Research Paper

Experimental investigation on the thermal performance of a light emitting diode headlamp with a flexible woven heat sink

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HIGHLIGHTS

• A flexible woven heat sink (FWHS) is designed for the LED headlamp.
• The FWHS with adjustable expanded form can be installed in limited spaces.
• The characteristics of the headlamp with FWHS are tested under the effect of different factors.

Abstract

Flexible woven heat sink (FWHS) is proposed to meet the heat-dissipation demand of a light emitting diode headlamp, which can be installed in limited spaces. The heat sink comprises three copper belts manufactured by weaving copper wires, with a structural advantage of high flexibility. The thermal-resistance network model of the headlamp with the FWHS was established. A test system was implemented to analyze the factors affecting the heat transfer, such as the expanded forms, input power, ambient temperature, and wind speed. The expanded form of the FWHS can be adjusted by changing the inclination angles $\alpha$ and $\beta$. $\alpha$ means the inclined angle between the adjacent woven belts, and $\beta$ means the inclined angle of each woven belt expanded along the folding part. The optimal expanded form is the status with $\alpha = 25–90^\circ$ and $\beta = 25–40^\circ$. The overall temperature of the headlamp increases almost linearly with the increase in the input power and the ambient temperature. The cooling effect of the FWHS is enhanced with the increase in the wind speed; the optimal wind speed is approximately 2 m/s.

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1. Introduction

Light emitting diodes (LEDs) are a new type of solid-state lighting. Compared to traditional light sources, LEDs have several advantages, such as high efficiency, low energy consumption, long lifetime, and faster responses [1–3]. LEDs have been widely used in display, back light, and general lighting applications [4]. Currently, LEDs are being employed in the field of automotive electronics [5]. The U.S. Department of Energy [6] reports that the efficiency of photoelectric conversion of LED luminaires has increased up to 30%, whereas the efficiencies of the halogen and xenon lamps are only 5% and 20%, respectively. If LED headlamps completely replace the traditional ones, the amount of energy consumed by automotive lighting will decrease to 10%, thereby reducing CO₂ emissions by approximately 1–3 g/km [7]. Although LED lighting has a high photoelectric-conversion efficiency compared to other lighting methods, more than 70% of the input power converts into heat, which drastically increases the junction temperature. This increase attenuates the luminous intensity, reduces the lifespan, and causes complete failure [8,9]. Several scholars studied the thermal management methods of LED devices, such as heat dissipation fins, heat pipes, and phase-change material [10–13], which are highly reliable and cost effective. However, the thermal management of automotive headlamps is complicated because of space constraints, temperature of the environment, and many other factors, which need to be considered prior to the development of cooling methods. Hence, an effective thermal design is essential for generalizing the LED headlamps.

Currently, studies focus on improving the heat-dissipation effects of LED headlights for an optimal design of the heat sink.
Zhao et al. [14] employed heat conductive plates (HCPS) for connecting the LED chip and the heat-dissipating fin, which is a novel cooling device for LED headlights. The optimal length of the HCPS is 47 mm, with the lowest junction temperature and external thermal resistance. Wang et al. [15] proposed an enhanced cooling model based on the thermoelectric cooler (TEC) for the LED headlight. The cooling effect of the heat sink and TEC with a dimension of $84 \times 70 \times 40$ mm or a cold plate and TEC with a dimension of $40 \times 40 \times 12$ mm is more outstanding than that of pure air cooling or liquid cooling. Lai et al. [16] developed an active cooling device based on the combination of the water-cooling plate and heat sink. They established a cooling water circulation system between the high beam LED, low beam LED, and heat exchanger for the cooling of an LED headlamp. To a particular extent, the thermal design of the heat sink of an LED headlamp strengthened the effect of heat transfer by optimizing the material, structure, etc. However, the aforementioned study did not adequately consider the limited space constraints for practical application. Hence, the LED headlamp cannot be applicable for automobile applications because of the narrow space constraint.

Recently, there are some attractive inventions [17] and products [18,19] about the flexible woven heat sink (FWHS) installed on the headlamp. The FWHS is proposed to improve the heat-dissipation effect of LED headlights by adjusting the expanded form in limited space. To achieve the flexibility of the heat sink, the fins of the heat sink are manufactured by weaving copper wires instead of the traditional plate. With the structural advantages, such as a high flexibility and a close internal link [20,21], the woven belts are able to overturn or fold such that maximum amount of heat is transferred in the limited space. The FWHS shows significant effectiveness for solving the heat-dissipation problem of the LED headlamps in the narrow space. In this study, the FWHS is designed and applied to the LED headlamp system. Thereafter, the headlamp testing system is fabricated and investigated to test the characteristics of the headlamp under the effect of different factors such as expanded form, input power, ambient temperature, and wind speed. The heat-dissipation performances of the heat sink affected by the above factors are discussed. Finally, the optimal working state of the FWHS is determined.

2. Experimentation

2.1. Constructional design

The FWHS proposed in this study has a high thermal conductivity and meets the flexibility requirements via adjusting the expanded form. Copper has an excellent thermal conductivity of $398 \text{ W/}(\text{m} \cdot \text{K})$ in addition to having good ductility and processing convenience. Hence, copper was selected as the material for the heat sink. Fig. 1 shows the different types of working states in
practical application and the microstructure of the FWHS. There are several basic working states of the FWHS installed in the headlamp housing, such as straight state, expanded state, and tightened state. The FWHS comprised three copper woven braids with a nickel-plated surface. The copper braid was weaved in the DH440 high-speed knitting machine with 12 bunches of copper strips. Each bunch of copper strip contained 12 copper wires with a diameter of 0.15 mm. The copper braid manufactured in the form of weaves had a particular flexibility because of the interstices between the copper wires. Compared to the traditional-fin heat sink, the woven braid was more adaptable in narrow spaces. As the experimental object, the headlamp consists of two LEDs of CREE XHP-50 [22], an aluminum alloy lamp base, and the FWHS soldered to the lamp base. Table 1 lists the relevant parameters of the LED headlamp with the FWHS.

### Table 1

<table>
<thead>
<tr>
<th>Name</th>
<th>Value/material</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED lamp</td>
<td>CREE-XHP 50 (Maximum junction temperature 150 °C)</td>
</tr>
<tr>
<td>Lamp base material</td>
<td>Aluminum alloy</td>
</tr>
<tr>
<td>Woven braid material</td>
<td>Copper</td>
</tr>
<tr>
<td>Woven braid size</td>
<td>80 × 15 × 4 mm</td>
</tr>
</tbody>
</table>

Fig. 2 illustrates the test apparatus and arrangement of the LED headlamp. The test system comprises a data acquisition module for measuring the temperature, a DC stabilized power supply (QJ21005X; 50 V, 5 A), and an incubator. The test apparatus is set up for the heat-transfer performance test of the FWHS under the condition of natural convection. The incubator provides a stable and adjustable ambient temperature without the interference of outside airflow. The data acquisition module comprises a data acquisition card (Advantech USB-4718), six K-type thermocouples, and a computer. Fig. 2 shows the measurement points of the six K-type thermocouples labeled T1–T6. The data acquisition positions for the transient temperature of the headlamp are the LED chip (T1), the junction between the lamp base and the heat sink (T2), the intermediate point of the middle belt (T3), the intermediate point of the broadside belt (T4), the end of the middle belt (T5), and the end of the broadside belt (T6). The measured value of the LED chip (T1) is selected as the junction temperature of the LED, because the substrate of the LED is made of cermet, which has a high thermal conductivity, and the temperature difference between T1 and the junction temperature would be small.

Fig. 3 shows the forced convection test system for the thermal performance test of the headlamp. The test system comprises a YWE-2E axial fan, two louvers, a polymethylmethacrylate pipeline, and a test chamber. The test apparatus is designed for the heat-transfer performance test of the FWHS under the condition of forced convection. The louvers with adjustable blades can improve the turbulence intensity of the air flow, and then affect the heat transfer process and the cooling effect [23]. The air flow is measured by a Testo 405-V1 thermal anemometer (measurement accuracy ± 0.01 m/s). To make sure that the air flow is uniform, the thermal anemometer is placed on the exit of the main duct to measure the wind speed at each measuring point of 3 x 3 array. The blades of the louvers are adjusted until the measurements of each point are consistent.

The systematic errors of the temperature measurements are mainly caused by the heat ex-change deviation between the measured object and the thermocouples. The method of reducing the errors is that the probes of the thermocouples are inserted into the surface gaps of the woven belts to reduce the heat transfer loss. The experimental uncertainty is estimated based on the random errors of the temperature measuring process. The accuracy of the K-type thermocouple measurement \( (dT) \) is ±0.1 °C. The resolution of the data acquisition card Advantech USB-4718 \( (dT_{data}) \) is 0.1 °C. The input-power tolerance of the DC stabilized power supply \( (U_{power}) \) is 0.13% [24]. The total uncertainty \( (U_T) \) can be calculated using the following equation:

\[
U_T = \sqrt{\left( \frac{dT}{T_{ave}} \right)^2 + \left( \frac{dT_{data}}{T_{ave}} \right)^2 + U_{power}^2}
\]

where \( T_{ave} \) is the time-averaged temperature of each measuring point.
2.3. Thermal resistance analysis

The thermal resistance is an important technical index that describes the thermal characteristics of electronic devices, which is defined as the ratio of the difference in temperatures between any two points to the power that generates the temperature difference between them under thermal equilibrium [25]. Fig. 4 shows the thermal-resistance network of the LED headlamp with the FWHS. The heat generated by the LED chip is transferred from the chip to the aluminum-alloy lamp base and then, in turn, to the flexible heat sink. Finally, it is transferred to the ambient air via heat convection. The thermal contact resistance between the interfaces of the chip and the base as well as the base and the heat sink is ignored to simplify the thermal-resistance network. The thermal contact resistance of the chip and the lamp base on the total thermal resistance is calculated using the following equation.

\[
R_{\text{cond}} = R_{\text{chip}} + R_{\text{base}} + \frac{R_{\text{cond}} \times R_{\text{conv}}}{R_{\text{cond}} + R_{\text{conv}}}
\]  

where \( R_{\text{cond}} \) is the thermal resistance of the chip and the lamp base, and \( R_{\text{conv}} \) is the convective thermal resistance of the FWHS (the convective thermal resistances of the LED chip and the lamp base are ignored, because the lamp base is installed into the headlight cavity, and the convective effect is negligible). The total thermal resistance is calculated using the following equation:

\[
R_{\text{tot}} = R_{\text{chip}} + R_{\text{base}} + \frac{R_{\text{cond}} \times R_{\text{conv}}}{R_{\text{cond}} + R_{\text{conv}}}
\]

\[
R_{\text{cond}} = \frac{T_{s1} - T_{s2}}{Q \cdot \eta}
\]

\[
R_{\text{conv}} = \frac{1}{h \cdot A}
\]

where \( T_{s1} \) and \( T_{s2} \) are the average temperatures (°C) of the head and tail of the FWHS, respectively; \( Q \) is the input power (W); \( \eta \) is the conversion coefficient that the input power converted into the thermal power, with the measuring value of 69.47%; \( h \) is the air convective heat transfer coefficient (W·m⁻²·K⁻¹); \( A \) is the total superficial area of the heat sink (m²).

The junction temperature of the LED chip can be calculated using the following equation:

\[
T_j = T_\infty + Q \cdot \eta \cdot R_{\text{tot}}
\]  

where \( T_j \) is the junction temperature of the LED (°C); \( T_\infty \) is the ambient temperature (°C).

As given in Eq. (5), the factors that affect the junction temperature of the LED include the ambient temperature, input power, and total thermal resistance. To reduce the junction temperature and maintain the performance of the headlamp, it is efficient to reduce the input power or ambient temperature. When the power and ambient temperature are immutable, enhancing the cooling capacity of the heat sink and decreasing the total thermal resistance will be beneficial for reducing the junction temperature. The effects of the thermal resistances of the chip and the lamp base on the total thermal resistance are negligible, and their optimized space is limited. Hence, the focus must be on reducing the conductive and convective thermal resistances.

3. Results and discussion

Under the condition of natural convection, the factors influencing the heat-transfer performance of the FWHS include the expanded form, input power, and ambient temperature.

3.1. Effect of the expanded form of FWHS

Fig. 5 shows the two types of expanded forms of the FWHS, which are defined as Type I and Type II. Type I refers to the woven belts inclined at a specific angle (expressed as \( \alpha \)) along the same plane. Type II shows each woven belt inclined at a specific angle (expressed as \( \beta \)) along the folding part with respect to Type I. Type I and Type II are the typical expanded forms in practical application.

Fig. 6(a) shows the effect of the variation in the Type I angle on the temperature of the headlamp. The angle \( \alpha \) gradually increases from 0° to 90°. In the range of \( \alpha = 0 – 25° \), the overall temperature of the headlamp declines sharply. As the angle increases, the junction temperature decreases from 94.8 °C to 88.4 °C. When \( \alpha > 25° \), the temperature tends to equilibrium, whose amplitude is below 2.7%. This is because, when the angle of Type I ranges from 0° to 25°, the thermal boundary layer of the woven belts develops more fully with the increase in the angle. Hence, the efficiency of the convective heat transfer of the FWHS is enhanced. When \( \alpha > 25° \), the convective interference of the thermal boundary layer is negligible, despite the continuous increase in angle. The heat-transfer
performance of the FWHS tends to be stable. Hence, the optimal Type I angle of the heat sink could be considered for \( \alpha > 25^\circ \). For the following analysis, an optimal angle \( \alpha = 60^\circ \) is selected.

Fig. 6(b) shows the effect of the variation in the Type II angle on the temperature of the headlamp. When \( \alpha = 60^\circ \), angle \( \beta \) of Type II gradually increases from 0\(^\circ\) to 45\(^\circ\). The temperature of the headlamp declines gradually in the range of \( \beta = 0–25^\circ \), and tends to stabilize when \( \beta = 25–45^\circ \) for a junction temperature of 84.5 \(^\circ\)C. This is because when \( \beta \) increases from 0\(^\circ\) to 25\(^\circ\), the area of convective heat transfer of the woven belts increases, and the heat-convective interference decreases between the two sections of a belt. When \( \beta = 25–45^\circ \), the influence of further increasing \( \beta \) on the heat-dissipation area is insignificant. However, when \( \beta \) reaches 45\(^\circ\), the temperature of the headlamp tends to increase again (three repetitive measurements show the same trend). A reasonable explanation is that the increase in \( \beta \) reduces the distance between the adjacent woven belts, which disturbs the development of the thermal boundary layers and the convective heat-transfer process. Hence, to attain the best cooling effect of the FWHS, \( \beta \) of Type II should be maintained in the range of 25–40\(^\circ\).

As shown in Fig. 7, the total thermal resistance of the headlamp changes along with the angles of Types I and II (defined as \( R_a \) and \( R_b \)). When \( \alpha \) is below 25\(^\circ\), \( R_a \) decreases significantly with the increase in the angle. When \( \alpha \) is greater than 25\(^\circ\), \( R_a \) stabilizes with slight fluctuations at approximately 6.15 \(^\circ\)C/W. Similar to \( R_a \), \( R_b \) decreases with the increase in \( \beta \) when the angle is below 25\(^\circ\), and tends to remain constant when \( \beta > 25^\circ \). Furthermore, the balanced thermal resistance \( R_{\text{b}} \) is approximately 5.72 \(^\circ\)C/W, which decreases by 0.43 \(^\circ\)C/W compared to \( R_a \). This indicates that the enlarged dissipation area and decreased convective interference owing to the increase in \( \beta \) could strengthen the convective heat transfer ability of the heat sink. The total thermal resistance becomes smaller, thereby improving the heat-transfer effect of the heat sink. According to the temperature and thermal resistance analyses of Types I and II, the FWHS will achieve the optimal cooling effect when \( \alpha \) and \( \beta \) are in the ranges 25–90\(^\circ\) and 25–40\(^\circ\), respectively. The adjustable inclination angles \( \alpha \) and \( \beta \) show excellent adaptability advantage of the FWHS, which are suitable for the application of LED headlamps installed in narrow spaces. In practical application, the expanded form of FWHS can be fixed by the metal clip. And it can be appropriately adjusted according to the optimal state and the practical condition.

3.2. Effect of the input power on the FWHS

To study the influence of the input power on the changes in the temperature of the headlamp, the ambient temperature of the testing system is set at 25 \(^\circ\)C. Type II is selected as the optimized expanded form of the heat sink with \( \alpha = 60^\circ \) and \( \beta = 30^\circ \). Fig. 8 shows the change curves for the temperature and total thermal resistance. The input power increases from 5 W to 25 W in steps of 5 W. The balance temperature of the whole headlamp increases linearly, and the increasing amplitude of the chip temperature \( T_1 \) is the highest. When the input power is less than 15 W, the total thermal resistance of the headlamp decreases significantly with the increase in the power. Thereafter, the total thermal resistance decreases slowly when the input power increases from 15 W to 25 W. When the input power is 25 W, the thermal resistance of
the headlamp can be as low as 5.15 °C/W. This is because the increase in the input power will have an impact on the thermal resistances of the chip and the heat sink. For the thermal resistance of the LED chip, the change in power results in a change in the current, thereby changing the effective area of the chip, known as the current concentration effect [26,27]. As the power increases, the effective area of the chip increases, and the heat can be transferred out of the chip more consistently and evenly, thereby decreasing the thermal resistance of the chip [28]. The thermal resistance of the heat sink is associated with the temperature difference between the head and tail of the heat sink and the input power. When the input power is 5 W, the average temperature of the tail of the heat sink is reduced by 3.60 °C (7.5%) compared to that of the head. When the input power increases to 25 W, the difference in the temperatures increases to 18.59 °C (16.2%). When the input power is below 15 W, the heat transferred from the LED chip to the heat sink increases with the increase in the power, which leads to a significant decrease in the thermal resistance of the heat sink. When the input power is greater than 15 W, the junction temperature of the LED is at a high level, and the difference in the temperatures between the head and tail of the heat sink increases, which reduces the impact of the power and decreases the descend range of the thermal resistance of the heat sink. The analyses show that the increase in the input power can keep the headlamp at a high temperature, but the thermal resistance of the headlamp with the FWHS decreases.

### 3.3. Effect of the ambient temperature on the FWHS

Most of the headlamps in cars are installed in the engine compartment. The ambient temperature of the headlamp rises because the engine dissipates heat, which is inevitable while driving [29]. Fig. 9 shows the curves of the equilibrium temperature and total thermal resistance for the headlamp at different ambient temperatures. According to the testing standard of the AEC regulations [30], the ambient temperature is raised from 30 °C to 80 °C in steps of 10 °C. The temperature differences of T1 at various ambient temperatures are \( \Delta T_{12} = 9.80 °C \), \( \Delta T_{23} = 10.20 °C \), \( \Delta T_{34} = 13.47 °C \), \( \Delta T_{45} = 14.33 °C \), and \( \Delta T_{56} = 14.45 °C \) (\( \Delta T_{12} \) is defined as the temperature difference of T1 at 30 °C and 40 °C, and so on). The result indicates that the temperature difference of T1 is gradually increasing. In other words, as the ambient temperature increases, the dissipation of heat from the heat sink becomes considerably difficult. When the ambient temperature is in the range 30–50 °C, the total thermal resistance of the headlamp maintains at a substantially stable value of 4.42 °C/W. Thereafter, the thermal resistance increases sharply, reaching 5.61 °C/W at 80 °C. This is because when the ambient temperature is at a low level, the...
increase in the ambient temperature has little effect on the cooling process of the headlamp. However, further increase in the ambient temperature decreases the temperature deviation significantly between the headlamp and the surroundings. The efficiency of the convective heat transfer decreases, and the junction temperature of the LED increases dramatically. The cooling effect becomes worse. In this case, more powerful cooling methods, such as adding a device of forced convection, should be adopted to achieve good heat dissipation.

3.4. Effect of the wind speed on the FWHS

Forced convection is an effective heat dissipation mode that improves the efficiency of the convective heat transfer and reduces the junction temperature of the LED [31]. The airflow disturbance while driving, and the DC fan around the headlamp would provide forced convection and improve the heat-transfer efficiency [32]. In the experiment, the forced convection testing system can provide a forced convection environment to study the characteristics of the FWHS. The inclination angles are set as \( \alpha = 60^\circ \) and \( \beta = 30^\circ \). The input power of the headlamp is 15 W, and the ambient temperature is 25 °C. The wind speed is adjusted to 0 m/s, 0.5 m/s, 1.0 m/s, 1.5 m/s, 2.0 m/s, and 2.5 m/s measured by the thermal anemometer. Fig. 10(a) shows the junction-temperature curve for the operating headlamp with different wind speeds. The temperature oscillations appear with no-wind condition (0 m/s) because the hot airflow around the headlamp interferes with the temperature measurement under natural convection. With the increase of wind speed, the interference of the hot airflow is weakened, and the oscillations subside in the presence of forced convection. In the initial stage, the junction-temperature curves under different wind speeds show an almost overlapping upward trend. At 22 s (30 °C), the junction-temperature curve under a no-wind condition begins to separate from the others and continues to rise with the highest increasing rate. After 45 s, the junction-temperature curve at each wind speed separated. The temperature differences gradually increase, whereas the rate of increase is gradually decreasing. The steady-state time and junction temperature under the different wind speeds are 1198 s/74.10 °C (0 m/s), 619 s/59.95 °C (0.5 m/s), 500 s/50.76 °C (1.0 m/s), 447 s/45.99 °C (1.5 m/s), 339 s/42.91 °C (2.0 m/s), and 337 s/41.83 °C (2.5 m/s). Evidently, the improvement in the wind speed can accelerate the junction temperature to stabilize and decrease the balance temperature. As shown in Section 3.1, the optimal values of \( \alpha \) and \( \beta \) have resulted in the largest dissipation area and the least convective interference of the FWHS. The forced convection still further enhances its cooling effect significantly, because the fan accelerates and disturbs the ambient airflow around the headlamp, which improves the convection heat-transfer coefficient of the FWHS. Even if the wind speed is only 0.5 m/s, the junction temperature is lower than that of the no-wind state by 14.15 °C (19.1%). Moreover, when the wind speed is up to 2.5 m/s, the temperature difference can reach 32.27 °C (43.5%).

Fig. 10(b) shows the equilibrium temperature of the headlamp changing with the variation in the wind speed. When the wind speed is in the range of 0–2.0 m/s, the equilibrium temperature of the headlamp significantly decreases with the increase in the wind speed. This is because the convective heat-transfer coefficient of the heat sink improves with the increase in the wind speed when the heat-sink surface area is constant. The convective thermal resistance between the heat sink and the surroundings decreases, resulting in the decrease of the total thermal resistance. When the wind speed exceeds 2 m/s, the equilibrium temperature of the headlamp is almost stable with the increase in the wind speed. This is because when the wind speed increases to a particular value, the convective thermal resistance becomes negligible compared to the thermal resistance of the chip, lamp base, and conductive thermal resistance of the heat sink. Even if the wind speed continues to increase, the junction temperature will not reduce further. Instead, it will increase the energy consumption and reduce the reliability of the system. Hence, if a DC fan is installed to increase the heat dissipation capacity of the FWHS, the optimal wind speed is approximately 2 m/s, when the heat sink has the highest cooling capacity, and the energy consumption of the system is the lowest.

4. Conclusion

Flexible woven heat sink (FWHS) is proposed for the cooling demand of the headlamp in narrow spaces. The factors that affect the heat-dissipation effect of the FWHS are analyzed through establishing the thermal-resistance network model and the experimental test. Based on the above discussions and analyses, the following conclusions are drawn.

- The expanded forms of the FWHS can be adjusted for the limited space via changing the inclination angles of Types I and II to improve the cooling capacity. The convective heat-transfer
coefficient improves effectively, and the total thermal resistance decreases. The optimal expanded form is Type II with \( \alpha = 25–90^\circ \) and \( \beta = 25–40^\circ \).

- The temperature of the headlamp increases almost linearly with the increase in the input power and the ambient temperature. The total thermal resistance of the headlamp decreases with the increase in the power, which is as low as 5.15 \(^\circ\)C/W when the input power is 25 W. With the increase in the ambient temperature, the total thermal resistance maintains at a stable value of 4.42 \(^\circ\)C/W, and then increases when the ambient temperature is greater than 50 \(^\circ\)C.

- Under the forced convection, the cooling effect of the FWHS increases with the increase in the wind speed. The optimal wind speed is approximately 2 m/s, when the heat sink has the highest cooling capacity and the energy consumption of the system is the lowest.

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