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Research Paper

Experimental investigation of high-power light-emitting diodes' thermal management by ionic wind

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HIGHLIGHTS

- Multi-needle (wire)-to-net ionic wind blower for HPLED cooling is developed.
- Ionic wind generator has good performance for HPLED cooling.
- The ionic wind velocity mainly depends on the Coulomb force.
- The maximum electric field density would be obtained at the tip of needles.

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ABSTRACT

It is urgently necessary to find an effective way to solve the problem of thermal management in high-power light-emitting diodes (HPLED) because most of the input power is converted into heat, which leads to a high junction temperature. Novel ionic wind generators have been developed in the present work for effective cooling of high-power LEDs. The working performance of the ionic wind using 'wire-to-net' and 'needle-to-net' electrodes were investigated experimentally. The electric field intensity distribution of 'needle-to-net' ionic wind generator was described mathematically. The results indicate that better cooling performance could be obtained when thin wire or pointed needle were used at smaller discharge gap with reasonable electrode spacing under negative corona discharge. The maximum electric field intensity could be obtained at the tip of needles. Finally, the advantages of using ionic wind for cooling the LEDs were confirmed to be higher in efficiency, lower in energy consumption and mechanical noise.

1. Introduction

As an alternative to conventional general lighting sources, light-emitting diodes (LEDs) have been widely applied in many fields due to their significant advantages, such as high working efficiency, low power consumption, good reliability and long lifetime [1–3]. However, nearly 80% of the input electrical power will be consumed as heat in HPLED. The continuous accumulation of heat in the chip package will result in a rapid rise in junction temperature, which leads to accelerated light output degradation, sometimes even risking catastrophic failure [4,5]. Therefore, effective thermal management is in urgent need. Many researchers have proposed the use of active cooling methods for HPLED, such as micro-jet array cooling, liquid cooling, thermoelectric cooler, oscillating heat pipes, etc. [6–9]. Nevertheless, the applications of these methods have been greatly restricted for complex structure, low working efficiency, and high cost.

Ionic wind based on corona discharge is one of many ways that convert electric energy into driving force. This is known as electro-hydrodynamics (EHD) gas flow. Lots of research work on the applications of corona discharge has been performed in a variety of fields. Recently, studies have been focused on increasing the ionic wind velocity or enhancing the resulting flow rate and improving the electromechanical efficiency of such devices. Chen et al. used the thermal resistivity to evaluate the working performance of ionic wind for low power LED chips cooling experimentally [10,11]. Their study indicated that an ionic wind blower with point emitting electrode under negative corona discharge show the best cooling performance for low power LED chips cooling, and the thermal resistance can be reduced by half. Shin et al. suggested a 'needle-to-plate' ionic wind blower. They measured the temperature profile, calculated the heat transfer coefficient and enhancement factor to analyze the cooling performance of ionic wind [12]. In the study by Jung and Kim, a 'multiple needle-to-ring' ionic

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Nomenclature

q_e	the charge density
$\boldsymbol{E}$	the electric-field vector
$q_e\boldsymbol{E}$	the Coulomb force
$\frac{1}{2}\boldsymbol{E}\nabla\varepsilon$	the dielectrophoretic force
$\frac{1}{2}\nabla\left(\rho\frac{d\varepsilon}{d\rho}\boldsymbol{E}^2\right)$	the electrostrictive force
$\boldsymbol{v}$	the ionic wind velocity
ρ	the fluid density
P	the static pressure
$[\bar{\bar{\tau}}]$	the viscous stress tensor
I	the forward driving current of LED chip
U	the forward driving voltage of LED chip
η	the thermal efficiency
$R_{\mathrm{th,j\text{-}c}}$	the thermal resistance of chip junction to pin
d_h	the corona zone thickness
r_w	the emitting electrode curvature radius
V	the high voltage applied between emitting electrode and collecting electrode
l	the discharge gap
ε_0	the dielectric constant of air
I_c	the current in each single needle
k_e	the migration coefficient for an ion
i	the current linear density
J_0	the mean current areal density at the mesh surface

wind blower was proposed. They showed that the electric field would vary from applied voltage, discharge gap and distance between needles, which directly affect the cooling performance of ionic wind [13]. Moreau et al. experimental studied the EHD force produced by a corona discharge between a wire active electrode and several cylinder electrodes [14]. Elagin et al. used wire electrode generator to investigate the cooling performance by corona discharge ionic wind experimentally [15]. Peng investigated heat transfer enhancement by EHD in a rectangular channel and found that the closer the electrode was to the inlet, the larger the enhanced cooling factor was [16]. Dau et al. developed a unique bipolar discharge configuration for ionic wind generation and studied the working behavior of ionic wind experimentally and numerically. The results show that the maximum ionic wind velocity would be 1.25 m/s while the corona current was only 5 μA, and the kinetic conversion efficiency was 0.65% [17].

The focus of the present study is to investigate the feasibility and potential of the proposed ‘multi-needle (wire)-to-net’ ionic wind generator for heat dissipation of HPLED. Research work is conducted experimentally by change structures of both emitting electrode and collecting electrode and the input electrical parameters. The quantitative analysis of the electric field intensity distribution for a ‘needle-to-net’ ionic wind generator is carried out. The system’s cooling performance is assessed by the case temperature of HPLED and velocity produced by ionic wind blower.

2. Generation of ionic wind

The air near the tip of emitting electrode will ionize and produce a corona as long as the applied high voltage reaches the threshold voltage. For positive corona discharge, electrons accumulate to anode under the strong electric field which is called an electron avalanche, forming a negative streamer moving toward the anode. The motion of photons is ahead of electron avalanche for the velocity of photons is much higher than that of electrons. Thus, a strong ionization and excitation occurs along the moving direction, resulting in secondary electron avalanche. The positive ions pass through the corona layer and move to the cathode to form positive corona wind. For negative corona discharge, there is a strong ionization and excitation in the cathode corona region and the current density is strong. The electrons move to the periphery of the negative corona and combine with oxygen atoms in the air rapidly to form negative oxygen ions. The negative oxygen ions move toward the collecting electrode and collide with the neutral particles in the air. They carry negative electricity and move together with ions, thereby to form negative corona wind [18].

The charged particles will accelerate under the action of the applied high voltage to form ion jet. The electric driving force can be described based on the principle of electromagnetism [12,19].

$$\boldsymbol{f}_e = q_e\boldsymbol{E} - \frac{1}{2}\boldsymbol{E}\nabla\varepsilon + \frac{1}{2}\nabla\left(\rho\frac{d\varepsilon}{d\rho}\boldsymbol{E}^2\right) \tag{1}$$

In Eq. (1), the Coulomb force is the main factor affecting the drift velocity of the charge. In this study, the influence of the dielectrophoretic force and the electrostrictive force on the electric field force could be neglected because the flow field is an airflow field. It is a single-phase flow field and there is no interface, an assumption has been made that the dielectric constant distributed uniformly in the space. Accordingly, the Coulomb force is the main factor which controls the moving speed of the space charges in the discharge area.

$$\boldsymbol{f}_e \approx q_e\boldsymbol{E} \tag{2}$$

According to Newton second law, the formation of ionic wind complies with the momentum conservation, and it can be expressed by the Navier–Stokes’s equation [12,20].

$$\rho\frac{d\boldsymbol{v}}{dt} = \rho\left(\frac{\partial}{\partial t} + \boldsymbol{v}\cdot\nabla\right)\boldsymbol{v} = -\nabla P + \nabla\cdot[\bar{\bar{\tau}}] + \boldsymbol{f}_e \tag{3}$$

In the present study, assumptions will be made that the working fluid is incompressible, non viscosity fluid in steady state conditions. Thus, Eq. (3) can be simplified to Eq. (4).

$$\frac{1}{2}\rho|\boldsymbol{v}|^2 = \boldsymbol{f}_e \tag{4}$$

Eqs. (2) and (4) show that the fluid density, the charge density and the electric field intensity are the main factors which determine the ionic wind velocity.

3. Experimental system

3.1. Details of ionic wind blower

The designed ionic wind cooling systems are shown in Fig. 1 and they can be identified as ‘wire-to-net’ generator and ‘needle-to-net’ generator. The emitting electrodes in Fig. 1(a) are stainless steel wires and in Fig. 1(b) they are tungsten steel needles. The collecting electrodes are both stainless steel meshes. The specific dimensions of the major components of the generator are listed in Table 1. The arrangement of the wire (or needle) electrode and the discharge gap can be adjusted. Ionic wind perpendicular to the wire electrode (or in parallel to the direction of the needle electrode) will be produced when the applied voltage is high enough.