Thermal management technology of high-power light-emitting diodes for automotive headlights

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Abstract: The heat dissipation problem of high-power LEDs (Light-Emitting Diodes) limits their applications in automobile headlights. The heat demand for cooling LED headlights is analyzed based on heat transfer theory. This study proposes an initiative heat dissipation technology of temperature feedback control combined heat pipe and heat sink. The corresponding hardware and software control processes are designed. The temperature feedback control is realized with an MCU (Micro Control Unit) that judges and controls the synthetic jet device working process. A 3D model for the heat pipe radiator is constructed using CATIA. The model is optimized with the fluid thermodynamic simulation software FLOEFD. Finally, a sample lamp is prepared and tested with an infrared thermometer. The temperature distribution on each LED light source and radiator fin is quantitatively measured and analyzed. These results confirm that the designs of the thermal management system and the proposed technique solve the heat dissipation problem of high-power LED automotive headlights under the ambient temperature 50 °C indeed.

Keywords: LED automotive headlight, thermal management, cooling structure, thermal simulation, temperature feedback

Classification: Electronic instrumentation and control

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1 Introduction

LEDs can be applied in different devices because of their small size, long life, low energy consumption, vibration resistance, fast start-up time, and environmental friendliness. In automotive lighting, LEDs are used in brake lights because of their short start-up time. In recent years, the luminous flux of high-efficiency white LEDs has been further improved with semiconductor materials and packaging technology advances. LEDs in automotive lighting applications have gradually expanded from high brake lights to rear combination lamps. High-power, high-brightness white LEDs may be used in automobile headlights. Hence, LEDs gradually become “fourth-generation” light by replacing traditional incandescent, halogen, and xenon lamps for automotive lighting [1, 2, 3, 4, 5, 6]. High-power LED is one of the promising candidates for future automotive lighting systems with efficient energy consumption. However, a low electro-optical conversion efficiency of LEDs can induce a high percentage of input power that transforms into redundant heat. This leads to an increase in the junction temperature [7, 8]. It is well known that high junction temperature in the LED would lead to reliability problems such as low quantum efficiency, wavelength shifts, short lifetime, and even catastrophic failure. The performance of high power LEDs strongly depends on the junction temperature [9, 10, 11]. Therefore, proper thermal management is critical for LEDs to be adopted in high efficiency lighting systems. The high junction temperature issues have to be resolved before gaining more market penetration. Various studies on thermal management of micro-electronics and LED devices had performed. In early 1981, a proposed micro channel heat sink was first used for cooling a large-scale integrated circuit [12]. Later a micro channel with diamond-shaped interrupted micro-grooved cooling fins was used to enhance the performance and reduce the LED junction temperature [13]. Several methods have been discussed in the past decade to solve the high junction temperature issue, such as fans, heat sinks, heat pipes and the micro-thermoelectric devices [14]. Recently, in order to increase luminous efficiency and light output for general lighting applications, high-power LED array packages have been proposed and active cooling systems have been used to provide heat dissipation solutions, even though the passive cooling systems are preferable due to cost concern [15, 16]. As to high power LEDs, system level thermal management with external active cooling is necessary and of crucial importance. Currently, fin-heat sink is still the mainstream method in industry due to its highest reliability and lowest cost [17]. Meanwhile, heat pipe is becoming a good option for emerging high power LEDs [18]. As to extremely high flux heat dissipation requirements, water cooling and liquid cooling is widely studied [19, 20]. But relatively large system volume, coolant leakage and evaporation problems are the main disadvantages for its practical application in heat dissipation of LEDs.
Except for that, some novel and advanced methods also emerged, such as micro-jet array cooling [21, 22], electro hydrodynamic approach [23], thermoelectric cooling [24], phase change phenomenon based on micro electromechanical (MEMS) technology [25] and piezoelectric fan [26]. But these strategies often involve complex design process, reliability, cost issues or poor cooling capability, which are the main obstacles for their commercialization and utilization.

At present, there are many different thermal management methods for high power LEDs. Among them, fin heat sink and heat pipe are the mainstream methods due to their higher reliability and lower cost [27, 28]. The introduction of high power LEDs has brought extensive challenges with regard to thermal design, from chip level to system level thermal management. As high power is required for lighting LED headlights, much more attention needs to be paid to comparisons with other lighting applications in automobiles. LED automotive headlights are located close to the engine compartment. These lamps require a high seal, shock resistance, and stability with a high ambient temperature and small space. Therefore, an effective thermal design is important to ensure the normal operation of LED headlights [29, 30]. Therefore in order to improve the performance of LED automotive headlights, attention must be focused on providing the highest convective heat transfer coefficients possible within reasonable energy constraints while improving the cooling design. Thus, the consideration of solutions combination the advantages of different methods will be of primary importance to the development of LED automotive headlights. The present study aims to design an effective cooling structure combined with temperature feedback control heat dissipation and to meet the cooling requirements of high-power LED automotive headlights. Heat sink combined with heat pipes technology is adopted to improve the heat dissipation performance.

2 Thermal design of LED headlights

The heat of LED automotive headlights comes from the LED’s PN junction. The heat passes through the LED packaging structure, radiator, and then exchanges with outside air. This thermal path is followed by most headlights. LED lighting is caused by the photons released through the energy level transition at the PN junction. The lighting ability is inversely proportional to the temperature at the PN junction. Serious light fading or even dead light phenomenon occurs when the junction temperature exceeds a certain value. Hence, the LED junction temperature is an important control indicator during heat dissipation design [31, 32]. The junction temperature $T_j$ of a LED chip can be expressed as

$$T_j = T_a + R_{ja} \times P$$

(1)

where $T_a$ is the environment temperature of the package, $R_{ja}$ is the environmental resistance from the PN junction to the environment, and $P$ is the package thermal power. The thermal resistance $R_{ja}$ mainly consists of three parts.

$$R_{ja} = R_{jc} + R_{cs} + R_{sa}$$

(2)

where $R_{jc}$ is the thermal resistance from the junction to the package bracket, $R_{cs}$ is the thermal resistance from the bracket to the heat sink, and $R_{sa}$ is the thermal
resistance from the heat sink to the air. The junction temperature can be reduced by reducing the thermal resistance of LEDs, providing a good cooling mechanism, reducing the thermal resistance of the heat sink installation interface, controlling the rated input power, and lowering the ambient temperature. At a constant ambient temperature and heat power, the junction temperature decreases as the thermal resistance of LEDs decreases. The thermal resistance of LEDs can be affected by many factors, such as packaging mode and materials.

Three integrated packages of white LEDs are used in the study. The luminous flux of a single LED is 900 Lumens. Three heat pipes are designed to correspond to the three LEDs. Heat pipe is a cooling technique that uses the heat absorption or dissipation of the phase change process. The thermal conductivity of the heat pipe is a hundred times better than that of copper [33, 34]. A good convection heat sink must be configured to dissipate heat to the environment. In the design, heat dissipation is realized through a temperature feedback active cooling device that combines the heat pipe condenser section with the aluminum pipe sink. A synthetic jet is also installed because of its strong convective heat dissipation. A thermal analysis model of the cooling system is shown in Fig. 1. The thermal resistance is mainly contributed by the lamp-house bracket, heat pipe, and fins of the heat pipe condenser.

The base of the LED packaging is copper bracket, where the copper heat pipe can be soldered directly. This design not only minimizes the contact thermal resistance between the bracket and the heat pipe but also ensures good heat transfer. The thermal resistance of a single LED ranges from $R_1$ to $R_7$. A three-way LED shares thermal resistance $R_8$. The thermal resistance generated by all sectors is analyzed as follows.

(1) $R_1$ is the thermal resistance from the LED bracket surface to the contact surface of the heat pipe evaporator section.

$$R_1 = \frac{\delta_1}{\lambda_1 A_1}$$

where $\delta_1$ is the thickness of the welding layer, $\lambda_1$ is the thermal conductivity of the material, and $A_1$ is the contact area of welding.

(2) $R_2$ is the thermal resistance from the outer wall to the inner wall of the heat pipe evaporator section.

![Fig. 1. Thermal resistance network diagram of the cooling system](image-url)
\[ R_2 = \frac{\delta_2}{\lambda_2 A_z} = \frac{1}{2\pi \lambda_2 l_1} \ln \frac{d_1}{d_2} \]  

(4)

where \( \delta_2 \) is the wall thickness of the heat pipe, \( \lambda_2 \) is the thermal conductivity of the heat pipe material, \( A_z \) is the heat conductivity area of the heat pipe evaporator, \( l_1 \) is the evaporator section length, \( d_1 \) is the outer diameter of the heat pipe, and \( d_2 \) is the inner diameter of the heat pipe.

(3) \( R_3 \) is the thermal resistance of the heat pipe evaporator section.

\[ R_3 = \frac{1}{h_1 A_1} = \frac{1}{\pi d_1^2 h_1} \]  

(5)

where \( h_1 \) is the heat conductivity between the inner wall and working fluid of the evaporation section and \( A_1 \) is the surface area of the inner wall in the evaporation section.

(4) \( R_4 \) is the saturated steam thermal resistance from the evaporator section to the condenser section of the heat pipe. This resistance can be considered zero because of the approximate isothermal heat transfer.

(5) \( R_5 \) is the thermal resistance of the heat pipe condensing section.

\[ R_5 = \frac{1}{h_2 A_2} = \frac{1}{\pi d_2^2 h_2} \]  

(6)

where \( h_2 \) is the heat conductivity between the inner wall and working fluid of the condensing section, \( A_2 \) is the surface area of the inner wall in the condensing section, and \( l_2 \) is the condensing section length.

(6) \( R_6 \) is the thermal resistance from the inner wall to the heat sink substrate of the heat pipe condensing section.

\[ R_6 = \frac{\delta_2}{\lambda_2 A_1} = \frac{1}{2\pi \lambda_2 l_2} \ln \frac{d_1}{d_2} \]  

(7)

where \( A_1 \) is the heat conductivity area of the heat pipe condenser section.

(7) \( R_7 \) is the thermal resistance of the heat sink.

\[ R_7 = \frac{\delta_3}{\lambda_3 A_3} \]  

(8)

where \( \delta_3 \) is the thickness of the cooling fin, \( \lambda_3 \) is the thermal conductivity of the cooling fin material, and \( A_3 \) is the heat-transfer area of the heat sink. The thermal resistance \( R_7 \) can be ignored because the thickness of the cooling fin is considerably less than the thermal conductivity and heat dissipation area.

(8) \( R_8 \) is the thermal resistance from the condenser section heat sink to the environment.

\[ R_8 = \frac{1}{h_3 A_3} \]  

(9)

where \( h_3 \) is the heat conductivity coefficient between the heat sink and cooling gas and \( A_3 \) is the total surface area of the heat sink. In this study, the thermal resistance is composed of the cross-ventilation of the entire radiator fin and ambient. The three-way LED shows a parallel relationship; the thermal resistance of a single light source is \( 3R_8 \).

The thermal resistance from a single light source to the surroundings can be expressed as
A significant difference exists between the environment of automobile headlight and other lighting fixtures. Automobile headlights are usually used in fast-driving cars. Reverse wind is an important factor. With the rational design of a lamp shell duct and headlight house, the reverse wind that acts on the heat sink fins of the heat pipe condenser section is used to cool the headlight of a car driving at normal speed. An initiative heat dissipation device of temperature feedback control is designed for the real-time monitoring of the temperature in the light source. The sensor is connected to the MCU. The MCU automatic control synthetic ejector operates once the temperature exceeds a preset point. The ejector generates a powerful micro jet stream to reduce the temperature of the heat pipe condenser section. As a result, the temperature of the LED light source is lowered and controlled within an appropriate range. The designs consider the cooling demand of a car working in different driving conditions. Thus, it ensures the long-term stability of LED automotive headlights.

After heat transfer calculation and structural design, a 3D model of the actual heat sink is built with the design software CATIA. The LED headlight radiator structure is shown in Fig. 2.

In the figure, 2-1 is the heat pipe evaporator section, 2-2 is the heat pipe condenser section, 3-1 is the heat sink fins, 3-2 is the flat plate of the heat sink used for mounting the synthetic jet device, 4 is the synthetic jet device that can produce various rib parallel airflows, 5 is the temperature sensor DS18B20 installed on the bracket of the LED light source, and 6 is the MCU and associated circuit box used to control the temperature feedback and initiative heat dissipation.

### 3 Modeling and simulation

To evaluate and optimize the design effect, the thermal fluid software FLOEFD is used for simulating the temperature distribution and thermal dissipation situation. The cooling effect is simulated in the ambient temperature $50^\circ\text{C}$ and driving speed $45 \text{ km/h}$. The FLOEFD simulation results of the above designed radiator are shown in Fig. 3.
The figure shows that the air flow around the radiator is in the same direction as the fins. The air flow is caused by the pressure difference generated by temperature difference. This finding verifies that the arrangement of the radiator fins is correct. The figure shows that the maximum temperature of the radiator is 92.9 °C. The junction temperature of the LED is 124.6 °C with a fixed temperature difference of 31.7 °C (6.34 W × 5 °C/W) between the bracket and the PN junction. These conditions meet the design requirements of the junction temperature (i.e., <125 °C) in the simulation ambient temperature and driving condition. However, if the conditions are worse than those of simulation, such as higher ambient temperature or lower driving speed, the junction temperature of the LED will exceed the design requirement, reduce the lighting efficiency, and even ultimately damage the LED. Then, the active cooling device with temperature feedback control will function.

4 Test and result discussion

A sample LED headlight with the thermal management designed above is prepared to verify the performance of this radiator. An experimental test is performed with an infrared imaging thermometer. The sample lamp with the radiator is placed in an
obturation room. The imaging thermometer is placed 0.5 meter in front of the sample lamp. The sample lamp is in the stationary state, and the ambient temperature is 50 °C. The experimental test is started until the sample lamp is stable. The experimental test image is shown in Fig. 4.

The active cooling with feedback control is particularly important in the radiator design. The MCU temperature control limit is set according to several experimental tests. The MCU control opens the synthetic jet when the sensor detects the high limit $T_h$. The controller closes the synthetic jet device when the sensed temperature is lower than the lower limit $T_l$.

The real-time image and data of the experimental test are recorded and analyzed. The run time of the synthetic jet and the highest temperature of each test position are shown in Fig. 5.

The results show that the temperature of light source 2 is higher than those of light sources 1 and 3. The heat pipe is connected to the middle of the radiator fins.
that the heat radiation lags that of the edge. The temperature of LED3 is relatively lower than that of the others. This result can be attributed to the fact that LED3 is located at the bottom. The synthetic jet flow is injected from the bottom upwards. The figure shows that light temperature is stable after 10 min of run time of the synthetic jet.

Fig. 6 shows the light source temperature changes of the imaging thermometer. The curve shows that the sample lamp temperature is lowered by 18 °C when the synthetic jet is running for at least 10 min. At this time, the temperature of the light source has already reached a steady state.

The ejector automatically opens and closes at the set limit temperature when the temperature feedback control active cooling technology is applied. However, the temperature of the three LEDs is different according to the experimental tests, and
their junction temperature does not exceed the design requirements. This system has achieved the expected goal. The experimental test verifies the feasibility of the design, which meets the requirements of high-power LED headlight dissipation.

5 Conclusion

The study analyzes the cooling requirements of LED headlights under different conditions. The passive heat pipe cooling technology which relies on the reverse flow of driving and active cooling technology of temperature feedback control are proposed. Radiator structure and sample lamp are designed with CATIA. The FLOEFD simulation and experimental results show that the junction temperature of the LEDs are in an appropriate range when the ambient temperature is 50 °C under motionless condition. The highest temperature can be controlled within the required range. The proposed technology provides an approach for solving the heat dissipation problem, which limits the application and popularization of high-power LED headlights.

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