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NUMERICAL STUDY ON AN IONIC WIND PUMP WITH MULTI-WIRE CORONA ELECTRODES FOR CHIP COOLING

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ABSTRACT

Due to its noiselessness, low energy consumption and compact structure, ionic wind has become a hot research field in recent years. In this study, an ionic wind pump with multi-wire corona electrodes is designed. Each wire electrode corresponds to a pair of parallel plate electrodes which are used to collect charged ions. The change of ionic wind velocity caused by different electrodes configurations and its influence on the cooling effect of a heated plate with a constant power were studied by numerical simulation. The result shows that both the air flow velocity and the mass flow rate increase with the increasing plate electrodes length, and there is approximate a 1 °C temperature drop with a 10 mm increase in electrode length when using the ionic wind pump to cool a plate heated by a 1.5 W power. The maximum temperature drop is approximate 110 °C, compared with the natural convection condition.

Keywords: ionic wind pump, multi-wire electrodes, heated plate, wire-plate configuration, numerical optimization

1. INTRODUCTION

Ionic wind can be widely used in electronic components cooling, air flow control, dust removal and other fields. In the field of using ionic wind for heat transfer enhancement of electronic components, many studies were published in recent two years, and this study also focus interest on this field. In the published researches, many ionic wind devices with different electrode configurations has been proposed. For example, Feng J et al.[1] experimentally studied the ionic wind devices with needle-mesh and needle-fin electrodes and compare their cooling performance, and concludes that the needle-fin configuration has a superior performance compared with the needle-mesh

NONMENCLATURE

c	Specific heat, $J\cdot kg^{-1}K^{-1}$	V	Voltage, V	*ε*	Air permittivity
d	Gaps between two electrodes, mm	*P*	Power, W	*δ*	Environmental factor
D	Diameter of wire electrode, mm	*p*	Pressure, Pa		
E	Electric field intensity, $V\cdot m^{-1}$	*q*	Space-charge density, $C\cdot m^{-3}$	***Subscripts***	
F	Electric force, N	U	Velocity, $m\cdot s^{-1}$	0	Standard value or wire No.
h	Heat transfer coefficient, $W\cdot m^{-2}K^{-1}$			1,2	Wire No.
I	Current, mA	***Greek Symbols***		a	Ambient value
J	Current density, $A\cdot m^{-2}$	*μ*	Ionic mobility, $m^2\cdot V^{-1}s^{-1}$	e	Value related to electric field
l	Length of the plate electrode, mm	*ν*	Kinematic viscosity, $m^2\cdot s^{-1}$		
T	Temperature, K	*ρ*	Density, $kg\cdot m^{-3}$	max	Value of maximum

configuration. Wang J [2, 3] proposed a electrostatic fluid accelerator (EFA) with multi- needle to mesh electrodes and clarify the ionic wind flow characteristics. Wang's experimental results revealed significant effects of discharge gap, radius of needle tip curvature, power polarity, etc. on ionic wind flow distribution. Wang concluded that the designed ionic wind generator had good cooling performance close to cooling fan, coupled with lower energy consumption and less mechanically induced noise. Wang J [4] also coated grapheme on the surface of needle tip, and then this new ionic wind cooling system obtain a higher wind velocity than the originally designed system. Wang gives the explanation that the graphene on the needles' surface acted as new emitting electrode with a smaller curvature radius.
Besides the experimental method for ionic wind study, many researchers have investigated the ionic wind characteristics via numerical simulation. Ramadhan AA [5] proposed an optimized EHD blowers integrated with a plate-fin heat sink is presented. This cooling system can be used for thin consumer electronics. Ramadhan developed a 3D numerical model and validated it to solve the coupled equations of EHD flow and conjugate heat transfer, and predicted the cooling performance of the integrated EHD system. Zhang J [6] numerically examined Heat transfer enhancement using corona wind generators in a square channel, and then three configurations of the corona wind generator are investigated for their effectiveness in the enhancement of heat transfer as well as the pumping power requirement. Chen S [7] investigated ionic wind by a DC corona discharge under different conditions with an emphasis on the effects of voltage polarity and the transition between different discharge regimes. One of the highlights of this study is that the gas temperature of a DC corona which is important when it is to be used for cooling purposes is considered. The aforementioned applications of ionic wind in electronic products cooling show that EHD technique has a great potential. All these ionic wind devices developed in above studies were used to cool a single heat source with a uniform heat flux, and these devices might not be suitable for a heat source with a non-uniform heat flux, such as a heat flux with a hot spot.

In this study, we designed an ionic wind pump with multi-wire corona electrodes. Each wire electrode corresponds to a pair of parallel plate electrodes which are used to collect charged ion, which is quite different from the electrodes configurations in above mentioned studies. We then numerically optimized the ionic generator to obtain a maximum wind velocity which can effectively cool a heated plate. Above all, this ionic wind device can be used to cool a heated plate with an uneven heat flux by changing the voltage of each individual wire electrode, which is close to the outlet of the ion-wind device.

2. PHYSICAL MODEL AND MATHEMATICAL FORMULATION

2.1 Physical model

This ionic wind pump consists of three wire-electrodes and six plate collecting electrodes, and each wire electrode corresponds to a pair of parallel plate electrodes which constitute a partial ionic wind unit, as shown in Fig 1. All the wire electrodes are made of wolfram, and the diameter D is 0.4 mm. The plate electrodes are stainless steel foil which has a thickness of 0.2 mm. In order to avoid vortices in the flow, each wire is located near the rear corner of the plate electrode edges[8].

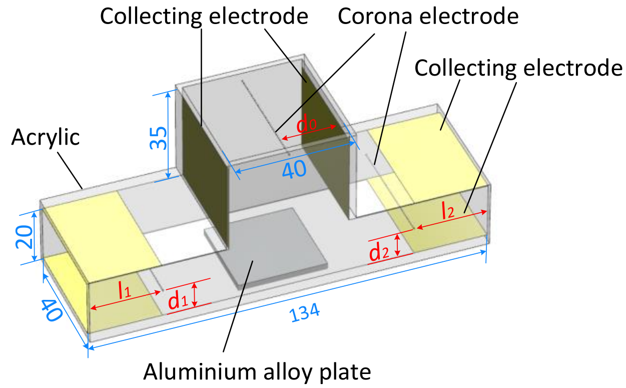

Fig 1 ionic wind pump and some of its dimensions

2.2 Governing equation and boundary conditions

Since the electrostatic field is coupled with the space charge density field, the following Poisson's equation and the current-density-conservation equation should be solved simultaneously.

$$\nabla^2 V = -\frac{q}{\varepsilon} \tag{1}$$

$$\nabla \cdot \vec{J} = 0 \tag{2}$$

Then the three classical conservative equations of fluid mechanics are solved to obtain the fluid flow and heat transfer. The continuum equation,

$$\nabla \cdot \left(\rho \vec{U}\right) = 0 \tag{3}$$

The momentum-conservation equation,

$$\vec{U} \cdot \nabla\left(\vec{U}\right) = -\frac{1}{\rho}\nabla p + \nu\, \nabla^2 \vec{U} + \frac{\vec{F_e}}{\rho} \tag{4}$$

The energy-conservation equation

$$\nabla\left(\vec{U}T\right)=\nabla\left(\frac{\lambda}{\rho c_p}\nabla T\right) \quad (5)$$

Besides, the following relations are also needed for solving the above equations.

$$\vec{E}=-\nabla V \quad (6)$$

$$\vec{J}=\mu_e q\vec{E} \quad (7)$$

$$\vec{F_e}=q\vec{E} \quad (8)$$

For boundary conditions, in the electrostatic field, all the wire electrodes are applied with a constant DC voltage and the plate electrodes are set to be grounded. In fluid flow field, ambient pressures are assigned to the inlet and outlet of the ionic wind pump, and no-slip boundary conditions are applied to the surfaces of the electrodes and other walls. For heat transfer, the temperature of the air flow inlet is set to be ambient temperature 28 °C, and only convection appears on the outlet of the pump, which means that the temperature gradient is zero.

For the charged ions transport, the common approach is to neglect the ionization zone and handle it by a boundary condition for charge density on the wire electrode surface. In this simulation, the Kaptzov hypothesis and the Peek formula is adopted to obtain the space charge density on the wire electrode surface for different corona discharge voltages. For a wire[9], Peek's value is

$$E_{onset}=3.1\times10^{6}\delta\left(1+\frac{0.308}{\sqrt{\delta r}}\right), \quad V/m \quad (9)$$

Where δ is the environmental factor, and it is

$$\delta=\frac{T_0}{T}\frac{P}{P_0} \quad (10)$$

T_0 and P_0 are 273.15 K and 101325 Pa, respectively. T and P are the actual temperature and pressure of air.

2.3 Simulation method and its verification

The finite-element method (FEM), as implemented in COMSOL® MultiPhysics software, is conducted to establish the simulation model and solve the coupled equations (1)-(8). Fig 2 shows the verification of numerical results with the experimental results, which is obtain in a controlled environmental chamber under a negative polarity corona discharge by a single wire with two parallel plate electrodes.

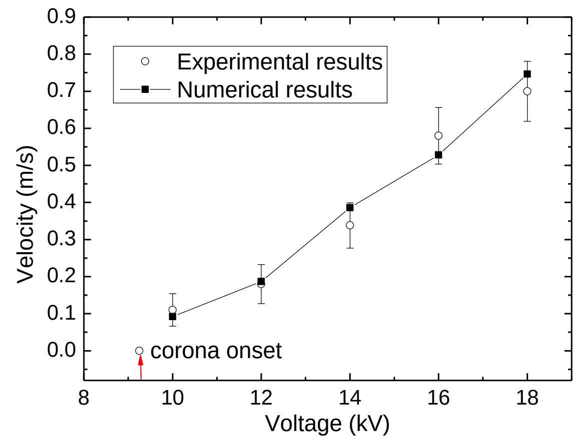

Fig 2 Comparison of simulated velocities with experimental values under different corona discharge voltages The experimental condition is 28 °C in temperature and 55% RH in humidity.

Fig 3 is the photo of the experiment. The ionic wind is measured at the point that is 30mm below the outlet of the ionic wind pump and located under the wire. We can see from Fig 2 that the simulated wind velocities and the experimental results are in good agreement, which indicates that the simulation method is reliable.

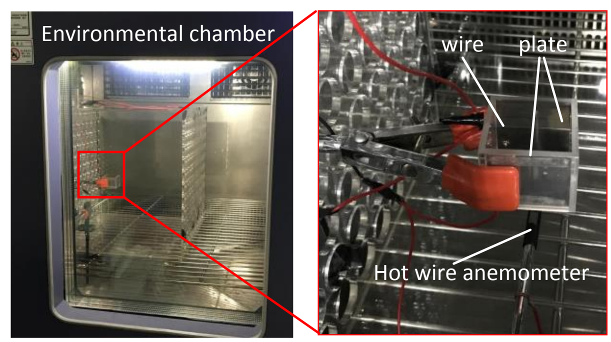

Fig 3 photo of experiment for numerical method verification

3. AIR FLOW AND HEAT TRANSFER OF IONIC WIND PUMP

The wire electrode located near the inlet of the ionic wind pump, as well as its corresponding plate electrodes, is fixed in dimensions and locations in this study. This wire is in the middle in the channel and 3 mm near the pump inlet.

3.1 Effect of plate electrodes length l_1 and l_2

In this study, we make the four electrodes close to the pump outlet have the same electrode length, i.e., l_1 and l_2 have the same value which equals to l. In addition, these electrode edges are aligned with the pump outlet, and the two wires are located in the middle plane of the channel. The point, at which the air velocity is monitored, is at the outlet center of the top ionic wind unit, as shown in Fig 4. As we can see from Fig 4 that air flow getting into the ionic wind pump directly impinges on the surface of the plate and then are accelerated once again to flow out of the two pump outlets.

Fig 5 shows the monitored velocity and air mass flow rate variation with electrode length. Both the air flow velocity and the mass flow rate increase with the increasing plate electrodes length *l*. This is because the increase of electrode length leads to the expansion of ions drift zone during corona discharge, and thus the number of collisions between the charged ions and air molecules increases. That is to say the air accelerated region by the electric force expanded. The final result is an increase in wind velocity and air mass flow rate.

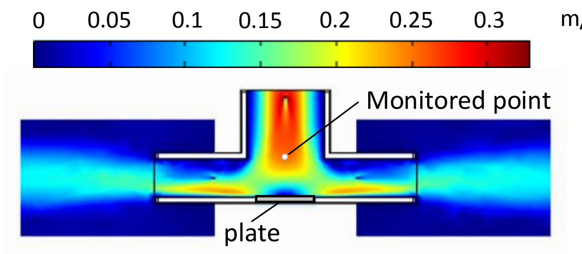

Fig 4 Flow field of the ionic wind pump with plate electrodes length 30mm (14kV)

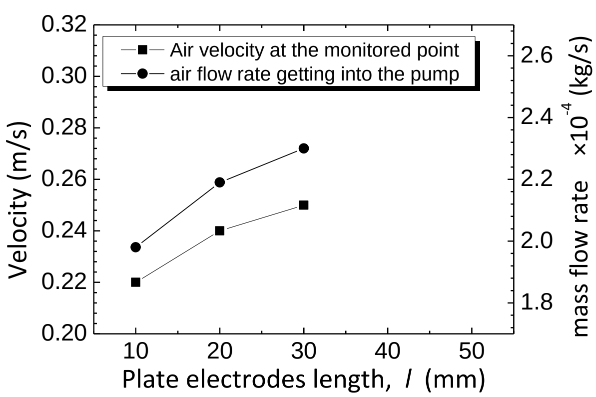

Fig 5 Variation of velocity at monitored point and air mass flow rate with plate electrodes length *l* (14kV)

3.2 Cooling performance of the ionic wind pump

Cooling of a plate (30×30mm) heated by a 1.5 W heating power using the ionic wind pump is simulated and the temperature distribution is shown in Fig 6. The result shows that there is approximate a 1 °C temperature drop with a 10 mm increase in electrode length.

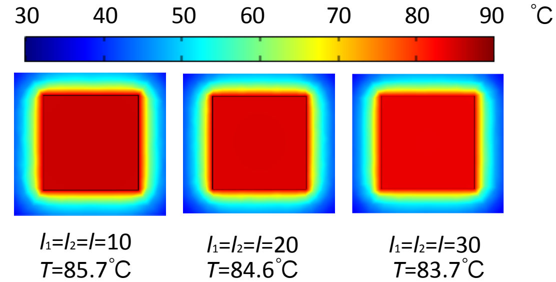

Fig 6 plate temperature distribution at the heated side with different plate electrodes lengths

Supposing that the plate is heated by a 1.5 W power under the natural convection, under which the heat transfer coefficient is close to 10 W/(m^2·K), the plate surface temperature will reach 195 °C according to the Newton’s law of cooling.

This designed ionic wind device can serve as a noiseless thermal management equipment for large area LED illumination devices or LED screens.

CONCLUSIONS

This work designed a multi-wire electrodes ionic wind pump and numerically studied its flow and heat transfer characteristics. The following are some conclusions.

- Both the air flow velocity and the mass flow rate increase with the increasing plate electrodes length l_1 *and* l_2.
- There is approximate a 1 °C temperature drop with a 10 mm increase in electrode length when using the ionic wind pump to cool a plate heated by a 1.5 W power. The maximum temperature drop is approximate 110 °C, compared with the natural convection condition.

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