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The effects of vent channels and metal conductive base on thermal characteristics of the active graphite-composite cylindrical heat sink☆

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ABSTRACT

This study proposed a novel configuration of active LED graphite-composite heat sink and experimentally investigated the effects of vent channels and metal conductive base on the fluid flow and heat transfer characteristics of this active heat sink. The heat sink was made of the graphite powders, aluminum-alloy powders, and adhesive mixed in specific proportion by the vacuum-pressure injection technique. The cost and weight of this graphite-composite material are much lower than those of aluminum alloy. The configuration of heat sink is a hollow circular cylinder with multiple radial fins. Different motor fans can be put in the chamber of heat sink, with various vent-channel positions and orientations (vertical vent channels, horizontal upper-row vent channels, and horizontal bottom-row vent channels) and numbers of channels (24, 36, 48, and 72) in the heat sink to enhance overall cooling performance by driving through airflow. The results indicate that the overall Nusselt number (Nu) of the graphite-composite heat sink with motor fan was 2.23–2.50 times that without motor fan. The numbers of vent channels in heat sink were positively related to the total flow rate of through air. Thus, the heat sink with the most vent channels had the maximum Nu in the motor-fan mode. When an additional annular aluminum-alloy conductive base was mounted in the graphite-composite heat sink with the most vent-channel configuration, the Nu was 35% higher than that without conductive base in motor-fan mode, proving the metal conductive base was effective. The optimal vent-channel configuration in this study was also used for the full aluminum-alloy heat sink, the corresponding Nu of the models without/with motor fan were compared with the full aluminum-alloy heat sink without vent channel, the heat transfer enhancements were about 13% and 127%, respectively.

1. Introduction

Light-emitting diodes (LED) are characterized by energy saving, good color-rendering index, compactness, and zero mercury compared with halogen lamps and filament lamps on the market. The color-rendering index refers to the difference between the color of the object in artificial light and that in the sunlight. With a high color-rendering index, the illuminated object is more likely to reveal the original color. The LED is also characterized by long life, which is 10 times of traditional filament lamps and 16 times of energy-saving bulbs. However, this characteristic is only applicable to low temperature environment. To replace traditional lamp lighting market, the luminous efficiency of LED must be increased to at least 60 lm/W. In other words, as the power increases, if the waste heat generated by LED in working environment cannot be exchanged with the environment effectively, the high temperature will cause severe decrease in the luminous efficiency of LED. If based on the junction temperature, and the working temperature is maintained lower than 50 °C, the service life of LED is almost 20,000 h. When the temperature rises to 100 °C, the service life is only 5000 h. Therefore, the development of high power LED heat sink is the key factor affecting the lighting market share of LED lamps [1].

Many recent studies have analyzed LED heat sink and proposed improvement programs. The relevant researches aim at the effects of material, placement angle, and configuration design on the overall heat transfer performance at natural cooling and forced cooling conditions respectively. In terms of material, most of common LED heat sinks on the market are made of aluminum alloy. The aluminum alloy has better thermal conductivity, but the heat sinks made of aluminum alloy still have relatively heavy weight and high cost. Therefore, research and development of alternative materials of LED heat sink gain more and more attentions. The thermal conductivity of pure graphite is higher than 800 W/m/K, being very conducive to conduct heat. The heat spreader made of graphite material has particular grain orientation, and it conducts heat efficiently in a specific direction. Its overall weight is about 75% lower than copper heat sink and 25%

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Nomenclature

A_{heat}	heating surface area [m^2]
D	diameter of film heater [m]
g	gravitational acceleration [m/s^2]
Gr	Grash of number, Eq. (1)
H	heat sink height [m]
I	electric current [A]
k	thermal conductivity [W/m/K]
Nu	Nusselt number, Eq. (2)
Q_{flow}	airflow rate through heat sink [m^3/s]
Q	heat [W]
T	temperature [°C]
V	electric voltage [V] or air velocity measured at the open end of vent channel [m/s]

Greek symbols

β	coefficient of volume expansion [K^{-1}]
ρ	density [kg/m^3]
μ	dynamic viscosity [N-s/m^2]

Subscripts

0	the ambient environment
1	vertical vent channels
2	horizontal upper-row vent channels
3	horizontal bottom-row vent channels
ave	Average value
f	fluid
Loss	heat loss
plate	horizontal plate
t	total
w	heated wall

Superscripts

*	effective

lower than aluminum heat sink. It is a good lightweight heat-sink material in comparison to aluminum alloy. Therefore, the application of graphite material to the development of 3C electronic products and high power LED heat sinks has gain more attentions.

There are two cooling modes of LED heat sinks. One is the passive cooling, and the other is the active cooling. The passive cooling is to conduct the heat generated by the LED substrate to the fins of heat sink, and then the heat is dispersed to the ambient via natural convection. For the active cooling mode, a fan is mounted outside or inside the heat sink. The rotating blades push air and import cold flow to form forced convection, and then the waste heat generated by LED substrate can be carried away effectively, enhancing the overall heat transfer capacity greatly. However, the fan cooling increases somewhat the overall weight and cost. In order to obtain a better design of LED heat sink taking into account the weight, cost, and cooling performance, this paper would investigate effects of material and configuration of heat sink on the overall heat transfer and try to propose the optimum design in line with the above objectives.

In terms of the literatures about the heat transfer of graphite material, Stoessel et al. [2] indicated that the heat transfer coefficient of general heat sinks was lower than 180 W/m/K, and they used the improved hollow cathode magnetron method to make a 800 W/m/°C composite material combined graphite fiber and strengthened copper array. It could be used as the spreader with high thermal conductivity. Zhong et al. [3] infiltrated compressed expanded natural graphite into Wood's alloy to form a phase-change heat-storage material with high thermal conductivity. The thermal conductivity of the composite material is 2.8–5.8 times of pure Wood's alloy, and the latent heat can reach 29.27–34.20 J/g. Fu et al. [4] combined three graphite materials, graphene, graphite nanofiber, and pure graphite with epoxy resin respectively to make composite thermal grease and used experimental method to discuss the heat transfer characteristic of the composite material. The results showed that the measured thermal conductivity was 4.01 W/m/°C when the maximum addition level of graphene in the composite thermal grease was 10.10%, the thermal conductivity was 22 times of epoxy resin, 2.2 times of composite thermal grease with graphite nanofiber, and 2.4 times of composite thermal grease with pure graphite. The results show that the addition of graphite material to the epoxy resin material can enhance the overall conduction performance effectively. Tzeng et al. [5] experimentally studied the heat transfer characteristics of aluminum-alloy and graphite-composite heat sinks. The experiments found that the natural convection heat transfer of graphite-composite heat sink was 66% of aluminum-alloy heat sink, but the total weight was only half of aluminum alloy and the cost was low. With the adjustments of graphite-composite components and heat-sink configuration, the graphite composite may be a potential alternate material for heat sinks. Chen [6] experimentally studied the natural convection heat transfer characteristics of graphite-composite heat sink. The experimental results indicated that the heat transfer performance of graphite-composite heat sink was next to the pure aluminum-alloy heat sink, but the light decay was not worse than the aluminum-alloy one. This graphite-composite heat sink with low-cost and lightweight has great commercial potential in related domains. Solmus [7] used numerical method to discuss forced convection heat transfer characteristics of rectangular channel full of graphite foam material. The mathematical model used a two-equation model to simulate energy transfer and used a Brinkman–Forchheimer-extended Darcy model to simulate momentum transfer. The results showed that at the condition of large pressure drop, the heat transfer of graphite foam material was better than aluminum foam material, and the numerical result proved that the temperature of graphite foam material was very different from the temperature of the air through the same position, conforming to the assumption of two-equation model.

In terms of the literatures about the natural convection cooling application, Jang et al. [8] discussed the angular effect on the natural convection heat transfer of annular radially arrayed finned heat sink and used numerical simulation and experimental method for analysis. The results indicated that the angular effect on the overall heat transfer of heat sink increased with the fin length and the number of fins, but it did not change though the fin height increased. The empirical equation proposed in their study can be used to calculate the Nusselt number value of annular finned heat sink at different tilt angles. Shen et al. [9] discussed the effect of angle on the heat transfer characteristics of square finned heat sinks with various fins. It was found that the denser the fins were, the greater was the effect of angle on the overall heat transfer performance. Their study created an empirical equation at last, so as to estimate the Nusselt number value of the heat sink at multiple angles. Jang et al. [10] investigated the angle effect of annular finned heat sink on the overall thermal resistance. The experiment indicated when the heat-sink angle was $0^\circ < \theta < 90^\circ$, the overall thermal resistance of the annular heat sink with radial plate fins increased with the angle; the thermal resistance of the annular heat sink with axially equidistant fin array firstly decreased and then increased as the angle increased. Ahmadi et al. [11] proposed the heat transfer of axially discontinuous finned heat sink in natural convection. The results indicated when the axial fins of heat sink combined more discontinuous spaces, the overall heat transfer performance of heat sink could be enhanced more effectively. Charles et al. [12] proposed the novel fins to enhance natural convection heat transfer. The fin shapes included plate, trapezoid, and inverted trapezoid. The findings indicated that the heat transfer coefficient of inverted trapezoid finned heat sink was higher than trapezoid finned heat sink by 25% and higher than plate