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Research Paper

Regulation-controlling of boundary layer by multi-wire-to-cylinder negative corona discharge

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HIGHLIGHTS

- Heat transfer has been enhanced by multi-wire-to-cylinder corona discharge.
- The unipolar model for boundary layer investigation is used.
- The velocity of boundary layer can be increased with the voltage.
- The distribution of corona wire can regulate velocity field and temperature field.
- Field synergy for heat transfer enhancement is introduced.

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ABSTRACT

Multi-wire-to-cylinder corona discharge was studied for better understanding of the electrohydrodynamic phenomena which directly relate to the performance of heat transfer enhancement. A unipolar approximation model was established and numerical simulations were conducted to determinate the heat transfer and velocity distribution of ionic wind. The numerical and experiments results show good agreement. It indicates that higher applied voltage and more corona wires can help decreasing thermal boundary layer thickness and increasing velocity gradient of boundary layer, resulting in the enhancement of heat transfer. When the applied voltage increases from −7 kV to −11 kV and the number of wire increases from corona wire number 1–3, there will be a 39.8% decrease of the thickness of thermal boundary layer. In the condition of $U = -11$ kV, the maximum local forced convection heat transfer coefficient for corona wire number $N = 3$ is 12 times and the average value is 8 times higher than that of natural convection.

1. Introduction

The basic corona discharge physics in atmospheric air has already been well-known for over one hundred years, and it can be depicted as a self-sustaining electrical gas discharge occurring around the active electrode with the smallest curvature radius and on which the high voltage is applied [1]. A significant amount of researches have been conducted into the unipolar/bipolar and AC/DC corona discharge [2,3]. According to the polarity of the active electrode, there exist two DC corona discharge forms named positive corona and negative corona. And corona discharges are non-equilibrium plasmas with an about 10^{-8}% degree of ionization (the ratio of the number of charged species to the number of neutral species). There exist two regions, ionization region and drift region. The ionization region round the active electrode is filled with electrons and ions. Positive or negative ions are subjected to Coulomb force and drifting towards the grounded collecting electrode in the drift region. These ions impact on the neutral air molecules, resulting in a momentum transfer that produces a gas flow from the active electrode to the grounded collecting one. This phenomenon is well-known as Electrohydrodynamic (EHD), and the induced flow is usually called ionic wind [4–9]. It has been experimentally and theoretically studied in recent years due to its potential applications such as enhancement of heat transfer [10], electrostatic precipitation [11], aerodynamic flow control [12,13] and electric propulsion [14–16].

Till now, most of the experiments about ionic wind enhancing heat transfer focused mainly on finding the average heat transfer coefficient and there has been some progress. By changing the

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shape of electrode, the efficiency of heat transfer is enhanced as high as 100–400% in most of the experimental studies. For instance, Go et al. [17] studied the heat transfer enhanced by corona discharge with wire-plate electrodes. The result showed that ionic wind increased local forced convection heat transfer coefficient to more than twice, compared with natural convection. Owsenek et al. [18] applied needle-plate to generate corona discharge and ionic wind. They proved that local forced convection heat transfer coefficient exceeds 65 W/m^2 K, which was 25 times higher than natural convective heat transfer coefficient (2.6 W/m^2 K). Besides, scholars also studied the mechanism of ionic wind heat transfer at hot spot with MEMS technology to microminiaturize corona discharge electrodes. Ong et al. [19] adopted mesh-needle-mesh electrodes (the mesh sizes are 2.1×0.9 mm, the distance of needle and mesh is 1 mm) to investigate the influence of the sizes of hole in mesh electrode and the gap of need-mesh electrode on ionic wind. The heat flow rate by microminiaturized ionic wind actuator reached to 40 mW and the temperature of hot spot decreased 4 K, when the forced convection heat transfer coefficient reached the maximum 3200 W/m^2 K.

Large amount of breakthroughs in promoting ionic wind velocity have been achieved. For instance, when optimizing EHD gas pump with needle-mesh electrodes in a hollow tube, Moreau and Touchard [5] measured maximum velocity up to 10 m/s. The average ionic wind velocity was about 2 m/s and the efficiency of electric energy converting to air kinetic energy was 1.73%. Besides, Colas et al. [21] employed wire-cylinder-plate electrode and also recorded maximum velocity up to 10 m/s. The average velocity was nearly 4.5 m/s and the efficiency of electric energy converting to air kinetic energy was 1.33%. Other academics also acquired 1 m/s–10 m/s velocity with several types of electrodes [1,6,7]. The results are coordinated with the theoretical predictions of Sigmond [22] and Goldman et al. [23]. The above researches have proven that the single stage ionic wind actuator has reached the plateau in promoting ionic wind velocity and energy converting efficiency. Rickard et al. [6], Qiu et al. [9] and Kim et al. [24] sought to improve ionic wind velocity with multistage configuration. The research shows that ionic wind velocity is in direct proportion to the square root of stage number. Specifically, Qiu et al. used six needles-mesh electrodes in tube as single stage ionic wind actuator and 25 stages were in serial. The maximum ionic wind velocity reached around 16.1 m/s. However, the energy converting efficiency was 2.2%.

Leger et al. [25] studied the influence of corona discharge produced ionic wind on the velocity boundary layer with wire-plate electrodes configuration. The research illustrates that the velocity of boundary layer can be promoted while ionic wind is applied and the maximum flowing velocity in this boundary layer is 3 m/s, compared with 1.8 m/s without ionic wind. And similar result has been given by Moreau [12]. The massive experimental researches indicate that with the flowing velocity of ionic wind in boundary layer improved, the thickness of boundary layer is reduced to lower the thermal resistance and enhance the heat transfer.

In thermodynamics, non-dimensional Prandtl number P_r is generally adopted to represent the relationship of the thickness of thermal boundary layer δ_2 and velocity boundary thickness δ_1: if $P_r > 1$, it means the thermal boundary layer is relatively thin and the heat transfer is effective; if $P_r < 1$, it means the thermal boundary layer is thick and the heat transfer is poor. In order to achieve the heat transfer enhancement target, the thermal boundary thickness should be decreased to some extent so as to increase the fluid average velocity or decrease the velocity boundary layer thickness. In present, most of the works on heat transfer enhanced by ionic wind are focused on the increase of average and maximum flowing velocity. However, this paper is devoted in changing the electrode structure to control the velocity field in boundary layer and regulate thermal boundary layer. As a result, heat transfer will be enhanced.

The numeric simulation calculation of ionic wind is a complementary method for experimental study on local velocity field, such as the velocity of boundary layer. In the numeric simulation, single/multiple wires-double parallel plates is widely used, which prevails in ESP. Traditionally, unipolar approximation model is applied in ionic wind simulation, which ignores the thickness of corona sheath and only takes the single polar particles in drift region into consideration. Zhao and Adamiak et al. [26–28] made a simulation of ionic wind produced by single stage needle-mesh and needle-plate corona discharge with finite element method (FEM), boundary element method(BEM) and method of characteristic (MOC). Martins [29] and Colas et al. [30] simulated ionic wind velocity field by utilizing the electrodes type, a positive HV wire, two grounded cylinders and two negative HV plate electrodes and their results are coordinate with each other. Kim et al. [24] simulated the multiple stage ionic wind actuator and drew the conclusion that the flowing velocity was in direct proportion to the square root of stage number, which also agreed with the experiment. Jewell-Larsen et al. [31] and Ong et al. [19] investigated the influence of ionic wind on local enhancement heat transfer through microminiaturizing the electrodes. They also optimized the electrodes structure by simulation and acquired satisfying results.

Today, many applications in which wire-to-cylinder electrode configuration are being used, such as aerodynamics [32] and ozone generator [33]. In the industrial field of heat transfer, both the in-line and cross-line pipes are used to dissipate heat through natural convection or forced convection. At present, there are few reports on the heat dissipation enhancement of ion wind around the pipeline. Therefore, this paper studied ionic wind velocity field of multiple wires-to-cylinder corona discharge and heat transfer enhancement of cylinder surface by experiments and simulations. To enhance the heat transfer on the cylinder surface, the thickness of thermal boundary layer was decreased by changing the wire amount and the applied voltage on it. Through the study of this paper, it can provide positive significance and reference value for the application of the ion wind technology produced by corona discharge to the pipeline heat dissipation.

2. Experimental setup

Fig. 1 shows the schematic diagram of experimental setup used to measure the velocity field of ionic wind and the performance of heat transfer intensified by corona discharge. Four types of electrodes configuration are used in experiments and simulations, as shown in Fig. 2. The wire with radius of 25 μm was utilized and connected to a negative DC high voltage supply ($0 \sim -50$ kV) in series with a resistance (R = 10 MΩ). It was placed 10 mm away from the cylinder which is made of stainless steel and has a diameter of $D = 16$ mm and length of 100 mm. The cylinder was grounded via a micro ammeter. The wall thickness of cylinder was 0.8 mm, inside of which was nichrome resistance wire twined on the magnesium oxide bar and magnesia powder filled up the gap. The wall is heated through DC power source (0–200 V). The calibrated infrared thermometer (IS-CFL500AD series, resolution 0.1 K) was fixed on a displacement platform and 100 mm away from the surface of cylinder. The thermometer was manipulated to scan the temperature of the cylinder surface in the length direction (10 data points) and in the circumferential direction (2 data points), and 20 temperature data were processed to obtain