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A simplified model for estimating heat transfer coefficient in a chamber with electrohydrodynamic effect (corona wind)

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ABSTRACT

A negative corona wind generated in air by high electric potential difference is numerically modeled here. To simulate the ion generation and drag phenomenon, a unipolar approximation method is applied which takes into account both electrons and negative ions. The significance of this simulation method is replacing the complexity of ionization kinetics with the simplicity of a single boundary condition on the active electrode. To the knowledge of the authors, this is the first application of this method to the investigation of heat transfer coefficient. The results verified that increasing the applied voltage increases average convection heat transfer coefficient, peaking at 23.5 W/(m2.K).

1. Introduction

Electrohydrodynamics (EHD) is broadly defined as that branch of fluid mechanics that deals with electrical force effects. The principle of EHD is based on the ionic drag phenomenon generated in dielectric fluids by a moving space charge pulled through by an externally applied field. The space charge is a collection of a large number of positively or negatively charged particles. Electrohydrodynamic is believed to mechanically enhance heat transfer of single-phase fluids through various means including electrophoretic and dielectrophoretic forces, EHD-induced flows in liquids, and the flow of corona (electric) wind in gasses. Electric (corona) wind is a phenomenon associated with the induction of electric charges into a dielectric gas at one electrode of a two-electrode assembly. The electric field acts on the plume of the charges and the electric body force accelerates the charges towards the other electrode. The moving charges drag the inert gas molecules surrounding them and cause a fluid flow. The drag is sometimes referred to as “the ion drag” phenomenon [1]. As a significant difference in the curvature of the electrodes is needed for the corona wind to take place, the common electrode pairs include point-plane, wire-plane, and multiple-wire.

In 2002, Wangnipparnto et al. [2] reinforced heat transfer in a thermosyphon heat exchanger for air using corona wind from a set of wire electrodes parallel to the heat pipes. Their study encompassed only low Reynolds numbers (58–230) and realized that the effect of EHD on heat transfer coefficient is only significant above 15.5 kV of applied voltage and its enhancement decreases from 15 to 10% with increasing Reynolds number. In 2003, Wangnipparnto et al. [3] proposed a numerical method to simulate the experimental set up of [2]. They compared the effectiveness of using EHD solely in the evaporator or the condenser section of the heat exchanger, and realized the later solution to be more effective. In 2007, Kasayapanand and Kiatsiriroat [4] numerically studied the performance improvement of a double-flow solar air heater which utilizes a strong DC electric field in order to boost the heat transfer coefficient. They observed that the improvement in heat transfer coefficient increases with the applied voltage but decreases with the total mass flux ratio. In order to maximize the collector efficiency, they found the optimized electrode spacing to be equal to the channel height. In the same year, they [5] numerically and experimentally studied the effect of electrode arrangement on heat transfer from wire electrodes in an enclosure and found a uniform arrangement of electrodes gives the best performance at lower Rayleigh numbers.

In 2008, Stishkov and Samusenko [6] used Fokker-Planck equations in order to simulate negative corona discharge in an inert gas in wire-cylinder electrode assembly. They found peculiarities exclusive for inert gases which precludes the application of the results to air medium. They also found that steady state solution is only applicable for voltages over a threshold value. An enhancement factor was defined by Yang et al. [7] in their experimental work for investigating convective heat transfer enhancement of water in a jacket-tube heat exchanger with EHD effect. High voltage DC electric field with potentials ranging from 0 to 40 KV was employed. They found that the maximal enhancement coefficient was sensitive to flow rate, such that in lower flow rates the enhancement is more obvious. Therefore it can be perceived that flow turbulence is a determining factor, and lower turbulence permits higher heat transfer augmentation with EHD. Moreover, in the same flow rate

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Nomenclature

j_e	electron flux (current density)(A/m)
j_i	Negative ion flux (current density)(A/m)
j_0	seed electron flux(A/m)
γ	secondary electron emission coefficient(1)
M	ionization collision number(1)
τ	characteristic time of avalanche development(s)
φ	electric potential(V)
e	Elementary charge(C)
ε_0	permittivity of free space($S^4.A^2/(kg.m^3)$)
n_i	number density of negative ions(mol/m^3)
n_e	Number density of electrons(mol/m^3)
$\overrightarrow{E}$	electric field vector(V/m)
E	Electric field magnitude(V/m)
α(E)	Effective ionization coefficient(V/m^2)
D_i	Diffusion coefficient of negative ions in air(m^2/s)
D_e	Diffusion coefficient of electrons in air(m^2/s)
$\overrightarrow{P}$	Pressure vector(Pa)
μ	Air dynamic viscosity($N.s/m^2$)
η	Air kinematic viscosity(m^2/s)
$h_{avg,\ x}$	average heat transfer coefficient in x($W/(m^2.K)$)
$h_{avg,\ L}$	average convection heat transfer coefficient on a line with length L($W/(m^2.K)$)
k	thermal conductivity of air(W/(m.K))
u_∞	free air stream velocity(m/s)
Pr	Prandtle number(1)
U_a	Magnitude of the applied voltage(V)
$\overrightarrow{e_x}$	unit vector of electric field in x direction(1)
μ_i	Negative ion mobility($m^2/(V.s)$)
μ_e	Electron mobility($m^2/(V.s)$)
$\overrightarrow{v}$	Air velocity vector(m/s)
ν_{att}	Electron adhesion rate(1/s)
ρ	Air density(kg/m^3)
$\overrightarrow{n}$	normal vector of dielectric walls(1)

the enhancement peaks at an optimal voltage. The maximum heat transfer enhancement coefficient was observed to be 1.224 at 0.1 m^3/h. In 2009, Huang et al. [8] implemented a needle array electrode in a plate fin heat sink in order to enhance heat transfer in a controlled environment. They altered, electrode geometry, number of electrodes, corona polarity, and applied voltage, in order to find the best system configuration in terms of heat transfer enhancement in comparison with natural convection. The best enhancement ration they recorded was 3–5. Evaporation heat transfer enhancement with electrohydrodynamic effect was studied by Posew et al [9]. in 2009, where they found in practice that R-134 evaporates 1.25 and 1.15 times more under electric field in smooth and micro-fin tubes, respectively.

In 2012, Alamgholilou and Esmaeilzadeh [10] experimentally investigated the simultaneous effect of active (corona wind) and passive (perforated surface) measures on heat transfer enhancement from a set of ribs situated at the bottom of a rectangular duct. They reported an average heat transfer enhancement of up to 206%. They also found that the effect of corona wind in low Reynolds numbers is more dominant. In 2013, a review paper was published on the numerical models of simulating electrostatic precipitators. The study exhausted many of the mainstream methods for electric field, chemistry, and gas flow modeling, as well as different boundary conditions suggested up to the date [11]. In 2014, the study of Yazdani and Yagoobi [12] on the heat transfer enhancement of backstep flows applying EHD flow in the backstep region revealed that electrode configuration is determinant in whether the heat transfer improves or deteriorates. They also stated that EHD heat transfer enhancement in backstep flows is more suitable for micro applications due to their low Reynolds numbers. In 2014 [13], a hyperbolic emitting electrode was studied regarding heat transfer enhancement capabilities. The working medium was a dielectric fluid which in the form of an impinging jet cooled a hot flat plate directly situated under the hyperbolic electrode. The significant Nusselt number elevations due to EHD flow were confirmed by this study. In 2014, Dinani et al. [14] mathematically modeled EHD drying of mushroom slices under hot airflow of corona wind. They tried ten different mathematical model to find the one that best predicts the practical data. In a numerical study in 2009, Kasayapanand and Kiatsiriroat [15] investigated convection heat transfer from a set of fins under electric wind conditions and found an optimum fin spacing. They also reported that flow and heat transfer enhancement are decreasing functions of Rayleigh number.

In 2015, Ashikhmin et al. [16] compared simulation and experimental data of electric wind in point-torus and sphere-torus electrode systems. For the simulation, they used the so-called *unipolar approximation* method, taking into account the presence of both electrons and ions in the outer zone of the corona in order to enhance the precision, and utilized particle image laser velocimetry for extracting the air velocity field in practice. The I-V characteristics and velocity profiles of simulation were in good agreement with experiment. In 2016, Zhidkova and Samusenko compared commonplace simulation models with the model that takes into account the presence of electrons in the outer region of corona and has a boundary condition on electron flux on the high voltage electrode. Having had found their proposed model is significantly more accurate, they proposed correlations for air velocity, volumetric flow, and voltage as functions of electric current – based on the model results.

The fact that EHD heat transfer enhancement is more significant in lower turbulence flows was verified by Vatan et al. [17] where they experimentally studied natural convection heat transfer augmentation in a rectangular air duct with wire electrodes passing across the duct. Constant heat flux was applied through one of the duct walls which simultaneously acted as the plane electrode. They also found that the effect of corona wind was higher in acute duct angles and lower heat fluxes. In 2015, Nasirivatan et al. [18] studied the effect of electric field on natural convection of a solar chimney power plant (SCPP) pilot at its absorber plat. They could improve the efficiency of the power plant with enhancing heat transfer coefficient from the absorber plate as well as the air velocity inside the chimney. The 15 KV corona wind increased the heat transfer and air velocity 14.5% and 72%, respectively. Therefore, the output power of the plant was expected to increase 5 times. In 2016, Alami and Campo [19] investigated the optimum arrangement of wire electrodes over the hot ribbons in the duct in order to achieve the highest convective heat transfer coefficient with forced air stream. Hanafizadeh et al. [20] simulated the two-phase flow of R-134 inside a horizontal coaxial double-tube system, where the central tube acts as a heat source and is at a high voltage up to 5 KV, the outer tube is grounded and a uniform DC electrical field exists between the tubes where the refrigerant flows. They investigated the EHD effects on heat transfer enhancement and flow pattern and found that enhancement ratio is directly proportional to voltage, and it is reversely proportional to electrode diameter, mass flux, and inlet volume fraction. The longitudinal positioning of a single wire electrode, as well as longitudinal arrangement of multiple electrodes in a rectangular channel with air flow, was studied by Peng et al. [21] in 2016. The factor particularly defined to evaluate the level of EHD-induced heat transfer was the ratio of average heat transfer coefficient with EHD to that without EHD. They found that local heat transfer coefficient peaks at the electrode's position and its amount is the highest when the electrode is placed nearer to the channel inlet. They also found that further increasing the number of electrodes over a certain value only