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Experimental optimization of ion wind generator with needle to parallel plates for cooling device

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ABSTRACT

An efficient cooling system is needed for Light Emitting Diode (LED) devices since they consume 70% of the applied power as heat. Thus, much research on cooling devices has been performed this century. However, most of the developed systems do not have high enough cooling efficiency, and are accompanied with other demerits such as noise, weight, and size problems. Therefore, an ion wind generator was suggested for use as a new cooling device in this study. The characteristics of the ion wind from the needle to parallel plate electrodes were analyzed for developing optimized cooling devices. Temperature changes induced by the ion wind were measured under various conditions for quantitative analysis. The efficient cooling performance of the ion wind was confirmed by the experimental and numerical results. Finally, optimization of the ion wind generator as a cooling device was accomplished.

1. Introduction

Although Light Emitting Diodes (LEDs) have the highest energy efficiency among lighting devices, they still consume 70% of the applied power as heat [1]. Thus, proper temperature performance is required for LEDs to enhance the lighting efficiency and avoid thermal damage [1–4]. The general methods employed for cooling LEDs are natural convection with a heat sink and forced convection with a fan. However, in the case of natural convection with a heat sink, lower cooling performance is obtained than for forced convection, and other demerits such as heavy weight and large size are also present. In addition, forced convection with a fan also has many disadvantages such as noise, vibration, short lifetime, and large size, since it contains mechanical moving part [2–4]. Thus, an ion wind generator using corona discharge was suggested for a new cooling device for LEDs in this study because it overcomes all the demerits of the other cooling devices.

Corona discharge has been used for industrial applications for a few decades now (e.g., electrostatic precipitators). Thus, much research has been performed for the development of applications using corona discharge, for which the ion wind generator is the most representative work. The ion wind is a flow of air induced by ions and electrons from the corona discharge, and it is also commonly called corona wind in atmospheric conditions. Ion wind research has actively progressed since Robinson's work [5] in last five decades. The study of ion wind can be classified into two parts: analyzing the characteristics of ion wind in various electrode arrangements, and verifying its cooling performance in various conditions. Study on the characteristics in various electrode arrangements has been performed since the 1960's, and many cases such as plate to plate [6], parallel plates [7], wire to cylinder [8], wire to plate [8], rod to plate [9], sphere to sphere [9] and needle to plate [10] have been studied so far. However, a needle to parallel plate-type electrode arrangement was developed in this study, since there is relatively insufficient research data on this arrangement even though it has a simple and more appropriate structure for the micro cooling of LEDs.

Study on the verification of the cooling performance and application of ion wind has recently been performed widely. Kalman [11], Molki [12], Go [13], and Sheu [14] proved the cooling performance of ion wind for wire to plate, wire to cylinder, wire to flat plate, and point to flat plate electrode arrangements. Kasayapanand [15] analyzed the cooling performance of ion wind for a vertical fin array using the computational fluid dynamics technique, and Chen [16] verified the cooling performance of ion wind for LED devices by measuring the thermal resistivity of the LEDs.

In the present study, the cooling performance of ion wind by the needle to parallel electrodes was analyzed by measuring the temperature distribution, and was quantitatively verified by calculating the heat transfer coefficient and enhancement factor. From the results, important parameters defining the cooling performance of ion wind were discovered, and empirical correlations were derived. Finally, the advantage of using the ion wind

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Nomenclature

P	pressure	Lc	characteristic length
F_e	electric force	k	conductivity of air
Q	applied heat	V	applied voltage
Q_e	total amount of space charges	E	applied electric field intensity
q_e	total amount of space charge in unit length	d	distance between electrodes
h	heat transfer coefficient	H	needle position
T_s	surface temperature	D	diffusivity coefficient
T_∞	ambient temperature	ϵ	dielectric permittivity
i	discharge current in unit length	K	ion mobility
ρ	density of air	He	heat loss
u	velocity of ion wind	R	resistance
L	length of plate		

generator as an effective tool for cooling the LED was confirmed, and optimization of the generator using the needle to parallel plate electrodes was performed through use of the empirical correlations.

2. Theoretical background

2.1. Generation mechanism of ion wind

If an electric field is applied between a sharply curved electrode (discharge electrode) and a blunt surface electrode (collecting electrode), a micro current starts flowing in the place between the electrodes called the discharge area. A corona discharge then occurs at the tip of the discharge electrode when the applied voltage in the discharge electrode is high enough to reach the threshold voltage. Air molecules are ionized into ions and electrons by the local discharge at the tip. In the range of the corona operating voltages, the same phenomenon is repeated to generate a considerable amount of ions and electrons in the discharge area, which is called an electron avalanche. The charged ions and electrons move in the opposite directions due to their polarities as space charges. As shown in the experimental setup of Fig. 1, the ions move to the plate electrodes while the electrons move to the needle electrode. Since heavy ions move in the discharge area, the ions transfer their moving inertia into the air molecules by collision between the accelerated ions and air molecules. Thus, the flow of air molecules occurs, which is called ion wind or corona wind.

2.2. Numerical study

The range of the operating voltage of ion wind is defined as that between the onset voltage and the spark-over voltage in this study. In general, ion wind occurs right after occurrence of the corona discharge, and the onset voltage of the corona discharge, in the case of wire to cylinder electrodes, is defined by Eq. (1), named Peek's law [17].

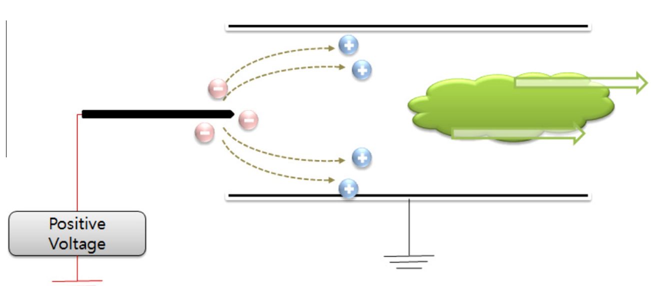

Fig. 1. Mechanism of ion wind generation.

$$V_c = m_v g_0 \delta r \left(1 + \frac{c}{\sqrt{\delta r}}\right) \ln\left(\frac{d}{r}\right) \tag{1}$$

where m_v is an irregularity factor to account for the condition of the wires, g_0 is a disruptive electric field, c is an empirical dimensional constant, r and d are the radius and distance between the wires, and δ is an air density factor with respect to SATP (25 °C, 76 cm Hg) (Eq. (2)).

$$\delta = \frac{\rho}{\rho_{SATP}} = \frac{PT_0}{P_0 T} \tag{2}$$

The definition of the spark-over voltage of ion wind has shown little discrepancy between studies, unlike the definition of the onset voltage. In this study, the spark-over voltage of the ion wind was defined as the transition voltage from the glow corona discharge to the spark discharge, which is called a spark over. When an electric field is applied in the discharge area, the burst corona discharge occurs, making a fine current for the flow between the electrodes at the low voltage section near the onset voltage [17]. If the applied voltage becomes higher, the streamer and glow corona discharge occur to make a very stable electric field zone in the discharge area [17]. Thus, the discharge current has an exponential relation with the applied voltage in this section [18]. However, if the applied voltage becomes even higher, spark discharge occurs, making a spark noise and an electric shock wave. By the spark over, the discharge current rapidly increases and the ion wind velocity starts to decrease with a large undulation. Thus, the spark-over voltage in the present study was defined as the finishing voltage section of the ion wind.

To study the ion wind, the electric field and the space charge should be considered at first. The electric field E is given by Eq. (3).

$$E = -\nabla V \tag{3}$$

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

$$\nabla^2 V = -\frac{q}{\epsilon} \tag{4}$$

where V is the electric potential, q is the space charge density and ϵ is the dielectric permittivity of free space. The momentum transfer between the moving space charges and the air molecules is defined by the charge transport equation as follows:

$$\nabla \cdot (-D\nabla q - K\nabla V q) + U \cdot \nabla q = 0 \tag{5}$$

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. (5) is the conduction force to define the motion of the ions under the electric field relative to entire air flow which is the main force to make the momentum transfer mechanism. Since it has a preponderant role in the momentum transfer mechanism, the other two terms