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The effect of corona discharge on free convection heat transfer from a horizontal cylinder

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ABSTRACT

Free convection heat transfer from an isothermal horizontal cylinder in the presence of DC positive corona discharge with a blade edge emitter electrode has been studied experimentally and numerically. A Mach–Zehnder interferometer was used to determine the local Nusselt numbers. The effect of corona discharge on heat transfer from the cylinder was investigated at Rayleigh numbers in the range between 1500 and 5000. To find the details of the flow patterns and to further verify the experimental results, numerical simulations were also performed. It was found that the numerical results are in good agreement with experimental data. By increasing the applied voltage up to 15.5 kV, the corona discharge generates a recirculation zone around the blade and below the lower stagnation point of the cylinder. The effect of the recirculation zone becomes stronger near the breakdown voltage (17 kV) and it is responsible for a local decrease in the cooling of the cylinder around the lower stagnation point. The results indicate that corona discharge has a significant effect on the average Nusselt number at lower Rayleigh numbers whereas it has smaller effect at higher Rayleigh numbers.

1. Introduction

Establishment of 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. The corona discharge and ionic wind 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 toward the grounded surface. Electrostatic cooling devices operate without any moving parts, which reduces the mechanical vibration, its energy losses, and associated noises. Therefore, the electrostatic cooling is potentially attractive.

Corona enhancement of heat transfer from various objects has been the subject of many investigations because of a comparatively significant local enhancement of heat transfer coefficient with small corona discharge power consumption. For the first time, Marco and Velkoff [1] reported a 500% enhancement of average heat transfer coefficient and even higher local enhancements from a vertical heated plate in the presence of corona wind. The momentum integral analysis was carried out to further verify the experimental results. The theoretical results were in good agreement with experimental studies.

Yabe et al. [2] investigated the enhancement of heat transfer from a horizontal downward-facing plate with 40 μm wire electrode in a Plexiglass chamber connected to a high voltage source. A Langmuir probe was used to measure the space charge distribution and to verify the numerical results. They were able to model the recirculation flow inside the chamber and achieved a good agreement with their experimental results.

O'Brien and Shine used an interferometer to measure the ElectroHydroDynamic (EHD) enhancement of local heat transfer from a vertical isothermal flat plate for various air pressures [3]. They concluded that the boundary layer was distorted in the vicinity of the plate surface and the heat transfer coefficient increased with corona current.

Franke and Hogue [4] studied the corona wind effect on a heated horizontal cylinder using both a multi-emitter electrode and a wire electrode. The average heat transfer enhancement was quantitatively calculated by a heat-balance method and qualitatively with a Mach–Zehnder interferometer. Enhancement of heat transfer from the cylinder due to the corona discharge was reported as much as six times the free convection heat transfer. The authors found that the multi-emitter electrode was more effective compared with the stretched wire electrode. However, they did not report the local heat transfer coefficient around the cylinder.

Owsenek et al. [5] experimentally investigated the corona wind heat transfer enhancement from a horizontal flat plate. Needle electrodes with different height were used as the corona electrode.

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Nomenclature

b	ion mobility ($m^2\,V^{-1}\,s^{-1}$)
C	Gladstone–Dale coefficient ($m^{-3}\,Kg^{-1}$)
C_p	specific heat ($J\,kg^{-1}\,K^{-1}$)
D	diameter of cylinder (m)
D_i	ion diffusion coefficient ($m^2\,s^{-1}$)
$\mathbf{E}$	electric field ($V\,m^{-1}$)
$\mathbf{f}$	electric body force ($N\,m^{-3}$)
$\mathbf{g}$	gravitational acceleration ($m\,s^{-2}$)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
I_c	corona current (A)
$\mathbf{J}$	current density ($A\,m^{-2}$)
k_f	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
l	length of cylinder (m)
Nu	Nusselt number
P	pressure (Pa)
r	radial distance from the cylinder surface (m)
R_o	gas constant ($J\,kg^{-1}\,K^{-1}$)
Ra	conventional Rayleigh number based on temperature, $g\beta(T_s - T_\infty)D^3/\upsilon\alpha$
T	temperature (K)
$\mathbf{u}$	velocity field vector ($m\,s^{-1}$)

Greek symbols

α	thermal diffusivity ($m^2\,s^{-1}$)
β	volumetric thermal expansion coefficient (K^{-1})
ε	shift fringe
ε_o	vacuum permittivity ≈ air permittivity ($A\,s\,V^{-1}\,m^{-1}$)
φ	electric potential (V)
φ_o	voltage applied to corona electrode (V)
λ	laser wave length (m)
ρ	air density ($kg\,m^{-3}$)
ρ_c	charge density ($C\,m^{-3}$)
σ	electrical conductivity ($\Omega^{-1}\,m^{-1}$)
ν	kinematics viscosity ($m^2\,s^{-1}$)

Subscripts

S	referred to surface
θ	referred to periphery angle
∞	referred to infinite medium

An enhancement of more than 25:1 over free convection was reported. More recently [6], the same authors continued their theoretical and experimental studies and focused on a comparison between single and multiple wire electrodes. They concluded that for a given applied voltage, multiple wire electrodes yield smaller heat transfer enhancement per wire electrode than that of a single wire electrode. It was also found that dual recirculation may be formed between wire electrodes. Numerical simulations of novel electrode geometries revealed that this inefficiency may be eliminated through the use of a blade geometry.

Franke [7] investigated heat transfer from a vertical plate in the presence of corona-generated vortices. The vortices were generated by the corona discharge from parallel wires supplied with alternate high voltage and ground electrodes. He also visualized the thermal boundary layer using a Mach–Zehnder interferometer and measured the resulting heat transfer through both an energy balance and interferograms. A doubling of the convective component of total heat transfer with an applied corona voltage above the corona onset value was reported.

The literature review shows that finding the average heat transfer rate for external free convection flows in the presence of corona discharge has been the subject of several investigations. Various heated test sections, such as horizontal plate [8,9], vertical plate [10], horizontal tube bank [11–14], were investigated. Although enhancement of free convection heat transfer through corona discharge has been widely studied, few experimental studies have been performed to find the local heat transfer rate for external free convection flows in the presence of corona discharge. Moreover, previous studies on ionic wind-enhanced heat transfer show that the corona discharge has comparatively smaller effect on high-Reynolds force convection [15]. However, investigation of the interaction between the corona discharge and buoyancy-driven flow has not been studied.

In most of the previous interferometric studies, the EHD enhancements in heat transfer investigations have been limited to a qualitative visualization of the thermal boundary layer. In those studies, the average Nusselt number was determined using the energy balance method. This investigation involves a quantitative interferometric study of the positive corona discharge on the local heat transfer enhancement from an isothermal horizontal cylinder for different Rayleigh numbers. A circular cylinder was selected as the test section, because the circular tube is widely used in typical heat exchangers. Considering the limitations of the interferometer plates, the diameter of the cylinder and the surface temperature were selected to obtain an appropriate range of Rayleigh number ($1500 < Ra < 5000$) which is frequently encountered in conventional HVAC systems. In order to generate a uniform distribution of discharge effects along the laser beam which is needed for the two-dimensional interferometric studies, a sharp tip blade was used as a high voltage corona electrode. Moreover, compared with other electrode geometries, alignment of the blade electrode can be achieved more precisely along the laser beam. In order to find the details of the flow patterns and to further verify the experimental results, a numerical simulation was also performed.

2. Experimental setup

The apparatus used in this experiment consisted of three major components: (i) an isothermally heated surface, heating facilities, instrumentation, and control, (ii) high voltage apparatus and measurement devices and (iii) temperature field visualization system. The schematic of the experimental setup and apparatus is presented in Fig. 1a.

The test section was an extruded aluminum hollow cylinder with a highly polished outer surface. The details of the test section are shown in Fig. 1b. The length of the cylinder was chosen as 160 mm (16 times of diameter) which causes the induced flow to be two-dimensional. In order to minimize the thermal end effects, two wooden fiber end caps with $k = 0.05\ W/m^2\ K$ were installed at both ends of the test section. In order to position the cylinder in the horizontal direction, two plastic rods were connected to these end caps and installed on the XYZ holders. The cylinder had an axial cavity to facilitate installation of a coiled nickel–chromium wire heater element at the center of the cavity. The space between the heater coil and inner wall of the hollow cylinder was filled with magnesium oxide powder. Four holes with 0.55 mm diameter were drilled into the base surface of the cylinder at 30, 50, 60 and 80 mm from the base ends in different peripheral angles. Four calibrated K-type thermocouples were inserted and fixed in these holes. All the temperatures were monitored continuously by a TESTO 177 data logger which was connected to a PC. The maximum difference