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Thermal analysis of high power LED package with heat pipe heat sink

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ABSTRACT

The goal of this study is to improve the thermal characteristics of high power LED (light-emitting diode) package using a flat heat pipe (FHP). The heat-release characteristics of high power LED package are analyzed and a novel flat heat pipe (FHP) cooling device for high power LED is developed. The thermal capabilities, including startup performance, temperature uniformity and thermal resistance of high power LED package with flat heat pipe heat sink have been investigated experimentally. The obtained results indicate that the junction temperature of LED is about 52 °C for the input power of 3 W, and correspondingly the total thermal resistance of LED system is 8.8 K/W. The impact of the different filling rates and inclination angles of the heat pipe to the heat transfer performance of the heat pipe should be evaluated before such a structure of heat pipe cooling system is used to cool high power LED system.

1. Introduction

Light-emitting diode (LED) is a kind of solid-state semiconductor devices that directly convert electrical energy into light. High power LED is attracting interest 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. However, at present, the heat fluxes of LED chips are more than 100 W/cm^2 [3], and the thermal problem that is brought by heat generated within the LED itself is still a bottleneck that limits the stability, reliability and lifetime of high power LED. Therefore, effective thermal design LED packages with low thermal resistance are critical to improve the performance of LED [1,2,5–12].

At present, the methods used to resolve the heat problem of LED system are mainly by changing the LED packaging material [1–6,12]. However, when the high-power LED is applied to lighting and other occasions, the control of cost is very important, the external heat sink size of LED is not allowed to be large and fans are not permitted to be used for additional cooling (from the view points of economy and reliability). 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 pipes with cylindrical evaporator have been investigated in some research [13,14].

In this paper, the thermal analysis of high power LED package with heat pipe heat sink is discussed, and the thermal characteristics, including startup performance, temperature uniformity and thermal resistance of heat pipe, have been investigated experimentally.

2. Description of experiment

2.1. Flat heat pipe

In order to meet the requirements of the high-power LED packages, a new type structure of flat heat pipe (FHP) cooling device for high power LED is developed, as shown in Fig. 1. The FHP consists of an evaporator, an adiabatic section and a condenser. The FHP circulates the vapor and liquid in the same pipe line. The FHP is a copper/water unit; namely, the material of FHP is copper, the working fluid in the loop is water and the porous wick structure material is copper mesh. Under steady state condition, when enough heat load is supplied to the evaporator, the liquid water in the evaporator is vaporized, and flows along the adiabatic section to the condenser, where the heat is removed by phase change to the ambient environment and the working fluid turns back to liquid phase, and then reflows to the evaporator through the porous wick on the wall of the FHP, so the working fluid is circulated by capillary forces is supplied by the wick structures, and forms a thermal circulation.

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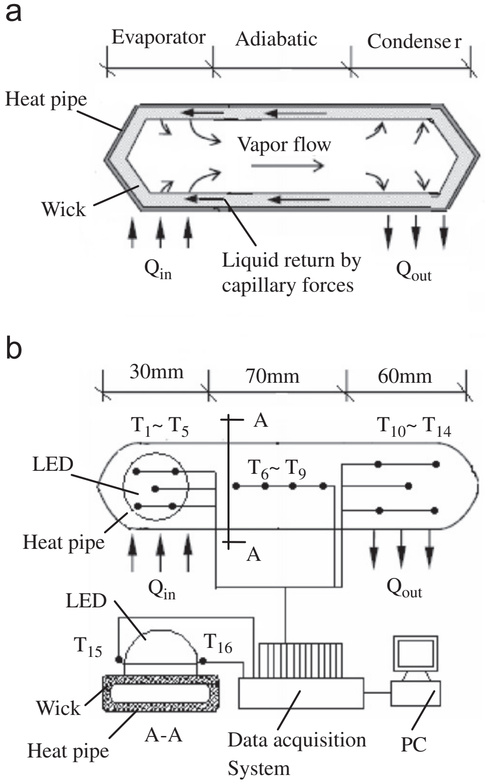

Fig. 1. Schematic structure of the developed FHP: (a) schematic diagram of the proposed FHP and (b) the placement of the thermocouple points.

In the experimental set, the heat load is applied by a LED chip attached to the wall of evaporator by the thermal grease (1.15 W/m K). The temperatures in the flat heat pipe cooling device for high power LED are measured by 16 pairs T-type thermocouples (with deviation of ± 0.3 °C at 100 °C), the thermocouples T_1–T_5 are at different positions on the evaporator wall;the thermocouples (T_6–T_9) are on the different positions on the adiabatic pipe wall; 5 pairs of thermocouples (T_{10}–T_{14}) are at different positions on the condenser wall; the thermocouples T_{15} and T_{16} are on the two pins of high power LED.

2.2. Experimental conditions

The thickness, width and total length of the flat heat pipe are 5 mm, 15 mm and 160 mm, respectively. The copper mesh number is 500 and thickness is 0.25 mm.

The surface area and shape of the copper plate are the same as those of the flat heat pipe.

The input power of the high power LED is varied in the range of 0.1 W–3 W.

The filled ratio of work liquid (the ratio of work liquid volume to the total volume of the heat pipe) is about 30 %.

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

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

A constant-current driver is chosen to deliver the desired current, with enough forward voltage output to accommodate the maximum input voltage of the LED source. The electrical parameters for each LED chip used in this experiment are given in Table 1.

Table 1
Electrical parameters for each LED used in this experiment.

Input power (W)	0.5	1	1.5	2	2.5	3
Voltage (mV)	3500	3700	4080	4100	4200	4800
Current (A)	0.143	0.27	0.37	0.488	0.595	0.625

3. Theoretical investigation for measuring junction temperature of high power LED

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

$$T_J = T_p + PR_{J-P} \tag{1}$$

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

Where T_J, T_p, P, V_f, I_f, P_{light} and R_{J-P} are the LED junction temperature (°C), pin temperature of LED (°C), junction power dissipation (W), the forward voltage of high power LED (V), the forward current of high power LED (A), the light output power of the high power LED (W, measured by integrating sphere) and thermal resistance coefficient (K/W, supplied by the LED chip manufacturer or measured by the Voltage-Method [6]) from the junction to the pin, respectively.

The junction temperature of high power LED is decided mainly by the ambient temperature and the total thermal resistance between the junction of chip and the ambient. The thermal resistance analysis of the high power LED system is shown in Fig. 2, where T_J, T_S, T_T, T_E and T_A are the temperature of the high power LED chip junction (°C), the inner heat sink (°C), the thermal grease (°C), the evaporator interface of the flat heat pipe (°C) and the ambient temperature (°C), respectively.

The total thermal resistance R_{J-A} from the junction of chip to the ambient of the high power LED can be expressed as (K/W)

$$R_{J-A} = \frac{\Delta T_{J-A}}{P} = \frac{T_J - T_A}{V_f I_f - P_{light}} \tag{3}$$

The R_{J-A} (K/W) is the sum of several thermal resistances of the high power LED system, as shown in Fig. 2 That is

$$R_{J-A} = R_{J-S} + R_{S-T} + R_{T-E} + R_{E-A} \tag{4}$$

Where R_{J-S}, R_{S-T}, R_{T-E} and R_{E-A} are the thermal resistance between junction of chip and inner heat sink (K/W), between inner heat sink and thermal grease (K/W), between thermal grease and the evaporator (K/W) and between the evaporator of heat pipe and the ambient (K/W), respectively.

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

4. Results and discussion

4.1. Variation of voltage and junction temperature with time

LEDs are semiconductors with light-emitting junctions designed to use low-voltage, constant current power to produce light. Too little current and voltage will result in little or no light, and too much current and voltage can damage the light-emitting junction of the LED. The voltage has a acute influence on the junction temperature; a small change in drive voltage produces a large change in junction temperature. Fig. 3 shows the variation process of voltage and junction temperature with time of the LED package with heat pipe heat sink (0° incline angle of the heat pipe) at input powers of 0.5 W, 1 W, 2 W and 3 W at the same operating conditions. The *Y*-axis at the left represents the drive voltage, while at the right provides the junction temperature. On observing the curves, it is obvious that the higher the junction temperature the lower the drive voltage; however, the junction temperature should not be too large when drive voltage is sinking because of the heat dissipation capability of the LED package with flat heat pipe heat sink. It can be seen that, for a given time in the unstable process, a small change in drive voltage produces a large change in junction temperature. As LED heats up, the forward voltage through the LED drops and the junction temperature of the LED increases. If nothing removes the heat in time, the P–N junction will fail due to the accumulated heat. By driving LED light sources with a regulated constant-current power supply the light output variation and lifetime issues resulting from voltage variation and voltage changes can be eliminated. Therefore, constant current drivers are generally recommended for powering LED light sources.

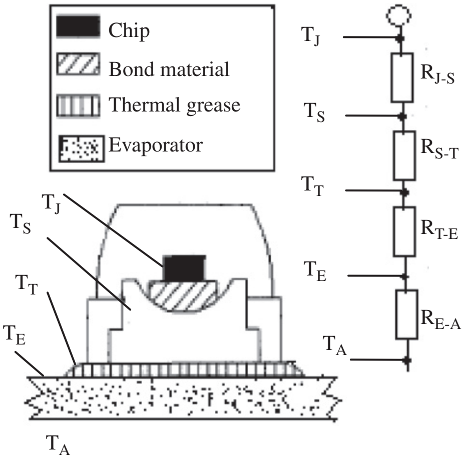

Fig. 2. Thermal resistance model for cooling system of LED.

4.2. Startup and shut down tests of high power LED

The thermal capabilities, including startup, temperature uniformity and shut-down, are very critical in evaluating the design and reliability of the FHP for the thermal control of the high power LED device. Fig. 4 shows the startup, temperature uniformity and shut down process of the FHP (0° inclination angle of the heat pipe) at input powers of 1 W and 3 W at the same operating condition. From a comparison of the startup profiles, it is noted that the startup time required for low input powers is longer than that of high input powers. As presented in Fig. 4, for 1 W input power, the startup of the FHP took about 7 min (T_{10}–T_{14}), for 3 W, less than 6.5 minutes and the junction temperature (T_J) of LED is 38 °C and 52 °C, respectively. This means that the FHP is easier to start at high input power. The junction temperature of LED increased rapidly under the startup, while it decreased rapidly under the shut-down. This indicates that the heat accumulation capacity of LED chip is feeble. If the cooling device for high power LED is effective, the heat dissipation of high power LED will be easilyy removed from the junction of LED chip; else, the heat dissipation of high power LED will be accumulated at the junction of high power LED. Therefore, the FHP can effectively meet the requirements of the thermal management of high power LED.

4.3. Junction temperature in response to input power

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 designs. Fig. 5

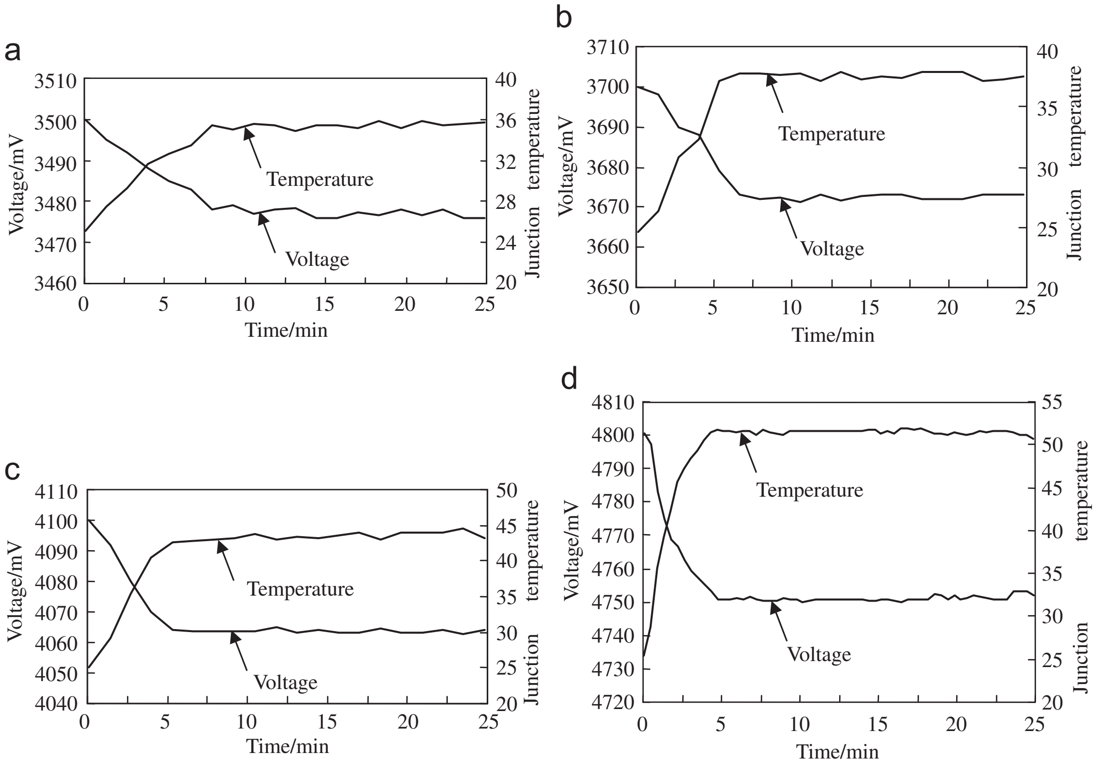

Fig. 3. Variation of voltage and junction temperature with time. (a) 0.5 W, (b) 1 W, (c) 2 W and (d) 3 W.

presents the dependences of the junction temperature of the high-power LED on input power with different inclination angles of the heat pipe. At the filling ratio of 30%, the input power in the range of 0.1–3 W and the inclination angles in the range from 0° to 30°, the junction temperature of the high-power LED increases with the increasing of input power. For input power in the range of 0.1–3 W, the junction temperature lies between 31 °C and 61 °C, as shown in Fig. 5. Minimum value of junction temperature of the high power LED and the best heat transfer capabilities of heat pipe are achieved at the optimal inclination angle of 15°. Therefore, in order to effectively meet the reliability of the thermal management of high-power LED, the impact of the different inclination angles of the heat pipe to the heat transfer performance of the heat pipe should be evaluated before such a structure of heat pipe cooling system is used to cool high power LED system.

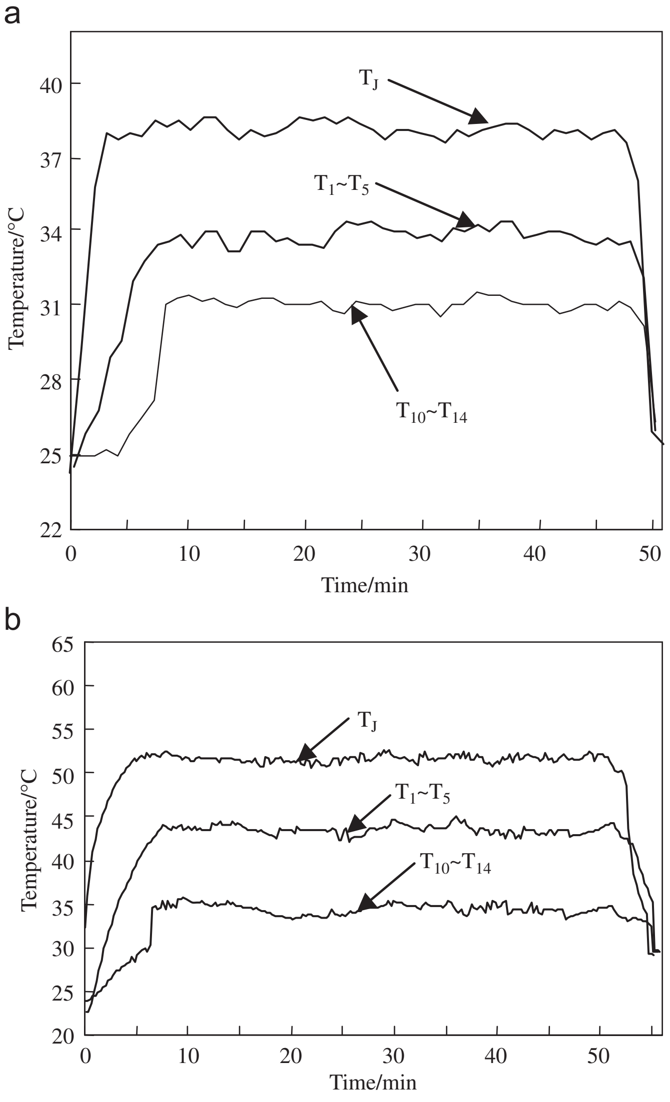

Fig. 4. Characteristic diagram of the startup and shut-down of LED. (a) 1 W and (b) 3 W.

4.4. *Thermal resistance of high power LED system*

Fig. 6 presents the dependences of the thermal resistance of the high-power LED system based on heat pipe heat sink on input powers with different inclination angles of the heat pipe (the filling ratio of 30%). The obtained result indicates that the heat pipe of 15° incline angle has better thermal capabilities than that of 0° and 30° inclination angles. However, comparing the different inclination angles , the thermal resistance of the high-power LED system gradually decreases with the increase of input power and the trend curve is gentle correspondingly. The obtained results indicate that the total thermal resistance of LED system is 8.8 K/W for the input power of 3 W.

At low input powers, as the mass flow rate of vapor is small, the majority of the condenser is occupied with the liquid and compensation chamber is only partially filled. With increasing input powers, the mass flow rate of vapor increases so that large area of condenser will be required for the phase change process. In order to claim area of the condenser, the vapor displaces the liquid from the condenser to the compensation chamber. As a result, the average temperature of the condenser increases; the temperature difference between the evaporator and condenser becomes smaller correspondingly, so the thermal resistance of the high-power LED system based on heat pipe heat sink becomes smaller.

4.5. *Effect of liquid filled ratio on junction temperature of LED*

This filling rate range aims to get the best heat dissipation. Fig. 7 shows the effect of the filling ratio of heat pipe on the junction temperature of LED, for 3 W input power and the same operating condition. It is found from Fig. 7 that the junction temperature is at the minimum when the filling ratios is about 30% for water. For other filling ratio, the present experiment has confirmed that the junction temperature was higher than that of the filling ratio of 30%. Therefore, it could be concluded that there existed an optimal filling ratio to the heat pipe and this optimal

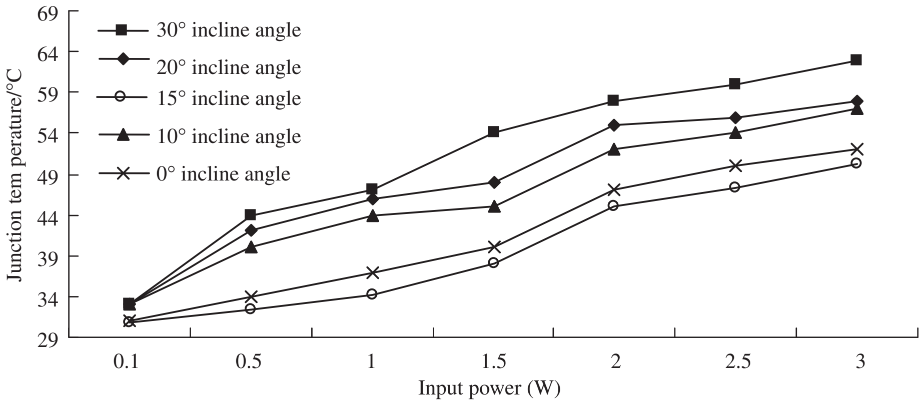

Fig. 5. Input power vs. the junction temperature of LED.

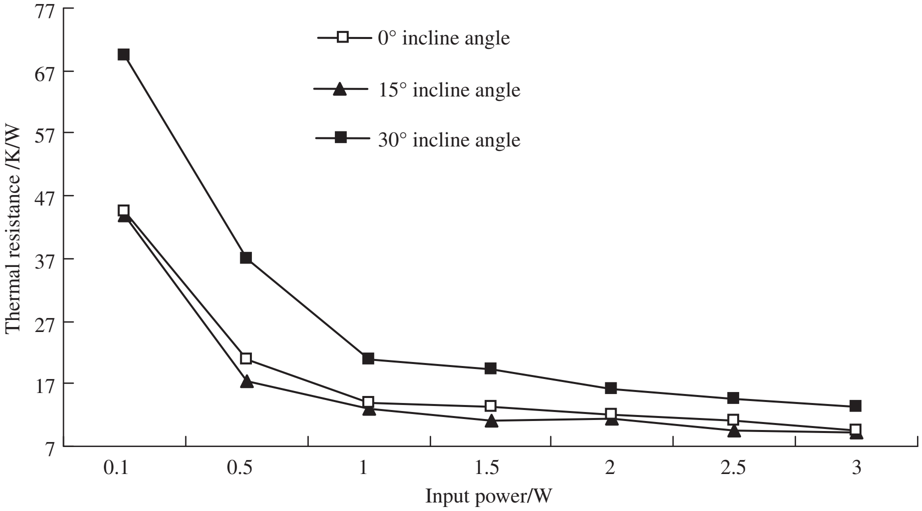

Fig. 6. Thermal resistance vs. input power.

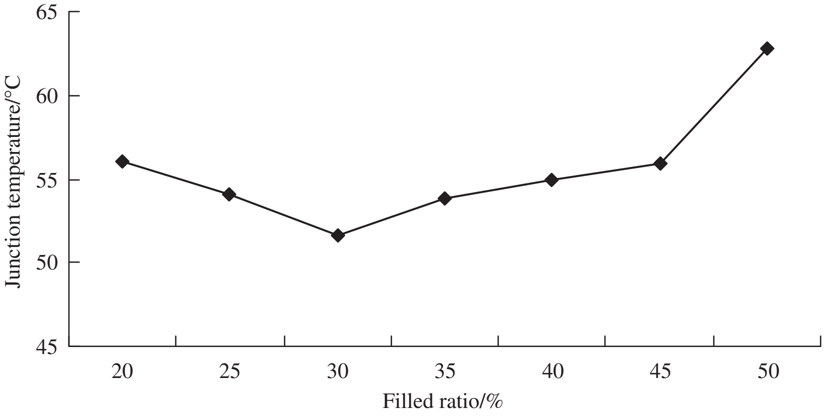

Fig. 7. Filled ratio vs. the junction temperature of LED.

filling ratio was about 30%. The experimental results indicate that the filling ratio can influence the equivalent heat transfer coefficient significantly. Therefore, the impact of the different filling rates of the heat pipe to the heat transfer performance of the heat pipe should be evaluated before such a structure of heat pipe cooling system is used to cool high power LED system.

5. Conclusions

A novel flat heat pipe cooling device for high power LED is developed and the heat-release characteristics of high power LED package are analyzed. The thermal capabilities, including startup performance, temperature uniformity and thermal resistance of high power LED package with flat heat pipe heat sink, have been investigated experimentally. The obtained results indicate that the junction temperature of LED is about 52 °C for the input power of 3 W, and correspondingly the total thermal resistance of LED system is 8.8 K/W. The impact of the different filling rates and inclination angles of the heat pipe to the heat transfer performance of the heat pipe should be evaluated before such a structure of heat pipe cooling system is used to cool high power LED system.

The experiments under special conditions, in addition, such as the lifetime of different input powers LED with FHP, using liquid silicon instead of water and the most extreme ambient temperature, e.g., the ambient temperature of 40 °C, and whether the cooling system can achieve the cooling requirements should be a topic for further research.

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