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Combined convection and radiation heat transfer of the radially finned heat sink with a built-in motor fan and multiple vertical passages

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ABSTRACT

This work proposed a novel finned heat sink with the air-driving device and vertical flow passages for LED lamp. The heat sink, made of aluminum alloy, was a cup-shaped cylinder with multiple externally radial fins. Various motor fans were mounted in the hollow chamber of the heat sink. Coupling with the multiple vertical passages in the ring wall of the heat sink and the separation board in the chamber of the heat sink, the air flow was driven through the internal of the heat sink. The measured air velocity within the vertical passages and the smoke flow visualization demonstrated that the present air-driving device did work. The heat-transfer experiments for the systems with the built-in motor fan and compressed air flow were performed, respectively. The overall heat transfer mechanism of the present cooling device was the combination of the internally forced convection and the externally natural convection coupling with radiation heat transfer. The overall Nusselt number of the heat sink with the built-in motor fan was 28–102% higher than that without motor fan. In general, bigger motor fan drove more air flow to enhance heat transfer. Finally, a theoretically empirical formula was proposed to predict the Nusselt numbers of the present combined convection and radiation heat transfer. The applied range was Grashof number $Gr = 2.37 \times 10^5$–5.92×10^5 and Reynolds number $Re \leqq 343$. The maximum deviation of the total Nusselt number between the predictions and the experimental data of the system with compressed air flow was ±11%.

1. Introduction

About 85% consumption of electric power of the light-emitting diodes (LEDs) is converted to waste heat. If the waste heat is not effectively dissipated, high temperatures will cause the LED light failure and shorten the lifetime of use. The waste heat of LEDs is generally transferred from the LED substrate to the fined heat sink via thermal conduction, and then carried away from the fins by the air-flow thermal convection. Two cooling mechanisms of thermal convection are often used. One is using the temperature difference between the high-temperature fins and the ambient to generate the passive cooling of natural convection whose advantages are no additional power element required, high reliability and energy saving; the other is employing the air-driven device to lead the active cooling of forced convection, which is especially suitable for high power LEDs. In the assembly of the current LED heat sink, to facilitate the process, LED is welded to the printed circuit board (PCB) of the glass substrate (FR4), which is attached to a metal plate. The metal of high thermal conductivity such as aluminum or copper can help in dissipate heat. This is the Metal Core PCB (MCPCB) of high thermal conductivity. The main purpose of MCPCB is to uniformly spread the highly concentrated heat generated from LEDs, to increase the contact area with the air, so that the junction temperature of LEDs can drop quickly. However, for LEDs of growing power, MCPCB alone is unable to meet cooling requirements because the local ultrahigh heat flux generated from high power LED cannot be uniformly dispersed by the conventional thermal conductive plate, in addition to the insufficient spreader heat dispersing area. Therefore, as shown in Fig. 1, highly efficient spreader and heat sink are installed on MCPCB to uniformly disperse the heat and significantly increase the contact area of per unit volume with air, so that heat conduction and heat convection will be more sophisticated to get better heat dissipation.

Many studies have adopted the heat pipes, such as loop heat pipes and vapor chamber plates, to be the highly efficient spreaders of LEDs. Shen et al. [1] developed a high-intensity LED headlight to replace the traditional high-pressure mercury headlight as autonomous underwater vehicle lighting. Their study presented a self-adjusting micro vapor chamber to reduce the high

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Nomenclature

A	surface area (m^2)
d	diameter of vertical passages (m)
C_p	specific heat (W/kg/°C)
D	diameter of film heater (m)
D_{in}	inner diameter of cylindrical chamber of heat sink (m)
$\hat{F}$	effective radiation view factor of all exposed surface of heat sink
Gr	Grashof number, Eq. (1)
Gr_{Din}	Grashof number, Eq. (10d)
h	heat transfer coefficient ($W/m^2/°C$)
H_1	length of vertical passages (m)
H_f	vertical length of fins or height of heat sink (m)
I	input current (A)
k	thermal conductivity (W/m/°C)
n	umber of vertical passages
Nu	average Nusselt number, Eq. (3)
Q	heat (W)
Q_{flow}	volumetric air flow rate (m^3/s)
Re	Reynolds number, Eq. (2)
Re_{Din}	jet Reynolds number of the region b, Eq. (10d)
T	temperature (°C)
T_0^*	the bulk mean temperature of air through the region a
T_0^{**}	the bulk mean temperature of air through the region b
T_0^{***}	the bulk mean temperature of air through the region c
V	input voltage (V) or air velocity in the vertical passage (m/s)

Greek symbols

σ	Stefan-Boltzmann constant [$W/m^2/K^4$]
η	fin efficiency

Subscripts

0	the ambient environment
1	the first path (internal cooling path)
2	the second path (external cooling path)
a	region a (the vertical inlet passages of heat sink)
b	region b (the cylindrical chamber of heat sink)
c	region c (the vertical outlet passages of heat sink)
ext	external surface of heat sink
fc	forced convection
$heat$	heating surface
$Loss$	heat loss
nc	natural convection
$plate$	horizontal plate
rd	radiation
s	solid part of the heat sink
t	total
vp	vertical plate
w	heating wall

consumption of heat by 100 W/cm^2, the use of composite moisturizing structures to improve the moisturizing efficiency of the micro-device inside the vapor chamber. Therefore, vapor chamber is able to maintain the original heat transfer capability and its gravitational effects can be reduced. Lu et al. [2] used the flat heat pipe to improve the cooling of high-power LED and conducted a series of experiments to investigate the heat transfer characteristics. That study pointed out that the performance of flat heat pipe is affected by the placement angle of inclination. Wang [3] experimentally and theoretically explored the heat transfer performances of three LED substrates. He found that the heat-transfer capacity of the vapor chamber plate is better than that of the copper or aluminum substrate when the input power is higher than 5 W. Xiang et al. [4] developed a new phase-change heat sink for high-power LED lamps. Its three-dimensional structure consists of the circumambient spiral micro grooves and the radial micro grooves. It can help to the phase-change refrigerant to evaporate by heat while circulating refrigerant is powered by the siphon force provided by the sintered copper-beads wick on the inners surface of the heat sink. Lin et al. [5] experimentally investigated the heat transfer characteristics of aluminum flat heat pipe, using acetone as the working fluid in the heat pipe. The heat pipes are arranged on the plane in a zigzag way to form a serially connected structure of a number of sharp 180-degree turns. At both sides of the plane, it is connected with the condenser and evaporator. That study indicated that an increase in the cross-sectional area and the number of turns of the internal passage can improve the heat transfer capability. Hsieh et al. [6] designed a flat heat pipe of mixed siphon structure of wick and copper mesh layer as the cooling device for the LED lamp. They found that this flat heat pipe can reduce the LED junction temperature by 28%, and make the LED substrate temperature uniform. Dehuai et al. [7] used the phase-change heat sink to improve the cooling of high power LED by developing 3D integral-fin boiling structures. Inside the micro grooves, there are two different fin structures. The cooling characteristics of using them in high power LED were analyzed. Wang [8] explored the possibility of integrating high power LED with thermoelectric generator for waste heat recovery. That study combined the vapor chamber plate with LED PCB substrate to increase the heat transfer. The result suggested that the combination could help heat transfer performance, illumination and thermoelectric conversion. Lin et al. [9] experimentally discussed the performance of applying the loop heat pipe of dual parallel condensers in high power LED. The loop heat pipe, under the operating conditions of natural convection, can get the thermal resistance from 1.0 to 0.4 °C/W with thermal load ranging from 30 W to 300 W.

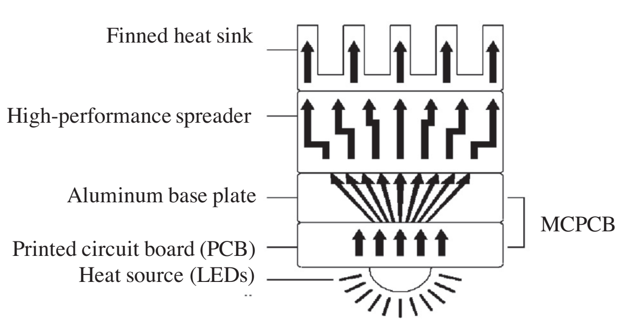

Fig. 1. Schematic diagram of cooling-device model for LEDs.

The heat transfer studies of LED heat sink can be divided into natural convection [10–20] and forced convection [21–27] by heat convection mechanism. LED cooling is the coupled heat transfer of heat conduction and heat convection. For natural convection, heat sink type, material and the direction of placement have a significant impact on the overall heat transfer performance. Yung et al. [10] analyzed the effect of placement angle on the natural convection heat transfer of high power LED packaged on PCB, and found that it is an important factor affecting heat transfer. Shyu et al.