Electrohydrodynamic Single-phase Convection Heat Transfer Enhancement Techniques: Direct ionic wind and Vortex induction

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***Abstract*— Generation of the corona discharge between a sharp electrode and a grounded heated surface usually induces an ionic wind, whose momentum can be used for enhancement of heat transfer. The previous studies are mainly devoted to exploitation of the normal velocity component, resulting from the direct ionic wind momentum. However, the normal velocities can produce streamwise longitudinal vortices. Although these longitudinal vortices can be applied for active-vortex induced heat transfer enhancement, several researchers have reported a dramatic decrease in the local heat transfer coefficient due to poor understanding of the generated vortex properties and improper design of the system. In the present paper, a comprehensive literature review is presented. The effect of the active-vortex induced by corona discharge is emphasized to obtain a better understanding of the enhancement mechanism.**

I. INTRODUCTION

Corona discharge between a sharp electrode and a grounded heated surface usually induces an ionic wind, whose momentum can be used for enhancement of heat transfer from the heated surface. Both phenomena are caused by the ionization of air molecules in the intense electric field region around the sharp electrode that accelerates ions and drags the air molecules towards the grounded surface. The drag flow pattern is typically rotational due to the nonuniformity of the imposed electric field and space charge density. The non-uniform electric body force induces vorticities depending on the electrode configuration and geometry. The drag flow pattern produced through corona discharge is called corona wind or ionic wind.

The corona discharge-assisted single-phase heat transfer enhancement is possible through two distinctive mechanisms. The first mechanism corresponds to the direct convective heat transfer enhancement technique using the ionic wind momentum. In this technique, the heated surface becomes an electrode, which is a blunt grounded electrode and the corona discharge is established using a sharp electrode separated from the surface. By imposing the electric field, a jet-like drag flow is established and both hydrodynamic and thermal boundary layers become thinner due to the air convection. Even more enhancement can be obtained by increasing the strength of electric field. In the second mechanism, augmentation is obtained through vortex generation using a multiple energized electrode arrangement. The vortex strength depends on the imposed electric field and the electrode arrangement. In Table I, a summary of the selected literature review is provided and the type of enhancement mechanism is indicated.

Comparing the two different techniques, the directional ionic wind cooling has been the subject of many investigations. Although in this technique, some undesired vortices appeared as a drawback to decreasing the electrode spacing, authors did not study the effect extensively. A dramatic decrease in the heat transfer rate due to the vortex generation has been reported by many authors. Understanding the vortex generation mechanism helps to mitigate its undesired drawbacks or even exploit them to achieve more augmentations.

In the present work, the literature on single-phase heat transfer enhancement from external objects through corona discharge is comprehensively reviewed. Two distinctive corona-assisted enhancement techniques, (1) direct ionic wind exploitation and (2) vortex induction, are identified. The vorticity transport equation in the presence of corona discharge is revisited and the vortex generation mechanism is discussed. The contribution of vortex generation as an enhancement mechanism is highlighted and discussed in detail.

II. GOVERNING EQUATIONS

Convection heat transfer in the presence of corona discharge is affected by the distribution of space charge density and electric field. The combination of the buoyancy body force and corona-driven flow can potentially induce various flow patterns. The electric body force can be expressed as [1]:

$$\mathbf{f} = \rho_c \mathbf{E} - \frac{1}{2}|\mathbf{E}|^2 \nabla \varepsilon_o + \frac{1}{2}\nabla\left[|\mathbf{E}|^2 \rho \left(\frac{\partial \varepsilon_o}{\partial \rho}\right)_T\right] \qquad (1)$$

The first term on the right side of the Eq.(1) is the electrophoretic, or Coulombic, force that results from the net free charges in gas. The second term, known as the dielectrophoretic force, arises from permittivity gradients. The last term, called the electrostrictive force, is important only for compressible fluids. The corona wind arises completely from the electrophoretic force term. Therefore, only the first term contributes to the corona wind generation. The bulk flow is laminar and two-dimensional. The buoyancy effect is estimated using the Boussinesq approximation. The governing equations are as follows [2]:

$$\nabla \cdot (\rho \mathbf{u}) = 0 \qquad (2)$$

$$\nabla \cdot (\rho \mathbf{uu}) = -\boldsymbol{\nabla} \mathrm{p} + \mu \nabla^2 \mathbf{u} + \mathbf{g}\beta(\mathrm{T} - \mathrm{T}_\infty) + \rho_c \mathbf{E} \qquad (3)$$

$$\mathbf{u} \cdot \nabla \mathrm{T} = \alpha \nabla^2 \mathrm{T} + \frac{\rho_c \mathrm{b} |\mathbf{E}|^2}{\rho C_\mathrm{p}} \qquad (4)$$

The second term on the right hand side is Joule heating heat caused by ionic current. The electric field around the sharp tip, which is responsible for ionization, is distorted by the free charges in the ionized medium and is governed by Poisson's equation:

$$\boldsymbol{\nabla} \cdot \mathbf{E} = \boldsymbol{\nabla} \cdot (-\nabla \varphi) = \frac{\rho_c}{\varepsilon_o} \qquad (5)$$

The generated ions are moved from the high voltage electrode towards the grounded surface through the electric force. The ion transport is governed by the charge conservation equation:

$$\boldsymbol{\nabla} \cdot \mathbf{J} = 0 \qquad (6)$$

where current density is defined as:

$$\mathbf{J} = \rho_c \mathrm{b} \mathbf{E} - \mathrm{D_i} \nabla \rho_c \qquad (7)$$

The ion mobility and ion diffusion coefficient are typically $b = 1.88 \times 10^{-4}$ $\mathrm{m}^2 \mathrm{V}^{-1} \mathrm{s}^{-1}$ and $\mathrm{D_i} = 3.50 \times 10^{-5}$ $\mathrm{m}^2 \mathrm{s}^{-1}$, respectively.

In order to understand the origin of vortex generation, the derivation of the vorticity transport equation may help understand the mechanism of rotational flow generation in the discharge medium. By taking the curl of momentum equation (3), the vorticity transport equation in the steady state condition can be obtained:

$$\mathbf{u}. \nabla \omega = \omega. \nabla \mathrm{u} + \nu \nabla^2 \omega + \beta \mathbf{g} \times \boldsymbol{\nabla} \mathrm{T} + \frac{1}{\rho} \boldsymbol{\nabla} \rho_c \times \mathbf{E} \qquad (8)$$

The vorticity is produced by two source terms (third and forth terms on the right hand side) and is transported by vortex stretching and diffusion mechanisms. The third term is generated by buoyant force and the forth one by the electrophoretic body force. Equation (8) reveals the physics of vortex generation in the presence of corona discharge. An EHD vortex is generated by a nonparallel gradient of charge density and electric field. The strength of vortices depends on the strength of electric field and the associated charge density in the air. The maximum of both gradient of charge density and electric field occur around the tip of the electrode. In contrast, the gradient of charge density becomes smaller around the ground electrode. The thermal gradient in air also produces vorticity. The third term is associated to the thermal gradient vorticity generation and its direction is inverse in respect with the electrohydrodynamic vorticity source term in the present case. Therefore, the momentum equation balance depends on the magnitude of these two source terms. At the onset of corona discharge, the electric field and the gradient of charge density are comparatively small and the thermal vorticity generation has a dominant role around the grounded object; the flow pattern is dominantly determined by buoyant and viscous forces. By increasing the corona voltage, the electric field and the gradient of charge density becomes greater and can induce stronger vorticity. At a specific applied voltage beyond some critical value, the effect of electrohydrodynamic vorticity becomes dominant and the buoyancy driven flow can be affected. As a specific example, the heat transfer rate around a object can be changed by generating strong enough electrohydrodynamic vorticities at higher corona voltages.

The gradient of space charge density is a function of electrode configuration. For two configurations, coaxial cylinders (concentric wire-cylinder) and parallel-plate geometry, the electric field and space charge density are uniform. The gradient of the space charge is perpendicular to the field vector and the electric body force is not rotational. Therefore, in these configurations, the nonuniformities in space charge and electric field do not create rotational flow field [3]. For all other configurations, the flow field is rotational and the nonuniformity in space charge density and electric field plays an important role in vortex generation [3,4] and potential turbulences [5-9].

III. EHD FLOW PATTERN VISUALIZATION TECHNIQUES

Since the electric body force creates various rotational flow patterns, many investigations have been performed to find the ionic wind patterns for various electrode configurations. Flow visualization is important for understanding the heat transfer mechanism and provides interesting benchmarks for further numerical analysis. The Mach-Zehnder (MZI) interferometer has been used to visualize the thermal boundary layer [10-13]. However, the interferometric studies were mostly qualitative and very few quantitative analyses have been performed to obtain the local heat transfer enhancement due to the corona wind from interferograms [10,13]. Although MZI can be used only for thermal boundary layer visualizations, it may give some fingerprints of hydrodynamic flow pattern around the heated surface. In addition a few Schlieren flow visualizations have been performed to capture the circular flow patterns for nonisothermal electrodes [14]. In these previous investigations, seed particles have been mainly used to visualize the ionic wind streamlines around objects [15-23]. However, very few intrusive techniques were used to visualize both the hydrodynamic and thermal boundary layers. As it will be shown, the particle based visualization analysis for heat transfer application is not reliable due to the particle-space charge-electric field interactions.

In order to show that the smoke test is not an appropriate tool to visualize the EHD flow pattern, the vorticity transport equation is re-formulated to highlight the importance of current density distribution and the ion mobility contribution in EHD vortex generation. Substituting the conservation of charge and neglecting the diffusion reveals the importance of current density distribution and ion mobility contribution is vortex generation process in the presence of corona discharge

$$\mathbf{u}.\nabla\omega = \omega.\nabla\mathrm{u} + \nu\nabla^2\omega + \beta\mathbf{g}\times\nabla\mathrm{T} + \frac{1}{\rho}\nabla\rho_c \times \left(\frac{\mathbf{J}}{\rho_c \mathrm{b}}\right) \qquad (9)$$

As it can be seen in Eq.(9), the vortex generation is influenced by the current density distribution and ion mobility of the gaseous medium. This justifies a conclusion that changing the corona discharge medium could affect the rotational flow patterns. This is particularly important as many authors have used particle seeds, or smoke particles, for visualization purposes. By introducing the particles to the discharge medium, the ion mobility reduces to one or three orders of magnitude compared with air molecule ion mobility. This significant change in ion mobility may remarkably undermine the strength of vortex generation or completely change the flow pattern. Moreover, in heat transfer applications, the reduced current density due to the additives may dramatically reduce the heat transfer as well. Low heat transfer enhancements in a few experimental works [15,16] are believed to be due to the presence of smoke particles in the velocity field visualization process. It is noteworthy to mention that the ion mobility also decreases as a function of temperature [24,25]. This dependency changes the flow pattern as well, as the corona V-I characteristic curve [13,27]. This is also important when a stream of hot particles such as cigarette smoke is used for EHD flow visualization. According to discussion the above, the EHD flow visualization results using either cold or hot particles are questionable.

V. DIRECT IONIC WIND HEAT TRANSFER ENHANCEMENT TECHNIQUE

Electrohydrodynamic heat transfer enhancement from various objects through the direct technique has been investigated extensively. In this, the momentum of the drag flow produced by strong ion injection from a sharp electrode is generally used to develop a flow field around the target. By varying the strength of the field and other physical parameters, which influence the corona discharge, the heat transfer rate can be readily controlled. Experimental studies showed that the magnitude of the current density is a primary factor in determining the rate of heat transfer [28-30]. Most of the previous experimental studies have been focused on finding the average heat transfer coefficient. The heat transfer is enhanced impressively as high as 100-400% for most of the experimental studies. As expected, when the magnitude of electric body force is comparable with other forces like inertia or buoyant forces (for low *Re* and *Ra* regimes, respectively), the resulting augmentations are high [31,32]. Particularly in the low Rayleigh regime, the main flow is influenced by the electric force and the role of corona discharge is prominent [33]. For low Rayleigh free convection, which is encountered in a number of applications, significant heat transfer enhancements have been reported through the literature [13,31,34 ,35].

Most recently, authors have focused on exploiting the ionic wind to enhance local high transfer due to its potential applications in hot spot reduction and electronic cooling. However, since the corona discharge is produced with a nonuniform electric field and space charge density, it can potentially produce rotational flow. Although the vortex generation have been recognized as an enhancement technique [12, 36], several experimental measurements showed dramatic suppression in heat transfer [see 35,37]. In order to understand the unexpected heat transfer suppression, a review for longitudinal vortex generation technique will be presented.

Table. I. Selected literature review

Author	Application	Type of analysis	parameters	Flow visualization
Marco and Velkoff [14]	Vertical plate-wire	Experimental/Theoretical Local/average/Direct	500% enhancement	Schlieren
Yabe et al.[52]	Horizontal plate-wire	Experimental/Numerical /Direct		
O'Brien[10]	Vertical plate-wire	Experimental Direct	Various pressures	MZI
Franke and Hogue [11]	Horizontal cylinder/wire	Experimental Average Direct	600% enhancements	MZI
Owsenek Seyed-Yagoobi[30]	Horizontal plate/single needle	Experimental Direct	2500%	-
Owsenek Seyed-Yagoobi[53]	Horizontal plate/multiple needle	Experimental Direct		
Franke [12]	Vertical plate/wire	Experimental/ Average Vortex generation	200% Enhancement	MZI
Kalman, Sher[54]	Vertical plate/wire	Experimental/ Average Direct	230% Enhancement	-
Rashkovan et al.[15]			80% Enhancement	Smoke particle
Yonggang et. Al [55]	Vertical plate/needle	Experimental/average Direct	1200% enhancement positive corona	-
Kohya et. Al[56]	Tube bank/wire	Experimental/Direct	-	-
Kuriyama et.al[57,58]	Tube bank/wire	Experimental/Direct	-	-
Wangnipparnto et. al[16,18]	Tube bank/wires	Experimental/Direct	16% enhancement	Smoke particles
Vithayasai et. al[59]	Louvered fin and flat tube/wire	Experimental/Direct	Enhancement <25% , 100<Re<600	-
D.Go et. al [37]	Horizontal plate/wire	Experimental/Numerical Direct	Local heat transfer suppression due to the vortex generation	-
Robinson [29]	Corona wire	Experimental/Direct	-	-
Kasayapanand [31]	Enclosure/multi - wires	Experimental/Numerical Direct	100% at $Ra=10^6$	-
Kasayapanand [35,60]	Enclosure /multi - wires	Numerical/Direct	400% at Re=100	
Mahmoudi et. al [13]	Horizontal cylinder/blade	Experimental/Numerical Direct	200% at Re=1500	MZI
Kasayapanand and Kiatsiriroat [35]	Wavy channel/Multi-wires	Numerical/Direct	440% enhancement Local suppression due to the vortex generation	

VI. INDUCED VORTEX HEAT TRANSFER ENHANCEMENT TECHNIQUE

An early experimental study of the effect of vortex generation on hydrodynamic boundary layer and delay in separation phenomenon was conducted by Schubauer and Spangenberg [38]. To the best of the author's knowledge, the impact of vortex generation on heat transfer enhancement was first proposed by Johnson and Joubert [39]. A local heat transfer enhancement of 200% was achieved by a winglet vortex generator on a cylinder in a cross flow. Although the local heat transfer showed remarkable augmentation, the average heat transfer was not promising. The heat transfer measurements of local heat transfer enhancement due to the axial Taylor vortices in an inner rotating-outer stationary cylinder configuration provided a good picture of neighboring vortices integrations [40]. The heat transfer was locally augmented where the neighboring vortices direct the flow toward the heated surface. In contrast, the measurements revealed local heat transfer decrease for those neighboring vortices which induce the outward flow. The observed evidence suggested the local thinning of the boundary layer is responsible for the significant enhancements. Further experiments by Shizawa and Eaton [41] confirmed that the sign of vortices are essential in their interactions with the boundary layer. They observed that if the vortex-induced velocity is in the same direction as the external flow, then boundary layer thinning occurs and the corresponding perturbations decay rapidly. Strong traverse separation was reported for the opposite sign of the vortex.

According to the discussion above, the sign of the induced vortex with respect to the mean flow around the wall is extremely important [36]. This concept is general and can be applied to the case where the vortices are generated by the corona discharge to control boundary layer separation [42]. Proper electrode arrangement may result in local and average heat transfer augmentations. Two alternative electrode arrangements for corona vortex induced enhancement technique are illustrated in Fig.1. In the first design, the sign of the generated vortex and the external flow are opposite and boundary layer separation is expected. The outward ionic induced vortex and opposite external flow interaction result in a boundary layer separation and decreases in the local heat transfer. However, in the downstream region, the boundary layer mixing enhancement due to the turbulence persistence leads to an increase in heat transfer. Depending on the corona discharge parameters and dimensions of the heated surface, a significant decrease in average heat transfer coefficient is expected. For the second design, the vortex sign is in the same direction of the external flow. Significant increases in both local and average heat transfer can be achieved through thinning of both thermal and hydrodynamic boundary layers. Therefore, the direction of the induced vortex velocity with respect to the external flow in the vicinity of the wall can determine the rate of heat transfer enhancement. As an example of improper arrangement, Go et. al [37] performed extensive sets of experiments using an upward facing grounded plate in the presence of external flow and corona discharge. The corona wind was established through a stretched wire over the test section. The external flow was in the opposite direction of the vortex induced velocity due to the ionic wind. They reported significant heat transfer suppression (even lower that the heat transfer in the absence of corona discharge) in a main portion of the experimental test section. Although, they did not describe the origin of such strong suppression of local heat transfer coefficient [43], the observed decrement in local heat transfer is believed to be due to the strong vortex generation-main flow interaction and boundary layer separation phenomenon. By inversing the main flow direction (second design), the rotational flow created by corona discharge around the heated surface becomes stream-wise and one expect augmentation in heat transfer rate in lieu of suppression. Fig.2 qualitatively shows the impact of vortex sign on thickness of the boundary layer.

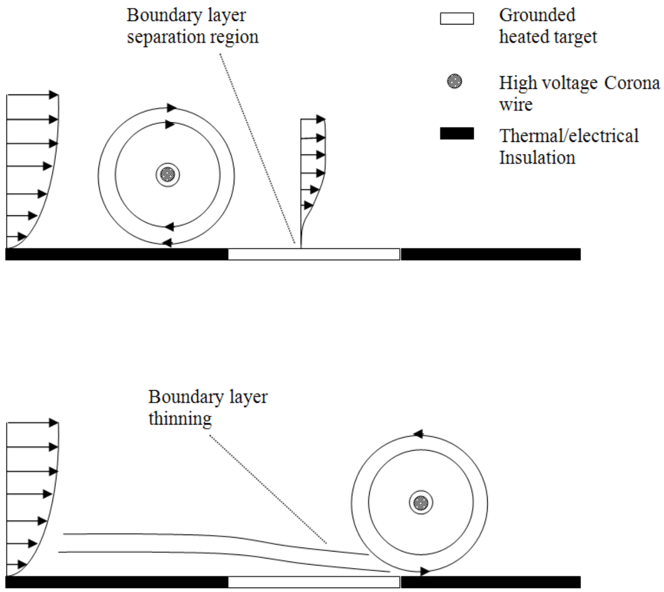

Fig 1. Schematic of corona discharge vortex –induced flow patterns. The traverse flow is in opposite direction (a) and in the same direction (b) of the vortex around the wall (b).

VII. OTHER CONSIDERATIONS

Although significant heat transfer enhancement can be achieved through corona discharge, one should be cautious about the effect of corrosive by-products of the discharge. This can be particularly important when the reliability of the enhancement technique is of great concern. Ozone generation and other reactive species can chemically react with the electrode surfaces [44-46]. Electrode corrosion could increase the onset of corona voltage and affect the corona characteristic curve. The reduced electric current due to the electrode oxidization may affect the flow patterns and performance of ionic discharge heat exchangers. The reactive ions could also deteriorate the substrate surface and shorten their life time. Many authors suggested that this technique is theoretically applicable for electronic cooling applications [12-18, 47]; however, according to the author's knowledge, no systematic investigation has been performed to justify the reliability of the technique.

Heat transfer rate is a function of corona discharge parameters in a specific gaseous medium [10,48,49]. Relative humidity, operating pressure, configuration of electrodes and temperature of the gas due to Joule heating of the external object effect [50] determine the discharge characteristic curve and the rate of heat removal [51]. For instance, increasing the humidity of the discharge medium results in reduced corona current at a given applied voltage and reduced heat transfer rate. By increasing the operating pressure, the corona current increases at a given applied voltage and heat transfer shows enhancements. For corona discharges at higher gas temperature, the corona current

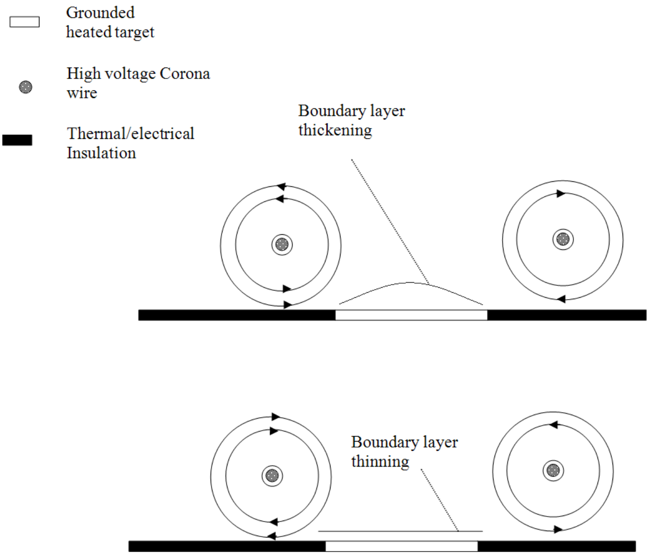

Figure 2. Schematic of corona discharge vortex–induced flow patterns through two corona wires. Both induced velocity of the vortices (a) are outward and toward (b) of the heated surface. The effect of boundary layer thickening (a) and boundary layer thinning (b) are illustrated.

decreases due to the decrease in ion mobility and results in reduced heat transfer. Finally, the curvature radii of electrodes, their polarity and configuration change the characteristic curve and spatial distribution of the current density. It is also noteworthy to mention that the corona discharge characteristics, and its corresponding heat transfer enhancements, are very dependent on the ambient gas conditions, such as pressure, relative humidity, temperature, number of particles per volume of discharge medium, and the electrode profile and one may find very few enhancement correlations for EHD flow.

CONCLUSIONS

A comprehensive review of heat transfer enhancement through corona discharge is reviewed. Two distinctive mechanisms for EHD enhanced heat transfer, direct momentum enhancement and vortex induced technique are discriminated and discussed in detail. It was concluded that the two conditions, non-parallel space charge gradient and strong electric field, should coexist to generate ionic wind vortices. The legitimacy of flow visualizations based on seed particle techniques is questioned.

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