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Development of heat sink with ionic wind for LED cooling

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ABSTRACT

A heat sink with ionic wind has been developed in this study for a new cooling device of a Light Emitting Diode (LED). The characteristics of the ionic wind using wire to parallel-plate-electrodes were analyzed using the Computational Fluid Dynamics (CFD) technique suggested in this study. Also, the cooling performance of the heat sink applied by the impinging flow of the ionic wind was investigated by parametric studies. The CFD results were verified from the experimental results of the ionic wind velocity and temperature. A developed prototype of the heat sink with the ionic wind was then manufactured and tested for its cooling performance. Finally, the advantages of the heat sink with the ionic wind for cooling the LED were confirmed.

1. Introduction

The Light Emitting Diode (LED) has attracted attention as an energy saving device since it has the highest energy efficiency among existing lighting devices. Thus, many studies on a cooling device for the LED have been performed. The heat dissipation rates of LED devices have increased, and the demand for efficient cooling systems therefore now exceeds the current technology. In accordance with the increasing demand for a compact size, the cooling system should also become smaller and lighter. A heat sink is the most common cooling device for all electronics because of its high productivity. However, the cooling performance of the heat sink is proportional to its size and weight in general since the heat transfer by natural convection is strongly affected by the surface area of the heat sink. Thus, it is natural that the heat sink is becoming larger and heavier in accordance with increasing power of a LED. However, too large and heavy heat sink is not applicable in industrial and commercial fields. Although market share of the LED lighting is now starting to include high-power LEDs, there still is a problem for the lack of a proper cooling technology. Nevertheless, very few studies have been performed for the high-power LED over than 150 W up to date [1–3]. For the high-power LED greater than 150 W, natural convection with the heat sink has a limit for the application as a lighting device because of its size and weight. Thus, research about optimization of the heat sink using a fan for the LED cooling have been published in these days for enhancing the cooling performance of the heat sink, and at the same time, minimizing the system compared to the heat sink without the fan [4–7]. The LED lighting used in the room, however, requires silence and vibrationless characteristics of the cooling device. Therefore, the studies for a piezoelectric fan [8,9] or an ionic wind blower [10–12] have a great attention for the cooling device of the LED recently.

Thus, a heat sink using ionic wind is suggested for a new cooling device for the LED in this study to overcome the disadvantages of other cooling devices. This new cooling system does not need any mechanical moving parts to create a flow. Because an impinging jet is made using a single wire, the required compact size of the device can be achieved. Also, it does not have any vibration that can cause noise and wear.

Although study on the impinging flow of a synthetic jet on the heat sink is very new, a few researchers such as Chaudhari [13–15] and Lasance [16] have already carried out many tests and proved its relatively high value due to the heat transfer performances. The impinging ionic wind has been proven to have a higher heat transfer augmentation to natural convection and many advantages compared with fan cooling [17–20]. Moreover, most recently, Chen [12] analyzed the effect of ionic wind and demonstrated its advantages for cooling the LED. However, no report on the practical development of the heat sink with the ionic wind has been presented. Thus, in this study, the parametric study of the heat sink with the ionic wind was conducted using Computational Fluid Dynamics (CFD). Also, a performance test of the prototype was carried out experimentally. The results presented in this paper can be used practically in the industrial field for the optimum

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Nomenclature

P	pressure	q	space charge density
H	heat transfer coefficient	ϵ	dielectric permittivity
h_e	enthalpy	R_i	ionization zone radius
T_s	surface temperature	R_c	curvature of discharge electrode
T_∞	ambient temperature	D	diffusivity of ions
ρ	density of air	K	ion mobility
$\mathbf{u}$	velocity of ionic wind	μ_t	eddy viscosity
$\mathbf{V}$	applied voltage		
$\mathbf{E}$	applied electric field intensity		
$\mathbf{U}$	velocity vector of flow		

design of an ionic wind generator with the heat sink. The results of the impinging ionic wind with the developed heat sink are expected to have practical utility.

2. Theoretical background

2.1. Generation of ionic wind

If the threshold electric field is applied between a wire (a discharge electrode) and a plate electrode (collecting electrodes), a corona discharge occurs at the wire. From this local discharge at the wire, air molecules are ionized into ions and electrons. The charged ions and electrons then move in opposite directions due to their polarity as space charges. Positive ions moved to the plate electrode after positive voltage was applied on the wire in this study. During this travel, heavy ions impact with air molecules to transfer an inertia force. From the collision between accelerated ions and air molecules, flow can be generated, known as ionic wind or corona wind.

2.2. Numerical study

To find out the velocity of the ionic wind according to the position of the wire, three pre-coded models such as 'transport of diluted species', 'electrostatics' and 'laminar flow' in 'Comsol Multiphysics 4.3' were used. And 'Ansys CFX 13' was used to calculate the temperature of the heat sink according to various conditions of the ionic wind since it provided a parametric study mode for the three-dimensional analysis of the heat transfer in the heat sink. Firstly, the average outlet velocity of the ionic wind by various conditions was calculated at 10 mm away from the plate-electrodes, where the cooling-target would be placed, by using 'Comsol Multiphysics.' And then, 'Ansys' was used for calculating the heat transfer mechanism of the forced convection with the ionic wind. In that case, the flow was applied as the ionic wind from the electrodes with the proper boundary conditions to obtain the same average velocity, which was calculated by 'Comsol.'

The calculation domain of the ionic wind can be divided into an ionization zone and a drift zone. In the ionization zone, all the mechanisms that involve generating space charges and emerging from the boundary of the ionization zone are considered. Moreover, the space charges transfer their momentum inertia to the air molecules to create a flow in the drift zone. All governing equations explained in this paper were considered only in the drift zone. Using the present simulation method, proper boundary conditions were set on the surface of the ionization zone to consider the generated space charge density.

The electric field E is given by Eq. (1).

$$E = -\nabla V \tag{1}$$

In addition, the electric potential V is obtained by solving the Poisson's equation as follows:

$$\nabla^2 V = -\frac{q}{\epsilon} \tag{2}$$

where V is the electric potential, q is the space charge density, and ϵ is the dielectric permittivity of the free space. The initial space charge density was set up as an input boundary condition on the surface of the ionization zone. It was calculated using Eqs. (1) and (2) with some assumptions based on Kaptsov hypothesis [21] and Peek's law [22]. Using Kaptsov hypothesis, the electric field intensity on the boundary surface of the ionization zone is kept constant as the dielectric breakdown strength of air (30 kV/cm) after the corona discharge is initiated. In addition, the radius of the ionization zone can be calculated by following Peek's empirical formula.

$$R_i = R_c\left(1 + 2.62 \cdot \frac{10^{-2}}{\sqrt{R_c}}\right) \tag{3}$$

where R_i is the ionization zone radius and R_c is the curvature of the discharge electrodes. Eq. (1) is substituted into Eq. (2) to solve the gradient using Eq. (3) and the electric field intensity on the surface of the ionization zone (30 kV/cm). Then, the initial space charge density can be calculated [23]. The calculated initial space charge density was set for the proper boundary condition on the wire in the CFD.

The momentum transfer between the moving space charges and the air molecules is defined by the charge transport equation as follows:

$$\nabla \cdot (-D\nabla q - K\nabla V q) + U \cdot \nabla q = 0 \tag{4}$$

where D is the diffusivity coefficient of ions, U is the velocity of airflow, and K is the ion mobility in an electric field. The second term of Eq. (4) is the conduction force used to define the motion of the ions under the electric field relative to the total air flow, which is the main force used to make the momentum transfer mechanism. Since it has a predominant role in the momentum transfer mechanism, the other two terms (convection, diffusion) were ignored in this study. Thus, the current density generated by the moving space charges is reduced to the following form.

$$J = KqE \tag{5}$$

Since this system is assumed to be in a steady state condition, the current density should also be conserved using the following equation.

$$\nabla \cdot J = 0 \tag{6}$$

The evolution of the space charge density in the drift zone is reduced to the following form, by substituting Eq. (5) into Eq. (6) and solving the divergence using Eqs. (1) and (2) [23].