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Enhancing LED Cooling Efficiency Through wind ionic Technology: A Numerical Analysis of Point-to-Plane and Line-to-Plane Configurations

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Abstract— LEDs are widely used and cover all possible applications of artificial lighting, both for low power in domestic lighting and for very high power such as stadium or airport lighting. In the case of high-power lighting, thermal management is a crucial element because it seriously affects energy efficiency but above all the life of the light source. Several cooling techniques exist (heat pipe, fan, etc.) but the use of ionic winds for cooling LEDs has many interesting advantages (no moving mechanical parts, high energy efficiency, etc.). This study provides a numerical analysis of this innovative cooling technology using ionic wind, by comparing two possible configurations: point-to-plane and line or wire-to-plane. The results present the cooling efficiencies associated with the two cases studied.

Keywords— LED Lighting, cooling, ionic wind, heat-sink, high luminance, high-power

I. INTRODUCTION

Light-emitting diodes (LEDs) have rapidly become a leading lighting technology, moving from the laboratory to the dominant global lighting solution in just a few decades. Today, LED lighting has an energy efficiency of over 160 lm/W while the latest generation of fluorescent lamps barely reach 110 lm/W and halogen lamps, at best, 15 to 20 lm/W. Despite its very high energy efficiency, 70% of the energy injected into the LED lamp must be evacuated in the form of heat and unfortunately, overheating degrades both the energy efficiency and especially the lifespan of the LED chips [1, 2]. Natural convection is most often used in LED luminaires but the size, weight and bulk of the heat sinks quickly increases with the power to be dissipated and this solution quickly becomes unsuitable when it comes to high-power luminaires. Some manufacturers have moved towards conventional fan-forced convection solutions, particularly for urban lighting, but this necessarily leads to unacceptable audible noise, a significant increase in the system's energy consumption and an increase in the risk of failure due to moving parts. An alternative is to develop the use of ionic winds for cooling high-power LED (HP-LED) luminaires. This technology is completely silent, has no moving parts and

is particularly effective in LED cooling applications [3, 4]. This study presents experimental and numerical results on the efficiency of ionic wind cooling under different configurations and is based on previously published work [4]. This technology also has very high energy efficiency compared to conventional forced convection active devices (especially fans). The optimum voltage range obtained is between 5 kV and 10 kV, because beyond 10 kV, the efficiency decreases, which makes it possible to reduce consumption while maintaining performance.

II. EXPERIMENTAL SETUP

The experimental device is placed in a closed plexiglass tunnel to avoid any movement of external air that could disturb the convection at the device level and the observations by schlieren optics. The power LED used is of the "Chip-On-Board" (COB) technology (Bridgelux brand, reference: BXRA-W3500-00S0E) with a nominal current of 2100 mA for a nominal voltage of 24.6 V [5].

In order to conduct our comparative study with and without forced convection by ionic wind, the LED was underpowered and the current was limited to 0.7A ($V=21.76V$). The experimental setup records the temperature evolution of the light source using a K-type thermocouple, connected to a data logger. The high-voltage power supply allows for wind velocity variation in the LED cooling system (Fig.1).

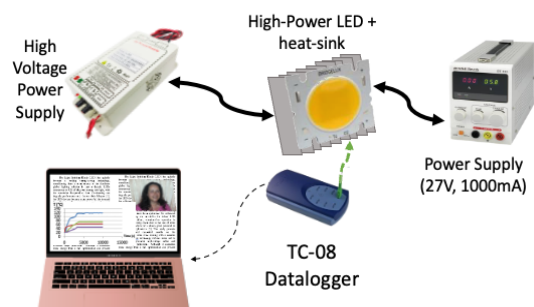


Fig. 1. Experimental setup with high voltage power supply for generation of ionic winds, power supply of the HP-LED and recording of measured temperatures

Temperature measurements are conducted using a Type K thermocouple, which has a temperature range of 0-1100°C, connected to a PicoLog TC-08 recording station (Fig. 1). The generation of ionic wind is facilitated by a high-voltage power supply with a range of 3-30 kV, complemented by a measuring probe that monitors the voltage applied to the tip (copper needle).

Fig.2, obtained using schlieren imaging technics, provides detailed information on the convection phenomena observed during the tests under a voltage of 7 kV between electrodes (needle-plate configuration):



Fig. 2. Schlieren optics visualization of forced ionic wind convection powered under 7 kV.

III. MODELING AND NUMERICAL SIMULATION

A. Domain equations applied to ionic wind generation

The simplified corona discharge model relies on current conservation between charged carriers but lacks self-consistency, using charge conservation and Poisson's equations for transport without deriving the electric field from first principles:

$$\nabla \cdot \mathbf{J} = 0 \quad (1)$$

And with the relationship between current density, mobility, charge density and electric field with Poisson's equation:

$$\mathbf{J} = z \mu \rho \mathbf{E} \quad (2)$$

$$\epsilon_0 \cdot \nabla^2 V = -\rho \quad (3)$$

Where J (A/m^2) represents the current density, z is the charge number μ ($m^2/V \cdot s$) is the mobility, ρ (C/m^3) is the space charge density, E is the electric field, V is the electric potential, and ϵ_0 is the vacuum permittivity.

$$\mu \left(\frac{\rho^2}{\epsilon_0} - \nabla V \cdot \nabla \rho \right) = 0 \quad (4)$$

where it is assumed that the mobility remains constant, this equation takes on a form commonly used to model space charge density in electrostatic precipitators:

$$\frac{\rho^2}{\epsilon_0} - \nabla V \cdot \nabla \rho = 0 \quad (5)$$

B. Boundary Conditions

In the examination of the corona electrode, the normal component of the electric field is employed as a boundary condition for Poisson's equation. This method ensures accurate representation of the electric field behavior at the electrode surface, enabling a more precise calculation of the electric potential distribution in the surrounding area.

$$\mathbf{n} \cdot \mathbf{E} = E_0 \quad (6)$$

Other boundary conditions for the electrodes:

- For the external electrode: $V=0$
- For the corona electrode: $V-V_0 = 0$, where V_0 is the imposed potential.

To achieve accurate predictive physical results, the electric field at the wire must closely approximate the actual value. In this context, Peek's law is employed.

$$E_0 = 3.10^6 / \delta (1 + 0.03 \frac{\delta}{r_i}) \quad (7)$$

where δ is a characteristic dimension of the system and r_i radius of the corona electrode.

C. Results of the Simulation in Point-to-Plane Configuration

In this configuration, the LED was powered with a current of $I = 0.7A$ with a voltage of $U = 21.76V$. The temperature evolution was recorded for the case of natural convection (Fig.3) and forced convection under ionic winds with an inter-electrode voltage of 7 kV (Fig.4). We then replicated these conditions numerically by Comsol[®] software, maintaining an inter-electrode distance of 7.5 mm.

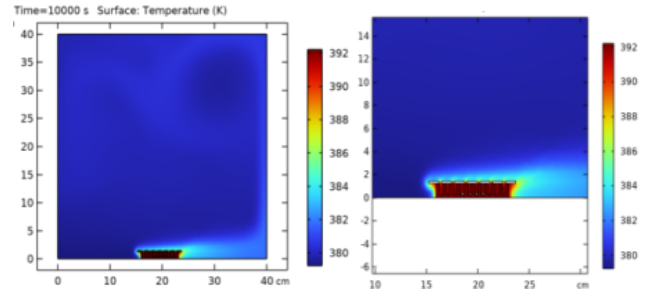


Fig. 3. Numerical results of temperature evolution in natural convection

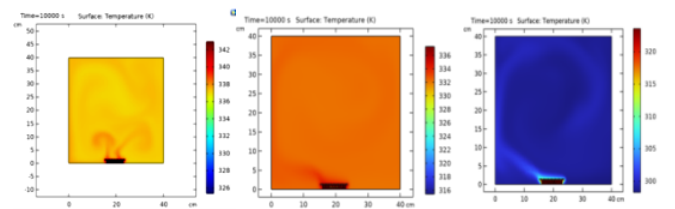


Fig. 4. Numerical results of temperature evolution with ionic wind under inter-electrodes voltages of 5 kV, 7kV and 10 kV (left to right, respectively)

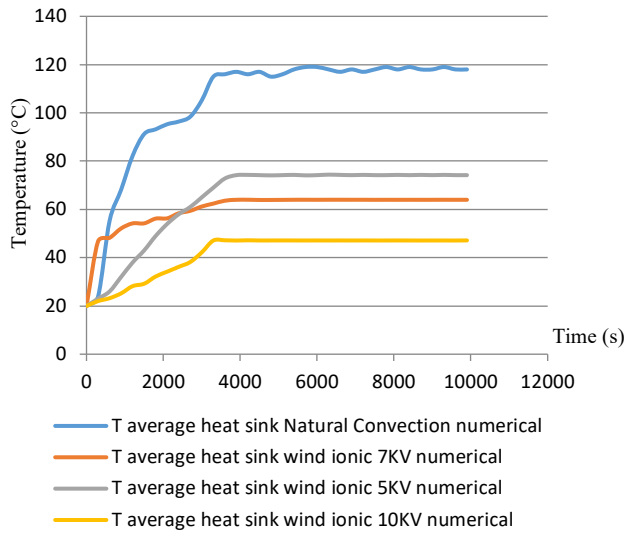


Fig.5. Ionic wind cooling effect under different inter-electrodes voltages

In the needle-to-plate configuration, the results obtained (Fig. 5) in natural convection give an average heat sink temperature of 118°C, with an ambient air temperature of 24.5°C. The introduction of the ionic wind improved the heat dissipation: at 5 kV, the temperature dropped to 74.2°C; at 7 kV, it reached 64°C; and at 10 kV, it dropped to 47.15°C. Thus, a 2 kV increase in voltage results in a temperature reduction of about 10°C.

Figure 6 shows the comparison between numerical and experimental results for natural convection and forced convection using ionic wind. The power injected into the LED is of the order of 15W. We have considered an energy efficiency of 30% which gives a power to dissipate of approximately 10.6 W. The temperature measurements obtained show an error range of 4 to 19%, which is explained by an overestimation of the energy efficiency value of these LEDs which degrades with the increase in temperature.

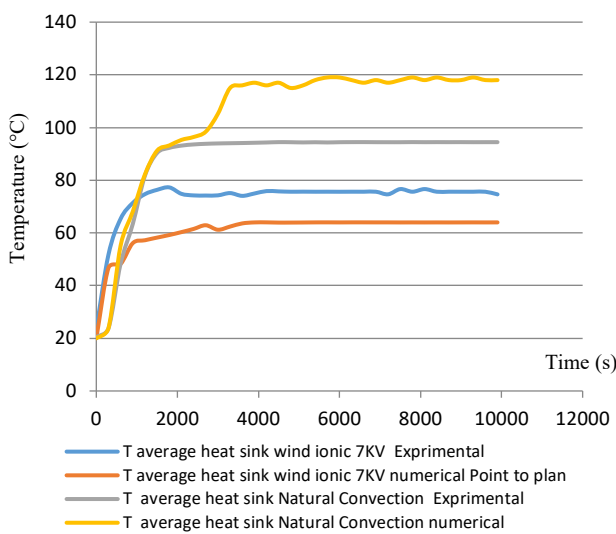


Fig.6. Temperature comparisons between experimental and simulation results of the temperature evolution as a function of time

D. Distribution of ionic wind speed as a function of applied voltage for the needle-to-plane configuration

Fig. 7 indicates that higher voltage on the electrode leads to increased maximum speed, as the voltage affects charge density and flow field.

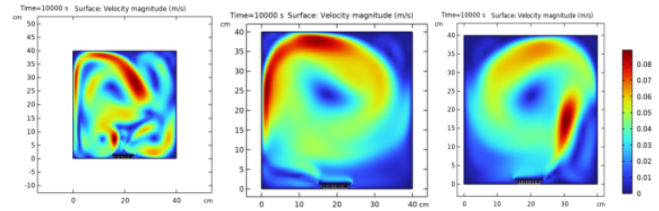


Fig.7. Ionic wind speed distribution for applied inter-electrode voltage of 5, 7 and 10 kV.

The Multiphysics model combines ion transport and Navier-Stokes equations to determine the distribution of the electric field, charge density, and flow field. An equation for maximum speed as a function of applied voltage is defined from Fig. 8.

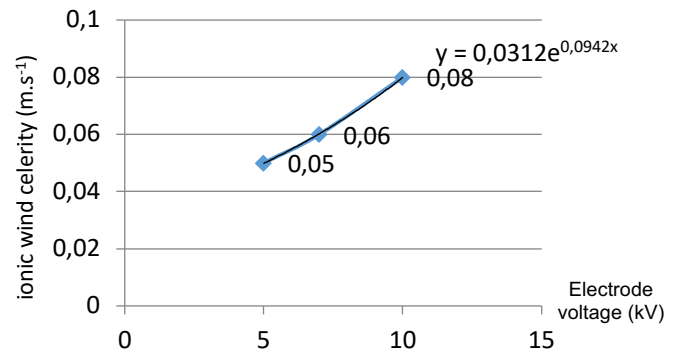


Fig. 8. Evolution of the maximum wind speed vs applied voltage.

$$V = 0,031e^{0,094*U} \quad (8)$$

With - V: Ionic Wind Velocity between electrodes

- U: applied voltage between electrodes

E. Simulation Results of Wire-to-plane Configuration

This section models a wire-to-plane configuration using 0.3 cm and 0.2 cm copper wires at the same ionic wind voltage and LED power, presenting the numerical results for temperature and velocity distribution in figures 9 and 10:

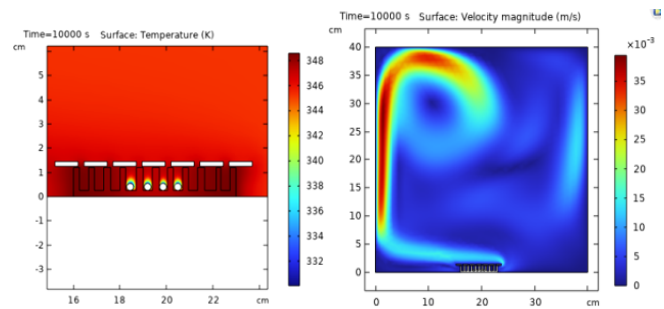


Fig. 9. Numerical results of the temperature evolution with ionic wind in the wire-to-plane configuration with a 0.3 cm diameter wire, along with the speed distribution.

The results show that a 0.3 cm diameter copper wire in the line-to-plane configuration is about 11 °C hotter than the point-to-plane configuration, while a 0.2 cm wire yields a lower heat sink temperature than the point-to-plane configuration. The graph below illustrates these results (Fig.11).

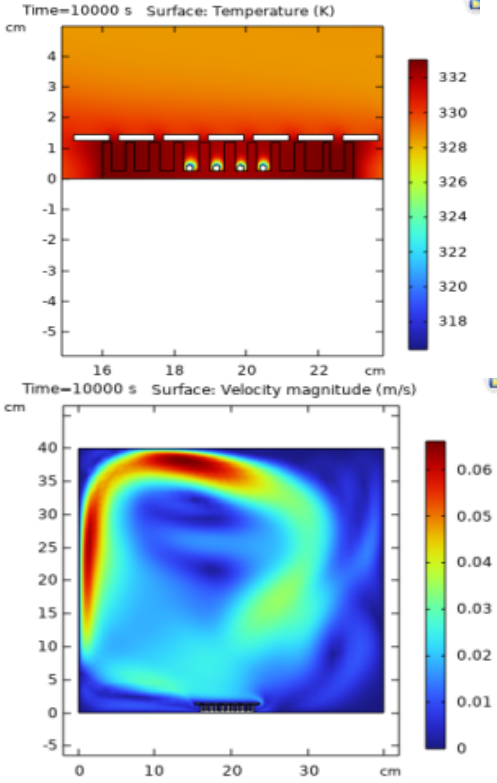


Fig. 10. Numerical results of the temperature evolution with ionic wind in the wire-to-plane configuration with a 0.2 cm diameter wire, along with the speed distribution.

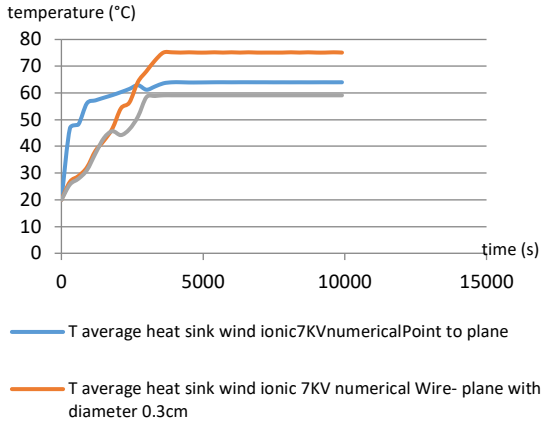


Fig. 11. Evolution of average temperature vs time for two configurations

The results show that a 0.2 cm diameter copper wire, resembling the point-to-plane configuration, is more effective due to its uniform electric field distribution and optimal heat dissipation, unlike the point-to-plane configuration, which generates a concentrated point electric field at the tip. In contrast, the 0.3 cm wire has a weaker electric field and reduced cooling efficiency because its larger surface area decreases current density. Thus, the 0.2 cm wire is optimal for current distribution and heat dissipation.

F. Relative Efficiency Percentage Compared to the Point-to-Plane Configuration

To evaluate the relative efficiency of each wire diameter, we can define it as the inverse of the temperature difference between the wire-to-plane and point-to-plane configurations:

$$\eta = \frac{1}{\Delta T} \quad (9)$$

Where $\Delta T = T_{\text{Wire-to-plane}} - T_{\text{point-to-plane}}$

- Wire diameter: 0.3 cm; $\eta = \frac{1}{11,1} \approx 0.0901 \text{ } ^\circ\text{C}^{-1}$
- Wire diameter: 0.2 cm; $\eta = \frac{1}{-4,8} \approx -0.2083 \text{ } ^\circ\text{C}^{-1}$

The relative efficiency percentage compared to the point-to-plane configuration can be calculated using the following formula:

$$E(\%) = \frac{T_{\text{Wire-to-plane}} - T_{\text{point-to-plane}}}{T_{\text{Wire-to-plane}}} \times 100 \quad (10)$$

At 7 kV, the point-to-plane configuration was 17.2% more efficient than the 0.3 cm wire-to-plane setup. However, with a 0.2 cm wire, the wire-to-plane configuration became 5.8% more efficient than point-to-plane. These findings emphasize the importance of choosing the right configuration and wire diameter for optimal cooling efficiency.

IV. CONCLUSION

This paper demonstrates that ionic wind significantly improves the cooling performance of an LED heat sink to dissipate 10.61 W of heat loss, with each 2 kV increase lowering the temperature by approximately 10 °C. At an inter-electrode voltage of 10 kV, the heat sink temperature dropped by 60%. When comparing point-to-plane and wire-to-plane configurations at 7 kV, wire diameter is a crucial parameter, and smaller diameters improve cooling efficiency in the wire-to-plane configuration. Therefore, optimizing the wire size is essential to maximize cooling efficiency. In the context of high-power LED lighting, the use of ionic winds is an essential solution to significantly reduce the size and weight of heat sinks while providing a quiet, reliable and highly efficient solution.

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