Numerical investigation of the effect of different heat sink fin structures on the thermal performance of automotive LED headlights

Seyfi Şevik[1], Özgür Özdilli[2], Furkan Akbulut[3*]

0000-0003-4063-0456, 0000-0002-9861-4793, 0000-0001-6826-7199

[1] *Electricity and Energy, Technical Sciences Vocational School, Hitit University, Çorum, Turkey*
[2] *Dept. of Machinery and Metal Tech., Technical Sciences Vocational School, Hitit University, Çorum, Turkey*
[3*] *Department of Motor Vehicles and Transportation Technologies, Technical Sciences Vocational School, Hitit University, Çorum, Turkey*

Abstract

The automotive lighting industry is changing at a rapid pace, thanks to advances in technology. Automotive lighting equipment is produced with more functionality and higher performance. However, with the increase in performance, undesirable heat generation also increases. Automotive headlights fail or perform poorly when exposed to high heat; therefore, unwanted heat has to be removed. This is accomplished with heat sinks. In this study, four different automotive light-emitting diode (LED) headlights have been designed as channelless, 4-channel, 8-channel, and 12-channel. The designed models were tested numerically at different LED powers (8, 10, 12, 14, and 16W). Thus, the impact of heat sink fin structures on the thermal performance of automotive LED headlights was investigated numerically. The heat dissipation performances of the designs were analyzed using the computational fluid dynamics software SolidWorks Flow Simulation. The simulation results showed that the designed products can be used as LED headlights. As the applied heat power increased, maximum temperatures also increased. While a continuous increase in performance was achieved in designs up to 8-channel, slight performance degradation was observed when the number of channels reached 12. As the applied heat power increased, the average temperatures increase whereas thermal resistance (Rth) decreased. From channelless design to 12-channel design, Rth values decreased from 6.8 °C/W to 5.31 °C/W.

Keywords: LED headlights, Heat sink, Fin structure, Thermal performance, Numerical investigation, Impact of channel

1. Introduction

The lighting sector is continuously evolving as technology advances, and product performance values rise. However, as performance rises, so does undesirable heat output. LEDs fail or perform poorly when exposed to high heat; therefore, unwanted heat has to be removed. This is accomplished with heat sinks.

There are many studies on LED cooling using heat sinks [1-7]. Jang et al. [1] optimized a pin-fin radial heat sink for LED cooling. They proposed a design that reduces the mass by more than 30%. Costa and Lopes [2] developed a radial heat sink for led lamp cooling and proposed a heat sink design procedure. Jeong et al. [3] studied on optimum design of a horizontal fin heat sink for LED cooling. The overall thermal resistance (Rth) of the proposed model was reduced by approximately 31% over the conventional unopened model at an orientation of 180° and heat power of 10 W.

Hsu and Huang [4] investigated the thermal performance of a heat sink for a compact LED downlight. They found the LED junction temperature of their design (121.7 °C) to be lower than the maximum temperature (135 °C). Şevik and Özdilli [6] designed the four different aluminum finned heat sinks (a deep heat sink with reflector, a deep heat sink without reflector, a shallow heat sink with reflector, and a shallow heat sink without the reflector) for LED cooling. They added reflector geometries to shallow and deep designs and numerically investigated the effects of the reflector and concave geometries at a heat power of 10W. While maintaining the mass of the design, a temperature increase of 1.89-4.24 °C was obtained however, the need for an additional reflector is eliminated. Şevik and Özdilli [7] tested the splay impact on the thermal performance in the standard cross-cut heat sink, a fixed-array splayed heat sink and a full splayed heat sink under natural

and forced conditions. The full spreading impact provided 5.46% and 2.59% lower junction temperature under natural and forced conditions, respectively. The thermal resistance of the full splayed heat sink was 7.1% at 3W and 2.6% at 10W lower than the flat fins and the fixed array wide fin heat sink. The most suitable flow direction for their study was determined as push. An LED heatsink with a heat pipe was designed and tested by Feyzioğlu [8]. Junction temperatures of 54 °C and 70 °C were obtained for the applied 11W and 15.5W, respectively, which is considerably lower than the maximum junction temperature predicted for the armature. The common interests of these studies are to reduce the junction temperature and to create optimum designs to reduce the mass of the product.

The automotive headlamp is a lamp positioned in front of the vehicle to provide vision to the driver when driving at night or in low light conditions. The headlamps are considered one of the most important safety parts in cars. It is reported that approximately 40% of fatal accidents occur at night, and the biggest reason for this is the decrease in visual performance [9, 10]. For this reason, the performance of the headlights is of severe significance for driving safety. This rate is expected to exceed 50% shortly. Furthermore, the efficiency of conventional methods is just 5% for halogen and 20% for xenon, respectively. When LED headlights replace all conventional headlights, it will drastically reduce fuel consumption for automotive lighting and reduce CO_2 emissions by about 1-3 g/km [11].

LED lamps, which are used in the headlights, taillights, turn signals, interior lights, and indicator lights of the vehicles in the automotive industry, have become an indispensable part of modern cars. While high-power LEDs are generally preferred in vehicle headlights and signal groups, medium-power LEDs are generally used in taillights. A headlamp requires 1000 lumens of light output, which is produced from the electrical energy of the battery supplied by the automotive engine. Researchers are making great efforts to solve the optical problems with studies such as the optical system for the LED headlamp [12], modular design [13], beam design methods, and simulation technology [14], and multiple surface method [15]. Researchers have also focused on heat problems in-vehicle LED headlights. Recent studies on automotive LED headlights have been focused on new designs [16-22]. Jang and Shin [16] investigated the thermal performance of a new cooling system for a light-emitting diode headlamp module. The LED headlamp module is designed with an air-circulated cooling system. According to the headlamp's operating conditions, precise fluid field modeling and heat transfer analyses were accomplished using computational fluid dynamics. The junction temperatures of the LEDs were observed to be decreased in the analyses conducted with the air cooling system. When the air circulation speed rose from 0 to 120 km/h, the LED array's junction temperature dropped from 70.6 °C to 30.25 °C. Also, the use of fins resulted in a temperature drop of 2 °C to 4 °C. Lai et al. [17] studied the different configurations of active liquid cooling systems for LED automotive headlights. Chen et al. [18] proposed a flexible woven heat sink for the LED headlights. They found that the total R_{th} of the headlight is 5.15 °C/W for 25 W. While the total R_{th} was

4.42 °C/W at 50 °C ambient air temperature, R_{th} also increased as the ambient air temperature increased. Huang et al. [19] optimized the heat pipe parameters and fin structure of LED headlights using ANSYS Fluent software. They noted that the use of heat pipes in combination with AlN ceramic substrates in high-power LED lights is effective against overheating. The maximum chip temperature was found to be 103.67 °C and 101.14 °C for experimental and simulation, respectively. Lu et al. [20] improved a three-dimensional (3D) vapor chamber to solve heat dissipation of LED automotive headlamps. The minimum thermal resistance was found to be 0.125 °C/W at a 50 W heating load. Sökmen et al. [21] investigated the cooling effects of automotive headlights having different fin designs and fin material on junction temperature at three different ambient air temperatures (25 °C, 50 °C, and 80 °C) and four different LED powers (0.5 W, 0.75 W, 1W, and 1.25 W). In addition, a new methodology for choosing the optimum cylinder blade structure under given constraints was described. The LED has reached the critical temperature at 1W power and 80 °C ambient temperature. As a result, the proposed method always suggested feasible fin structures with optimum properties for certain LED designs. Chidambaram and Arunachalam [22] have designed a new high power automotive LED headlight and tested it at 16 W. While the junction temperature was 116 ºC under natural convection, it was reduced to 87 ºC at 1.9 m/s air velocity. Singh et al. [23] offered heat pipe-based cooling solutions. The R_{th} of the heat sink with 12 aluminum fins was obtained as 7 °C/W at 25 °C of ambient air temperature and 20 W of heat power.

As can be seen from the literature, many different automotive LED headlight designs have been realized. Similarly, in this study, four different automotive LED headlight designs were made and their comparative numerical analysis was performed. Possible design options for the heat sink are discussed.

2. Material

Until the previous decade, halogen and xenon bulbs were the primary light sources in car headlamps. Halogen bulbs have tungsten filaments as a light source with high electrical resistance. There are no filaments in xenon bulbs, which are also known as high-intensity discharge lamps. The ionized gas inside the bulb emits white light when a high voltage is applied. When turned on, halogen lamps emit no UV radiation and light up instantaneously. Halogen bulbs can work for about 5000 hours; Xenon bulbs can work for about 3000 hours Due to the advantages of LEDs, LEDs are gradually being used instead of traditional Halogen and Xenon bulbs as the light sources of vehicle headlamps in the automotive industry. When compared to any other automobile light source, LEDs have the highest efficiency. LEDs are compact, generate white light (daylight), and use less power than other lights. The average operating life of a LED is around one hundred thousand hours when properly cooled. The average operating life of an LED is around one hundred thousand hours when properly cooled. The LED system's luminous efficiency, measured in lumen output per watt provided, is 160% higher than the Xenon system's [22]. For these and similar reasons, this study focuses on the LED headlight.

However, the junction temperature of an LED rapidly rises when turned on due to its compact size. Overheating the connection can result in a reduction in brightness and eventual LED failure. As a result, employing a cooling system it is necessary to keep the junction temperature under control and appropriately distribute the heat.

In high-power LED cooling systems, finned copper or aluminum heat sinks are commonly employed, which provide heat to the environment via convection and radiation. Thus, Aluminum (A6063), one of the most suitable materials for the heat sink, was selected as the material for the automotive LED cooling application. The features of Aluminum (A6063) are given in Table 1.

Table 1. Aluminum (A6063) features

Density (ρ)	2.7 g/cm^3
Specific heat capacity (c)	900 J/kgK
Thermal conductivity (k)	201-218 W/mK
Melting temperature (Tm)	615 °C
Linear thermal expansion coefficient (α)	2.34*10^{-5}/K (20-100 °C)
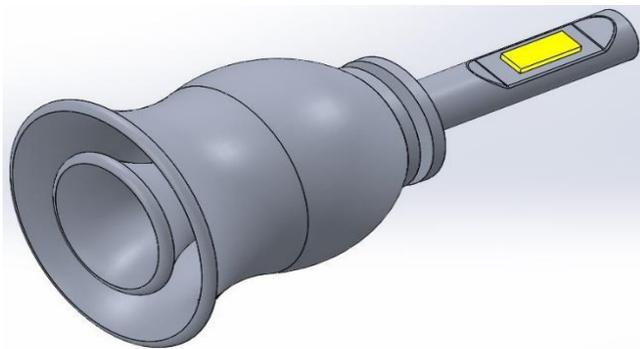
a)   Without channel
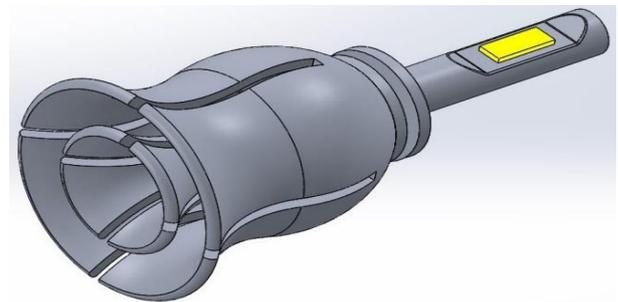
b)   4-channel
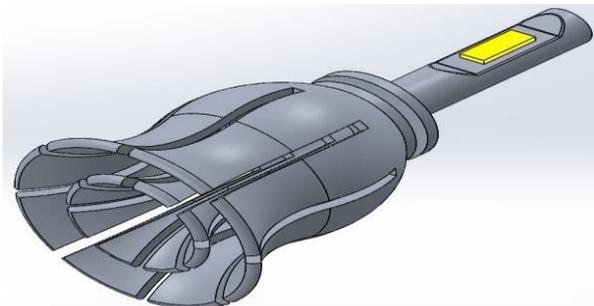
c)   8-channel
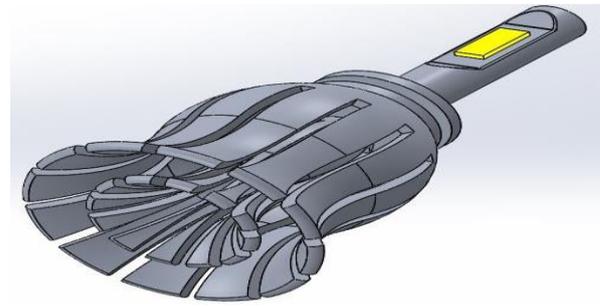
d)   12-channel

Fig. 1. Automotive LED headlight designs
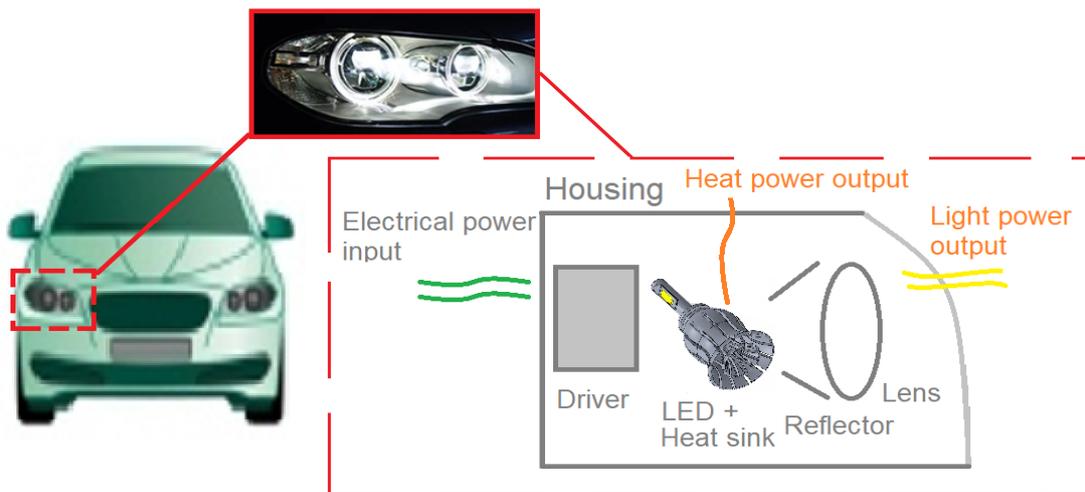
Fig. 2. Illustration of the LED headlight in a vehicle

In this study, four different automotive light-emitting diode (LED) headlights have been designed as channelless, 4-channel, 8-channel, and 12-channel. Fig. 1 shows a three-dimensional (3D) view of each automotive LED headlight design. Automotive LED headlight consists of LED lamp and heat sink. Also, the channels added to the heat sinks are shown in Fig. 1. The energy flow in the headlight components of a vehicle is shown in Fig. 2.

3. Theoretical analysis

LED lamp generates heat so this heat has to be removed, which can be done with high-performance heat sinks. On LED lamps, proper heat control is required. The power supplied to the LED lamp is converted into heat and light. The thermal power of the LED is calculated with [5]:

$$P_h = \eta P_{tot} = P_{ei} - P_{oo} \tag{1}$$

The optical power of the LED is calculated as:

$$P_{oo} = (1 - \eta)P_{tot} \tag{2}$$

Total power input to the LED is

$$P_{tot} = I_f V_f \tag{3}$$

Thermal resistance (Rth) is an expression that tells how many degrees of temperature elevation is caused when a unit of thermal power is applied to the LED. The Rth is expressed as:

$$R_{th} = \frac{\Delta T}{P_h} \tag{4}$$

a) Without channel
Total: 486927, Fluid: 484825, Solid: 8230

b) 4-channel
Total: 488677, Fluid: 481193, Solid: 7484

c) 8-channel
Total: 489310, Fluid: 481496, Solid: 7814

d) 12-channel
Total: 489781, Fluid: 482209, Solid: 7585
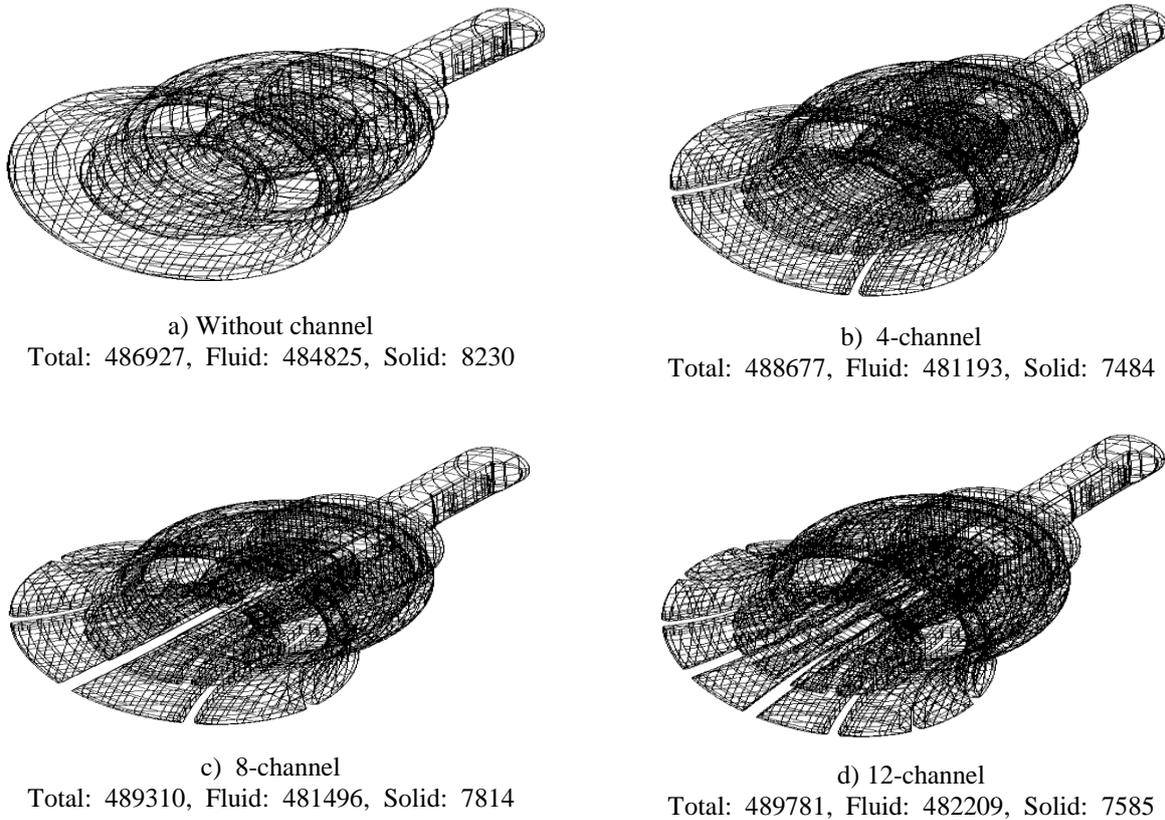
Fig. 3. Mesh images of each automotive LED headlight heat sink

4. Mathematical Model

Numerical analysis has a significant place in production processes. It offers the opportunity to design and produce the best at the least cost. Therefore, this study has focused on the finned LED heat sink. Simulations were carried out in the SolidWorks Flow Simulation program.

The simulation process is as follows;
- LED heat sink geometries were drawn in the 'Geometry' section of the SolidWorks,
- The mesh structures for the designs were created,
- Simulation boundary conditions were established,
- The flow simulation software was run by positioning the heat source,
- Different thermal powers were applied.

Flow simulation software operates Navier-Stokes equations with mass, momentum, and energy conservation laws and solves management equations with the cubic cartesian coordinate system.

Continuity equation:

$$\nabla(\rho\vec{V}) = 0 \tag{5}$$

Momentum equations are:

$$\nabla(\rho u \vec{V}) = -\frac{\partial p}{\partial x} + \mu \nabla^2 u$$
(6)

$$\nabla(\rho v \vec{V}) = -\frac{\partial p}{\partial y} + \mu \nabla^2 v$$
(7)

$$\nabla(\rho w \vec{V}) = -\frac{\partial p}{\partial z} + \mu \nabla^2 u - \rho g$$
(8)

Energy equation is:

$$\nabla(\rho \vec{V} T) = -\frac{k}{c_p} + \nabla^2 T + S$$
(9)
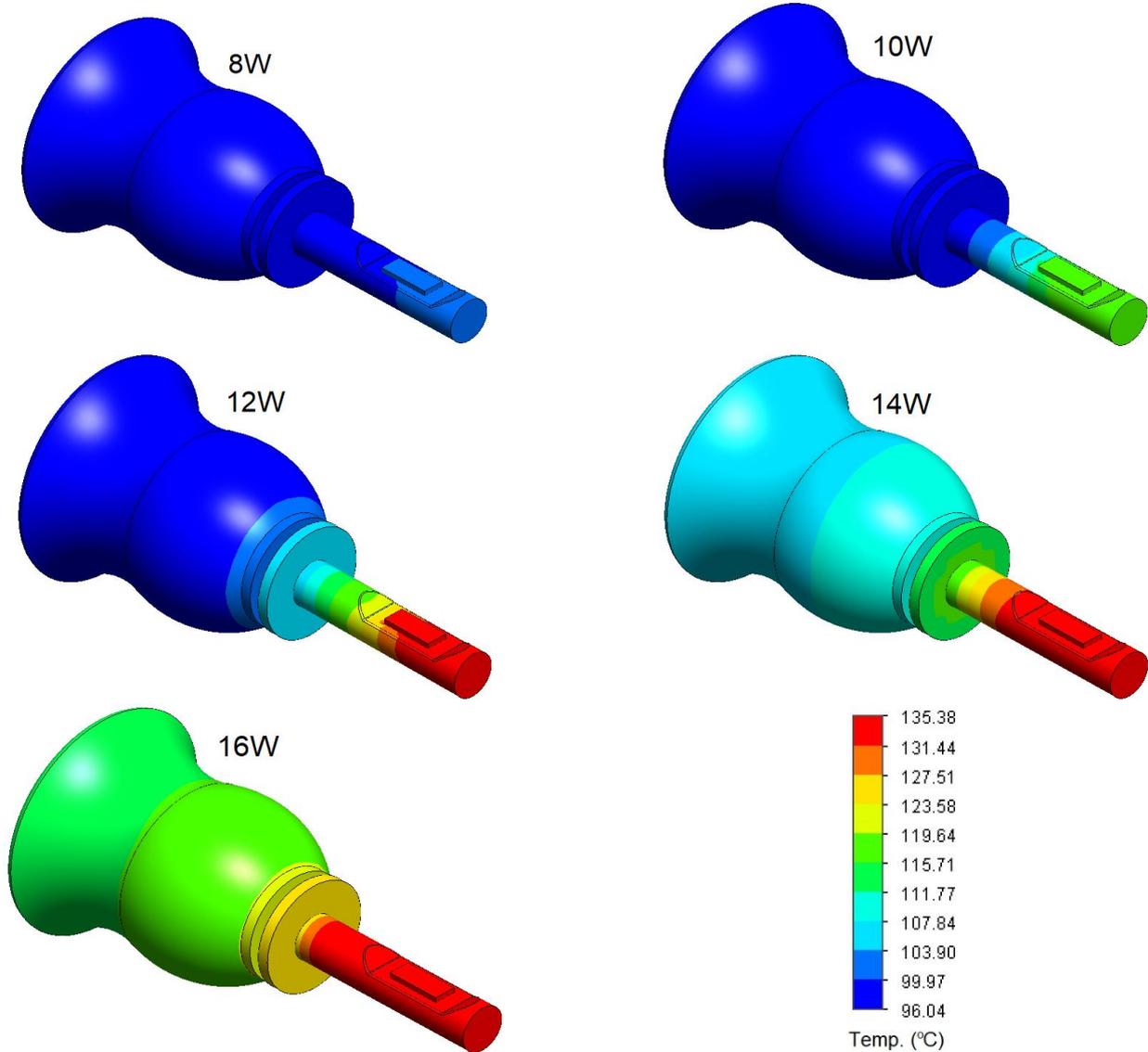
Fig. 4. The temperature contours of automotive LED headlight without channel for different powers

$$\nabla^2 T = 0 \qquad (10)$$

Mesh models are created and the total number of grid elements, the number of fluid grid elements, and the number of solid grid elements are obtained. Fig. 3 shows the mesh images of each automotive LED headlight heat sink. Grid element numbers are 486927, 488677, 489310, and 489781 for channels, 4-channel, 8-channel, and 12-channel, respectively.

5. Result and Discussion

Each automotive headlight was simulated under natural conditions with heat powers from 8W to 16W, which was corresponded to 10W to 20W in LED power. The temperature contours of each automotive LED headlight are given in Figs. 4-7. Fig. 4 shows the temperature contours of an automotive LED headlight without channel for different powers. As can be seen from the figure, solid temperatures are maximum in the regions close to the LED, whereas solid temperatures decrease as move away from the LED. As the applied heat power increases, the

colors in the thermal contours change towards warmer colors.

This means that the LED headlights work more healthily at low heat power applied. However, it shows that designs can be used at 16W heat power, depending on the LED datasheet. As expected, the maximum temperature of 166.29 °C was obtained in the channelless design at the highest LED power.

Fig. 5 shows the temperature contours of an automotive LED headlight with 4-channels for different powers. As expected, the maximum temperature was 158.85 °C at the highest LED power. Adding four channels to the LED headlight improves performance. When 8W power is applied, it is the safest application in

terms of temperature, whereas when the power doubles, ie 16W, it has the riskiest temperature.

Fig. 6 shows the temperature contours of an automotive LED headlight with 8-channels for different powers. When the number of channels increases to eight, the performance increases slightly. In fact, among the designs, the lowest temperatures occur in the 8-channel LED headlights. This means that the best performance is achieved with the 8-channel LED headlight.
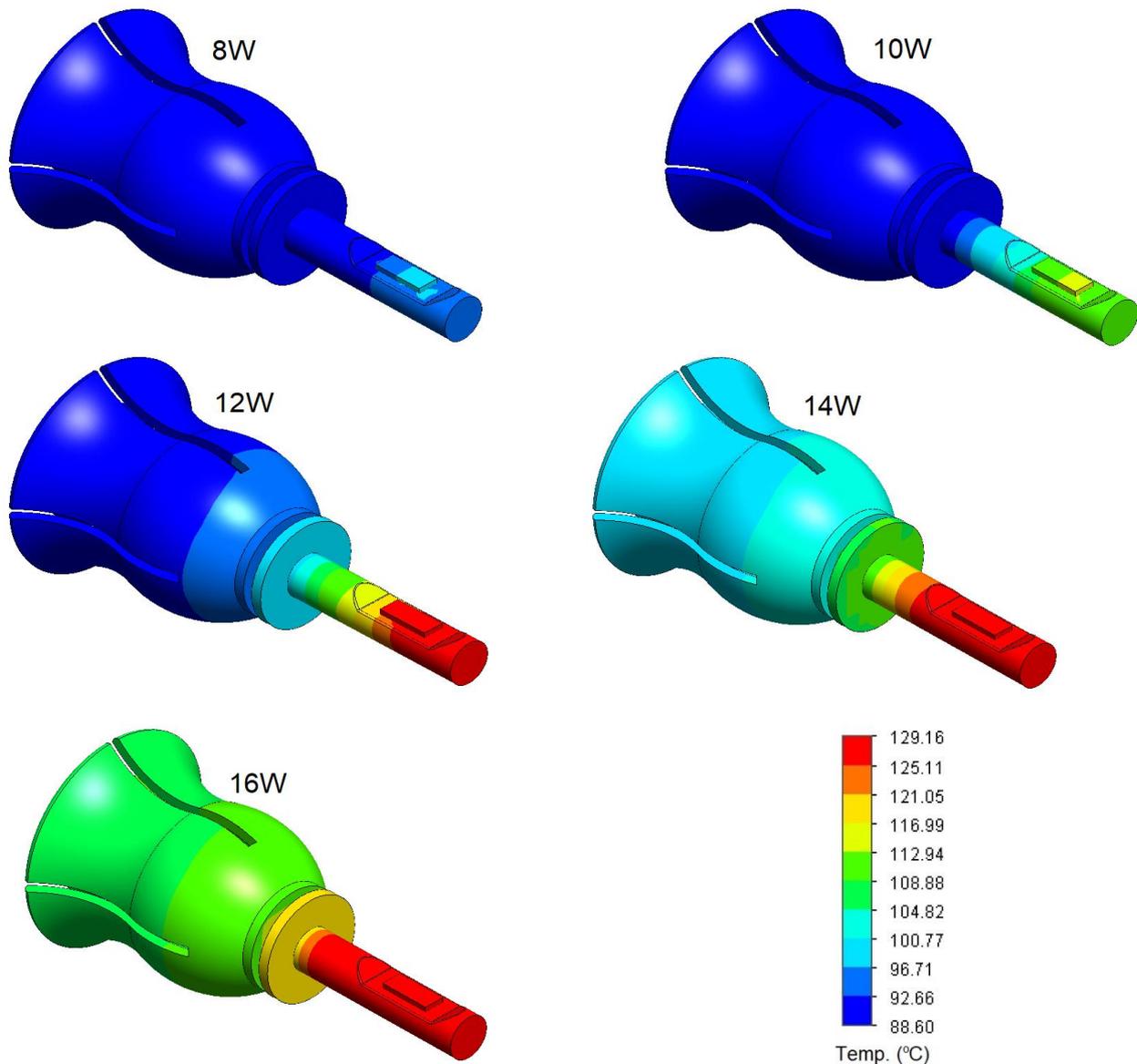

Fig. 5. Temperature contours of automotive LED headlight with 4-channels for different powers

Fig. 7 shows the temperature contours of an automotive LED headlight with 12-channels for different powers. As the number of channels increases, there is an improvement in temperatures, that is, its performance increases. However, 12-channel break this rule. While a continuous increase in performance was achieved in products up to 8-channel, the maximum temperature

increased by approximately 1.5 °C in the 12-channel design compared to the 8-channel design. When the number of channels is increased to 12, the performance of the LED headlight increases significantly compared to the channelless design, however; the performance drops slightly compared to the 8-channel. Natural convection and a drastic reduction in mass are the reasons behind this. When employing a fan, it will almost certainly provide higher performance than other models.

Fig. 8 shows the average and maximum temperatures of automotive LED headlights versus applied heat power. As the applied heat power increases, the average temperatures and maximum temperatures also increase. However, as the applied heat power increases, the gap between average temperatures and maximum temperatures widens. That is, the maximum temperatures increase more than the average temperatures, which means that as the LED power increases, the heat sink becomes less active.
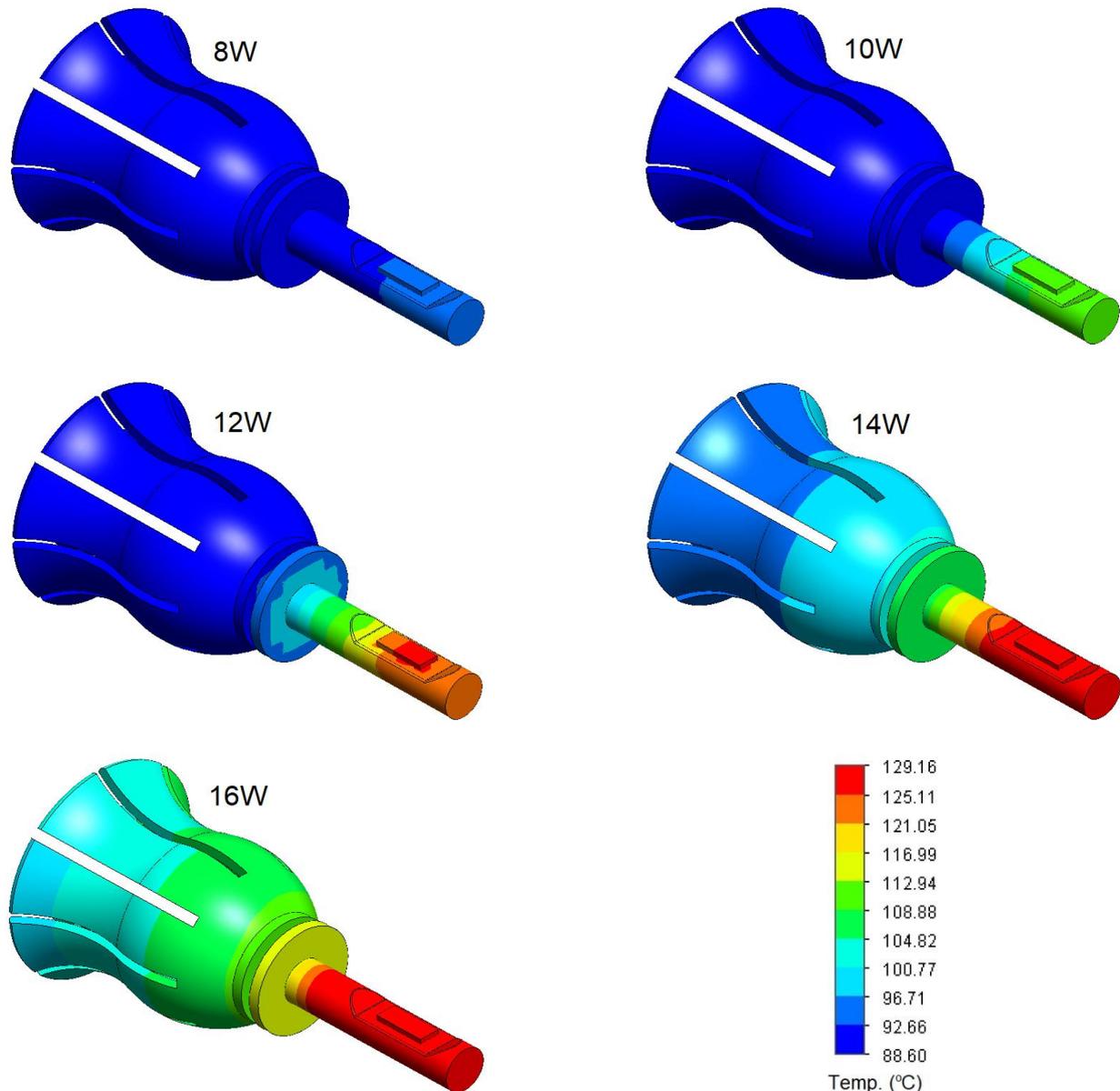

Fig. 6. Temperature contours of automotive LED headlight with 8-channels for different powers

Fig. 9 shows the average temperature and thermal resistance versus applied heat power. As the applied heat power increases, the average temperatures increase whereas as the applied heat power increases, R_{th} decreases. From channelless design to 12-channel design, R_{th} values decrease from 6.8 °C/W to 5.31 °C/W. While the highest R_{th} value was realized in the channelless LED headlight, the lowest R_{th} value was realized in the 12-channel LED headlight. Similarly, R_{th} of the heat pipe-based heat sink

with 12 aluminum fins was obtained as 7 °C/W at 25 °C of ambient air temperature and 20 W of heat power by Singh et al. [23]. In a study for a flexible woven heat sink by Chen et al. [18],

they found that the total R_{th} of the headlight is 5.15 °C/W for 25 W.
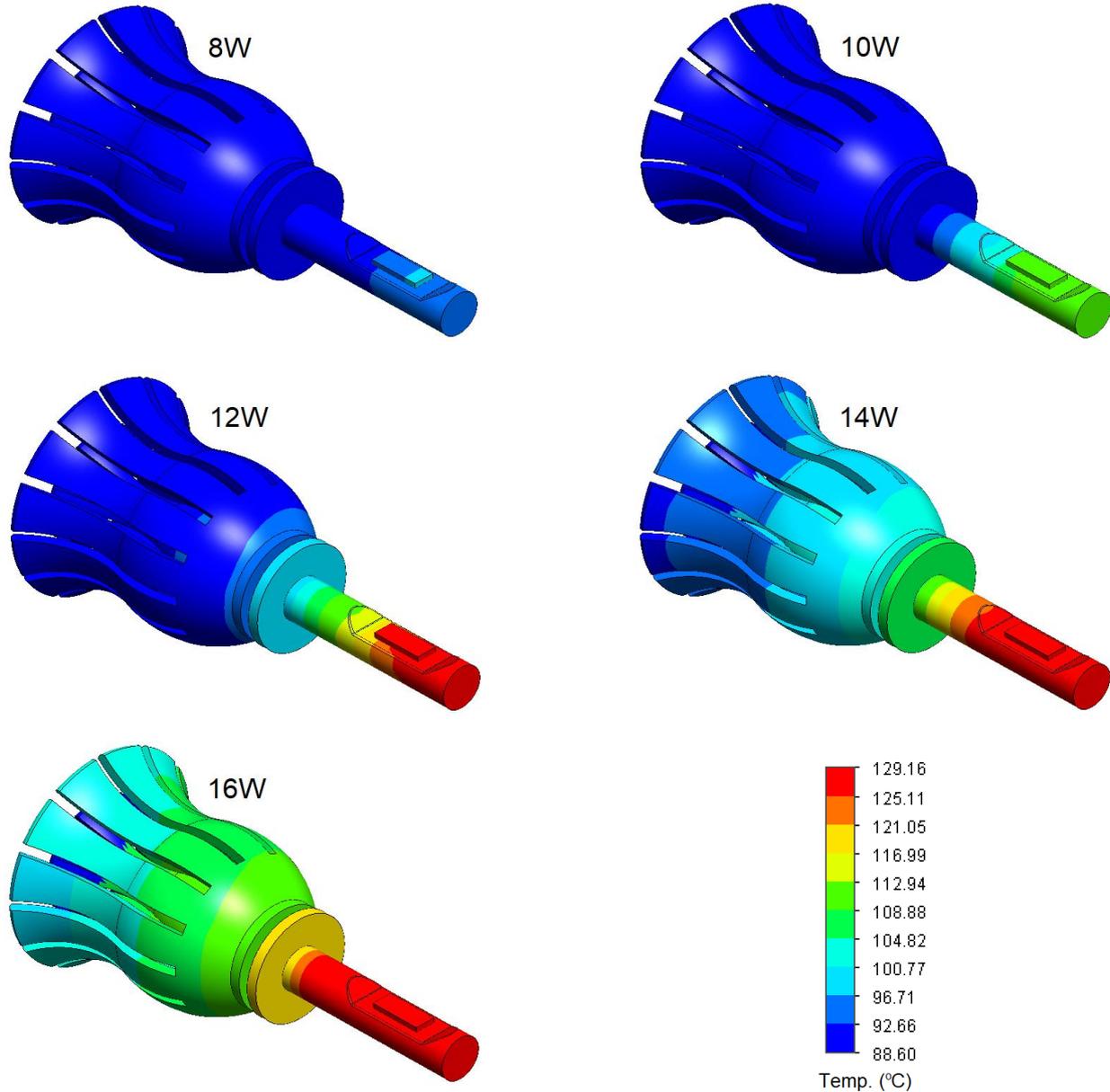

Fig. 7. Temperature contours of automotive LED headlight with 12-channels for different powers.

6. Conclusions

Four different automotive light-emitting diode (LED) headlights have been designed as channelless, 4-channel, 8-channel, and 12-channel. The designed models were analyzed numerically at different LED powers (8, 10, 12, 14, and 16W). The following results were obtained.

- As the applied heat power increases, the average temperatures and maximum temperatures also increase.
- While a continuous increase in performance was achieved in products up to 8-channel, the maximum temperature increased by approximately 1.5 °C in the 12-channel design compared to

the 8-channel design.
- As the applied heat power increases, the average temperatures increase whereas as the applied heat power increases, R_{th} decreases. From channelless design to 12-channel design, R_{th} values decrease from 6.8 °C/W to 5.31 °C/W.
- The maximum temperature of 166.29 °C was obtained in the channelless design at the highest LED power.

The simulation results show that the designed products can be used as LED headlights. In the future, products can be tested experimentally. It can also be analyzed under forced conditions.
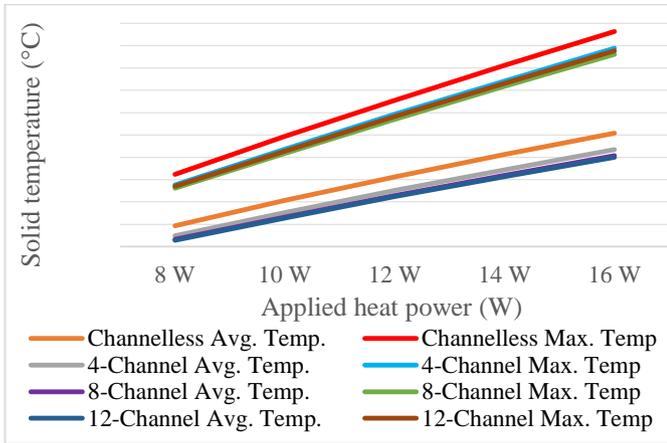
Fig. 8. The average and maximum temperatures versus applied heat power
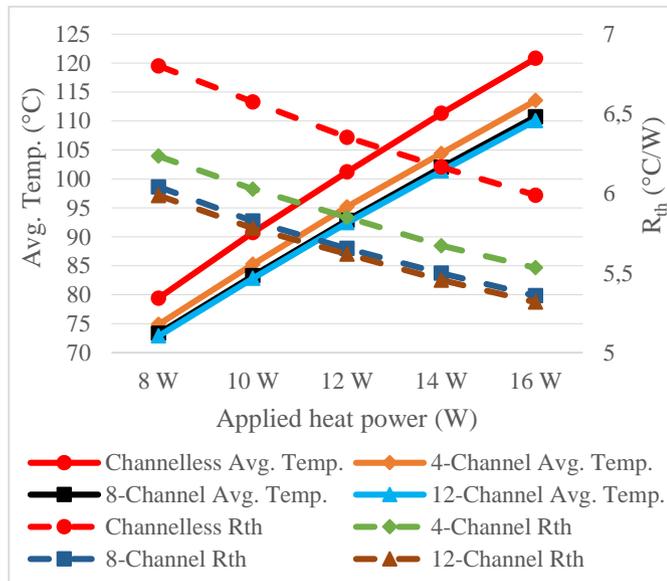
Fig. 9. The average temperature and thermal resistance versus applied heat power

Nomenclature

c_p	: heat capacity (kj/kg°C)
g	: gravitational acceleration (m/s²)
I_f	: forward current (A)
k	: thermal conductivity (W/m°C)
P_{ei}	: electrical input power (W)
P_h	: thermal power (W)
P_{oo}	: optical output (W)
P_{tot}	: total power (W)
R_{th}	: thermal resistance (°C/W)
S	: source term of the energy equation
T	: temperature (°C)
u	: fluid velocity (m/s)
V_f	: forward voltage (V)
$\vec{V}$	: velocity vector
η	: efficiency (%)
ρ	: density (kg/m³)

Conflict of Interest Statement

The authors declare that there is no conflict of interest.

CRediT Author Statement

Seyfi Şevik: Writing-original draft, Conceptualization, Supervision,
Özgür Özdilli: Conceptualization, Simulation, Validation,
Furkan Akbulut: Conceptualization, Formal analysis, Data curation.

References

[1] Jang D, Yu SH, Lee KS. Multidisciplinary optimization of a pin-fin radial heat sink for LED lighting applications. Int J Heat Mass Transfer 2012;55:515–521.

[2] Costa VAF, Lopes AMG. Improved radial heat sink for led lamp cooling. Appl Therm Eng 2014;70:131–138.

[3] Jeong MW, Jeon SW, Kim Y. Optimal thermal design of a horizontal fin heat sink with a modified-opening model mounted on an LED module. Appl Therm Eng 2015;91:105–115.

[4] Hsu HC, Huang YC. Numerical simulation and experimental validation for the thermal analysis of a compact LED recessed downlight with heat sink design. Appl Sci 2017;7: 4.

[5] Şevik S, Abuşka M, Özdilli Ö. Thermal performance analysis of a novel linear LED housing with inner and outer fins. Int Commun Heat Mass Transfer 2020;119:104970.

[6] Şevik S, Özdilli Ö. Design and thermal analysis of led downlight heat sink. 4. Asia Pacific International Congress on Contemporary Studies, 12-13 December 2020, Published: 25 December 2020, Subic Bay, Philippines.

[7] Şevik S, Özdilli Ö. Experimental and numerical analysis of the splay impact on the performance of splayed cross-cut fin heat sink. Int J Therm Sci 2021;170(4):107101.

[8] Feyzioğlu A. Experimental evaluation of cooling modules with high heat transfer capacity for illumination armatures and innovative product design. Çukurova University J Faculty Eng Archit 2020;35(3):575-582.

[9] Dewar Robert E, Olson P. *Human factors in traffic safety.* 2nd ed., Tucson: Lawyers & Judges Publishing Company, 2007.

[10] Bullough John D, Donnell Eric T, Rea Mark S. To illuminate or not to illuminate: roadway lighting as it affects traffic safety at intersections. Accid Anal Prev 2013;53:65–77.

[11] Long X, He J, Zhou J, Fang L, Zhou X, Ren F, Xu T. A review on light-emitting diode based automotive headlamps. Renew Sustain Energy Rev 2015;41:29–41.

[12] Jianghong J, Ben W. High efficiency reflector optics for LED automotive forward lighting. SPIE Proceedings Of Nonimaging Optics and Efficient Illumination Systems IV, 2007;6670:1–10.

[13] Chi-Chang H, Yan-Huei L, CHih-Ching H. Modular design of the LED vehicle projector headlamp system. *Appl Opt* 2013;52:5221–9.

[14] Ge A, Du Z, Wang W, Qiu P, Wang J, Cai J., et al. A composite optical system for a LED based headlamp low beam module. Ligh Res Technol 2013;45:752–7.

[15] Cvetkovic A, Dross O, Chaves J, Benitez P, Miñano JC, Mohedano R. Etendue-preserving mixing and projection optics for high-luminance

LEDs, applied to automotive headlamps. Opt Express 2006; 14:113014–20.

[16] Jang S, Shin MW. Thermal analysis of LED arrays for automotive headlamp with a novel cooling system. IEEE Transactions on Device and Materials Reliability 2008;8(3):561–564.

[17] Lai Y, Cordero N, Barthel F, Tebbe F, Kuhn J, Apfelbeck R, Würtenberger D. Liquid cooling of bright LEDs for automotive applications. Appl Therm Eng 2009;29:1239–44.

[18] Chen S, Chen K, Li Z, Tang Y, Zhuang B, Zhong G, Liang G. Experimental investigation on the thermal performance of a light emitting diode headlamp with a flexible woven heat sink. Appl Therm Eng 2017;127:1215–22.

[19] Huang DS, Chen TC, Tsai LT, Lin MT. Design of fins with a grooved heat pipe for dissipation of heat from high-powered automotive LED headlights. Energy Conver Manage 2019;180:550–558.

[20] Lu Z, Bai P, Huang B, Henzen A, Coehoorn R, Liao H, Zhou G. Experimental investigation on the thermal performance of three-dimensional vapor chamber for LED automotive headlamps. Appl Therm Eng 2019;157:113478.

[21] Sökmen KF, Yürüklü E, Yamankaradeniz N. Computational thermal analysis of cylindrical fin design parameters and a new methodology for defining fin structure in LED automobile headlamp cooling applications. Appl Therm Eng 2016;94:534–542.

[22] Chidambaram RK, Arunachalam R. Automotive headlamp high power led cooling system and its effect on junction temperature and light intensity. Yildiz Technical Univ J Thermal Eng 2020;6(12):354–368.

[23] Singh R, Mochizuki M, Yamada T, Nguyen T. Cooling of LED headlamp in automotive by heat pipes. Appl Therm Eng 2020;166:114733.