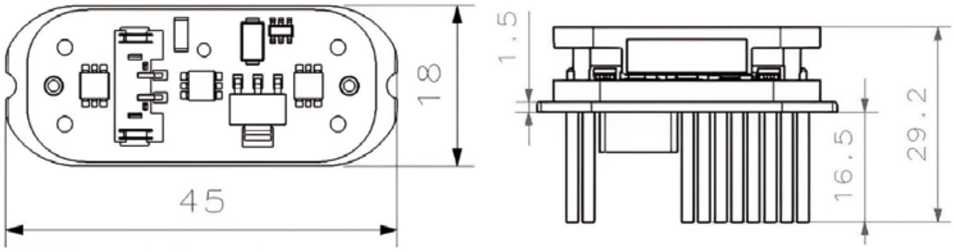


Fig. 2. Dimensions of the LED module

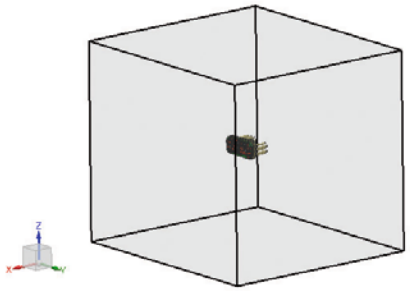


Fig. 3. Modelling of computational domain and solar radiation

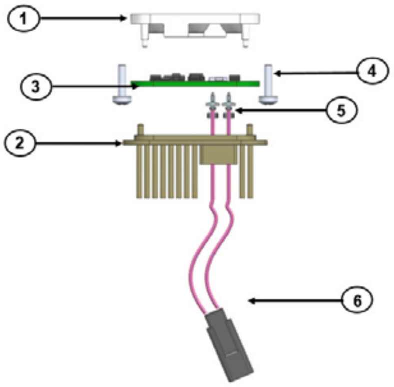


Fig. 4. LED module consists of six blocks: 1 – lens *PC Lexan LS2,* 2 – heatsink *AL 6063,* 3 – PCB *FR4 PCB, 4-* vida *Ejot Delta,* 5 – crimp *CuZn33,* 6 – cable *FLY-R Cable* 200 mm

with a voltage of 0.13 A and 1.8 V. One of the diodes draws 0.15 A and operates under 0.7 V. Transıstor operates with 0.3 A and under 1.4 V. The geometrical model and measurements of PCB used are shown in Fig. 2.

2.2. Numerical Simulations

The temperature estimations of electronic parts were calculated using computational fluid dynamics (CFD) method. *FloEFD2019*, *Mentor Graphics* software, was used to make the thermal analysis of electronic cooling. *FloEFD* can work with different CAD software, but this study *CATIA V5 R19*. With the direct integration of the simulation software in *CATIA V5*, a CAD program; the simplification and analysis process will be quite simple and rapid. The geometry of PCB and electronics were simplified for thermal analysis and imported from CAD data. Later on, a computational influence area was formed considering the sizes of PCB. The computational domain should comprise all parts of PCB to get correct results. Afterwards, the analysis conditions and solution methods are defined (Fig. 3).

Table 1. Number of Mesh and Junction Temperature of LED

Mesh number	T_j, °C
550986	95.2
687250	98.3
765687	105.4
863547	116.4
954376	117.1
1025468	117.0

Having created the computational domain, the boundary conditions were applied. The ambient temperature was set to 23 °C, and external analysis was selected as the analysis type for this study. The Monte Carlo radiation model and natural convection were selected. Photon radiation is applied with random access in Monte Carlo method. This process is repeated for N times, depending on the maximum of photons defined at the beginning of the analysis. The selection of proper N the repetition number of random access (previous number), is important in this method. In addition, the force of gravity is taken into account, and weight direction is (g = 9.81 m/s^2) is the -z direction. The thermodynamics parameters of computational domain are given for the pressure of 101325 Pa, and ambient temperature equal to 23 °C. Besides, the solar radiation model was located in the direction of x = –0.568562, y = 0 and z = –0.8226405, and solar density was defined as 1009 W/m^2.

All LEDs and electronic parts were mounted on *FR*4 PCB containing a double-sided layer of copper. The thickness of each copper layer is 35 µm, and that of PCB is 1.5 mm in total.

The types of material and electronic component should be selected properly to avoid of thermal risks. The list of materials and electronic components are shown in Fig. 4.

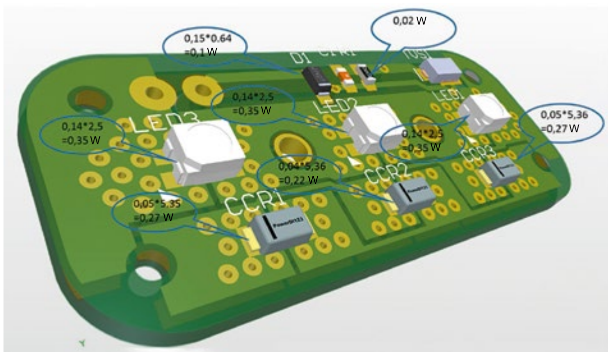


Fig. 5. Power of all electronics

Initially, the analysis verification study was conducted to see whether analyses yield correct results. In the verification study, the powers applied to components on PCB are shown in Fig. 5. All components were driven with the current of 140 mA.

In order to get a solution independent of the element number, the analyses were made with different element numbers, and the results of the analyses are shown in Table 1. It was seen that the results did not change after a certain number of elements, and the number of elements was defined in the analyses on condition that it should not be less than 954376.

FloEFD solves Navier-Stokes equations, the formulation of mass, momentum, and energy conservation for fluid flows. The obtained equations are confirmed by the fluency equations that define the structure of the fluid, and with fluid density, viscosity and empirical dependences of thermal conductivity. The time spend on heat distribution is very short, and heat convection time from LED and electronics to the other parts is not so long, because of that temporal behaviours can be taken into consideration. That is why in this study, preference was given to stationary conditions. The equations for stationary conditions are mass conservation equation, momentum equation, and the thermal energy conservation equation [21]. Eq. 1 determined the temperature of LED junction. The normalized luminous flux graphics associated with Tj and current value of *Samsung* LED used in the study are shown in Fig. 6 and Fig. 7.

$$T_J = T_{LED} + P_{LED} \cdot R_{jc} \quad , \qquad (1)$$

where T_j is the junction temperature, T_{LED} is the LED temperature, R_{jc} is the thermal resistance, P_{LED} is the LED power.

The normalized luminous flux values corresponding to Tj and the current value obtained from luminous flux catalogues of LEDs are calculated using (2), (3), and (4) by multiplying 32.4 lm, which is the maximum luminous flux at 140 mA included in the catalogue:

$$Luminous\ flux = 32.4 \cdot \beta \cdot \alpha \ , \qquad (2)$$

$$\alpha = 0.0068 \cdot I + 0.037 \ , \qquad (3)$$

$$\beta = -0{,}0014 \cdot T_j + 1.0237 \ , \qquad (4)$$

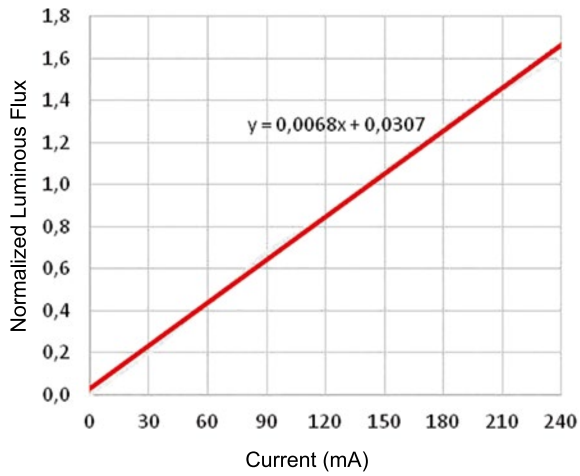


Fig. 6. Normalized luminous flux according to current

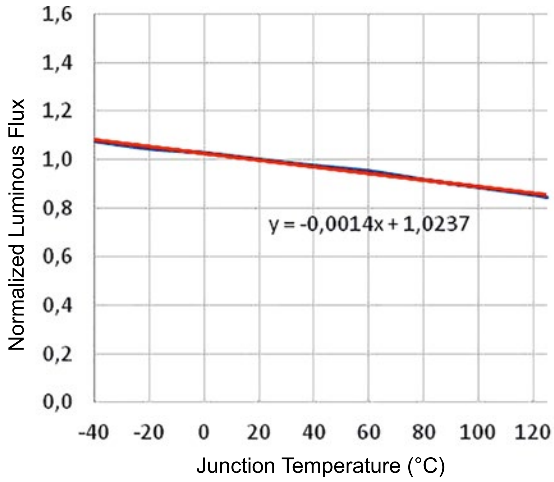


Fig. 7. Normalized luminous flux according to T_j

where α is the normalized luminous flux value corresponding to the current value is calculated using the function shown in Fig. 6, and β is the normalized luminous flux value according to junction temperature in Fig. 7, I is the current, Tj is the junction temperature.

2.3. Experimental Study

The thermal analysis should be verified using the laboratory experiment. Test equipment and their specification are shown in Table 2.

The test was performed in an air-conditioned room in a controlled environment, see Fig. 8. PCB was placed almost in the middle of the room.

The room air speed was kept at the minimum level to ensure natural convection conditions, as in numerical simulations. The thermal measurement system consists of thermocouples associated with data acquisition system by company *National In-*

Table 2. Test Equipment

Equipment	Trademark	Working range	Inaccuracy
Climatic oven	Angelantoni CST 157 2T	–80/+220 °C	+/-0.1 °C
Thermometer	APPA-50	–40/204 °C	+/-2.2 °C
Thermocouples	Standard (K type)		

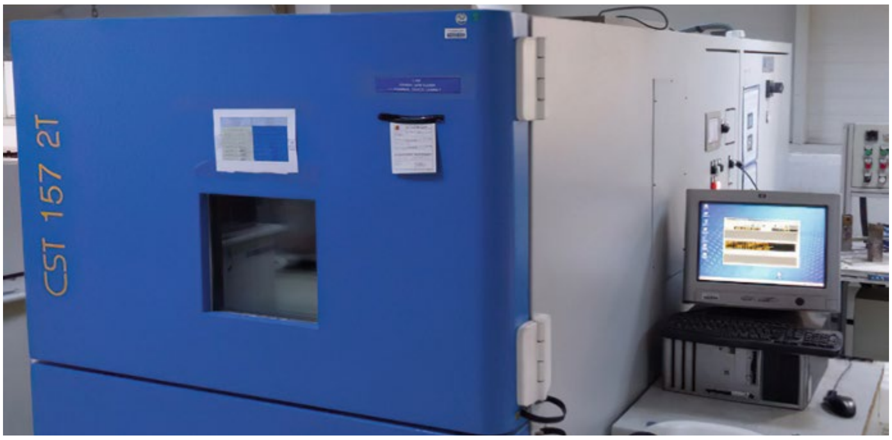


Fig. 8. The climate chamber

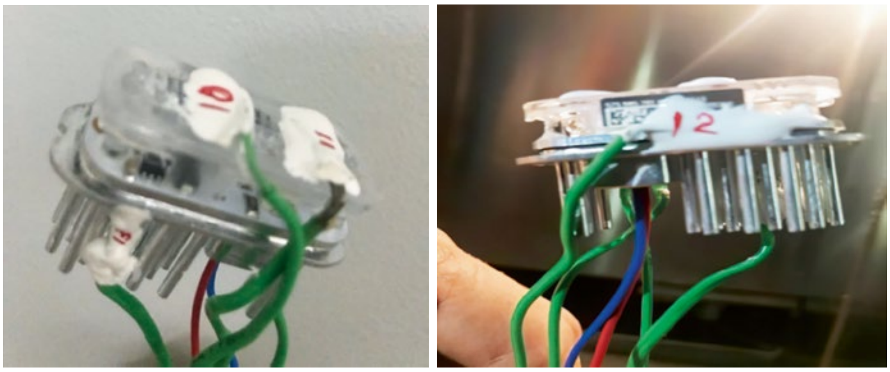


Fig. 9. Schematic demonstration of electronics measurement point

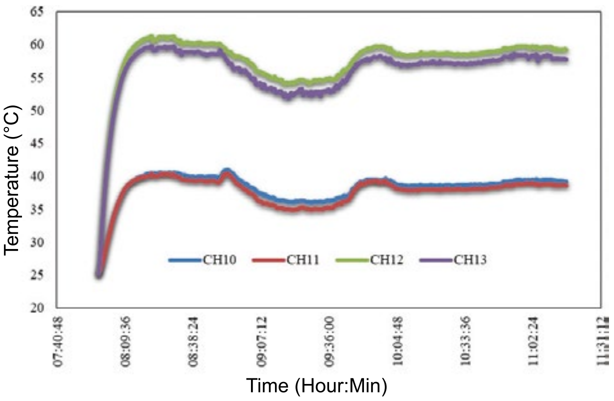


Fig. 10. Test results

strument. The temperature of the parts and electronics was monitored by software. The stable state data was collected after thermal stabilization had been ensured in a conditioned division.

Thermocouples were located on four LED modules, including two of them on lens, one on winglets, and one on PCB (Fig. 9).

The test measurements were performed three times depending on the time, and test results were shown in Fig. 10. It was determined that LEDs reached the maximum temperature in a short time and kept to maintain this temperature. As can be seen from Fig. 10, a decrease in temperature between 09:07 and 09:36 hours was found due to a decrease in current. Later, it was noticed that the temperature kept the same value with such small fluctuations. For this reason, permanent regime practice was carried out in the analyses. No time-dependent analysis was made. The results of the analysis are shown in Figs. 11.(a) – 11.(c), from the locations where thermocouples were connected. The comparison of the analysis and experiments are shown in Table 3.

After confirming the correctness of the calculation's analysis, the analyses were made with *Samsung PLCC4* LEDs, Table 4.

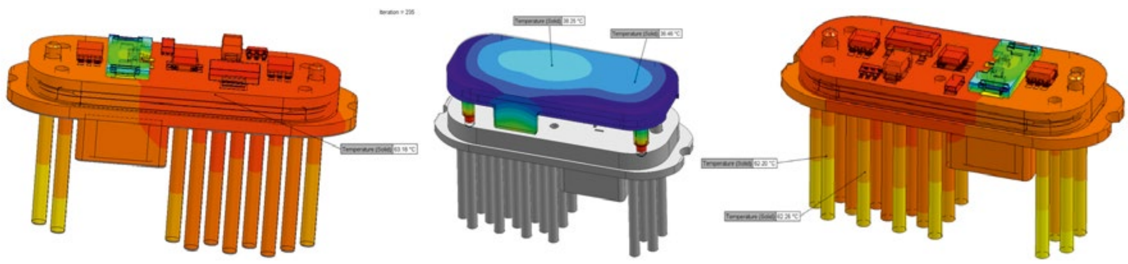
Table 3. Comparison of Tests and Analyses

LED module	CH10 (°C)	CH11 (°C)	CH12 (°C)	CH13 (°C)
Test-1	38.44	36.85	61.30	61.18
Test-2	38.26	37.73	62.59	62.07
Test-3	38.70	37.53	62.85	61.92
Analysis results	38.25	36.46	63.16	62.20

****Note to Table 3:** CH10 – CH13 – channels of the measuring device, to which the appropriate thermocouples are connected.

Table 4. Analysis' Conditions

Samsung PLCC4	Ambient temperature (°C)	Current (A)	Samples number (pc.)
Analysis-1	23 °C	0.14	101
Analysis-2	40 °C + rad	0.14	101
Analysis-3	23 °C	0.18	101
Analysis-4	40 °C + rad	0.18	101
Analysis-5	23 °C	0.18	202
Analysis-6 (with lens)	40 °C + rad	0.18	202
Analysis-7 (with lens)	23 °C	0.18	202



a) *b)* *c)*

Fig. 11. Experimental result of driver 1 with locations where thermocouples were connected for test-1 (a), test-2 (b), test-3 (c)

3. RESULTS AND DISCUSSION

After checking the results of the analysis, seven different analyses were performed (Table 4), and the effects of the factors, such as ambient temperature, radiation, samples number, lens effect, and the change of the current value that LED is driven with, on temperature *Tj* was investigated. The results are shown in Figs. 12 (a) – 12 (g). According to the analysis results, since the resistance temperatures of electronic parts except LED is 150 °C, they are not found to be at risk in terms of temperature.

As a result of seven analyses made during the study, the maximum *Tj* values calculated for LEDs are shown in Table 5.

In our study, because of seven analyses results of the new generation LED module, *Tj* values were found to be less than permitted junction temperature value. In analyses made at the current value of 0,14 A, and *Ta* = 40 °C radiation, and under two different weather conditions (analysis-1, analysis-2); an increase of 27.45 °C was seen in *Tj* and a decrease of 1.2 lm at luminous flux, with the increase of ambient temperature and radiation.

In the analyses made at the same ambient conditions by increasing LED driving current in order to increase the luminous flux (analysis-3, analysis-4); it was found that *Tj* increased 26.68 °C and luminous flux decreased 1.6 lm, with the increase of ambient temperature and radiation. While the increase in ambient temperature causes an increase in *Tj*, it also leads to a decrease in luminous flux. In order to better understanding the effect of radiation on the junction temperature, the increase in ambient air temperature was subtracted from temperature difference *Tj*, as in (5) and in (6):

Table 5. Junction Temperature and Luminous Flux for Seven Analyses

Samsung PLCC4	Junction temperature, °C	Luminous flux, lm
Analysis-1	87.10	28.7
Analysis-2	114.55	27.5
Analysis-3	102.86	35.8
Analysis-4	129.54	34.2
Analysis-5	102.64	35.8
Analysis-6 (with lens)	121.00	34.7
Analysis-7 (with lens)	94.74	36.2

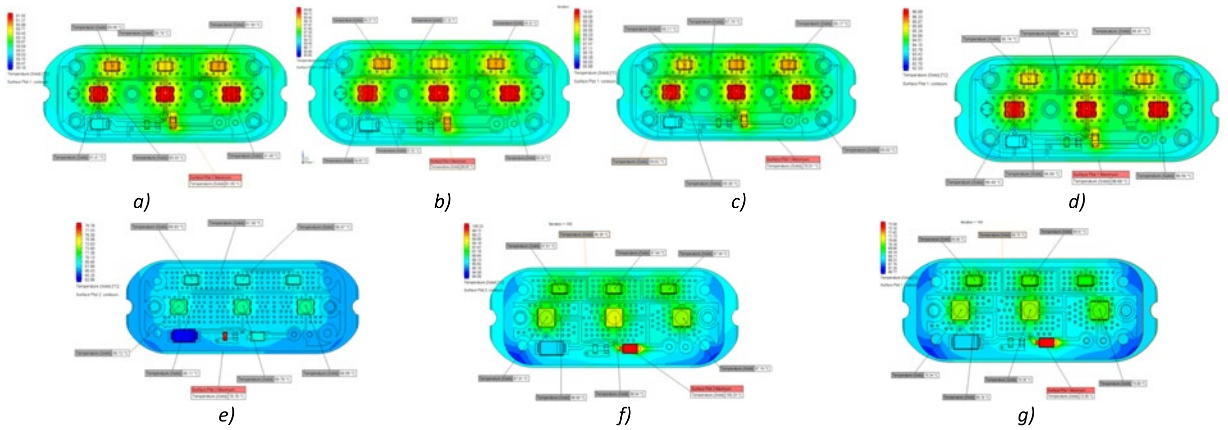


Fig. 12. Analysis results of LED module: result of analysis-1 (a), result of analysis-2 (b), result of analysis-3 (c), result of analysis-4 (d), result of analysis-5 (e), result of analysis-6 (f), result of analysis-7 (g)

$$T_{jdif(2-1)} = \left(T_{j\,analyse-2} - T_{j\,analyse-1}\right) - 17\ ^{o}C, \quad (5)$$

$$T_{j\ dif(4-3)} = \left(T_{j\,analyse-4} - T_{j\,analyse-3}\right) - 17\ ^{o}C, \quad (6)$$

where $T_{j\ dif}$ is the temperature difference, $T_{j\ analyse-1}$ is the junction temperature analyse-1, $T_{j\ analyse-2}$ is the junction temperature analyse-2, $T_{j\ analyse-3}$ is the junction temperature analyse-3, $T_{j\ analyse-4}$ is the junction temperature analyse-4.

When the increase of 17 °C in ambient air was subtracted from *Tj* temperature differences, as in the above equations, the values such as 10.45 °C and 9.68 °C were obtained. It is thought that these temperature values obtained came to exist by the effect of radiation. It was calculated that radiation caused an increase of 10 °C in temperature, which caused an increase of *Tj* in the range of (36–38)%. Since an increase of *Tj* decreased the radiant flux, as seen in Fig. 7, it also caused a decrease of 1.2 and 1.6 lm in the luminous flux for both ambient conditions. This is a negative effect for lighting. Samples number, which is 101 on PCB was rose up 202 so that the junction temperature would drop; analysis-5 was performed under the ambient condition was 0.18 mA and 23 °C. Although samples number doubled, when analysis-5 was compared to analysis 3, it was seen that there was only a *Tj* decrease of 0.22 °C, and that samples number was not so effective at the decrease of temperature, which is thought to be because of that the size of PCB is small. Analysis-3, analysis-5 were found to have the same value in terms of luminous flux. For this reason, samples number was neglected in analysis comparisons. In analysis (5–7), which was made in two different ambient environments, under 0.18 mA, and at 23 °C, by mounting lens on LED module, so as to examine the effect of lens on luminous flux, it was determined that lens caused a decrease of 7.9 °C at *Tj* temperature. It was determined that a 7.9 °C of *Tj* decrease caused 0.4 lm of increase in luminous flux. In analyses 4 and 6, which were made at 40 °C and +radiation, it was found that the lens causes a temperature drop of 8.54 °C. It was found that a decrease in temperature by 8.54 °C causes an increase in luminous flux by 0.5 lm. When comparing the results of analyses 5 and 6, it was seen that *Tj* increased by 18.36 °C, while there is an effect of increasing the ambient air by 17 °C and a radiation effect. It was calculated that this increase caused a decrease in lu-

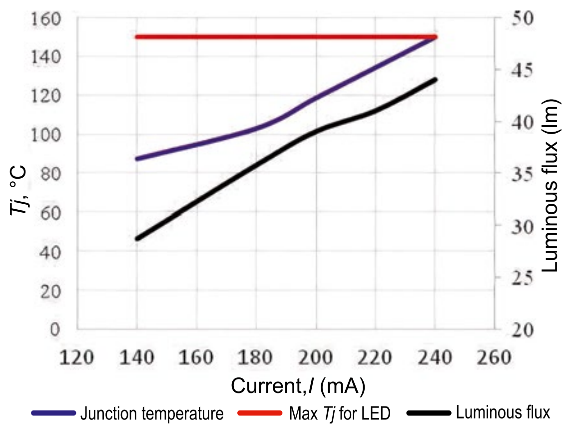


Fig. 13. *Tj* and luminous flux according to the current at the ambient temperature of 23 °C without lens

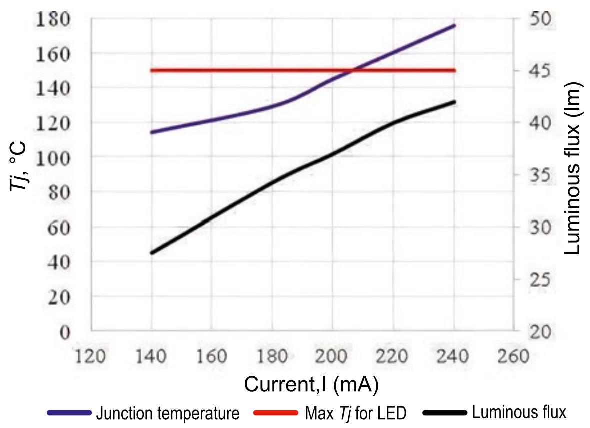


Fig. 14. *Tj* and luminous flux according to the current at the ambient temperature of 40 °C and radiation without lens

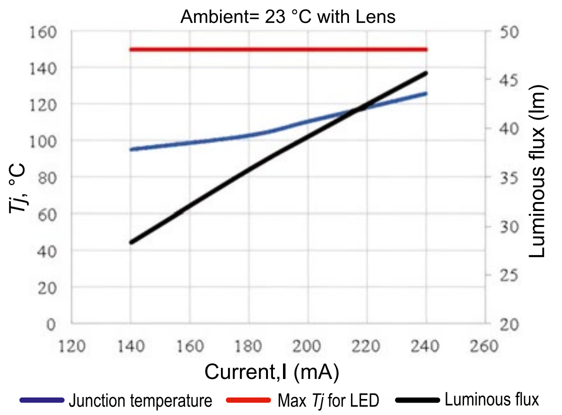


Fig. 15. *Tj* and luminous flux according to the current at the ambient temperature of 23 °C with lens

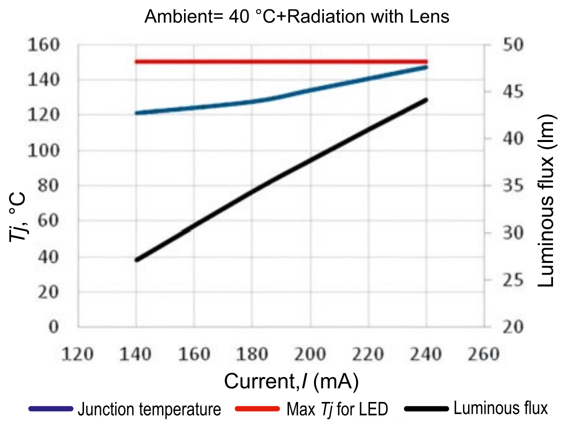


Fig. 16. *Tj* and luminous flux according to the current at the ambient temperature of 40 °C and radiation with lens

minous flux by 1.1 lm. Considering that 17 °C of the increase of 18.36 °C is the result of an increase in the ambient temperature, it is seen that 1.36 °C of this temperature is the result of radiation with lens. It was determined that lens usage seriously reduces radiation effect. Because of the study, it was found that an increase in temperature due to radiation, which will occur due to heat transfer, causes an increase in luminous flux. However, since the *Tj* value increased with increasing ambient temperature, luminous flux also decreased. In order to make the study more detailed, according to Fig. 6, the analyses were made to increase the current value from 0.14 A to 0.24 A in order to obtain the highest luminous flux from LEDs. In the analyses, the ambient air was assumed as 23 °C and 40 °C, and + radiation, the LED module was assumed both with and without lens. The results are shown in Figs. 13–16.

The effect of the lens piece is clearly seen when Fig. 13 and 15 are compared. According to Fig. 13, if the LED module offering the best lighting at 240 mA current value is without lens piece, whether *Tj* value is exceeded is determined from Fig. 13. In that case, the LED module will fail to perform lighting duty because *Tj* value has been exceeded. According to the analysis made with the lens piece, when Fig. 15 is examined at a current of 240 mA, it is seen that *Tj* value is below the permitted value, and highest lighting value is 44 lm.

This was also determined in a scenario where the ambient temperature was assumed as 40 °C and radiation was available. It was seen in Fig. 14 that the permitted *Tj* value was exceeded after 200 mA in the module without lens, that LED module failed in performing lighting duty, compared to Fig. 16. It was determined that the module with lens didn't exceed *Tj* value even at 240 mA, that luminous flux was 46 lm, and that module performed its duty, in the same ambient conditions. The effect of the changing the ambient air is striking in this part of the study. The ambient air in 40 °C and radiation clearly affect the module design without a lens; the permitted *Tj* value is exceeded after the current value of 200 mA,

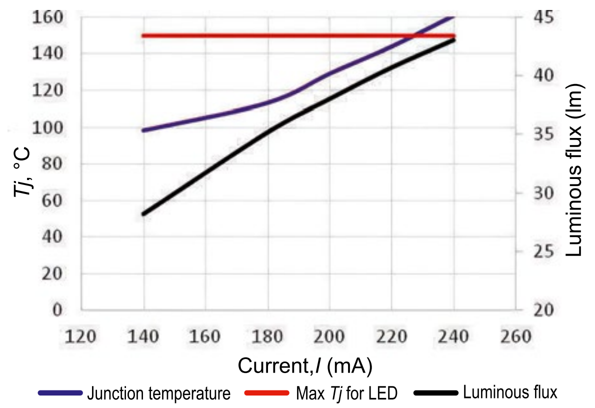


Fig. 17. *Tj* and luminous flux according to the current at the ambient temperature of 23 °C + radiation without lens

and at the ambient temperature is 23 °C and eliminating the radiation effect, then *Tj* value is exceeded at 240 mA, according to Fig. 14 (Fig. 13).

It was found that the boundary *Tj* value wasn't exceeded at 240 mA in both ambient conditions, while the lens was mounted at the LED module, and that the LED module would perform the lighting duty. This is shown in Fig. 15 and Fig. 16, which the module with the lens could operate in both ambient conditions.

To see how the lens piece would affect the radiation effect, the analyses with and without radiation lens were repeated only at ambient air of 23 °C. The results are shown in Figs. 17–18.

It was determined that the permitted *Tj* value was exceeded, reaching the value of 220 mA when exposed to radiation (Fig. 17). Fig. 18 showed that *Tj* value was not exceeded even at the current value of 240 mA, and an analysis performed under the same ambient conditions produced a luminous flux of 44 lm.

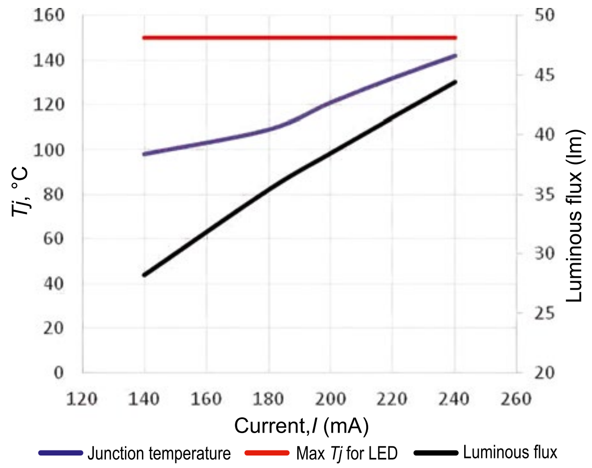


Fig. 18. *Tj* and luminous flux according to the current at the ambient temperature of 23 °C + radiation with lens

4. CONCLUSION

It was revealed in this study that convenient ambient conditions should be provided so that new generation LED modules could have catalogue lighting values. In particular, it was found that the effect of radiation on luminous flux was greater than expected. It was found that *Tj* value increased by 10 °C with the effect of radiation in LED module used in the study, and reached above the permitted *Tj* value. It was determined that the value of *Tj* increases by (2–2.5) °C when exposed to radiation in the module in which the lens piece was used, and that LEDs could perform lighting duty. According to these results, it was confirmed that the lens piece used in LED modules directly affects the module lifetime and lighting duty. As a result of the study, it was determined that LED modules should be placed in locations where the radiation effect is minimal, and that lens piece definitely should be used. The study results should be evaluated in detailed to get the desired performance from the new generation of LED modules. The study also found that computational fluid dynamics software should be widely used to determine the behaviours of LED modules in ambient conditions and to eliminate risks.

REFERENCES

1. Rosenberg E., Fidje A., Espegren K.A., Stiller C., Svensson A.M., Moller-Holst S. Market penetration analysis of hydrogen vehicles in Norwegian passenger transport towards 2050. International Journal of Hydrogen Energy. 2010. V35, #14, pp. 7267–7279. doi:10.1016/j.ijhydene.2010.04.153

2. Poppe A., Lasance CJM. On the standardization of thermal characterization of LEDs. Annual IEEE Semiconductor Thermal Measurement Management Symposium, 2009. #2, pp. 151–158. doi:10.1109/STHERM.2009.4810757

3. Kikuchi K., Hamashiam Y., Kobayashi Y. Prediction of LED junction temperatures with CFD for headlamp application. In: ISAL Symposium Proceeding, 2005.

4. Senawiratne J., Zhao W., Detchprohm T., et al. Junction temperature analysis in green light emitting diode dies on sapphire and GaN substrates. Physica status solidi (c), 2008. V5, #6, pp. 2247–2249. doi:10.1002/pssc.200778648

5. Weber R. Calculating an LED's Junction Temperature, 2015.

6. Application Guide, 2010.

7. Thermal Management of SMT LED Application Note, 2014.

8. Bider C. Effect of thermal environment on LED light emission and lifetime. LED Prof Rev May/June 2009, 2009.

9. Bielecki J., Jwania A.S., Khatib F. El., Poorman T. Thermal Considerations for LED Components in an Automotive Lamp. 23rd IEEE SEMI-THERM Symposium, 2007.

10. Rubenstein R.Y., Kroese D.P. Simulation and the Monte Carlo method, 2011.

11. Vora A.K., Vijaykumar P. Basic Thermal Guidelines for using PowerPSoC ®, 2009. #001, pp. 1–12.

12. Sheu G.-J. The heat dissipation performance of LED applied a MHP, 2005. p. 5941, 594113–594118. doi:10.1117/12.616355

13. Jen-Hau Cheng, Chun-Kai Liu, Yu-Lin Chao, Ra-Min Tain. Cooling performance of silicon-based thermoelectric device on high power LED. In: ICT 2005. 24th International Conference on Thermoelectrics, 2005. IEEE; 2005. pp. 53–56. doi:10.1109/ICT.2005.1519885

14. Arik M., Becker C.A., Weaver S.E., Petroski J. Thermal management of LEDs: package to system. Third Int Conf Solid State Light, 2004, 5187 (July 2014), 64. doi:10.1117/12.512731

15. Petroski J. Understanding longitudinal fin heat sink orientation sensitivity for Light Emitting Diode (LED) lighting applications. In: Advances in Electronic Packaging, 2003.

16. Yung K.C., Liem H., Choy H.S., Lun W.K. Thermal performance of high brightness LED array package on PCB. International Communications in Heat and Mass Transfer, 2010. doi:10.1016/j.icheatmasstransfer.2010.07.023

17. Zhong D., Qin H., Wang C., Xiao Z. Thermal performance of heatsink and thermoelectric cooler packaging designs in LED. In: Proceedings – 2010 11th International Conference on Electronic Packaging Technology and High Density Packaging, ICEPT-HDP 2010, 2010. doi:10.1109/ICEPT.2010.5582819

18. Cheng H.H., Huang D.S., Lin M.T. Heat dissipation design and analysis of high power LED array using the finite element method. Microelectron Reliab, 2012. doi:10.1016/j.microrel.2011.05.009

19. Weng C.J. Advanced thermal enhancement and management of LED packages. International Communications in Heat and Mass Transfer, 2009. doi:10.1016/j.icheatmasstransfer.2008.11.015

20. Lai Y., Cordero N., Barthel F., et al. Liquid cooling of bright LEDs for automotive applications. Applied Thermal Engineering, 2009. doi:10.1016/j.applthermaleng.2008.06.023

21. Raypah M.E., M.k. D, Devarajan M, Sulaiman F. Investigation on thermal characterization of low power SMD LED mounted on different substrate packages. Applied Thermal Engineering, 2016. doi:10.1016/j.applthermaleng.2016.02.092

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