Applied Thermal Engineering 114 (2017) 554–560

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Effects of relative humidity in the convective heat transfer over flat surface using ionic wind

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HIGHLIGHTS

- Effect of relative humidity on both positive and negative ionic wind was studied.
- Ionic wind velocity profile along vertical axis changes with relative humidity.
- Heat transfer decreases with increasing relative humidity due to lower air thermal conductivity.
- Positive ionic wind is more stable than negative ionic wind at all relative humidities.
- Maximum heat transfer enhancement ratio of 1.6 was achieved at low relative humidity of 30%.

ARTICLE INFO

Article history:
Received 1 August 2016
Revised 2 December 2016
Accepted 7 December 2016
Available online 9 December 2016

Keywords:
Ionic wind
Heat transfer enhancement
Relative humidity
Forced convection

ABSTRACT

This study investigates the effects of relative humidity (RH) on the generation of ionic wind and the subsequent convective heat transfer enhancement over a flat surface. The overall power consumption by the positive ionic wind was found to be 2.4 times lower than that of the negative ionic wind. Despite the differences in the power consumption, both positive and negative ionic wind displayed similar average velocity at low RH levels (30–50%), while the negative ionic wind showed slightly higher average velocity compared to the positive ionic wind at higher RH levels (60–70%). Besides velocity magnitude, the velocity profile of the ionic wind along the vertical axis was also seen to change with increase in RH. On a similar note, the heat transfer coefficients of both positive and negative ionic wind was seen to decrease with increase in RH, attributed to the decrease in velocity. A comparison of the heat transfer enhancement ratio showed that the negative ionic wind produced better enhancement than the positive ionic wind, being able to enhance the heat transfer by 1.6 compared to 1.43 of the latter.

1. Introduction

Ionic wind enhancement of heat transfer has been the subject of many investigations because of its comparatively significant local enhancement of heat transfer coefficient with low power consumption. Due to its compact nature and lack of mechanical parts, ionic wind has since been intensively studied for its heat transfer capabilities as a potential replacement to conventional cooling devices such as mechanical fans [1–11]. Optimisation studies to increase the ionic wind capability include investigations to reduce the operating voltage of corona discharge [12,13], as well as manipulating the electrode geometries to provide insights to the governing factors of the phenomena [14]. Recent development of ionic wind demonstrates its growth as well as the potential to be assimilated in various applications. In a recent study by Zhang et al., a maximum wind velocity of as high as 7 m/s can be achieved under optimised conditions [15,16]. On a different note, Gilmore and Barret showed that the ionic wind can be implemented for propulsion, thus suggesting the potential of its feasibility at a small unmanned aerial vehicle (USA) scale [17].

In 2001, Kalman and Sher demonstrated an increase of a factor of more than two in their study of heat transfer enhancement of forced convection over a flat plate using ionic wind induced by a thin wire electrode which is confined by two inclined earthed wings [18]. Go et al. focused their study in enhancing forced convection by applying ionic wind onto a bulk flow [2,3]. Through optimisation of the arrangement of electrodes and spacing between electrodes, ionic wind was used to enhance the flow at the no-slip region by distorting the boundary layer of the bulk flow closest to heated surface, increasing local heat transfer coefficient by more than 200%. In another study, a comparison of single wire

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http://dx.doi.org/10.1016/j.applthermaleng.2016.12.030

electrodes and multiple wire electrodes showed that the multiple wire electrodes yield less heat transfer enhancement per wire electrode on a heated flat surface [19]. Recently, Gallandat and Mayor designed a heat sink utilising ionic wind for passive thermal management of grid-scale power routers, whereby the amount of heat rejected was found to be five times more than that of the natural convection, at an applied voltage of 5 kV [10]. Shabahangnia et al. investigated experimentally the effects of electrohydrodynamic on natural convection heat transfer in an inclined channel with constant heat flux [9]. The heat transfer in the presence of electrohydrodynamic is better at acute angles rather than obtuse angles; however, the opposite is the case when there is no external electric field. The highest cooling effect is found at the angle of 45° and 15 kV voltage, for about 61% over the natural convection. In other applications, studies were also conducted in utilising ionic wind for LED cooling. Chen et al. investigated the influences of discharge electrode types and alignment, as well as the collector electrode type on thermal resistance of the LED subjected to ionic wind [7,8]. Shin et al. designed and tested a new heat sink with ionic wind for LED cooling through Computational Fluid Dynamics (CFD) as well as developed a prototype for verification [11]. The highest ionic wind velocity tested was 2 m/s, however the optimum ionic wind velocity for the heat sink is found to be 1.5 m/s with enhanced performance of 150% as compared to natural convection using the same configuration.

As the formation of ionic wind involves the ionisation of air molecules, the surrounding environment would significantly affect its characteristics. To date, limited studies are found in the research area of effects of surrounding environment on the induced ionic wind. A study by Fouad and Elhazek [20] focused on the effects of air humidity on the corona inception voltage of a three electrode system while Zebboudj and Ikene [21] noted the effects of air density in a similar study using a wire-to-plane and wire-to-cylinder electrode system. In another study, the effects of air humidity on the ozone production from the ionic wind was also examined [22]. A more recent study by Nouri et al. [23] showed that the relative humidity can influence the behaviour of DC corona discharge and the current-voltage characteristics of an electrostatic precipitator. On a different note, the relative humidity was found to influence the aeolian electric field, an electric field generated through the charging of particles during the wind erosion process [24]. This study revealed that the aeolian electric field increased linearly with increased in relative humidity up to a critical value due to the increase of free charges in the ambient air.

From these studies, ionic wind has proved to be a useful alternative in enhancing cooling application and it is obvious that relative humidity can significantly affect both the generation of ionic wind as well as its convective heat transfer. Thus, this study aims to investigate the performance of both positive and negative ionic wind as well as its subsequent convective heat transfer enhancement on a heated surface under different relative humidities conditions. The results of this study would provide a useful insight to improve and optimise the quality of thermal management through the use of ionic wind under different environmental conditions.

2. Experimental setup

2.1. Equipment and materials

The schematic of the experimental configuration of the ionic wind to cool a heated block as well as the detailed geometries and connections involved in the experimental setup are shown in Fig. 1(a) and (b) respectively. The high voltage direct current (HV DC) power supply (FuG Model HCP 140-12500) which is used in this configuration is capable of supplying both positive and negative voltage up to a maximum of 12.5 kV and 10 mA current. The high voltage power supply is connected to the discharge and collector electrodes to create a strong electric field for the ionic wind initiation. As evident from Fig. 1, a cone-shaped stainless steel electrode of radius 4 mm and 21 mm length, with the angle of the sharp tip tapered at 22° is used as the discharge electrode while the stainless steel mesh used as collector electrode is of the size of 90 mm × 90 mm with grid size of 10.1 mm × 0.75 mm. In the subsequent heat transfer studies, a power supply from EA Elektro-Automatik (EA-PS 8160-04 LCD Power Supply) is used to heat up the heating block which is insulated using Rockwool to prevent heat loss. A telescopic straight probe anemometer (TSI Velocicalc Air Velocity Meter 9545-A) which is placed 9 cm away from the collector electrode, 9 mm above the heating block, is used for the measurement of the ionic wind velocity. Changes in temperature of the heated block are recorded with type K thermocouples coupled to a four channel digital thermometer model Center 309 data logger, whereby the thermocouples are placed as shown in Fig. 1. The experimental setup is enclosed in a controlled humidity chamber made of acrylic of size 450 mm × 900 mm × 600 mm (Model No. EW-03323-05, Cole Parmer).

2.2. Experimental procedures

The ionic wind velocity profile against the vertical axis at various relative humidities (30, 40, 50, 60 and 70%) is investigated by varying the position of the anemometer vertically from the reference point, which is the initial position, 9 cm in a direct distance away from the collector electrode. The velocity measurements are taken at every 2.5 mm increment vertically, up to a maximum height of 22.5 mm from the reference point. The gap distance between the discharge and collector electrodes of the induced ionic wind is kept constant at a distance of 2 cm.

In the latter study, a constant power of 5 W is supplied to the heating block to heat up the surface of the heating block to an equilibrium temperature before initiating the ionic wind. The surface temperatures of the heating block at steady state are recorded to investigate the convective heat transfer of the ionic wind. Both the current of the induced ionic wind and the average wind velocity are recorded simultaneously. The convective heat transfer of the ionic wind is investigated at ionic wind voltages of 9, 10, 11 and 12 kV at relative humidities of 30, 40, 50 and 60%. Relative humidities beyond 60% are not investigated as the high amount of moisture content in the air caused failure to the power supply used to provide heating power during the heat transfer experiment. All experiments are replicated for at least 5 times.

3. Data analysis

The heat transfer coefficient, h for the cooling of the heated surface by ionic wind at various relative humidity is calculated using Eq. (1),

$$h = \frac{P}{A_s \times (T_s - T_a)} \tag{1}$$

whereby P represents the power supplied to the heating block by taking into consideration the heat losses of the system, T_s represents the surface temperature of the heating block, which is the average of the temperature measured by the two thermocouples placed on the surface, while T_a represents the ambient temperature. A_s is the surface area of the flat plate.

Another performance indicator, namely the heat transfer enhancement ratio, is used to compare the results, calculated from Eq. (2),