Analysis of Materials Applied In Cooling Systems Of Led Lighting

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Abstract. In this article, the problems associated with the removal of heat from the LEDs are considered. Brief information about the materials included in the cooling system of LED lighting is presented. A comparison of materials such as copper, aluminum and alumina nitride ceramics, the use of which is possible in cooling systems of led lighting is conducted. Analyzing the current market relations that have a significant impact on the cost of metals, even in material terms, the use of a copper radiator does not look very expensive. Methods for calculating the heat removal are proposed, an example of the calculation is given. It was shown that at elevated operating temperatures, the lifetime of the LEDs is significantly reduced: at 105 °C, the lifetime of the LEDs is 200 thousand hours less than at 85 ° C. The maximum area of the plate on which the LED is installed, for its effective cooling, is about 24 cm² for a 1 W LED power.

Keywords: Cooling systems, led lighting, copper radiator, heat removal, luminous flux, thermal paste.

1. Introduction

The massive use of LEDs for industrial and domestic lighting showed their undoubted advantage over lighting systems used before that time - incandescent lamps, fluorescent and sodium lamps, etc. One of the main declared advantages of LED lamps, alongside with low energy consumption, is a longer service life, but possible with the proper design of the LED and the lamp as a whole [1]. The Reliability and durability of LED depends on the quality of the design of the cooling system, which is why it is so important to pay special attention to the design of a reliable heat sink. Increasing the temperature of the active zone of the LED entails a drop LED efficiency and reducing its service life.

High temperatures lead to accelerated degradation of phosphors in white LEDs [2]. Whites LEDs contain a phosphor element that is extremely vulnerable to high temperatures,
which has a thermal quenching effect that impedes the operation LED when temperature rises. The effect of thermal blanking is observed already at 80-100 °C [3]. For cooling low-power LED systems, a conventional radiator will be quite sufficient; in some cases, active cooling may be required to remove heat from high-powered luminaires. Also, when developing new lighting devices, it is strongly recommended to perform calculations and modeling of the cooling system. This paper aims to analyze the materials applied in cooling systems of LED lighting.

2. Materials and methods
First of all, we are talking about cooling the LED (see Fig. 1). Curves labeled LM-80 show the time of the test, graphs labeled TM-21 show a reduction in luminous flux. In addition to reducing the service life, with increasing temperature the LED lamp also deteriorates [4]:
- the value of the luminous flux (see Fig. 2);
- decreases the value of the direct voltage drop, which reduces the light emission (see table. 1).

![Fig. 1. The lifetime of the LED series CREE MKR, depending on temperature](image)
In lighting systems, high power LEDs (from 1 W and up) are used. In this case, the efficiency of LEDs is not very high, about 30-40%. It means that loss is about 60-70% of which most of them are thermal. The practice of using CREE LEDs shows that 75% of the consumed power is converted into heat [5]. Then the dissipated thermal power can be approximately determined by the formula:

\[ P_t = 0.75 \cdot V_f \cdot I_f \]  \hspace{0.5cm} \text{(1)}

where \( P_t \) — is thermal power (W);
\( V_f \) — a direct voltage drop across the LED (V);
\( I_f \) — the current through the LED (A).

Heat removal from the LED is carried out by convection (2) and thermal conductivity (3)

\[ Q_{\text{conv}} = h \cdot A \cdot \Delta T \]  \hspace{0.5cm} \text{(2)}

where \( Q_{\text{conv}} \) — is the amount of heat dissipated by convection (W);
h — heat transfer coefficient (W / (m²*K)).

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**Tab. 1. The coefficients’ values of the voltage dependence on temperature for a series of LEDs MKR and MKR2**

| LED series | The coefficient of voltage versus temperature, mV / °C |
|------------|-----------------------------------------------------|
| MKR        | -7                                                  |
| MKR2       | -28                                                 |

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**Fig. 2. The dependence of the luminous flux on the transition temperature on the example of the LED series MKR CREE**

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With natural convection, the coefficient (h) is within 5…20 Вт/(м²*К).

And for systems with forced convection, the heat transfer coefficient can reach values of 100 W / (м² * K) with air cooling, and up to 1000 W / (м² * K) - with liquid cooling;

A — surface area of the light-emitting element (м²);
ΔТ — temperature difference between light-emitting element and surrounded area (К).

\[ Q_{cond} = -k * A * \frac{\Delta T}{\Delta x} \]  \hspace{1cm} (3)

Where \( Q_{cond} \) — the amount of heat transferred through the material (W);

k — material thermal conductivity coefficient (W / (м * K));
A — the area of intersection of materials through which heat passes (м²);
ΔT — temperature gradient (K);
Δx — the distance that the heat travels (m).

In LED lighting, natural air cooling is usually used; for calculating such systems, the value of the heat transfer coefficient can be taken equal to 10 W / (м² * K).

The area of the heat sink plate (S, м²) for convective heat exchange with a flat plate is determined by the formula (4) [6]

\[ S = \frac{Q}{\alpha * \Delta T^2} \]  \hspace{1cm} (4)

where Q – total heat flux. Let’s accept 1 W for the calculation;
α – heat exchange coefficient (5);
ΔT – temperature difference between the LED substrate and the environment.

In the calculations of the ambient temperature is taking 45 °C (maximum air temperature at night in Russia).

The average operating temperature of the substrate 85 °C. Then ΔT=85-45=40 °C.

\[ \alpha = \frac{N_u * \lambda}{l} \]  \hspace{1cm} (5)

where \( N_u \) – Nusselt criterion (6);

\( \lambda \) – air thermal conductivity at its temperature 40 °C and atmospheric pressure 1 atm. Let’s take it 0,0271 Вт/(м*К);

l – conventional length of the heat sink. In the calculations, we accept \( l = 1 \) м.
\[ N_u = 0.75 \times (Cr \times Pr)^{0.25} \] \( \text{(6)} \)

where \( Cr \) – Grashof number (7);

\( Pr \) – Prandtl criterion. In the calculations of convective heat transfer, it can be neglected because of the low heat flow rate and the small temperature difference.

\[ Cr = \frac{g^\frac{\Delta T}{T} \cdot l^3}{v^2} \] \( \text{(7)} \)

where \( v \) - kinematic air viscosity equal to \((2 \times 10)^{-10} \text{ m}^2/\text{s}\).

\[ Cr = \frac{9.8 \times 40}{320 \times (2 \times 10^{-10})^2} \times 1^3 = 0.6 \times 10^{10} \]

\[ N_u = 0.75 \times (0.6 \times 10^{10} \times 1)^{0.25} = 210 \]

\[ \alpha = \frac{210 \times 0.0271}{1} = 5.2 \]

\[ S = \frac{1}{5.2 \times 40 \times 2} = 0.0024 \]

Thus, the estimated maximum area of the plate on which the LED is mounted was determined for its effective cooling. For the operating mode of 1 W, the area was 24 cm².

The most common way to mount an LED on a printed circuit board is shown in Fig. 3
When designing a heat sink, it is modeled as thermal resistances, the wiring diagram of which depends on the specific case (example in Fig. 4).

In this case, the equivalent circuit will consist of n thermal resistance “LED-to-contact transition” (\(Q_{j-sp}\)) connected in parallel. Then - from n thermal resistance "contact - printed circuit board" (\(Q_{sp-pcb}\)). It is also necessary to take into account the thermal resistances between the printed circuit board and the thermally conductive material (\(Q_{pcb-tim}\)), between the thermally conductive material and the radiator (\(Q_{tim-hs}\)) and, finally, between the radiator and the environment (\(Q_{hs-a}\)).

The temperature can be measured at the nodes of this equivalent circuit. For example, the Theatsink point is the temperature of the radiator. The total amount of dissipated heat is calculated using the formulas for parallel and series connection of resistors.

Cooling radiators for LED lamps are made in various designs: flat, round, plate, ribbed, rod, with a different base (circle, polygon). For optimal heat dissipation, the thickness of the base should be at least 10 mm, and the distance between the fins should be at least 4 mm (to ensure natural convection of air). In addition to the design (forms of heat sink), the properties of the material from which it is made are important for the radiator (see Table 2).

| Material | Thermal conductivity, W/(m*K) |
|----------|------------------------------|
| Air      | 0.024                        |

Fig. 3. Installation of the LED on the PCB

Fig. 4. Equivalent circuit of thermal resistances of the LED matrix of n LEDs mounted on a printed circuit board attached to the radiator [3]
The table 2 shows that for removal (transfer) of a large amount of heat, it is preferable to use three materials: copper, aluminum and alumonitride ceramics. Aluminum has a lower cost. But if it is necessary to reduce the dimensions of the lamp, a copper radiator is also in demand. Analyzing the current market relations that have a significant impact on the cost of metals, even in material terms, the use of a copper radiator does not look very expensive.

### 3. Results and discussion

To increase the thermal conductivity of materials an additional surface treatment should be done. For example, anodizing of the aluminum surface. Radiators can be used not only as an element of the cooling system, but also as a frame or housing. The most common technology for producing aluminum profiles is casting, stamping, forging. Each technology has its advantages and disadvantages.

Let us consider in more detail how such elements as the printed circuit board, heat-conducting materials, and the radiator contribute to the overall thermal resistance.

To improve heat dissipation in most LED light sources, LEDs are soldered to a metal substrate. The most common substrate is aluminum alloy. The thermal resistance of the aluminum substrate is 0.45 ... 1.5 °C / W, which is about 50 times lower than the thermal resistance of a fiberglass board, for example, FR4. This means that the chances of overheating of the LEDs are much less.

Taking heat from the LED, the circuit board should get rid of it. Simply transferring heat to the surrounding air is not a good solution, since heat transfer is slow and the amount of heat transferred is not large. Therefore, the printed circuit board is mounted directly on the radiator, which transfers its heat. To improve the heat transfer between the printed circuit board and the radiator, additional material is placed, for example, heat transfer paste. But other materials are also possible (see Table 3).

As can be seen from fig. 3 the resulting thermal transition has two thermal resistances. Thermally conductive materials can perform other functions, such as the insulation of electrical circuit nodes or the creation of mechanical fasteners.

| Thermal Interface Material | Advantages | Disadvantages |
|----------------------------|------------|---------------|
| Thermal paste              | High volume thermal conductivity, a small adhesive layer, low viscosity, do not harden | Quite dirty during production |
Phase change materials

High viscosity gives higher reliability compared to thermal paste, it is much more convenient to use, there is no delamination

Lower thermal conductivity, compared with thermal paste, surface resistance may be greater than that of thermal paste, the pressure is required to increase efficiency

Gels

Well fill surface bumps

Lower thermal conductivity compared with thermal grease, less adhesion than hot glue

Hot-melt adhesive

Well fill surface bumps

A cleaning process is required

When deciding on the use of thermal conductive material, it is necessary to take into account not only its thermal conductivity and mechanical properties, but also the thermal resistance, calculated by the formula (8)

\[ Q_{\text{tim}} = \frac{L}{kA} \] \hspace{1cm} (8)

where \( Q_{\text{tim}} \) — the thermal resistance of the thermally conductive material (°C/Вт);

\( L \) — layer thickness (m);

\( k \) — thermal conductivity (W/m*K);

\( A \) — contact area (m²).

From the formula (8) it can be seen that the thermal resistance is directly proportional to the thickness of its layer and inversely proportional to the contact area. If luminous flux of “very” high power is required with “normal” dimensions, various systems of forced cooling are used, the brief characteristics of which are presented in table 4.

| Type          | Dissipated thermal power, W | Characteristic                                                                 |
|---------------|-----------------------------|-------------------------------------------------------------------------------|
| Cooler        | <170                        | It is mounted directly on the radiator. Additional power is needed.            |
| Heat pipes    | <140                        | Heat pipes do not dissipate heat, they transfer it to another place, so a radiator is still needed. |
| Liquid cooling| <200                        | Designed to remove a large amount of heat, a rather expensive solution, about 10 times more expensive than heat pipes. |
| Peltier Modules       | <80 | Ineffective, limited cooling, high cost. Additional power needed. |
|-----------------------|-----|------------------------------------------------------------------|
| Jet cooling           | <80 | It is comparable to a cooler, but it works more quietly and is highly reliable. Requires a special radiator design. |
| Cooling system SynJet | <240| Smaller dimensions compared to conventional radiators. Hush compared to coolers. Long service life. The disadvantages include the need for a separate power source. |

Despite the external complexity, forced cooling is used in lighting systems. The most common forced cooling are heat pipes, cooler and liquid cooling.

4. Conclusion

The reliability and durability of LED devices depend on the quality of the design of the cooling system, which is why it is so important to pay special attention to the design of a reliable heat sink. For cooling low-power LED systems, a conventional radiator will be quite sufficient; in some cases, active cooling may be required to remove heat from high-powered luminaires. Also, when developing new lighting devices, it is strongly recommended to perform calculations and modeling of the cooling system. The CREE website provides many methods for calculating heat sinks and useful applications for the proper selection of cooling elements.

As can be seen from the graphs of fig. 1, at elevated operating temperatures, the lifetime of the LEDs is significantly reduced: at 105 °C, the lifetime of the LEDs is 200 thousand hours less than at 85 °C.

The calculation determined the maximum area of the plate on which the LED is installed, for its effective cooling, which was 24 cm² (for a 1 W LED power). If free cooling is not enough, you can use forced cooling systems.

5. References

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