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A study of heat transfer enhancement via corona discharge by using a plate corona electrode

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ABSTRACT

This paper is concerned with the corona discharge used to enhance heat transfer. Both theoretical and experimental procedures are employed. To examine the heat transfer resulting from corona discharge, a thin plate is employed as the corona electrode and a heated plate is grounded to form the collecting electrode. Experiments show that the heat transfer coefficient at the center of the heated plate is increased by a factor in the range 2.6–4.8 times comparing with natural convection. Optical images reveal that corona discharge occurs at the two side corners of the plate electrode when the corona voltage is low and a bluish sheet of discharge issuing from the front edge of the electrode is visible at sufficiently high voltages. Comparison between predicted temperatures and measurements indicates that significant differences exist at low corona voltages and good agreement is obtained when the voltage is high enough. This result is mainly attributed to the 2-D assumption employed in the simulation and the heat loss appearing in the experiment. The corona discharge is stronger for small electrode gaps. However, the corona voltage allowed before formation of the electrical spark is higher for large electrode gaps, leading to better heat transfer.

1. Introduction

The recent developments in electrical/electronic devices, especially the portable devices, require reduction of the size and increased performance. Thermal management becomes one of the most important issues to ensure safe and reliable operation. The conventional way to dissipate the thermal heat generated in the electronic system is the use of rotating fans through forced air convection. However, the demands for ever smaller portable devices and increasing power densities have prompted the search for alternative methods. The cooling system adapted from the EHD ionic wind pumps is attractive because its size can be small, it has no moving parts, operates in direct current mode, consumes little power, and offers silent operation. However, it possesses some disadvantages such as poor electric-to-fluid energy conversion, production of ozone, and degradation of electrodes over time. The integration of EHD technology into a laptop computer was demonstrated by Jewell-Larsen et al. [1]. The EHD approach was incorporated by Chen et al. [2] for cooling light-emitting diodes (LED).

The gas motion driven by the corona discharge recently drew much attention in the research of heat transfer enhancement. The corona wind effect was investigated by Owsenek et al. with a needle electrode suspended above a heated plate [3]. An enhancement of more than 25:1 over natural convection was reported. Molki and Bhamidipati [4] examined the heat transfer in the development region of circular tubes with Reynolds numbers ranging from 2500 to 13000. The maximum enhancements of the local and average heat transfer coefficients are 14–23% and 6–8%, respectively. In the experiments of Go et al. [5], a steel wire electrode and a copper tape are placed on a flat plate exposed to a bulk flow. The electrode pair are perpendicular to the bulk flow direction such that the ionic wind is in the same direction as the flow. Increase of heat transfer coefficients is more than 200% above those without corona discharge. In the study of Kalman and Sher [6], a thin wire is confined by two wings inclined to form a nozzle geometry. The resulting corona wind is directed towards a heated plate. It was found that the heat transfer coefficient can be increased by a factor more than two in comparison with natural convection.

More comprehensive physics can be revealed with numerical simulations. The mathematical models of the electrical field

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comprise a Poisson's equation for the electrical potential and a transport equation for the electric charge density. An algorithm based on finite difference methods (FDM) was developed by McDonald et al. [7] to solve for both the electrical field and the gas charge. The computational space is covered by a Cartesian grid and the corona wire is treated as a point source of charges. This approach was also adopted by others to study the corona discharge induced flow [8–10]. It is apparent that the geometry of the electrodes cannot be resolved with use of this method. One method to avoid this problem is to use finite element methods (FEM) and/or boundary element methods (BEM) for the Poisson's equation and the method of characteristics (MOC) for the charge transport equation because it is of the hyperbolic-type PDE [11–13]. Since the characteristic lines do not pass through the mesh nodes, interpolating or extrapolating charge values onto the nodes are necessary. This interfacing issue is a significant limitation upon the methodology [14]. To solve the transport equation using the FEM, upwind-biased treatments, such as the donor cell methods [15] and the flux corrected transport methods [16], are necessary to tackle the hyperbolic characteristics. Applications of the FEM to study the above mentioned corona discharge problems can be found in the literatures [17–20].

Instead of a needle or a wire used in previous works, a thin plate is employed as the corona electrode in the present study. The heat transfer over a plate resulting from the corona wind is under investigation by both the experimental and numerical means. To generate corona discharge, the positive corona is chosen in favor of its much reduced ozone and increased durability of the electrode in comparison to negative corona. We will examine if a suitable electric field can be generated between the electrodes and if the heat transfer can be effectively enhanced. One original reason for using this kind of plate electrode is to expect that the corona discharge will take place along the full front edge of the electrode plate so that the resulting heat transfer effect can cover a large heated area. The numerical methods for both the electrical field and gas flow field are based on the finite-volume methods (FVM) suitable for using unstructured grids. The merit of the FVM is that the properties, such as the fluid mass and charge current, are conserved. In the simulation, the problems are assumed to be two-dimensional. The experimentally determined current-voltage relationships are incorporated in the boundary conditions. The temperature and heat transfer coefficient at the center of the heated plate obtained by both numerical simulations and experimental measurements are compared.

2. Experimental setup

The experimental setup shown in Fig. 1 mainly comprises a heated collecting plate, a mica heater, and a copper electrode. These components are placed in an acrylic chamber of size 0.3 m × 0.3 m × 0.3 m to minimize surrounding flow interference. A constant power of 7.5 W is supplied (GW Instek GPR-7550D) to the mica heater used to heat the collecting plate, which is monitored by a power meter (Yokodawa WT-230). A low-thermal-conductivity Bakelite board of size 50 mm × 50 mm × 10 mm is attached to the mica heater to reduce heat loss. Three type-T thermocouples are installed in the Bakelite block. Two of them are placed at different locations on the axis through the center of the Bakelite block, which are used to measure heat loss from the back of the board. The third one is locate at a side position to estimate the loss from the sides of the block. The data signal is processed by an acquisition system including a recorder (Yokogawa MX100) and a personal computer. The heated plate is made of aluminum and has a size 70 mm × 50 mm × 3 mm. This plate, being grounded, serves as the collector for the corona discharge. A copper plate of length 110 mm is placed in a position perpendicular to the heated plate to work as the corona electrode. Its leading edge where the corona discharge occurs has a thin, rectangular geometry of the size 10 mm × 0.1 mm. A high-voltage DC power supply (You-Shang Tech. Corp.) is used to supply various positive voltage differences between the two electrodes, which is monitored by a multimeter to measure the resulting current. The corona voltage ranges from 6 to 19 kV, depending on the inter-electrode gaps. Three gap distances are under consideration: 10, 15, and 20 mm. A thermal couple is inserted into the collecting electrode to measure the temperature at the center of this heated plate, which is used for analysis of the heat transfer and for comparison with numerical simulations.

3. Mathematical modeling

The electric field is determined by the Poisson's equation.

$$\nabla^2\varphi = -\nabla\cdot\vec{E} = -\frac{q}{\varepsilon} \tag{1}$$

where φ is the electric potential, q the electric charge density, and ε the electric permittivity ($=8.8542\times10^{-12}$ F/m for air). The intensity of the electric field $\vec{E}$ is given as

$$\vec{E} = -\nabla\varphi \tag{2}$$

The electric charge must be conserved, which is governed by the following transport equation representing continuity for the electric current.

$$\frac{\partial q}{\partial t} + \nabla\cdot\vec{J} = 0 \tag{3}$$

Here $\vec{J}$ is the current density, in general, being the sum of three contributions: drift due to electric field, convection due to fluid flow, and diffusion due to charge gradients:

$$\vec{J} = \mu_E\vec{E}q + \vec{V}q - D\nabla q \tag{4}$$

where μ_E is the ionic mobility ($=1.43\times10^{-4}$ m^2/V s for air), $\vec{V}$ the fluid flow velocity, and D the coefficient of ionic diffusion. The diffusion of the charge is usually much lower than the drift motion and can, thus, be neglected. In comparison with the drift, the fluid convection effect can also be negligible if no strong enforced bulk flow appears in the field. This point will be evidenced in the testing calculations later.

Since the velocity of the electrohydrodynamic flow is low, incompressible gas flow is assumed. The conservation equations for the mass, momentum and energy are expressed as

$$\nabla\cdot\vec{V} = 0 \tag{5}$$

$$\frac{\partial\rho\vec{V}}{\partial t} + \nabla\cdot\left(\rho\vec{V}\otimes\vec{V}\right) = -\nabla P + \nabla\cdot\left(\mu\nabla\vec{V}\right) + \vec{F} \tag{6}$$

$$\frac{\partial\rho C_P T}{\partial t} + \nabla\cdot\left(\rho\vec{V}C_P T\right) = \nabla\cdot(k\nabla T) + \sigma_E\left|\vec{E}\right|^2 \tag{7}$$

where ρ is the fluid density, P the pressure, T the temperature, μ the dynamic viscosity, k the thermal conductivity, C_p the specific heat capacity, and σ_E the electrical conductivity.

In the modeling, there is no consideration of buoyancy and the density ρ is constant. The last term in the energy equation represents the Joule heating effect. This effect is usually insignificant and, thus, not accounted for in the calculations. The body force