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Electrically-induced ionic wind flow distribution and its application for LED cooling

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HIGHLIGHTS

- Uneven electric field leads to inhomogeneous ionic wind distribution.
- Higher velocity and energy efficiency is obtained with more pointed needles.
- The maximum cone angle of the designed EFA is 61.6°.
- The designed EFA is effective for heat dissipation of high power LEDs.

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ABSTRACT

Enhanced heat transfer based on electrohydrodynamic (EHD) is considered as energy efficient non-thermal technology appropriate for thermal management of microelectronic products. A ‘multiple-needles-to-mesh’ electrostatic fluid accelerator (EFA) was proposed and experiments were carried out to clarify the ionic wind distribution characteristic and to evaluate the energy efficiency of the device. A developed prototype of EFA was then manufactured and applied for cooling high power LEDs. The results revealed significant effects of discharge gap, radius of needle tip curvature, distance between adjacent needles, power polarity and corona power on ionic wind flow distribution. The electric current density is highly uneven which lead to inhomogeneous ionic wind distribution. The maximum ionic wind velocity was obtained close to the emitting electrode and the maximum cone angle of the designed EFA is 61.6°. The experimental study indicated that the designed EFA was effective for heat dissipation of high power LEDs in application. The attenuation rate of luminous flux and the rise rate of junction temperature were much lower than traditional cooling devices.

1. Introduction

Application of electrohydrodynamics (EHD) has been verified to be an effective way for flow distribution improvement and heat transfer enhancement [1–3]. EHD blower which is also known as electrostatic fluid accelerator (EFA) converts electrical energy into kinetic energy of the flowing gas stream by applying high voltage between two asymmetric high-voltage electrodes during corona discharge [4–6]. When the charged particles move between the electrodes, they collide with the inert particles of the fluid to transfer their momentum and thus creating a bulk flow, it is called ionic wind, which is also referred to as corona wind. Ionic wind 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.

Chattock [7] is a pioneer researcher to quantitative study the phenomenon of ionic wind. He used a ‘pin-to-plate’ EFA to dissolve the gas into ions and electrons and showed by the velocity and mass identity of ions. In 1961, Robinson [8] investigated the subject in deep and the basic theory underlying ionic wind was developed. However, it is difficult to verify the theory due the complexity of ionic wind generation until the modern research methods are developed in recent decades. Fylladitakis et al. [5] presented a mathematical model establishing the velocity limit of EFAs with ‘pin-to-plate’ and ‘cylinder-to-plate’ configurations. Experiments were also performed to validate the developed mathematical model. Nguyen et al. [9] proposed a methodology to solve numerically for the drift region of a DC glow corona using the usual approach of collapsing the ionization region to the electrode surface. They predicted that the effect of the wind was to reduce the extension of the corona over the wire and to shift the center of the ion distribution upstream of the flow. Go et al. [10] used a ‘wire-to-tape’ EFA to study the corona discharge current and heat transfer

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performance experimentally. The local heat transfer coefficients were shown to increase by more than 200% and it was shown to be related to the fourth root of the corona current. Ramadhan et al. [4] developed a numerical model for a 'wire-to-grid' EFA and investigated the influence of key design parameters on EFA working efficiency. The improvements in the average outlet velocity were between 9% and 15%. Zhao and Adamiak [11] numerically and experimentally investigated the I-V and flow distribution characteristics in the 'pin–to-plate' and 'pin–to-grid' configurations. The airflow velocity profiles and the pressure distribution were greatly affected by the applied voltage as well as by the corona device configuration. Rickard et al. [12] investigated methodologies for increasing ionic wind velocities both theoretically and by experiments. The behavior of ionic wind generators was analogous to that of fans and their modifications have more than doubled the maximum previously reported ionic wind velocities.

Recently, EFAs have been proposed for on-chip thermal management of microelectronics because they can reduce to microscale dimensions. Wang et al. [13] compared and contrasted EFAs' design and performance metrics to those of other airside cooling technologies used in small form factor applications. They pointed out that airflow and pressure head, operating voltage, and ozone production were three critical parameters for adopting EFA technology in the thermal management of microelectronics. Chen et al. [14,15] applied ionic wind to enhance heat transfer in a light emitting diode (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. [16] 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. Knap et al. [17] optimized the structure and material of EFAs and then cooled high power light-emitting diode (LED). It achieved the best result by cooling down the LED 34.4 °C. Our previous study [18,19] 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. However, the flow distribution characteristic of ionic wind velocity and EFA working efficiency has not been sufficiently investigated for application.

In the present study, a 'multiple-needles-to-mesh' EFA is developed and experiments are conducted to investigate the gas flow distribution characteristic and the energy efficiency of the device in uniform electric field. Finally, a prototype of the ionic wind generator was manufactured and applied for cooling high power LEDs to confirm the practical utility.

2. Generation of ionic wind

The ionic wind flow results from corona discharge between emitting electrode and collecting electrode and their radii of curvature are obviously different. The field lines and current density distribution in corona discharge for a 'needle-to-mesh' EFA is presented in Fig. 1 [20]. The electric field is much stronger near the tip of emitting electrode, causing local air ionization and the whole discharge gap is filled with ions and electrons accelerated by electric field. The moving ions and electrons collide with neutral air molecules, dragging them towards the collecting electrode. It creates ionic wind which is consisted of ionized and neutral molecules. The major driving force of ionic wind can be represented as electrostatic pressure gradient ∇p_E [8].

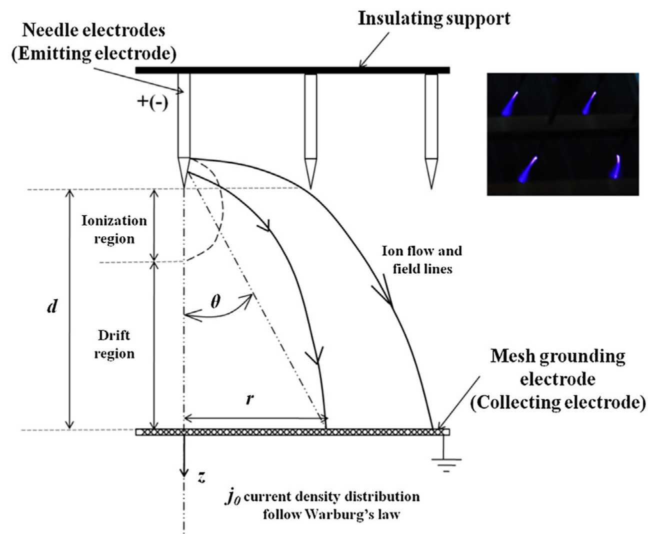

Fig. 1. Field lines and current density distribution in corona discharge.

$$\nabla p_E = q_e E \tag{1}$$

where q_e is the space charge density and E is the electric field strength.

Robinson's research indicates that the ionic wind velocity at the up surface of the mesh electrode can be estimated by the momentum conservation equation [8].

$$\frac{1}{2}\rho_{air} v^2 = \int_0^d q_e E dx \tag{2}$$

where d is the discharge gap, ρ_{air} is the air density and v is the ionic wind velocity.

In most of the previous study, the electric field was considered as uniform in the same horizontal plane to simplify the research. For instance, Barthakur and Al-Kanani assumed that the air density was constant and independent of electric charge density. Then, they derived the relationship between the electric field strength and the ionic wind velocity [21].

$$v = \sqrt{\frac{\varepsilon_0}{\rho_{air}}} E \tag{3}$$

where ε_0 is the dielectric permittivity in vacuum, $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m.

3. Experimental system

The designed EFA with 'needles-to-mesh' configuration is shown in Fig. 2. The emitting electrode is tungsten steel needles and the collecting electrode is a stainless steel mesh. The specific dimensions of the major components of the EFA can be referenced in our previous work [19]. The configurations of both electrodes and the discharge gap are adjustable. Ionic wind will be produced if the applied voltage is sufficiently high to dissolve the air.

Fig. 3 presents the test system which is composed of the insulated test chamber, the power supply system for the LEDs, the DC high voltage power supply for the EFA and the data acquisition instrument. A closed chamber was used to maintain constant and uniform temperature in the experiments. A DC power supply (TC4080; Teslaman, Dalian, China) was chosen in order to reduce the influence of AC voltage on LED performance. A multi-channel temperature inspection instrument (ZJ-16A, Zhongjie Electronics Co. Ltd, Changzhou, China) was used for temperature measurement. A hot-wire anemograph (TESTO512-3; Testo Industry Corportion, Germany) was used to measure the ionic wind velocity and dynamic pressure. An LED thermal