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Phase-change immersion cooling high power light emitting diodes and heat transfer improvement

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ABSTRACT

A new cooling method of ethanol direct-contact phase-change immersion cooling was proposed in the thermal management of high power light emitting diodes (LED) and the feasibility of this cooling method was investigated. The heat generated by LED was measured firstly using two types of power systems: DC power and LED driver. Then the heat dissipation performance was evaluated under different experimental conditions. The results indicate that startup process of the cooling system is quick and only 450 s is needed to reach steady-state under heat load of 42.78 W. The minimum thermal resistance of 1.233 °C/W is obtained when liquid filling ratio is 33.14%. The junction temperature of LED under different absolute pressures is much lower than the limited value of 120 °C. Baffle with total height of 140 mm, bottom space height of 20 mm and distance away from substrate surface of LED of 8 mm improves heat transfer performance best due to ethanol self-circulating in the cooling receiver. Overall, the ethanol phase-change immersion cooling is an effective way to make sure high power LED work reliably and high efficiently.

1. Introduction

Light emitting diode (LED), as a simple junction and solid-sate semiconductor, can emit continuous light when worked under a lower voltage. LED has shown powerful potential in lighting industry and been replacing the conventional lights within a few decades due to its advantages of high quantum efficiency, lower energy consumption, long life span and environmental friendliness [1]. Nowadays, the high power LED is developing in the light market, the power of modern LED chip is above 1 W, even up to 5 W, the area of chip is less than 1 mm^2 and the corresponding heat flux of LED chips is more than 100 W/cm^2 [2, 3]. Even though the chip of LED has a satisfactory progress in the photoelectric conversion efficiency, large amount of electric power driving LED devices still convert to waste heat. As a result, the working temperature of LED will increase sharply [4]. Thus, the luminous efficiency and lifetime of the chip will be threatened and even the chip may be out of order or damaged [5,6]. Therefore, it's a critical issue of finding efficient heat dissipation technologies to make sure performance reliability of LED, especially for high power LED [7]. Many researches have been dedicated for this issue. Deng [8] indicated liquid metal cooling was a powerful way for heat dissipation of high power LEDs. Hsieh [9] applied a single microspray to a four LED system and provided a highest average heat transfer coefficient of 9375 W/m^2 °C. Bladimir [10] indicated the minichannel cold plate showed better in thermal management than microjet for the cooling of high power LEDs. Wang [11] investigated a cooling system with thermoelectric cooler (TEC) and evaluated the cooling performance of different devices (air cooling & TEC, liquid cooling & TEC) by measuring the LED temperature. The results showed the junction temperature was 85.6 °C (air cooling & TEC) and 59.5 °C (liquid cooling & TEC) when the ambient temperature was at a severe condition of 65 °C. Tsai [12] presented an integrated LED/TEC module to remove the waste heat of LED. Shin [13] developed a heat sink with ionic wind and the optimum prototype showed an enhanced cooling performance of 150% compared with that of natural convection. Overall, the active cooling methods for heat dissipation of LED is effective, however, extra energy consumption is a shortcoming.

Phase-change heat sink exhibits better heat transfer performance comparing with traditional solid copper heat sink [14]. Therefore, it has been expected as a promising way to solve the thermal management problem of LED. Heat sink based on heat pipe has been applied for LED cooling. Kim [15] analyzed the thermal characterization of high power LED arrays and found the junction temperature of LED arrays with and without heat pipe was 63.3 °C and 87.6 °C. Tang [16] developed a columnar heat pipe (CHP) leadframe for high power LED and found the thermal resistance of $R_{l\text{-}s}$ (from the leadframe to the heat

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Nomenclature

C_p	specific heat of ethanol, kJ/(kg °C)
I_{in}	input current, A
P^*	absolute pressure of the cooling system, kPa
P	heat generated by LED, W
P_{array}	heat of the LED dense-array, W
P_b	mean value of heat generate by LED and the heat carried away by the cooling water in the condensation section, W
P_{single}	power of a single chip, W
$R_{j\text{-}sp}$	thermal resistance from the junction to the soldering points, °C/W
$R_{substrate}$	thermal resistance of the MCPCB, °C/W
R_{th}	thermal resistance, °C/W
t	heating time of ethanol, s
T_a	ambient temperature, °C
$T_{junction}$	junction temperature of LED, °C
T_s	saturated temperature of ethanol, °C
$T_{substrate}$	temperature of LED substrate, °C
ΔT_{avg}	average temperature difference, °C
V	volume of ethanol, m^3
V_{in}	input voltage, V
ρ	density of ethanol, kg/m^3

Abbreviation

CHP	columnar heat pipe
DC	direct current
FS	full scale
FHP	flat heat pipe
LED	light emitting diode
LHP	loop heat pipe
OHP	oscillating heat pipe
PCM-HP	phase-change material base heat pipe
TEC	thermoelectric cooler

sink) and $R_{j\text{-}a}$ (from the LED chip to the ambient) was 0.23 °C/W and 1.65 °C/W. Li [17] carried out a thermosyphon heat pipe heat sink for a 100 W LED, a very low thermal resistance was obtained under natural air convection. Lin [18] investigated the heat transfer characteristics of aluminum plate oscillating heat pipes (OHPs) heat sink and the temperature of a 64 W LED decreased significantly. Lu [19] studied the heat-release characteristics of high power LEDs package with a flat heat pipe (FHP). The junction temperature and thermal resistance of LED was about 52 °C and 8.8 °C/W for input power of 3 W. Yang [20] proposed a flat polymer heat pipe to enhance heat conduction through the wall of the polymer heat pipe for electronic device cooling. Furthermore, Wu [21] proposed a phase-change material based heat pipe (PCM-HP) and found it lowered the LED heating rate and temperature. Based on the results presented above, the heat sink based on heat pipe is an effective way for heat management of LED.

However, the thermal resistance in the interface between LED and heat sink is a bottleneck and the maximum heat flux removal depends on the interface resistance. The direct contact between coolant and LED can eliminate this interface resistance. Combining with our former study [22], liquid phase-change immersion cooling is a promising heat management method for high heat flux of solar cells array. To the best of our knowledge, few papers reported the liquid direct-contact phase-change immersion cooling applied for thermal management of LED.

In this paper, the feasibility of ethanol direct-contact phase-change immersion cooling applied for thermal management of a 100 W LED was investigated. The heat generated by LED under different input powers was firstly measured and the startup performance of phase-change immersion cooling system was evaluated. Junction temperature of LED and thermal resistance of phase-change cooling system were taken as evaluated targets, the operated absolute pressure of system, liquid filling ratio and the effect of baffle existed in the cooling receiver were investigated systematically.

2. Experimental setup

As shown in Fig. 1, the whole cooling system consists of evaporation section, condensation section, cooling water section and measurement section. The cooling system worked under pressure lower than standard atmospheric pressure, the function of which presented two sides: eliminating the effect of non-condense gas in the whole system on heat transfer performance and lower down the saturated temperature of ethanol. In order to decline the heat loss of the cooling system, the whole experimental setup was covered by thermal insulation cotton with thermal conductivity of 0.034 W/(m·K) and thickness of 10 mm. The detailed information about the equipment used in the experiment is given in Table 1.

The cooling receiver is the evaporation section of the whole system and the structure is shown in Fig. 2, which comprises of two glass plates, two iron plates and a LED. Visually, two glass plates with size of 170 mm × 70 mm × 12 mm and 120 mm × 70 mm × 12 mm were embedded in the milling slot of the iron plates and fixed with glue. The iron plates and the rubber gasket were tightened together by bolts to form a space and a high power LED (detailed parameter is shown in Table 2) was placed in the channel along the flowing direction.

Ethanol was chosen as coolant due to its preferable physical properties (lower boiling point and viscosity, higher latent heat, dielectric) and lower cost. Meanwhile, ethanol has showed better heat dissipation performance for higher heat flux of solar cells [22]. The high power LED (Fig. 2b) was immersed with ethanol in the cooling receiver (Fig. 2a).

The experimental process is described as follow. In the first, the whole system was exhausted using a vacuum pump to a fixed absolute pressure, and then open the valve in the bottom of the system till ethanol of fixed volume went into the cooling receiver. Then, the cooling water was pumped and the flow rate was adjusted by a valve and measured by a flow meter. Finally, turning on the LED and the whole cooling system started up till reaching steady-state (when variation of LED temperature less than ±0.2 °C). Varying the absolute pressure, liquid filling ratio and parameters of baffle, the heat transfer performance of phase-change immersion cooling LED under different operated conditions was obtained.

Thermocouples set in the inlet and outlet of evaporation section, condensation section and cooling water section, respectively. A thermocouple set on the back surface of LED to measure the substrate temperature. The temperature were all measured by K-type thermocouples (5 TC-TT-K-36-36, accuracy 0.1 °C, Omega Company, USA) and collected by an ART temperature acquisition module (accuracy ± 0.2%, ART Technology Development Co., Ltd). The input power of LED was adjusted by two types of power systems: DC power and LED driver. The input voltage and current of DC power was directly obtained from the equipment. While, the input voltage and current of LED driver were measured with multimeter (Uni-trend Co., Ltd), the accuracy for the voltage measurement was 1.5% FS (resolution 0.01 V) and for the current was 1.2% FS (resolution 0.01 A).

3. Analysis methods

Even though the chip of LED has a satisfactory progress in the photoelectric conversion efficiency, large amount of electric power driving LED still convert to waste heat. So, the heat dissipation of high power LED is necessary. In order to better understand the characteristics of

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