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Experimental study on optical-thermal associated characteristics of LED car lamps under the action of ionic wind

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ABSTRACT

The working temperature of a LED chip has a great influence on its photoelectric properties. This paper is concerned with the application of ionic wind produced by corona discharge to cool a LED car headlamp. Both theoretical and experimental procedures are studied. A DC 'needles-to-mesh' ionic wind generator was designed for the experimental study. The mechanism of the association between optical and thermal properties was explored. The results indicated that the ionic wind could weaken the red shifting of the chromaticity coordinates and reduce the radiant power. It also showed a better working performance when the corona discharge power increased, but it only changed slightly as the corona power continued increasing. Ultimately, it would result in more symmetrical and uniform light distribution and the illumination gradient varied gently, which was more suitable for the driving beam lighting. The luminous flux was 1957.6 lm and the junction temperature was 29.8 °C after 6 min working of the ionic wind generator under a corona discharge power of 3 W. All the test values complied with the regulatory requirements.

1. Introduction

Benefited from the advantages of being environmentally-friendly, energy saving, long lifetime and wide range of color temperature compared to traditional lighting sources, the light-emitting diodes (LEDs) are widely utilized in the automotive outdoor lighting system [1–3]. However, the LED headlamp is still not in large scale production. The primary cause lies in the existing challenges in heat management for high power LED. If the heat cannot be effectively dissipated, the luminous efficiency of LED will be reduced, the service life will be shortened and the peak wavelength will be shifted [4–6]. The purpose of thermal management of LED headlamp is to maintain the junction temperature of the LED as low as possible within the design space and cost.

LED chips are the core and functional part that produce light. Besides light emitting, heat will also be generated within the LED chips due to many different causes, such as nonradiative recombination, current crowding and overflow, light confinement, etc. [1]. The recombination of electrons and atoms in a LED chip can be split into two categories in the microscopic view, namely luminescent recombination, Sockley Read and Hall recombination (SRH). Energy is released in the form of photons during the process of luminescent recombination, while it is released as phonons during the process of SRH. The conduction of current in a LED chip will produce Joule heat when it works. Thomson heating is due to the fact that the junction can be modeled by electronic source and heat source come from the electrical power, but it is covered by light emission. Then, the semiconductor around active zone can absorb a part of light and this absorption create heat source. Another part of heat generation for white light source is in luminophore. The electronic transition from the blue light to the yellow one will cause a part of heat source and increase temperature [2].

In addition, the package volume and specific heat capacity of a LED chip are smaller than normal lighting sources and it is sensitive to temperature changes, which leads to fast heat accumulation. The spectrum of a LED chip is narrow, and the outgoing light does not have infrared band. Accordingly, the heat generated by a LED cannot be distributed by radiation, and only relies on heat conduction [7].

Generally, the thermal management of a LED headlamp involves the chip-level, the package-level, the board-level and the system-level [1]. Many studies have recently been conducted at the system-level. Also, most studies on LED thermal management have been confined to heat sink techniques (passive cooling), which are often combined with heat pipes, piezoelectric fans or vapor chambers to improve the thermal performance by reducing the spreading resistance [8–13]. Unfortunately, passive cooling has relatively limited efficiency. Researchers have also proposed active cooling methods, such as micro-jet array cooling, liquid cooling, thermoelectric coolers and oscillating heat pipes [14–16]. However, these techniques require complex structures

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and come with low working efficiency and high cost.

Ionic wind, which is produced in corona discharge, has various advantages, such as quick response to flow control, simplified implementation (requiring only electrode sand transformer), very low power consumption and the absence of noise compare to conventional cooling techniques. It has been theoretically and experimentally studied in recent years due to its potential application in heat transfer enhancement.

For instance, Chen et al. [17–18] used ionic wind to enhance heat transfer in an LED mounted on a substrate with various electrode configurations and electrical parameters. Their results indicated that an ionic wind generator with point emitting and mesh collecting electrodes under a negative corona discharge is optimal for low-power LED chip cooling, with approximately 50% reduction of the thermal resistance prior to the spark-over voltage compared to the original thermal resistance. A sharp needle provided the lowest threshold voltage. Shin et al. [19] proposed a heat sink with ionic wind for cooling LEDs after investigating the characteristics of the ionic wind using a wire to the parallel plate electrodes via computational fluid dynamics (CFD). The cooling performance of a heat sink applied under ionic wind impinging flow was also investigated by parametric studies. The results revealed that the ionic wind performance was optimal when the wire was placed near the rear corner of the plate edges and the prototype showed enhanced cooling performance by 150% compared to natural convection. Ong et al. [20] adopted mesh-needle-mesh electrodes to produce ionic wind, when the forced convection heat transfer coefficient reached the maximum 3200 W/(m^2·K), the driving power reached 40 mW and the temperature decreased 4 °C. W. Wang et al. [21] established a unipolar approximation model and conducted numerical simulations to determine the heat transfer and velocity distribution of ionic wind. Their results indicated that higher applied voltage and more corona wires could help to decrease the thermal boundary layer thickness and increase the velocity gradient of the boundary layer, resulting in the enhancement of heat transfer. Y. Y. Tsui et al. [22] used a thin plate as the corona electrode and investigated the heat transfer over a plate resulting from the corona wind by both experimental and numerical means. The experiments show that the heat transfer coefficient at the center of the heated plate was increased by a factor in the range 2.6–4.8 times compared with natural convection. Our previous study [23] also showed that better cooling performance for high power LEDs could be obtained when a thin wire or pointed needle was used at the smaller discharge gap with reasonable electrode spacing under negative corona discharge. The maximum electric field intensity could be obtained at the tip of the needles.

The above studies have proven that the single stage ionic wind actuator has reached the plateau in promoting ionic wind velocity and energy converting efficiency. However, the optical-thermal associated characteristics of a LED car lamp under the action of ionic wind have not been sufficiently investigated. In the present study, we conducted experiments on the output optical characteristics of a LED automotive headlamp under the action of ionic wind and to reveal the mechanism of the association between optical and thermal properties. The decrease scale of luminous flux was only about 2% and the junction temperature was 29.8 °C after stably working of the ionic wind generator under a corona discharge power of 3 W.

2. Generation of ionic wind

Ionic wind is produced during corona discharge. The air near the tip of the emitting electrode ionizes and produces a corona as long as the applied high voltage reaches the threshold voltage. The space between the emitting electrode and collecting electrode can be divided into two regions, namely the ionization region and the drift region. The ionization region around the emitting electrode is filled with electrons and ions. Positive or negative ions are subjected to Coulomb force and drifting towards the grounded collecting electrode in the drift region. These ions impact the neutral air molecules, resulting in a momentum transfer that produces a gas flow from the active electrode to the grounded collecting electrode. This phenomenon is known as electrohydrodynamic (EHD), and the induced flow is usually called ionic wind [21,23].

Ordinarily, the generation of ionic wind for steady state incompressible air flow can be described by mass, momentum and energy in the conservation equations [21].

$$\nabla\cdot\vec{u} = 0 \quad (1)$$

$$\rho_{air}(\vec{u}\cdot\nabla)\vec{u} = -\nabla P + \mu\nabla^2\vec{u} + \vec{f} \quad (2)$$

$$\rho_{air}c_p\frac{\partial T}{\partial t} + \rho_{air}c_p\vec{u}\cdot\nabla T = \nabla\cdot(\kappa\nabla T) \quad (3)$$

where ρ_{air} is the air density, P is the air pressure, u is the air dynamic viscosity, c_p is the specific heat capacity of air and T is the temperature.

The charged particles accelerate under the action of the applied high voltage to form an ion jet. The electric driving force was defined by Stratton [21,23].

$$\vec{f} = \rho_v\vec{E} - \frac{1}{2}E^2\nabla\varepsilon + \frac{1}{2}\nabla\left[E^2\rho_{air}\frac{\partial\varepsilon}{\partial\rho_{air}}\right] \quad (4)$$

The three terms on the right side of Eq. (4) represent the Coulombic force, the force due to the permittivity gradient and the electrostriction force, respectively. As the variation for air is < 0.1% over a range of 1000 °C, the second term is neglected. Moreover, only in a two-phase interface does electrostriction affect the flow. Accordingly, the body force was simply modeled as a function of the electric field and ion charge density. Additionally, compared to the body force, the buoyancy induced by the air temperature gradient is not considered [21]. Thus, the Coulomb force is the main factor which controls the moving speed of the space charges in the discharge area.

The proposed ‘needle-to-mesh’ ionic wind cooling systems for the LED car lamp in the present study is shown in Fig. 1. The emitting electrodes are tungsten steel needles and the collecting electrode is a stainless-steel mesh. The specific dimensions of the major components of the generator are listed in Table 1. The arrangement of the needle electrode and the discharge gap is adjustable. Ionic wind is produced in parallel to the direction of the needle electrode when the applied voltage is sufficiently high. The back of the LED substrate is mounted close and parallel to the mesh electrode in order to cool the lamp in a timely manner.

3. Experimental setup

3.1. The LED car lamp

A LED car lamp which can emit a driving beam was selected for this research study. The disassembled parts of the lamp are shown in Fig. 2. The lighting source of the LED lamp consists of eight LED chips (Cree XLamp MCE4WT; Cree Inc., Durham, NC, USA), the driving circuit and the substrate. The role of the optical lens is to form a driving beam type prescribed by ECE regulation No.112. Our research goal is to make sure that the LED car lamp can work normally and its optical characteristics meet the regulation requirements. To this end, the heatsink shown in Fig. 3 or the ionic wind generator shown in Fig. 1 will be used for cooling.

3.2. Details of the test system

The chromaticity property, luminous intensity and output flux of the LED car lamp under the action of different cooling devices will be experimentally studied. Two test systems were used in this research. The luminous intensities measurement system for automotive lamp (sms10; Optronik, Instrument Systems, Berlin, Germany) depicted in Fig. 4