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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%.

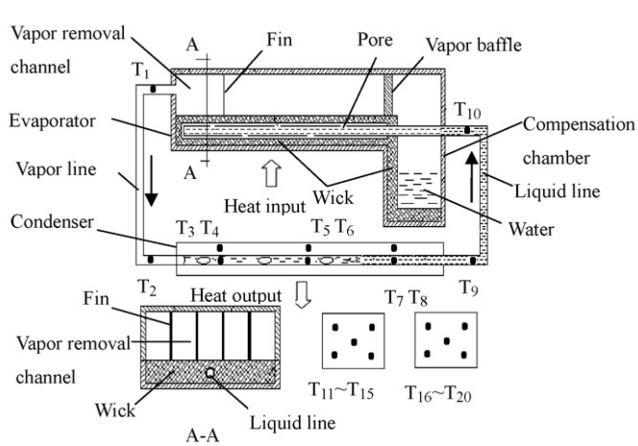

Fig. 1. Schematic structure of the developed LHP.

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

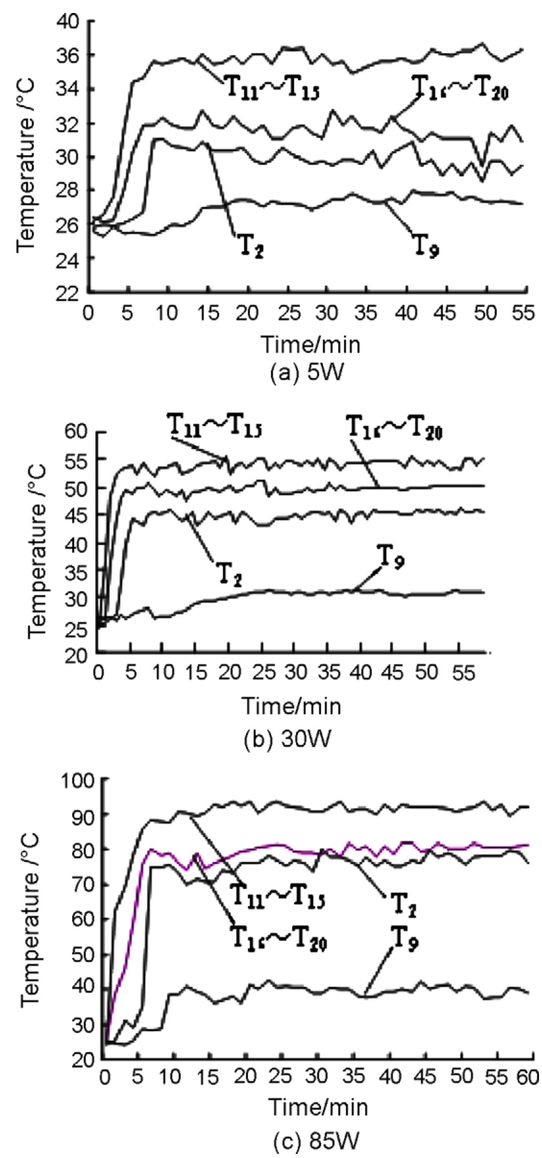

Fig. 2. Start-up of the LHP at different heat loads.