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Enhancement of external forced convection by ionic wind

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ABSTRACT

An ionic wind is formed when air ions are accelerated by an electric field and exchange momentum with neutral air molecules, causing air flow. Because ionic winds can generate flow with no moving parts and have low power consumption, they offer an attractive method for enhancing convection heat transfer from a surface. In the present work, corona discharges are generated between a steel wire and copper-tape electrode pair on a flat plate, perpendicular to the bulk flow direction such that the ensuing ionic wind is in the direction of the bulk flow. The corona discharge current is characterized, and experimental measurements of heat transfer from a flat plate are reported. Infrared images demonstrate that the cooling occurs along the entire length of the wire, and local heat transfer coefficients are shown to increase by more than 200% above those obtained from bulk flow alone. The magnitude of the corona current and the heat flux on the flat plate are varied. The heat transfer coefficient is shown to be related to the fourth root of the corona current both analytically and experimentally, and heat transfer enhancement is seen to be solely a hydrodynamic effect. Variation of the spacing between electrodes demonstrates that while the local peak enhancement is largely unaffected, the area of heat transfer enhancement is dependent on this spacing.

1. Introduction

Flow can be generated when air ions are accelerated through an interstitial atmosphere between two electrodes held at a potential difference. As the ions are acted upon by the electric field, they collide and exchange momentum with the neutral air molecules. At the millimeter scale, air ions can be generated by a dc corona discharge when a large voltage is applied between two electrodes, one sharp and the other blunt (collector electrode), in air. The electric field is geometrically enhanced very near the sharp electrode and accelerates naturally occurring free electrons toward the electrode. These electrons collide with neutral molecules and, if the collision occurs at sufficiently high kinetic energy, strip electrons from the neutral molecule to form air ions. The air ions are then pulled by the field toward the blunt electrode, colliding with other neutral air molecules and forming what is typically called an ionic or corona wind. If the ionic wind is generated in the presence of a bulk flow, the ionic wind acts as a Coulombic body force on the bulk flow, adding momentum and disrupting the boundary layer (Fig. 1). In this work, we investigate the use of an ionic wind to distort the boundary layer of an external bulk flow. The modulated boundary layer increases heat transfer at the wall in a manner similar to a passive turbulator or blowing/suction at the wall.

The phenomenon of ionic wind was first studied by Chattock [1] in 1899, and in the mid-twentieth century, Stuetzer [2] and Robinson [3] extensively investigated the subject and developed the basic theory underlying electrohydrodynamic pumps. As a method for heat transfer enhancement, ionic winds can either provide forced convection in environments that would otherwise be cooled only by natural convection and/or radiation, or enhance forced convection as discussed above. Marco and Velkoff [4] pioneered this research by examining enhanced natural convection using an ionic wind generated by a wire (sharp) electrode impinging on a plate (blunt) electrode. Similar point-to-plane configurations have been studied by Kibler and Carter [5] as well as Owsenek and Seyed-Yagoobi [6] and Owsenek et al. [7] The use of a corona discharge as a blower for duct flow between two plates (or fins) has also been suggested by Kalman and Sher [8] and Jewell-Larsen et al. [9]. Forced convection enhancement has been studied extensively for both laminar and turbulent internal flows [10–12]. Additionally, ionic-wind-enhanced heat transfer has been investigated by Ohadi et al. [13] for a shell-and-tube heat exchanger and by Wangnipparnto et al. [14] in a thermosyphon heat exchanger.

The use of ionic winds in the presence of a bulk flow to modulate an external boundary layer has been an area of growing interest in the aerospace community, but has received little attention for heat transfer enhancement. Soetomo [15], and more recently, Léger et al. [16] and Artana et al. [17], demonstrated the ability of corona discharges to reduce drag by modulating the boundary

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Nomenclature

A_{current}	cross-sectional area of ion current flow (m^2)
b	ion mobility in air (m^2/V s)
C_p	specific heat (J/kg K)
D_{IA}	mass diffusion coefficient of ions in air (m^2/s)
E	electric field (V/m)
f	body force (N/m^3)
G	electrode gap (mm)
H	electrode height (mm)
h	heat transfer coefficient (W/m^2 K)
i	corona current (μA)
k	thermal conductivity (W/m K)
KE	kinetic energy (J)
L	plate length (mm)
Nu	Nusselt number
q''	heat flux (W/m^2)
p	pressure (N/m^2)
P	heater power (W)
Ra^*	Rayleigh number based on heat flux
Re	Reynolds number
T	temperature (K)
u	velocity (m/s)
x	distance along the plate (mm)

Greek symbols

ε	permittivity of air (F/m)
ν	kinematic viscosity (m^2/s)
ρ	mass density (kg/m^3)
ρ_e	air ion density (C/m^3)
σ	electrical conductivity of air (Ω^{-1} m^{-1})
Φ	applied corona potential (kV)

Subscripts

avg	average
bulk	due to bulk flow only
forced	forced convection
free	free (natural) convection
ionic	due to ionic wind only
∞	ambient air value

Superscript

*	based on heat flux

layer on a flat plate. Using electrodes perpendicular to the flow and either flush or in contact with a flat plate, they demonstrated a near-wall ionic wind that accelerates the local boundary layer, promoting drag reduction. The only experiments reported in the literature on heat transfer enhancement by ionic winds in the presence of external flows were by Velkoff and Godfrey [18], who used an array of corona wires aligned with the flow and extended above a flat plate. With the flat plate acting as the collecting electrode, they demonstrated that heat transfer is enhanced in the low-velocity regime but that the ionic wind is swamped by the bulk flow, and thus ineffective, as the bulk velocity increases.

Recently, ionic wind devices reduced to microscale dimensions have been proposed for on-chip thermal management of electronic devices [19,20]. As the electrode gap is decreased to 10–20 μm, the ionization phenomenon is no longer due to the acceleration of free electrons (i.e. corona discharge) but rather the injection of electrons into air from the cathode by field emission. Our group has previously modeled and studied the ionization process [21,22] and demonstrated that, by using nanostructured carbon for geometric field enhancement, emission turn-on voltages can be reduced to approximately 20 V [23]. Whereas these studies explored microscale ionic winds to generate air under otherwise quiescent conditions, the focus of more recent work has been on the efficacy of using ionic winds for local heat transfer enhancement in existing bulk flows [24]. Recent experiments have revealed that ionic winds can increase the local heat transfer coefficient in an externally generated, low-velocity bulk flow over a flat plate by more than a factor of 2 for applied voltages of 2–4 kV [25]. The present work focuses on understanding the heat transfer enhancement due to the ionic wind, the correlation between ion current and heat transfer enhancement, and the impact of different geometric arrangements.

2. Theory of electrohydrodynamics

The interaction between ions and neutral molecules is typically called ion drag and is defined using the following body force equation consisting of the Coulombic force, the force due to the permittivity gradient, and the electrostriction force:

$$\vec{f} = \rho_e\vec{E} - \frac{1}{2}|E|^2\vec{\nabla}\varepsilon + \frac{1}{2}\vec{\nabla}\left[|E|^2\rho\frac{\partial\varepsilon}{\partial\rho}\right] \tag{1}$$

Electrostriction is only significant in cases in which a two-phase interface exists [6]. Also, the permittivity gradient is negligible in air (variation is less than 0.1% over a range of 1000 K [26]). Therefore, ion drag in air is due only to the Coulombic force ($\rho_e\vec{E}$) and is included in the standard momentum equation as a body force term:

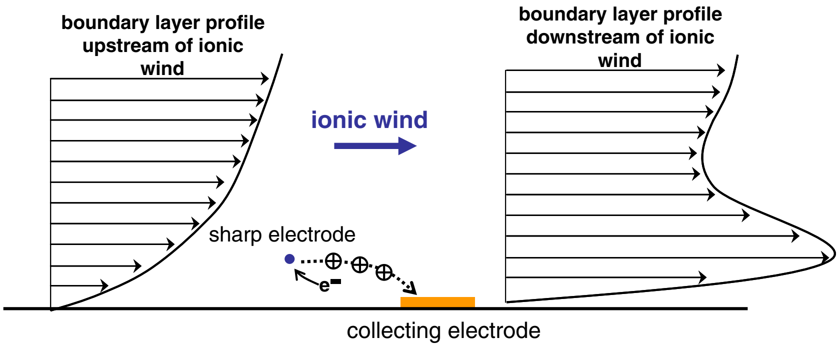

Fig. 1. Schematic showing an ionic wind generator in the presence of a bulk flow.