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THERMAL ANALYSIS IN FIXED, FLOWED AND AIRLESS ENVIRONMENT FOR COOLING IN LED LUMINAIRES

Mehmet Sait Cengiz[1] and Seda Yetkin[2]

Department of Technical Vocational School, Bitlis Eren University, Turkey
E-mails: [1]msaitcengiz@gmail.com, [2]syetkin@beu.edu.tr

ABSTRACT

In this study, a simulation study was conducted for the loss of efficiency caused by the heat emitted by the LED chips. The temperature change of LED luminaire was analysed for three different scenarios using finite element method. Due to the increase in the internal temperature of the luminaire and due to the air effect inside the LED luminaires, failure of the LEDs has been tried to be prevented. For this purpose, a passive cooling method was proposed in the simulation environment. So, in high power LED luminaires, the high heat emitted by the LED chips is reduced to low heat by an air flow method. In this way, efficiency in LED outputs has been achieved.

Keywords: LED lighting, LED temperature, thermal analysis, energy efficiency

1. INTRODUCTION

LED (light emitting diode) technology, which makes efficient lighting with less energy consumption, is preferred because of its features such as high luminous efficacy, good colour rendering, different colour options and long lifetime. In addition, as semiconductor technology continues to evolve, the efficiency of LEDs is constantly increasing. However, values of luminous efficacy are valid for experimental studies of LED chips in the laboratory environments. It is known that the luminous fluxes and lifetimes of LEDs are affected by temperature changes more than that of conventional light sources. When the optimal operating temperatures are exceeded, the distortion rate of the LEDs increases, the luminous fluxes decrease, and the colour properties worsen. As a result of this situation, high luminous efficacy, which are stated as advantages for LED light sources, suffer from loss of efficiency. Therefore, lighting installations using inefficient LED luminaires are seen in many applications [1–5].

According to ASSIST-2005, measuring LED chips requires a total of 6000 hours of LED operation. The first 1000 hours measurement lifetime are not included in the calculations, the last 5000 hours of the 6000 hours measurement are used. To be able to evaluate the LEDs as thermal, it recommends to measure temperature by connecting a temperature measuring device to the soldering point if possible. ASSIST specifies the soldering point temperatures as 45 °C, 65 °C, and 85 °C for high power LED chips with driving current of more than 100 mA. The luminous flux values obtained at the end of the first 1000 hours of measurement are normalized to 100 %. At 6000 hours, the luminous flux change is compared with the 1000-hour values. ASSIST publications provide an infrastructure for LED lifetime measurements, although some measurement and calculation methods are not fully recommended [6].

2. LED ARMATURE PARAMETERS

Today we live in a period when energy efficiency is very important. As the population grows, energy consumption increases at any time. For this reason, inefficient methods that cause energy consumption are abandoned and efficient methods are

Table 1. Heat Transfer Forms for Light Sources

Type of light source	Irradiance,%	Convection,%	Transmission,%
Incandescent	>90	<5	<5
Fluorescent	40	40	20
HID (discharge)	>90	<5	<5
LED	<5	<5	>90

sought. For this purpose, many methods of the energy efficient have been tested, both for improving the maintenance factors, as well as for automation and smart lighting. The main purpose here is to use energy more efficiently. For this reason, it has been searched for solutions to the problems of LEDs that provide energy efficiency in lighting [7–14].

Since the efficiency of the light source depends on the temperature in LED luminaires, thermal analysis is very important. Parameters that affect thermal design of the LED luminaire are luminaire body material, PCB elements, thermal intermediate filling materials, LED thermal powers, and ambient temperature.

Thermal analysis in LED luminaires is done for printed circuit board (PCB), on which the LED chip is mounted, and for the luminaire body. Because the heat produced by the LED chip is collected in the armature body due to the PCB. For the heat inside the armature body to pass outside, the thermal resistance must be minimal. Efficiency is directly related to thermal design, especially in luminaires that use high power LEDs. For thermal analysis, it is necessary to know the thermophysical properties of elements such as the LED chip, the housing material, PCB, thermal intermediate filling material that makes up the LED armature. As a result, in order for LED luminaires to work with optimal performance that will meet the necessary criteria for illuminance, it is necessary to perform optical analyses that corresponds to the type of luminaire and achieve the desired cooling solutions.

The heat transfer mechanisms of LEDs differ from other light sources. Conventional light sources generally transmit the generated heat to the environment through radiation. However, LEDs must transmit the heat they produce through transmission. This difference requires different solutions when designing systems for working with LEDs. A thermal path is required to exhaust the heat generated in the LEDs. Therefore, heat conduction problem must be solved in luminaire design. Disadvantages such as phosphor layer degradation, damage of lenses, and degradation of solders are encountered with high temperature effect in LED armatures [15]. In his study on the cooling of LEDs in 2006, James Petroski compared conventional light sources with LED light sources according to their heat transfer properties [16].Table 1 shows the heat transfer patterns for light sources [17].

In this research, we studied changes in the properties of LED light sources with temperature. For this purpose, thermal changes in the simulation environment were analysed using the finite element method for an LED luminaire used in road lighting.

3. LED ARMATURE THERMAL DESIGN

The heat produced in the LEDs affects the LED efficiency. As the driving current passing through the LED chip increases, the electrical power and luminous flux it draws increases. However, as the electrical power increases, heat is also released. Therefore, for LEDs driven at high currents, wider cooling surfaces are required. In this way, the temperature can be reduced, because the LED efficiency decreases with increasing temperature. LEDs transmit most of the heat they produce to the PCB, the armature body, or the ambient air inside the armature, which they use as a transmission path. Especially in high power LED armatures, metal cooling elements are used to transfer the heat generated by the LEDs to the ambient air. In addition, to reduce the luminaire temperature, thermal intermediate filling materials (thermal paste or thermal gel) are used. Because the heat accumulated in the spaces increases the junction temperature. Each part combined in the LED armature needs to be filled with solder, gel or paste. The lower the heat transfer resistances of the thermal intermediate filling materials, the easier it is to remove the heat generated in the LEDs. The thermal parameters of the LEDs are given below [1–7].

- Ambient temperature: the heat produced in the LED chips passes to the armature body through the conduction way, and then transferred to the out-

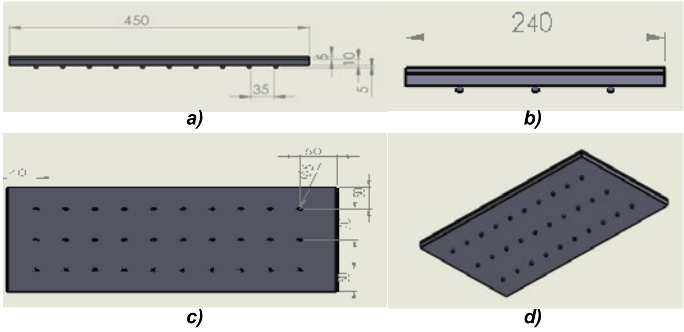


Fig. 1. The space between surfaces: 0 cm – without air flow ($A1$ – $P1$) scenario, front (a), left (b), bottom (c), and isometric (d) views

side air. Increasing the temperature in the luminaire leads to the fact that the lifetimes of the LEDs is reduced and they do not work. The heat accumulated in the armature body remains in the armature, increasing the junction temperature. For this study, the ambient temperature in the luminaire was selected as 22 °C.

- Thermal power of the LED chip: part of the electrical power in LED chips is emitted as optical power, the rest is produced as thermal power. For the LEDs to work efficiently, this thermal power produced must be removed from the LEDs. Increasing the thermal power of the LED chip increases the junction temperature. In particular, the junction temperatures of the LED chips driven above their rated currents become harmful with increasing thermal power. It is known that high temperature negatively affects luminaire efficiency and LED lifetime.
- Armature body material: different body materials effectively dissipate the heat produced in the LED chips and transport it to the external environment. In this way, the junction temperature values can be reduced. In this study, an aluminium body was chosen as body material for simulation.
- Printed circuit board: PCBs are the surface where LED chips or other elements are soldered. PCBs deliver the current from the LED driver to the LEDs. Therefore, heating occurs on PCBs.
- Thermal intermediate filling material: the main purpose of thermal intermediate filling material is to fill the gaps on the surfaces to be joined and prevent the high temperatures that will be created by the air gaps.

Therefore, important thermal parameters related to LEDs are the ambient temperature, the thermal power of the LED chip, the armature body material, PCB, and the thermal intermediate filling material. The thermal power of the LED chip is the factor that has the greatest impact on the junction temperature. *ANSYS* simulation was prepared in accordance with this approach.

4. SIMULATION AND PERFORMANCE ANALYSIS

The thermal efficiency depends on the junction temperature of the LEDs. It is known that luminous flux decreases with increasing temperature in LEDs. LED chip catalogues generally provide luminous flux at a junction temperature of 25 °C. These values (which are also referred to in the literature as cold luminous flux) are the luminous flux values obtained as a result of pulsed currents in the range of (10–20) ms in the LED production band [18]. In these measurements, the LEDs light for a very short time, and there is no increase in temperature at the junction. LEDs measured before reaching thermal equilibrium show lower performance under real operating conditions [19]. Luminaire designs usually 85 °C made with these luminous fluxes, which are called warm lumens, can give more realistic results. In this study, the initial temperature of the LED luminaire was simulated according to the junction temperature of 22 °C and the maximum temperature of 85 °C in *ANSYS* program. It is assumed that the simulated LED luminaire works ideally and operates in the temperature range of (22–85) °C. So, this LED luminaire is a quality error-free light source. While designing LED luminaire, luminaire and light source were evaluated as a single unit. Thanks to the simulation, it is easy to estimate the internal temperature of the LED armature or the LED junction temperature, which makes it easier to estimate the optical and colour characteristics of the LEDs used at that temperature. In this study, *ANSYS* program was used to predict LED junction temperatures. It is assumed that the heat discharged from the electronic element emerges from the junction point. It is assumed that part of the heat passes from the bottom to the printing circuit, and part from the top to the medium or the refrigerant block. The simulation was prepared in accordance with this principle.

Table 2. The Properties of Polyethylene and Aluminium Materials

Design-1 Materials	Density, kg/m^3	Isotropic thermal conductivity, W/(m·°C)	Specific heat, J/(kg·°C)
Polyethylene	950	0.28	950
Aluminium	2689	237.5	951

Table 3. Material Properties for (*A*2 – *P*2) Scenario

Design-2 Materials	Density, kg/m^3	Isotropic thermal conductivity, W/(m·°C)	Specific heat, J/(kg·°C)
Polyethylene	950	0.28	950
Aluminium	2689	237.5	951
Air	1.1614	0.026	1007

4.1. Simulation Scenarios

The structure, consisting of 2-layer polyethylene and aluminium, was made to represent an LED luminaire for outdoor lighting. There are 30 LED chips on the polyethylene surface. The thickness of the polyethylene surface is 10 mm (1 cm). The upper cooling surface is 0.5 cm thick (aluminium). If each LED chip emits a temperature of 85 °C, appropriate boundary conditions are simulated. According to the simulation designed by the finite element method, there is no air gap between these two surfaces. That is, the spaces are filled with thermal paste or thermal gel. In Fig. 1, representing the LED armature, the space between surfaces: 0 cm – without air flow (*A*1 – *P*1) scenario, front, left, bottom, and isometric views is seen.

Space between surfaces: 0 cm – without air flow (*A*1 – *P*1) scenario, as it consists of two parts, 2 different materials are defined. In Fig. 2, the first piece on the top is aluminium, and the second piece on the bottom is polyethylene. *ANSYS* form for the space between surfaces: 0 cm – without air flow (*A*1 – *P*1) scenario is shown in Fig. 2. The properties of polyethylene and aluminium material are given in Table 2 [15].

Space between surfaces: 0.5 cm – without air flow (*A*2 – *P*2) scenario, an air gap of 5 mm stays between the polyethylene plate and the aluminium plate. The circumference of the air gap between the two surfaces is closed. So, there is no air flow. In this design, the air showed an insulating effect, like double glass windows. Fig. 3 shows space between surfaces: 0.5 cm – without air flow (*A*2 – *P*2) scenario, front view, and left view.

Time-independent thermal analysis was performed in *ANSYS* program. In Fig. 4, an air gap of 0.5 cm is left between aluminium and polyeth-

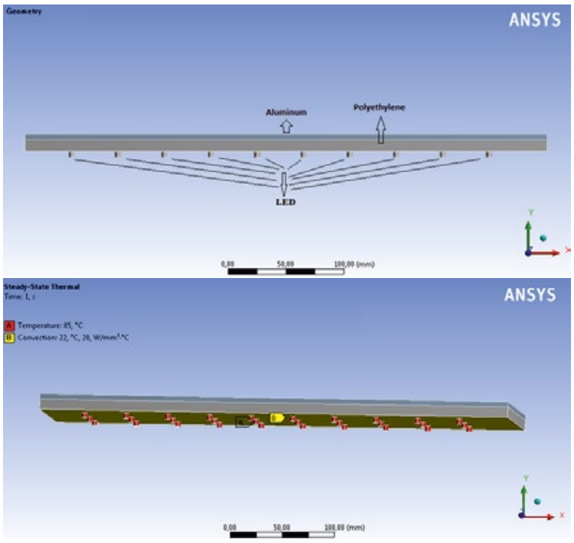
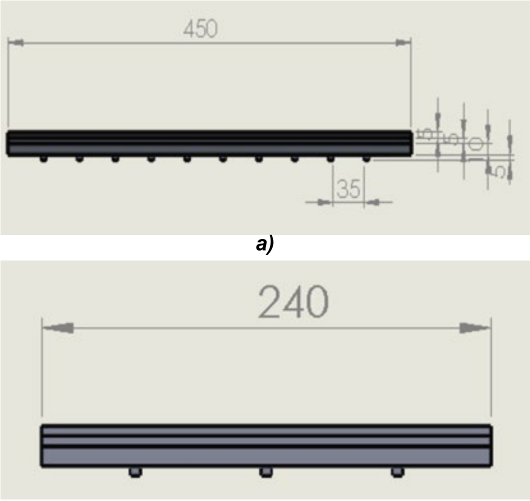


Fig. 2. *ANSYS* form for space between surfaces: 0 cm – without air flow (*A*1 – *P*1) scenario



a)

b)

Fig. 3. Space between surfaces: 0.5 cm – without air flow (*A*2 – *P*2) scenario, front view (*a*), and left view (*b*)

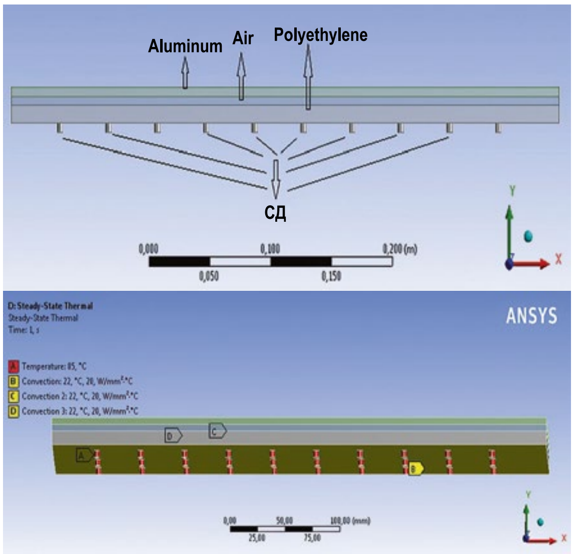


Fig. 4. *ANSYS* form for space between surfaces: 0.5 cm – without air flow (*A*2 – *P*2) scenario

ylene. In this way, a 3-storey design was formed. There is no air flow in this design. This design is called "space between surfaces: 0.5 cm – without air flow (*A*2 – *P*2) scenario". *ANSYS* form for space between surfaces: 0.5 cm – without air flow (*A*2 – *P*2) scenario is shown in Fig. 4. In Table 3, material properties are given for the (*A*2 – *P*2) scenario.

If all properties in Fig. 4 and Table 3 are equal, if there is air flow between the two plates, then the simulation used for this scenario is called "space between surfaces: 0.5 cm – air flow (*A*3 – *P*3) scenario".

4.2. Performance Analysis for Simulation

This study analyses 3 scenarios for thermal analysis of LED armatures. These scenarios has been named:

– Space between surfaces: 0 – without air flow (*A*1 – *P*1);

– Space between surfaces: 0.5 cm – without air flow (*A*2 – *P*2);

– Space between surfaces: 0.5 cm – with air flow (*A*3 – *P*3).

The simulation prepared by the finite element method was run. In the results of the thermal analysis of the top layer aluminium (*A*1, *A*2, *A*3), the bottom layer polyethylene surface (*P*1, *P*2, *P*3) is shown in Figs. 5, 6 and 7. The space between surfaces: 0 cm – without air flow (*A*1 – *P*1) scenario, as a result of the analysis in *ANSYS*, Fig. 5 shows the temperature distribution on the aluminium plate and the polyethylene plate, respectively.

As can be seen from Fig. 6, if there is a 0.5 cm air flow between the upper aluminium surface and the lower polyethylene surface, the heat rises very quickly. Since there is no air flow in the 0.5 cm air space between the plates, it is seen that the value of 22 °C of the polyethylene plate given as the boundary condition is exceeded even at $t = 1$ sec. In the (*A*2 – *P*2) scenario, it was observed that the temperature reached 22.46 °C for $t = 1$ sec on the aluminium plate and 26.22 °C on the polyethylene plate. In other words, regardless of the threshold temperature value, it produced air insulation. Such LED luminaries should not be used.

As can be seen from Fig. 7, if there is a gap between the upper aluminium surface and the lower polyethylene surface with an air flow of 0.5 cm, the heat does not increase. As the air flow occurred in the 0.5 cm air space between the plates, the temperature of the polyethylene plate of 22 °C, which was given as a boundary condition, allowed the plate to be exposed to low temperature. In the simulation, the maximum temperature rose to 22.02 °C. Under the conditions shown in Fig. 6, it is seen that the temperature in an armature with an air flow will not rise. A passive cooling method can be used to prevent the LED luminaries from heating up. This situation can be seen in Fig. 7. If the IPX protection standards are met, LED luminaires in the (*A*3 – *P*3) scenario exposed to air flow prevent heating. In Fig. 7 it is seen that the aluminium surface does not

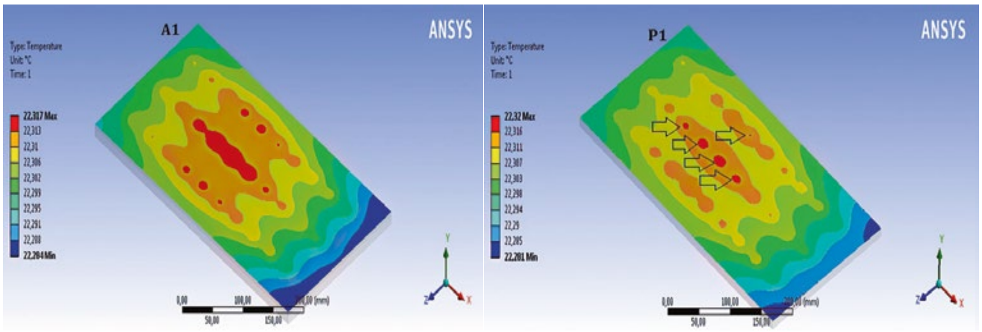


Fig. 5. The temperature distribution on the aluminium plate (*A*1) and the polyethylene plate (*P*1)

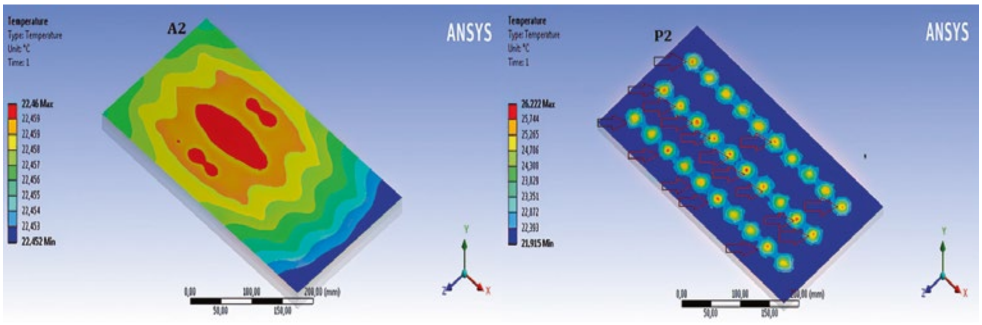


Fig. 6. The temperature distribution on the aluminium plate (*A*2) and polyethylene plate (*P*2) for the (*A*2 – *P*2) scenario

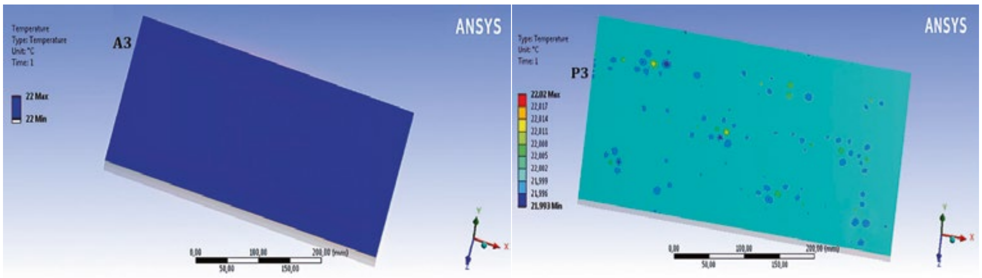
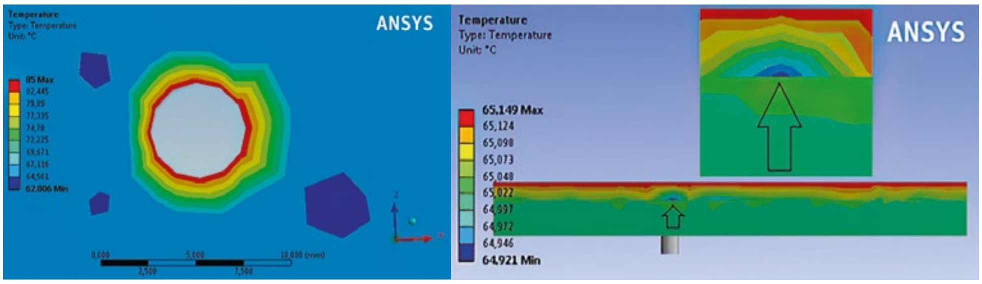


Fig. 7. The temperature distribution on the aluminium plate (*A*3) and the polyethylene plate (*P*3) for the (*A*3 – *P*3) scenario



a) b)

Fig. 8. Top and side heat dissipation for an LED chip, side cross-sectional temperature distribution for an LED chip(*a*), and overhead heat distribution for an LED chip (*b*)

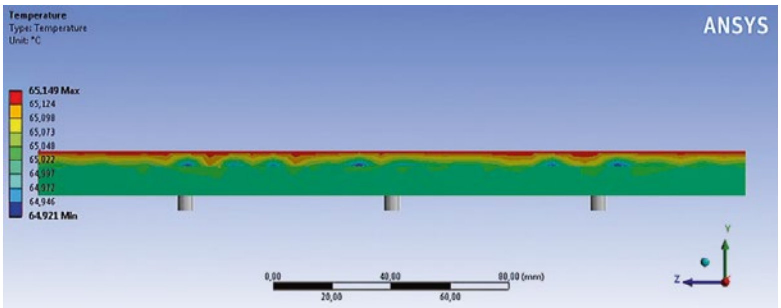


Fig. 9. Front section heat distribution for the LED luminaire

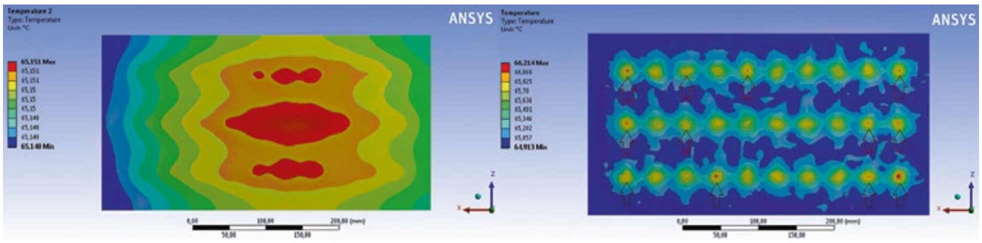
get heat up. In the (*A*3 – *P*3) scenario, although it is in equal conditions, it is seen in Fig. 7 that no LED on the polyethylene surface exceeds the threshold value. Whatever the threshold value, it does not isolate air. On the contrary, it makes air cooling. In this respect, cheaper materials can be used instead of aluminium on the upper cooling surface.

5. RESULTS AND DISCUSSIONS

When the scenarios were evaluated, the presence of an air gap layer brought the temperature to the highest level. Because it had the effect of air isolation. Therefore, there should be no air between the aluminium layer and the polyethylene layer in the LED armatures. For this purpose, thermal paste or thermal gel should be used.

As can be seen from Fig. 5, 5 LEDs exceeding the threshold temperature values were detected in $t = 1$ sec. There is no air gap between the aluminium plate and the polyethylene plate. It is clear that the aluminium layer will make sufficient cooling for the transfer.

However, in Fig. 6, if there is air in the closed area between the aluminium transfer surface and the polyethylene surface, cooling does not occur.



(*A*2) (*P*2)

Fig. 10. The temperature distribution on the aluminium plate (*A*2) and the polyethylene plate (*P*2) for the (*A*2 – *P*2) scenario (air temperature within armature 65 °C)

Because air is a very good insulating material. If the air flow does not occur, that is, if the air inside is stationary, then you can see that the polyethylene plate is subjected to more heat. As can be seen from Fig. 6, 17 LEDs exceeded the threshold temperature value specified in the simulation in $t = 1$ sec. As the LED armature operates, the temperature will continue to increase, and it is clear that the temperatures will be reached, which will deteriorate the LED, regardless of the threshold temperature value.

This was repeated for 65 °C specified in *ASSIST* standards in the simulation environment. In the simulation, the temperature of the threshold in the closed area was accepted as 65 °C under the conditions shown in Fig. 6. Fig. 8 shows top and side heat dissipation for the LED chip.

As can be seen from Fig. 9, when the air temperature inside the LED armature is 65 °C, the temperature covered the aluminium transfer surface. Due to the isolation of the air in the closed area, the temperature exceeds the threshold value in $t = 1$ sec. So, as soon as the LEDs started working, heating started. This shows that the temperature will increase over time. Since the air is in a closed area, it does not transfer the heat outside, like the double glass effect on the windows. The heat generated by the LED chips increases on the polyethylene layer and causes the LEDs to fail. It shows air insulating properties for the aluminium surface. Therefore, aluminium cannot transfer heat. Fig. 9 shows front section heat distribution for LED luminaire.

Fig. 10 shows that the aluminium surface heats up much more at a indoor temperature of 65 °C. However, it has an air isolation effect. Therefore, the heat transfer rate decreases. So, 12 LED chips exceed 65 °C in $t = 1$ sec. You can see that over time, this temperature will rise too much and cause the LEDs to malfunction. Fig. 10 shows the temperature distribution on the aluminium plate and the polyethylene plate for the (*A*2 – *P*2) scenario (air temperature within armature 65 °C).

6. CONCLUSION

The main factors affecting the junction temperature are the ambient temperature and the LED chip thermal power.

In this study, LED chips heat the polyethylene surface and the air inside the luminaire. Therefore, the LED chips on the polyethylene surface, which get too hot decay. The flowless air gap between the layers acts as an insulator and causes the temperature to rise more. Therefore, there should be no gap between aluminium and polyethylene plates. If there is a gap, heating can be prevented with thermal paste or thermal gel.

In addition, the heat can be reduced by applying passive cooling in LED armatures. If the flow of air accumulated in the gaps is provided, then cooling is provided. This situation can be seen in the simulation in Fig. 7.

The thermal power of the LED chip is the most effective parameter. As the LED chip's thermal power increases, the amount of heat released increases. When the LED armature system is examined in a holistic way, the heat emitted from the LED chip is transferred to the armature body and then to the ambient air. Increased heat in the armature in the indoor area damages the LEDs. This situation can be seen in the simulations in Fig. 6 and Fig. 10.

As a result, every parameter is important in high power LED luminaires.

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Mehmet Sait Cengiz,
Ph.D. He served as Director of Research and Development in the years 2000–2010. He had got his Master Degree in 2011 and Ph.D. in 2016. His spesialization area is electrical-electronics engineering (light). He still works in the field of applied lighting

Seda Yetkin,
M. Sc. She received her Master’s Degree in Fırat University (2017), faculty of technology, Department of Mechatronics Engineering. Now she is a Ph.D. student in the same department. She is currently working as a lecturer at Bitlis Eren University, Vocational School of Technical Sciences, Department of Biomedical Device Technologies