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David B. Go
Birck Nanotechnology Center, Purdue University, dgo@purdue.edu

Raul A. Maturana
Birck Nanotechnology Center, Purdue University, rmaturan@purdue.edu

Timothy S. Fisher
Birck Nanotechnology Center, Purdue University, tsfisher@purdue.edu

Suresh V. Garimella
Birck Nanotechnology Center, Purdue University, sureshg@purdue.edu

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External Forced Convection Enhancement using a Corona Discharge

David B. Go, Raul A. Maturana, Timothy S. Fisher and Suresh V. Garimella
School of Mechanical Engineering and Birck Nanotechnology Center, Purdue University
West Lafayette, Indiana 47907-2088 USA

ABSTRACT
An ionic wind is formed when air ions generated by a corona discharge 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, they offer an attractive method for enhancing the heat transfer from a surface that would otherwise only be cooled by natural convection and/or radiation. In the presence of an external, flat plate flow, ionic winds distort the boundary layer such that local heat transfer is enhanced at the wall, and recent work has suggested that integrating such devices can be useful for cooling electronic components locally. In this 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 discharge is in the direction of the bulk flow. The corona discharge current is characterized, and a corona glow and spark discharge are visualized. Experimental studies of the heat transfer from a heated flat plate are conducted using an infrared camera which indicated both upstream and downstream cooling along the entire length of the wire. Heat transfer coefficients are increased by more than 200% above those obtained from bulk flow alone and are correlated to the fourth root of the corona current. Preliminary parametric studies demonstrate the influence of the electrode-pair configuration on the cooling enhancement and suggest improved geometric designs.

KEY WORDS: ionic wind, corona wind, corona discharge, electrohydrodynamics, forced convection, enhancement

NOMENCLATURE

\[ b \] ion mobility in air, m²/V-s

\[ C_p \] specific heat, J/kg-K

\[ E \] electric field, V/m

\[ f \] body force, N/m³

\[ g \] electrode gap, mm

\[ h \] heat transfer coefficient, W/m²-K

\[ i \] corona current, \( \mu \)A

\[ k \] thermal conductivity, W/m-K

\[ Nu \] Nusselt number

\[ q^* \] heat flux, W/m²

\[ p \] pressure, N/m³

\[ P \] heater power, W

\[ Ra \] Rayleigh number

\[ Re \] Reynolds number

\[ T \] temperature, K

\[ u \] velocity, m/s

\[ x \] distance along the plate, mm

\[ y \] electrode height, mm

Greek symbols

\[ \delta_{wire} \] boundary layer thickness at the corona wire, m

\[ \epsilon \] permittivity of air, F/m

\[ \rho \] mass density, kg/m³

\[ \rho_e \] air ion density, C/m³

\[ \nu \] kinematic viscosity, m²/s

\[ \Phi \] applied corona potential, kV

Subscripts

avg average

d downstream

forced forced convection

free free (natural) convection

u upstream

∞ ambient air value

Superscript

* based on heat flux

INTRODUCTION

Flow can be generated when air ions are pulled through an interstitial atmosphere between two electrodes held at a potential difference. As the ions are accelerated by the electric field, they collide and exchange momentum with the neutral air molecules. At the meso-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), in air. The electric field is geometrically enhanced very near the sharp electrode and accelerates naturally occurring free electrons towards the electrode. These electrons collide with neutral molecules and, if the collision occurs at sufficient kinetic energy, strip electrons 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 corona discharge is generated in the presence of a bulk flow, the ionic wind acts as a Coulombic body force on the bulk flow. 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, much like a passive turbulator.

The phenomenon of ionic winds was first studied by Chattock [1] in 1899, and in the mid-twentieth century, Stuertz [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, such as impingement, in environments that would otherwise only be cooled 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 configurations have been studied by Kibler and Carter [5] as well as Owsenek et al. [6,7]. 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 including in channels [10] and in ducts [11,12]. Additionally, ionic-wind-enhanced heat transfer has been investigated for heat exchangers by Ohadi et al. [13] for a shell-and-tube exchanger and by Wangnipparunto 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 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 for heat transfer enhancement by ionic winds in the presence of external flows were by Velkoff & Gofrey [180], 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, miniature ionic wind devices have been studied at the microscale, and these devices may be suitable for on-chip thermal management of electronic devices [19,20]. As the electrode gap decreases to 10-20 μm, the ionization phenomenon is not due to the acceleration of free electrons (corona discharge) but rather due to the ejection of electrons from the cathode due to the large electric field (field emission). The authors’ group has modeled and studied the ionization process [21,22] and demonstrated [23] that, by using nanostructured carbon for geometric field enhancement, emission turn-on voltages can be reduced to the order of 10 V. Whereas earlier studies explored microscale pumps, the focus of this recent work has been on investigating the efficacy of using ionic winds for local heat transfer enhancement in existing bulk flows [24]. These experiments showed that ionic winds can increase the local heat transfer coefficient in an externally generated bulk flow over a flat plate by a factor of 2 for applied voltages of 2 to 4 kV [25]. Additionally, the local heat transfer trends were predicted using a numerical model and suggested that Joule heating plays a role in heating the plate at low ionization currents. The present work expands on the earlier experiments to investigate the heat transfer enhancement in greater detail as to conduct initial parametric studies to identify enhancement trends and suggest improved geometric designs.

**ELECTROHYDRODYNAMIC THEORY**

The interaction between the 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:

\[ \mathbf{j} = \rho \mathbf{E} - \frac{1}{2} |\mathbf{E}|^2 \nabla \cdot \mathbf{E} + \frac{1}{2} \nabla \left[ |\mathbf{E}|^2 \rho \frac{\partial \mathbf{E}}{\partial \rho} \right] \]  

(1)

Electrostriction is only significant in cases where there is a two-phase interface [6], and the permittivity gradient is negligible in air. Therefore, ion drag in air is due only to the Coulombic force and is included in the standard momentum equation as a body force term:

\[ \mathbf{\nabla} \cdot (\rho \mathbf{u}) = -\mathbf{\nabla} p + \mathbf{\nabla}^2 \mathbf{u} + \rho \mathbf{E} \]  

(2)

In addition to the exchange of kinetic energy, the ion current imparts thermal energy to the air which is included in the energy equation as a Joule heating term:

\[ \mathbf{\nabla} \cdot \left( \rho C_p T \right) = k \nabla^2 T + b \rho \mathbf{E}^2 - \mathbf{\nabla} \cdot (\rho \mathbf{E} \mathbf{u}) \]  

(3)

The second term on the right side of Eq. (3) is the Joule heating term [6], and the last term subtracts the kinetic work that the ions impart to the flow because not all of the ion energy is converted to heat. In previous work, modeling of the ion current and electrohydrodynamic interactions suggested that Joule heating can have a significant local effect on the air density which can result in upstream heating of the flow [25].
EXPERIMENTAL SETUP

Figure 1 depicts the basic experimental setup consisting of a flat plate exposed to a bulk flow with the corona electrodes being perpendicular to the flow such that the discharge current is aligned with the flow. The flat plate was made of 0.7 mm thick glass with a thin layer of indium tin oxide (ITO) on the back side. Silver epoxy electrodes were attached across the ITO layer, and a potential applied to heat the flat plate. In order to electrically isolate the two electrodes forming the corona electrode pair, the top of the flat plate was coated with 0.127 mm-thick teflon tape. The ITO heater was insulated on the back side with Styrofoam. The bulk flow was generated with an axial fan, and a 50.8 mm-thick honeycomb with 3.175 mm cells was placed upstream of the flat plate to condition the flow. Two parallel polycarbonate plates were used to prevent the flow from spreading laterally. The bulk velocities investigated were less than 1 m/s such that the experimental flow regime was entirely laminar (Re ~ 1000).

A corona discharge was generated between a 50 μm-diameter stainless steel wire (corona wire) and a 0.635 mm-wide piece of copper tape (collecting electrode). Both electrodes were perpendicular to the flow and the collecting electrode was attached to the flat plate. The corona wire was strung across the flow upstream of the collecting electrode and elevated above the flat plate by two ceramic blocks. The collecting electrode was placed 55.25 mm downstream of the leading edge of the flat plate, and this position was held constant. The height (y) of the elevated corona wire and the gap (g) between the two electrodes were varied.

Thermal measurements were taken with a FLIR ThermaCAM SC300 infrared (IR) camera located above the flat plate. The accuracy of the camera was assessed to be ±1°C over the range of 30-70°C using a blackbody calibrator. The flat plate was painted with Krylon Ultra Flat Black Spray 1602, which has a known emissivity of 0.96 [26], to ensure accurate IR readings. The bulk flow velocity was measured at the collecting electrode with a hand-held velocimeter with an estimated accuracy of ±0.05 m/s. The corona discharge was generated by applying a large voltage to the corona wire while the collecting electrode was grounded. The corona current was measured at the collecting electrode using a picoammeter.

RESULTS AND DISCUSSION

Corona Discharge Characterization and Visualization

The relationship between the corona current and applied potential was characterized for gaps of g = 0, 2, 4, and 6 mm for a constant corona wire height of y = 3.15 mm. Figure 2 shows a plot of the square root of the corona current as a function of the applied potential. The plot demonstrates that in this geometric configuration, the relationship between the square root of the current and the voltage is linear – a result predicted by Stuetzer [2] for simple geometries, and demonstrated experimentally in [5] and [7].

Figure 3 shows images of a corona glow and spark discharge. At moderately high voltages, the ionization processes in the region nearest to the wire generate a glow (Figure 3a) due to the formation of a weakly ionized plasma. At extreme voltages, very large electric fields break down the air, causing a spark of highly concentrated current (Figure 3b). In typical operation, the corona discharge is operated at lower voltages such that no glow is visible with no danger of spark discharges which can cause damage to the electrodes and also create a safety hazard.
the corona wire and collecting electrode due to excessive applied potential with a corona discharge in the presence of the bulk flow, where geometry was producing a current of 15 µA; at this corona condition, significant cooling enhancement occurs in the vicinity of the corona wire as well as downstream of the collecting electrode. To a lesser extent, convection enhancement also exists upstream of the electrode pair. Additionally, cooling enhancement occurs along the entire width of the wire.

Figure 5 shows infrared images of the temperature drop due to the corona discharge with respect to the bulk flow temperature profile for the above geometry at different corona currents. As demonstrated in [26], the local cooling effect is greatest at larger corona currents, and as the current decreases, the upstream enhancement decreases.

Because the corona discharge occurs along the spanwise length of the wire, the heat transfer effect is largely two-dimensional (x-y) along the direction of flow. Therefore, the temperatures along a single streamwise line along the plate were analyzed to determine heat transfer coefficients. The local heat transfer coefficient was determined based on an energy balance for the known heater power and accounting for radiative heat loss from the surface using the following

\[ h_x = \frac{q_{heater} - q_{plate, radiation}}{T_{plate, x} - T_{\infty}} \]  

Average upstream and downstream heat transfer coefficients were determined from the local data for each corona discharge current using the standard equation

\[ h_{avg} = \frac{1}{\Delta x} \int_{x_l}^{x_u} h_x dx \]  

The upstream value was based on a 5 mm-long region upstream of the collecting electrode (x = 50-55 mm), and the downstream value was based on a 5 mm-long region downstream of the collecting electrode (x = 62-67 mm). The uncertainty in the calculated heat transfer coefficients was based on the ±1°C accuracy of the camera and an error-propagation analysis [27].

Figure 6 shows the percentage increase in the local heat transfer coefficient for bulk flow with a corona discharge. The peak value is greater than 200% for a current of 15 µA and the local enhancement decreases with current to 50% improvement for a current of 3 µA. The heat transfer

Figure 3 (a) Image of a corona glow, as indicated by the purple hue, along the wire electrode, and (b) Image of a spark discharge between the corona wire and collecting electrode due to excessive applied potential.

**Heat Transfer Characterization**

Figure 4 shows a series of infrared, thermal contour images for a flat plate heater power of \( P = 4 \) W. The image at the top is of the hot plate prior to any forced convection cooling. The second image is of the heated plate exposed to a \( u = 0.28 \) m/s bulk flow. The final image is of the heated plate with a corona discharge in the presence of the bulk flow, where the ion current is aligned with the flow. The electrode geometry was \( y = 3.15 \) mm and \( g = 2.0 \) mm, and the corona discharge occurred under an applied potential of \( \Phi = 4.51 \) kV, producing a current of \( 15 \) µA. At this corona condition, significant cooling enhancement occurs in the vicinity of the corona wire as well as downstream of the collecting electrode. To a lesser extent, convection enhancement also exists upstream of the electrode pair. Additionally, cooling enhancement occurs along the entire width of the wire.

Figure 4 Infrared temperature contours (°C) for a heater power of \( P = 4 \) W and three cooling conditions for a geometry of \( y = 3.15 \) mm and \( g = 2.0 \) mm.

Figure 5 Contours (°C) of the temperature difference between a bulk flow alone versus a bulk flow with corona for five corona conditions for a geometry of \( y = 3.15 \) mm and \( g = 2.0 \) mm. The bulk velocity was \( u = 0.28 \) m/s, and the heater power was \( P = 4 \) W.
enhancement occurs both upstream and downstream of the electrode pair and peaks at the location of the corona wire. The upstream enhancement is not as great as the downstream enhancement and for low currents upstream heating is observed as localized Joule heating can dominate the body force interaction. The enhancement downstream of the collecting electrode decreases steadily as the effect of the ionic wind is dissipated. The two shaded regions represent the upstream and downstream areas over which $h_{avg}$ was calculated.

Previous work by the authors [24] suggested that the heat transfer coefficient is proportional to the fourth root of the Coulombic body force based on the conversion of the body force to kinetic energy and the relationship between the laminar boundary layer and the heat transfer coefficient. Because the main transport mechanism of ions in air is drift, as opposed to convection by the bulk flow or conduction, the ion current is defined as

$$i = b \rho_a \vec{E}$$

Equation (1) shows that the body force is proportional to the ion density and the electric field; therefore, assuming that the ion mobility is constant, the heat transfer coefficient is proportional to the fourth root of the corona current, $h \propto i^{1/4}$.

Figure 7 shows the difference between the average heat transfer coefficient with and without an active corona as a function of the 4th root of the corona current. The relationship is predominantly linear across the various corona conditions for both upstream and downstream heat transfer coefficients, confirming the suggested relationship. It is noted that a crossover between the upstream and downstream curves occurs at low currents, where the downstream enhancement exceeds that upstream. This trend is also observed in Figure 6. The peak enhancement location for curves (a)-(d) in this figure is in the vicinity of the corona wire and decreases downstream of the collecting electrode. However, the peak in curve (e) is not at the corona wire location. While further study is required to understand the precise physical mechanisms that govern this phenomenon, this characteristic may be exploited in practical designs.

Because the primary mechanism for heat transfer enhancement is assumed to be the corona wind, the measured heat transfer coefficients should be independent of the magnitude of the heat flux imposed on the flat plate. However, as the plate heat flux and therefore surface temperature increases, natural convection can play an increasing role in convective heat transport from the surface. The measured average heat transfer coefficient as defined in Eq. (5) can be written as a summation of the free and forced components using the following relationship for transverse flows [28]

$$h_{avg}^{1/4} = h_{forced}^{1/4} + h_{free}^{1/4}$$

(7)

The forced convection component here includes both the bulk flow and corona components, while the free convection value was estimated using the correlation [29]

$$\overline{Nu} = 0.54 Ra^{1/4}$$

(8)

where the Rayleigh number based on the known heat flux is

$$Ra = Ra \overline{Nu}$$

(9)

Figure 8 shows the forced convection component of the average upstream and downstream heat transfer coefficients with and without active corona for varying power inputs to the heated plate. The average heat transfer coefficients are largely constant to within experimental uncertainty across the range of power inputs although a slight increasing trend with heater power might be attributable to inaccuracies in the natural convection estimation.
Parametric Studies

Parametric studies were conducted in which both the electrode gap \(g\) and the height \(y\) of the corona wire were varied. For a constant corona wire height, \(y = 3.15\) mm, the gap spacing varied between 0 and 6 mm. Each geometric configuration was run to produce the same corona current, although under different applied voltages. Upstream and downstream average heat transfer coefficients were compared to those for bulk flow alone. The upstream coefficient was based on 10 mm upstream of the collecting electrode (45-55 mm) to account for affects due to the larger gap spacings investigated while the downstream coefficient was computed as discussed above. Figure 9 shows the difference in the forced convection component of the average heat transfer coefficient with and without active corona as a function of the electrode gap for a constant corona wire height of \(h = 3.15\) mm. The bulk velocity was \(u = 0.28\) m/s, and the heater power was \(P = 4\) W.

Figure 10 shows the difference in the forced convection component of the average heat transfer coefficient with and without active corona as a function of the electrode gap. The bulk velocity was \(u = 0.28\) m/s, and the heater power was \(P = 4\) W. Here, the general trend is that as the wire is elevated, greater heat transfer enhancement occurs. The elevated configuration generates a large body force component towards the plate effectively thinning the thermal boundary layer. Another issue is the neutralization or gathering of ions on the dielectric flat plate between the electrodes due to random collisions. As ions contact the plate, they can be trapped on the surface such that they no longer provide useful work to the flow. In configurations where the wire is very close to the plate, the ions are more likely to be trapped, possibly accounting for the decreased heat transfer. Additionally, the heat transfer enhancement tends to level off as the wire approaches the local boundary layer thickness. The increased local velocity farther from the plate can swamp the effect of the ionic wind.

These preliminary parametric studies suggest that increasing the electrode gap and raising the corona wire will generally increase heat transfer. However, one significant trade-off is that as either the gap or electrode height increases, greater voltages are required, and these must be accounted for in any design decisions. Further study is needed to fully understand these trends and the physical mechanisms associated with electrode geometry.

\[
\delta_{wire} = 5 \frac{V_{wire} y}{u} \quad (10)
\]

The general trend indicates that as the gap increases, the heat transfer enhancement increases both upstream and downstream of the collecting electrode. One explanation is that the ions travel a longer distance before being collected; they thus experience more collisions with neutral molecules, therefore exchanging more momentum. A local maximum suggests an optimal spacing for upstream enhancement, although this may be limited to the particular corona wire height tested.

\[
\text{Figure 8} \quad \text{The average heat transfer coefficient with and without active corona as a function of the applied heater power to the flat plate. The bulk velocity was } u = 0.28 \text{ m/s, and the corona current was } i = 15 \mu \text{A.}
\]
The electrode height for a constant corona wire gap of $y = 2$ mm. The bulk velocity was $u = 0.28$ m/s, and the heater power was $P = 4$ W.

CONCLUSIONS

Enhanced convection cooling has been demonstrated using a corona discharge. The corona discharge current was shown to be quadratically related to the applied voltage, confirming theory and observation by earlier investigators. The heat transfer coefficient due to the corona is linear with the fourth root of the corona current, qualitatively confirming the expected relationship based on analysis. Little variation of the corona-induced heat transfer coefficient with the heat flux imposed on the plate suggests that the electrohydrodynamic interaction is due to a corona wind and is fluidic in nature. Parametric studies on the electrode configuration suggest that larger electrode gaps and elevated electrodes increase the heat transfer enhancement, though at the expense of increased voltages.

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