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Flow and heat transfer in porous micro heat sink for thermal management of high power LEDs

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ABSTRACT

A novel porous micro heat sink system is presented for thermal management of high power LEDs, which has high heat transport capability. The operational principle and heat transfer characteristics of porous micro heat sink are analyzed. Numerical model for the micro heat sink is developed to describe liquid flow and heat transfer based on the local thermal equilibrium of porous media, and it is solved with SIMPLE algorithm. The numerical results show that the heated surface temperature of porous micro heat sink is low at high heat fluxes and is much less than the bearable temperature level of LED chips. The heat transfer coefficient of heat sink is very high, and increasing the liquid velocity can enhance the average heat transfer coefficient. The overall pressure loss of heat sink system increases with the increasing the inlet velocity, but the overall pressure drop is much less than the pumping pressure provided by micro pump. The micro heat sink has good performance for thermal management of high power LEDs, and it can improve the reliability and life of LEDs.

1. Introduction

High power light emitting diodes (LEDs), which depend on the semiconductor material to emit the light have attracted much more attention in recent years because of several advantages [1,2]. Currently, the common illumination technologies are incandescent lamps, halogen lamps, and fluorescent lamps. Compared with these light lamps, LEDs have many advantages, such as high quantum efficiency, high light emitting efficiency, long lifetime, energy saving, environmental protection, and so on [3–5]. Therefore, LEDs are considered as a potential candidate of the next generation lighting source.

For the current applications of LEDs, there are two problems to be solved, one is the optical extraction and the other is heat dissipation of the system. Especially for the high power and high brightness LEDs and LED arrays, thermal management becomes the most important problem. In theory, the light emitting efficiency of LEDs is very high, but due to lack of good thermal management technology, the actual efficiency of electrical energy converting into light energy is about 10–20%, it means more than 80% input power will convert into heat [6–8]. The power of modern LED chip for light is more than 1 W, even reached to 5 W, and the area of chip is less than 1 mm^2, these lead to the heat flux of LED chip, which is more than 100 W/cm^2, and the high heat flux will result in high junction temperature of LED [9]. The high junction temperature of LEDs will greatly reduce the output light efficiency and lead to a red-shift of the emission wavelength, which will change the color of the light and is undesirable for the special applications. In addition, the high junction temperature will accelerate the aging of LEDs and decrease the life time of LEDs [10–12]. Therefore, the junction temperature of LED must be controlled below (110 ± 5 °C) for guaranteeing high performance and the life of LEDs [13,14]. The low operational temperature is essential for high efficiency of LEDs, and the effective thermal management technology is needed for applications of high power LEDs.

In this paper, a novel porous micro heat sink system is presented for thermal management of high power LEDs. Because the porous micro heat sink is mainly composed of porous media, which has large specific surface area and high local heat transfer coefficient, the system has high heat transport capability and is considered a promising cooling method for dissipating increasingly higher power densities of LEDs. Based on the local thermal equilibrium of porous media, mathematical model for the micro heat sink is proposed to describe liquid flow and heat transfer in the heat sink, and it is solved with SIMPLE algorithm as a conjugate problem. The numerical results show that the porous micro heat sink system has a good cooling ability for the high power LEDs, and it can improve the reliability and life of LEDs.

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To the best of our knowledge, the porous micro heat sink system has not been proposed before in the context of heat dissipation for high power LEDs.

2. Porous micro heat sink system

Fig. 1 shows a schematic diagram of a porous micro heat sink system. As seen, the present system is composed of a porous micro heat sink that mainly consists of porous media, LED chips, a small heat exchanger, a micro pump, and liquid transport lines. The porous micro heat sink system is an active system and the micro pump provides force of working fluid though the loop to matches the total pressure loss in the whole system. The fluid velocity is mainly affected by the input power and pump pressure of micro pump, and the fluid velocity cannot exceed a maximum value that provided furthest by a micro pump. The LED chips are packaged on the upper surface of micro heat sink directly. During normal operation, working fluid in the closed system is driven into the porous micro heat sink through an inlet by the micro pump. The working fluid flows through the porous media inside the heat sink, and the heat created by the LEDs is transferred to working fluid by porous media, and working fluid is heated and its temperature increases after flowing out the heat sink. Then working fluid enters into a small heat exchanger, in which the heat can be dissipated to the external environment and working fluid will be cooled to the low temperature level. Low temperature liquid continues to flow through the liquid transport line and returns to the heat sink, completing the cycle.

The porous micro heat sink system has special advantages for the thermal management of high power LEDs. Firstly, the porous media used inside the heat sink is made up of sintered metallic wick or metallic mesh, and the effective capillary radius of porous media is in microns, which is small around 10 μm, or even around 3 μm. Therefore, the porous media has large ratio of heat dissipated surface to volume that results in high local heat transfer coefficient inside the porous media, and the system has high heat transport capability for thermal management of high power LEDs. Secondly, the present system has flexible transport lines, and the external heat exchanger can be placed where it is convenient to transfer heat from system to external environment. As a result, the porous micro heat sink system is suitable for cooling of electronic devices in the limited space, such as cooling of high power LEDs.

3. Mathematical model of porous micro heat sink

The heat sink is directly attached to the LED chips, and the temperature level of heated surface is very important parameter

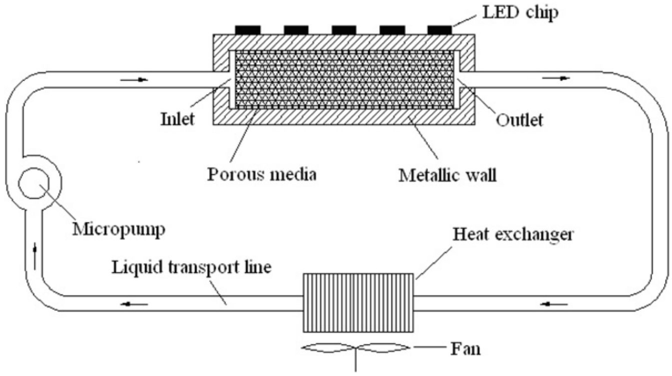

Fig. 1. Schematic diagram of a porous micro heat sink system.

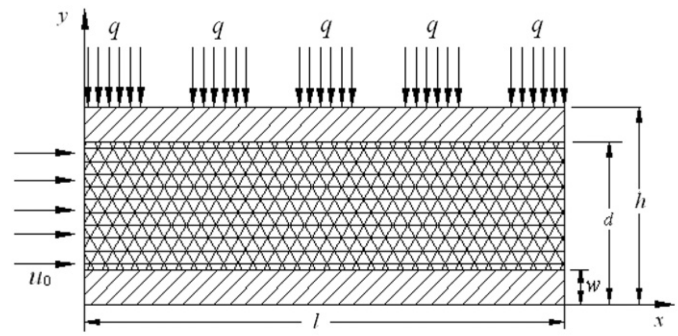

Fig. 2. Computational model of porous micro heat sink.

to influence the performance of high power LEDs. Lower temperature of heated surface is desired for the high power LEDs packaging. Consequently, a thorough understanding of the physical behaviors occurring within the heat sink is very important to estimate the performance of the present system for thermal management of high power LEDs. The copper wall is used as the metallic wall of heat sink, and the thermal conductivity of copper is very large (about 398 W/m K). Fig. 2 shows the computational domain and coordinate system of porous media inside the heat sink. The origin of coordinate system is located at the left bottom corner of the heat sink.

To develop the mathematical model, the main assumptions are made as follows:

(1) The porous media is rigid, homogenous, isotropic, and fully saturated with fluid.
(2) There is a local thermodynamic equilibrium between solid phase and liquid phase inside the porous media.
(3) The fluid is incompressible and has constant properties.
(4) Since the natural convection heat transfer coefficient is very low, air convection heat transfer along metallic wall can be negligible compared to the heat produced by LED chips.

The flow and heat transfer for the liquid in the porous media are based on the volume-averaged technique and Brinkman–Darcy–Forchheimer model of porous media.

The governing equations of the porous media can be written as follows.

Continuity equation:

$$\frac{\partial(\varepsilon\rho_f)}{\partial t}+\frac{\partial(\rho_f u)}{\partial x}+\frac{\partial(\rho_f v)}{\partial y}=0 \tag{1}$$

Momentum equation:

$$\frac{\rho_f}{\varepsilon}\frac{\partial u}{\partial t}+\frac{\rho_f}{\varepsilon^2}\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}-\left(\frac{\mu}{K}+\frac{\rho_f C}{\sqrt{K}}|\vec{V}|\right)u+\frac{\mu}{\varepsilon}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$\frac{\rho_f}{\varepsilon}\frac{\partial v}{\partial t}+\frac{\rho_f}{\varepsilon^2}\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}-\left(\frac{\mu}{K}+\frac{\rho_f C}{\sqrt{K}}|\vec{V}|\right)v+\frac{\mu}{\varepsilon}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

Energy equation:

$$(\rho c)_e\left(\frac{\partial\theta}{\partial t}+u\frac{\partial\theta}{\partial x}+v\frac{\partial\theta}{\partial y}\right)=\frac{\partial}{\partial x}\left(k_e\frac{\partial\theta}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_e\frac{\partial\theta}{\partial y}\right) \tag{4}$$