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Thermal analysis of loop heat pipe used for high-power LED

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ABSTRACT

The goal of this study is to improve the thermal characteristics of high-power LED (light emitting diode) package by using a loop heat pipe. The heat-release characteristics of high-power LED package are analyzed and a novel loop heat pipe (LHP) cooling device for high-power LED is developed. The thermal capabilities, including start-up performance, temperature uniformity and thermal resistance of loop heat pipe under different heat loads and incline angles have been investigated experimentally. The obtained results indicates that the thermal resistance of the heat pipe heat sink is in the range of 0.19–3.1 K/W, the temperature uniformity in the evaporator is controlled within 1.5 °C, and the junction temperature of high-power LED could be controlled steadily under 100 °C for the heat load of 100 W.

1. Introduction

Light emitting diode (LED) is a solid-state semiconductor device which directly converts electrical energy into light. High-power LED is keeping attracting interests due to its significant impacts on solid-state illumination industry [1,2], and it is a strong candidate for the next generation of general illumination applications [3,4]. LED demonstrates a number of benefits compared to traditional incandescent lamps and fluorescent lamp. With further improvement LED has a great potential to become a new illumination source [3]. However, at present, the heat fluxes of LED chips are more than 100 W/cm^2 [3], and thermal problem caused by the heat generated within the LED itself is still a bottleneck to limit the stability, reliability and lifetime of high-power LED. Therefore, effective thermal design of LED packages with low thermal resistance is critical to improve the performance of LED [1,2,5–7].

In order to guarantee the life of the device, currently, the junction temperature of LED should be controlled below the 110 °C [4]. At present, the methods used to resolve the heat problem of LED system are mainly by changing the LED packaging material [1–6]. However, when the high-power LED is applied to lighting and other occasions, the control of cost is very important, and the external heat sink size of LED are not allowed to be oversize; furthermore, fans are not permitted to be used for additional cooling. Therefore, the existing methods cannot overcome the thermal problem of high-power LED effectively.

Phase-change cooling is a promising method for cooling high heat flux devices. Heat pipe is one kind of phase -change heat-transfer devices using Phase-change cooling method. There are several reports on thermal characterization of LED packages with the traditional thermal siphon heat pipe [7,8], for the traditional thermal siphon heat pipe, the vapor and liquid circulate in the same pipe line, once the thermal siphon heat pipe is bended, the thermal performance of heat pipe facilitates to decline acutely. However, in the interest of meeting the need of shape of LED, heat pipe must be bended, therefore, the traditional heat siphon pipe cannot effectively satisfy the need of heat dissipation of high-power LED.

Loop heat pipes (LHPs) are two-phase heat-transfer devices with capillary pumping of a working fluid, they possess all the main advantages of conventional heat pipe [9], and the loop heat pipe conception to a considerable extent makes it possible not only to overcome the drawbacks of conventional heat siphon pipes, but also to obtain some additional advantages. If the existing loop heat pipe technology is directly applied to a high-power LED system, several shortcomings will encountered, such as the high cost of manufacturing, the inconvenient of machining and so on. In addition, the framework of the traditional LHP cannot meets the requirements of LED's general illumination and the capillary structure is too complex to manufacture.

In this paper, the thermal analysis of loop heat pipe used for high-power LED is discussed, a novel loop heat pipe cooling device for high-power LED is developed, and the thermal characteristics under the conditions of different heat loads and incline angles, including start-up performance, temperature uniformity and thermal resistance of loop heat pipe, have been investigated experimentally.

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2. Description of experiment

2.1. Flat-evaporator loop heat pipe

In order to meet the requirements of the high-power LED packages, a flat-evaporator loop heat pipe (LHP) has been developed, designed and fabricated in this paper, as shown in Fig. 1. The LHP consists of an evaporator, a condenser, a compensation chamber and several pipelines for vapor and liquid transportation. The evaporator and compensation chamber contain wicks, and the rest of the loop are made in smooth tubing. The loop heat pipe is a copper/water unit, namely, the material of LHP is copper, the working fluid in the loop is water, and the porous wick is copper mesh. Under steady state conditions, when enough heat load is added to the evaporator, the liquid water in the evaporator vaporizes and converts into vapor, and then flows into the condenser through the vapor pipeline, where the vapor releases the heat to the ambient environment and becomes water, finally the water reflows to the evaporator through the pores on the wall of the liquid line, so the working fluid is circulated by thermodynamic forces supplied by the wick, and forms a thermal circulation. The compensation chamber in the circle has two main functions: (i) to accommodate excess liquid in the loop during normal operation, and (ii) to supply the capillary pump wick with liquid at all times.

In the experimental set, the heat load is applied by a resistance heater attached to the wall of the evaporator. The surface area and shape of the resistance heater are the same as the evaporator's, the thickness is 0.7 mm, the heat capability is 120 W, and is attached to the wall of evaporator by the thermal grease (1.15 W/m K). The temperatures in the LHP are measured by 20 pairs T-type thermocouples (with deviation of ±0.5 °C at 100 °C): The thermocouple (T_1) is located at the evaporator outlet; the thermocouples T_2 and T_9 are located at the inlet and the outlet of the condenser respectively; 6 pairs of thermocouples (T_3–T_8) are located at the different positions on the condenser wall; the thermocouple (T_{10}) is located at the evaporator inlet; 5 pairs of thermocouples (T_{11}–T_{15}) are located at the resistance heater; and 5 pairs of thermocouples (T_{16}–T_{20}) are located at the evaporator as shown in Fig. 1.

2.2. Experimental conditions

The dimensions of the evaporator are $L \times W \times H$ = 70 mm × 55 mm × 8 mm; the diameter of the steam pipe line is 6 mm with length of 140 mm; the diameter of the liquid pipe line is 6 mm with length of 1100 mm.

The filled ratio of work liquid (the ratio of work liquid volume to the total volume of the loop pipe line including the compensation chamber) is about 50%.

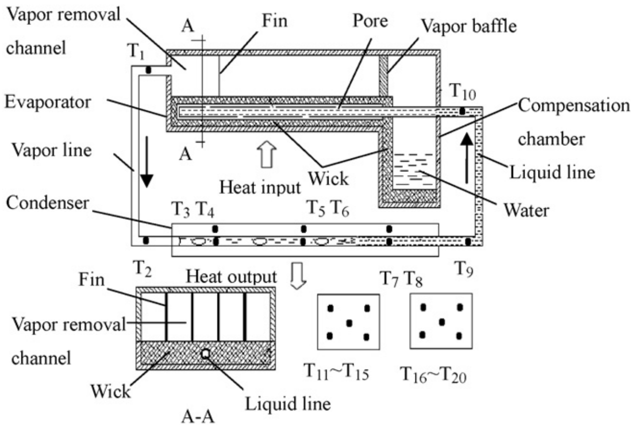


Fig. 1. Schematic structure of the developed LHP.

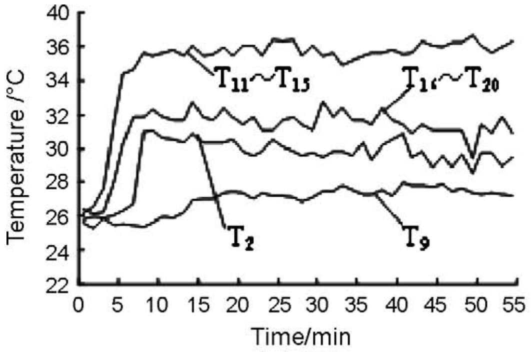
All the tests were conducted in the normal environment with condenser cooling by nature convection at ambient temperature of 25 ± 2 °C, and the air velocity measured by an anemometer is about 1 m/s.

The porosity of copper porous wick structures is 58%, the effective pore radius is 11 μm, the permeability is 6.09×10^{-12} m^2, and the thermal conductivity is 1.48 W/m K.

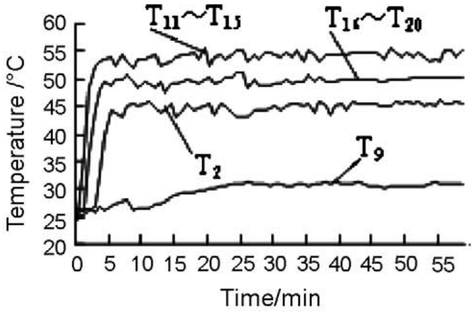
3. Results and discussions

3.1. Start-up tests of the LHP

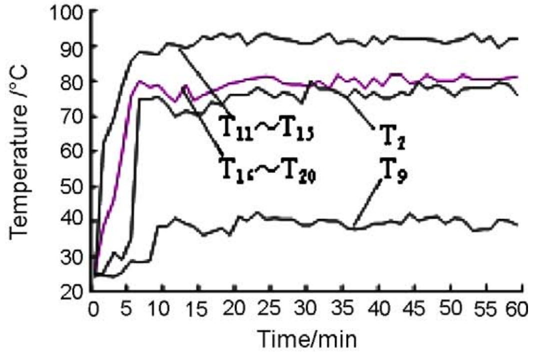
The junction temperature of the high-power LED increases with the increasing heat loads, this needs that the start-up of the LHP should be safety to run at different heat loads quickly, therefore, the start-up phenomenon is very critical in evaluating the design and reliability of the LHP for the thermal control of the high-power LED device. Fig. 2 shows the start-up process of the LHP at heat loads of 5, 30 and 85 W at the same operating condition, respectively. It is clear from the start-up trends that the LHP is able to achieve steady state conditions at both low and high heat loads within the range of



(a) 5W



(b) 30W



(c) 85W

Fig. 2. Start-up of the LHP at different heat loads.

applied heat load. From the comparison of the start-up profiles, it is noted that the start-up time required for low heat loads is longer than that of high heat loads. As presented in Fig. 2, for 5 W heat load, the start-up of the loop took is approx. 8 min; for 30 W, approx. 6 min; while for 85 W, less than 5 min. This means that the LHP is easier to start at high heat load. The start-up phenomenon involves satisfying two main conditions that includes: (i) setting up required capillary pressure difference across the wick that is necessary to circulate the working fluid around the loop; and (ii) clearing of liquid from evaporator vapor removal channel, vapor line and part of condenser for the loop, the start-up time is the actual time that required to accomplish these processes. In order to realize the first condition, development of steady capillary pressure difference generated by the wick inside the evaporator is necessary. At low heat loads, the menisci formation that may generate sufficient capillary pressure in the wick takes more time as heat is slowly transferred to the fluid, causing a longer time to start generating capillary forces. At high heat loads, the menisci forms more quickly and the capillary forces begin to act faster. The second condition is achieved by the vapor generated inside the evaporator which helps to displace liquid from vapor removal channel, vapor line and portion of condenser and accumulate it inside the compensation chamber. In this case, the rate of the vapor generation inside evaporator affects the time needed to achieve this condition. For low heat loads, the vapor generation process inside the evaporator is very slow which increases the start-up time. For high heat loads, the intensive generation of the vapor takes place inside the evaporator that results in early initiation of the fluid circulation and thus start-up procedure.

3.2. Temperature uniformity of the evaporator

As high-power LED chips are mounted to the wall of the evaporator by the ways of welding or attaching, the wall of the evaporator should have good temperature uniformity. The designed LHP can not only remove the heat dissipation of high-power LED to the ambient environment, but also provide a good temperature uniformity backstop surface which facilitates the installation of the high-power LED chip. For the results shown in Fig. 3, the temperature uniformity of the LHP for different heat loads (power loading was switched from 85 to 50 W, and then switched from 50 to 85 W) was controlled within 1.5 °C. The temperature of the evaporator was controlled steadily under 80 and 69 °C for 85 and 50 W, respectively, the performance of temperature uniformity of the evaporator is excellent.

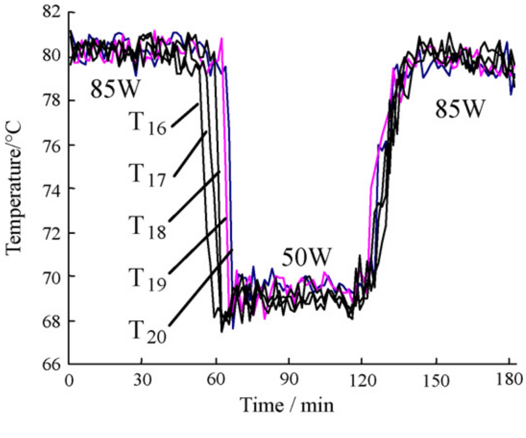


Fig. 3. Temperature uniformity of the LHP for different heat loads.

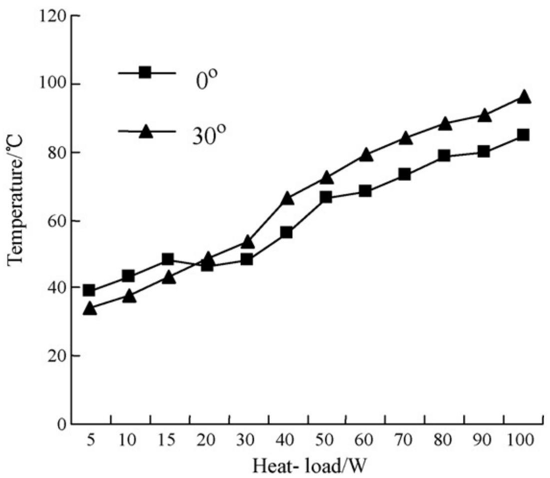


Fig. 4. Heat-load vs. the temperature of evaporator.

3.3. The temperature of the evaporator in response to heat loads

In order to apply the high-power LED to different occasions, the high-power LED must meet the requirements of different installation angles and consequential optical design. As presented in Fig. 4, the obtained results indicates when the heat load varies in a range of 5–100 W and the incline angle varies in a range from 0° to 30°, the operating temperature of evaporator increases with increasing heat load, in the whole range of changing heat loads and incline angles the temperature of evaporator could be controlled under 100 °C steadily. This can be explained as follows. At low heat loads, the condenser is able to cool the liquid in the condenser to near ambient temperature, so the large portion of the condenser is employed for subcooling purpose. Contrary to that, at high heat loads the active or two-phase length of the condenser increases that reduces the subcooling portion, as a result, in order to balance the amount of the reduced subcooling, the saturation temperature of the liquid that reflows to the evaporator must be increased accordingly. For heat load in the range of 5–20 W, the thermal dissipation characteristics of the LHP with the 30° incline angle are more effective than that of 0° incline angle, however, when the heat load varies in a range of 20–100 W, the changing trend is on the contrary. The reason is mainly that, at low heat loads, the thermal characteristics of the LHP is not utilized fully, only partial liquid water in the evaporator that absorbs the heat to change into the vapor, due to the impact of gravity, the liquid water in the wick in the evaporator of 0° incline angle is completely liquid filled, as a result, the integrative thermal conductivity of the wick in the evaporator for 30° incline angle is higher than that for 0° incline angle. By contraries, at high heat loads, the LHP begins to optimize the thermal characteristics, the liquid water in the compensation chamber for 0° incline angle is easier to be pumped into the wick in the evaporator than that for 30° incline angle. Therefore, the LHP can effectively meet the requirement of the thermal management of high-power LED.

3.4. The thermal resistance of high-power LED system

The junction temperature of high-power LED may be calculated by the following equations [6]:

$$T_J = T_p + P \times R_{J\text{-}P} \tag{1}$$

where T_J, T_p, P and $R_{J\text{-}P}$ are the temperature of the high-power LED chip junction, pin temperature of LED, junction power dissipation and thermal resistance coefficient (supplied by the LED chip man-

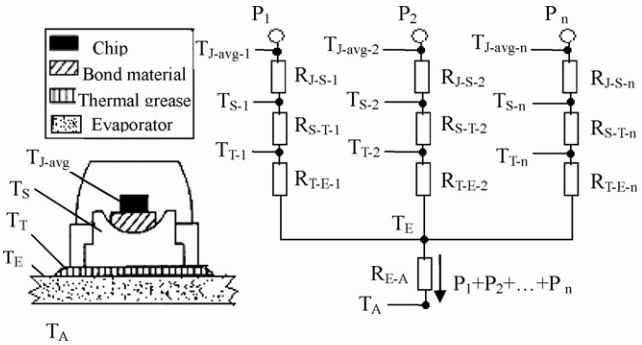


Fig. 5. Thermal resistance model of cooling system of LED array.

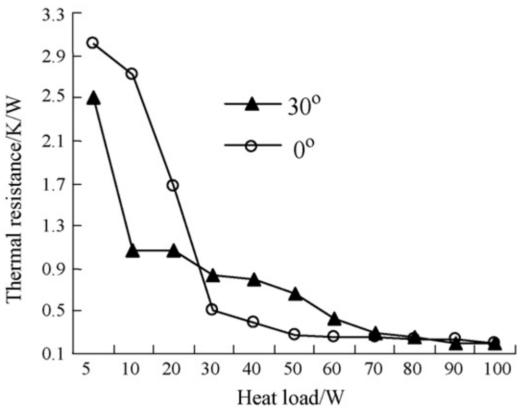


Fig. 6. Thermal resistance vs. heat loads.

ufacturer or measured by Voltage-Method [6]) from the junction to the pin, respectively.

$$P = V_f \times I_f - P_{light} \tag{2}$$

where V_f, I_f and P_{light} are the forward voltage of high-power LED, the forward current of high-power LED and the light output power of the high-power LED, respectively.

Effective thermal design and reliable thermal characterization of LED array are as important as for a single LED package. Thermal characterization of LEDs in an array is very different from that of single LED package. The thermal resistance analysis of a high-power LED array is shown in Fig. 5, where $T_{J\text{-}avg}$, T_S, T_T, T_E and T_A and are the average junction temperature of LED array, the inner heat sink, the thermal grease, the evaporator outside surface of the LHP and the ambient temperature, respectively. The LEDs are mounted on the wall of the evaporator, thus the temperature of the wall of the evaporator is assumed to be the same. Thermal resistance of LED arrays which have multiple heat sources can be described in the following expression with the average junction temperature of LED array, $T_{J\text{-}avg}$ (which can be validated by Eq. (1)) [1].

$$R_{J\text{-}avg} = \frac{T_{J\text{-}avg} - T_A}{P_{total}} \tag{3}$$

$$P_{total} = V'_f \times I'_f - P'_{light} = \sum_{k=1}^{n} P_k \tag{4}$$

where $R_{J\text{-}avg}$ is an average junction to ambient thermal resistance, P_{total} is the power dissipation of the entire packages, T_A is the ambient temperature, V'_f is the entire forward voltage of high-power LED array, I'_f is the entire forward current of high-power LED array, and P'_{light} is the entire light output power of the high-power LED array.

The junction temperature of LED array will be significantly influenced by ambient temperature and side effects from multiple chips. In generally, the junction temperature of high-power LED should be less than 110 °C [4]. Therefore, the average junction temperature of LED array ($T_{J\text{-}avg}$) may be expressed as the number of *i* chip, namely,

$$\begin{aligned} T_{J\text{-}avg} = {} & (R_{J\text{-}S\text{-}i} + R_{S\text{-}T\text{-}i} + R_{T\text{-}E\text{-}i}) \times P_i + \left(\sum_{k=1}^{n} P_k \right) \\ & \times R_{E\text{-}A} + T_A \le 110 \end{aligned} \tag{5}$$

where $R_{J\text{-}S\text{-}i}$, $R_{S\text{-}T\text{-}i}$, $R_{T\text{-}E\text{-}i}$, P_i are the thermal resistance between chip and inner heat sink, between inner heat sink and thermal grease, between thermal grease and the evaporator and the input power of the *i*th chip, respectively, and $R_{E\text{-}A}$ is the thermal resistance between the evaporator and the ambient.

Since $R_{J\text{-}S\text{-}i}$, $R_{S\text{-}T\text{-}i}$ and $R_{T\text{-}E\text{-}i}$ may be supplied by the LED chip manufacturer or be acquired through the method of test [1], the thermal resistance of the loop heat pipe $R_{E\text{-}A}$ is very important to the junction temperature of high-power LED system.

Thermal properties of a LHP are all reflected in the thermal resistance of the LHP, therefore, thermal resistance offered by the LHP (R) from evaporator to condenser external surface was used to access the heat transfer performance of the LHP, and the thermal resistance of a loop heat pipe may be calculated by the equation:

$$R = \frac{T_E - \bar{T}_C}{P_{total}} \tag{6}$$

where R is the thermal resistance of the LHP, K/W; T_E is the temperature of the evaporator outside surface, °C; $\bar{T}_C$ is the average temperature of the condenser, °C; $P_{total} = (V'_f \times I'_f - P'_{light})$ is the dissipated heat of the loop heat pipe, W.

Fig. 6 presents the dependences of the thermal resistance (R) of loop heat pipe on heat loads. When the heat load in a range of 5–100 W, and the incline angles in a range from 0° to 30°, the thermal resistance of LHP decreases with the increasing of heat load. For heat load in the range of 5–100 W, the thermal resistance of LHP lies between 0.19 and 3.1 K/W, as shown in Fig. 6. Minimum value of 0.19 K/W for R is achieved at the heat load of 100 W. At low heat loads, as the mass flow rate of vapor is small therefore majority of the condenser is occupied with the liquid and compensation chamber is only partially filled. With increasing heat loads, the mass flow rate of vapor increases that will now require large area of condenser for phase change process. In order to claim area of condenser, the vapor displaces the liquid from the condenser to the compensation chamber. As a result, the average temperature ($\bar{T}_C$) of the condenser increases accordingly, the temperature difference between T_E and $\bar{T}_C$ becomes smaller correspondingly, so the thermal resistance (R) of the LHP becomes smaller.

4. Conclusions

The present technical research on heat-release characteristics package of high-power LED are analyzed, a novel loop heat pipe (LHP) cooling device for high-power LED is developed; The thermal characteristics, including start-up performance, temperature uniformity and thermal resistance of loop heat pipe under different heat loads and incline angles, have been investigated experimentally; The obtained results indicates that the thermal resistance of the heat pipe heat sink is in the range of 0.19–3.1 K/W, the temperature uniformity in the evaporator is controlled within 1.5 °C, and the junction temperature of high-power LED could be controlled steadily under 100 °C for the heat load of 100 W; It is demonstrated that the loop heat pipe developed can effectively decreases the total thermal resistance of LED system, and is proved to be a good solution for controlling junction temperature of high-power LED systems.

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