Corona Discharge and Flow Characteristics of Wire-Plate Type Electrohydrodynamic Gas Pumps : Ground Plate Convergent Angle Effect

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An experimental investigation has been conducted to study the effect of ground plate convergent angles on time averaged discharge current, gas velocity and volumetric flow rate for a wire-plate type EHD gas pump. The experiments were conducted with four different convergent angles of the ground electrode under dc negative applied voltage from 0 to 17 kV at atmospheric pressure and room temperature, where air was working fluid. It was experimentally revealed that the gas flow direction, the gas velocity and the volumetric flow rate of electrohydrodynamically induced gas flow in a wire-plate electrode system were changed depending on the convergent angle of the ground electrode. Experimental results showed that (1) The gas flow direction for the cases of convergent ground electrode with over 3 degree was opposite to that for the case of parallel ground electrodes and (2) The volumetric flow rate and gas velocity increase with increasing dc negative applied voltage or EHD number.

1. Introduction

It has been well known that ionized gas molecule accelerated by electric field will collide with neutral gas molecules and exchange momentum to induce gas flow. This fluid motion was called electric wind, corona wind or ionic wind in the past work and now it is called electrohydrodynamic (EHD) flow. The EHD flow has been utilized for various fields, such as aerodynamics, heat and mass transfer, dust particle collection etc. [1]. The EHD gas pump is one of the applications based on this phenomenon. Although various types of EHD gas as pumps have been developed by many investigators [2]-[5], the effect of parameters, such as channel and electrode configurations, arrangement of electrodes, polarity and applied voltage etc., on the flow characteristics for EHD gas pump are not fully understood. The EHD gas pump finds application in heat and fluid transfer in channels, and its development is worthwhile to pursue considering its potential for effective removal of ever increasing heat flux generated in the electronic equipment and circuitry.

In this paper, the effects of ground electrode convergent angles on the discharge, gas velocity and volumetric flow rate characteristics were experimentally investigated under dc negative applied voltage in wire-plate type EHD gas pumps. The mechanism of EHD flow will be discussed in detail.

2. Experimental apparatus

The schematic of the experimental apparatus and the details of wire-plate type EHD gas pumps with a rectangular channel used in this study are shown in Figures 1 and 2 (a)-(d). In this experiment, air at atmospheric pressure and room temperature was used as working fluid. The dc negative high voltage from 0 kV to 17 kV was applied to the corona wire with a dc power supply (Glassman, PS/ER50R06.0- 11), after passing through a 4 MΩ ballast resistor. The applied voltage at the corona wire electrode and the discharge current through the GND electrodes were measured with a high voltage probe (Tektronix,

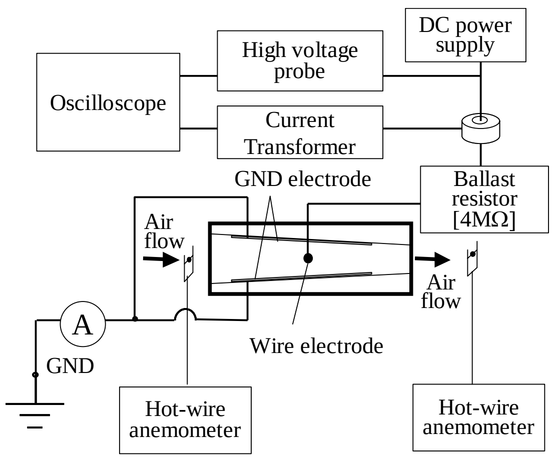

Figure 1 Schematic of the experimental set up.

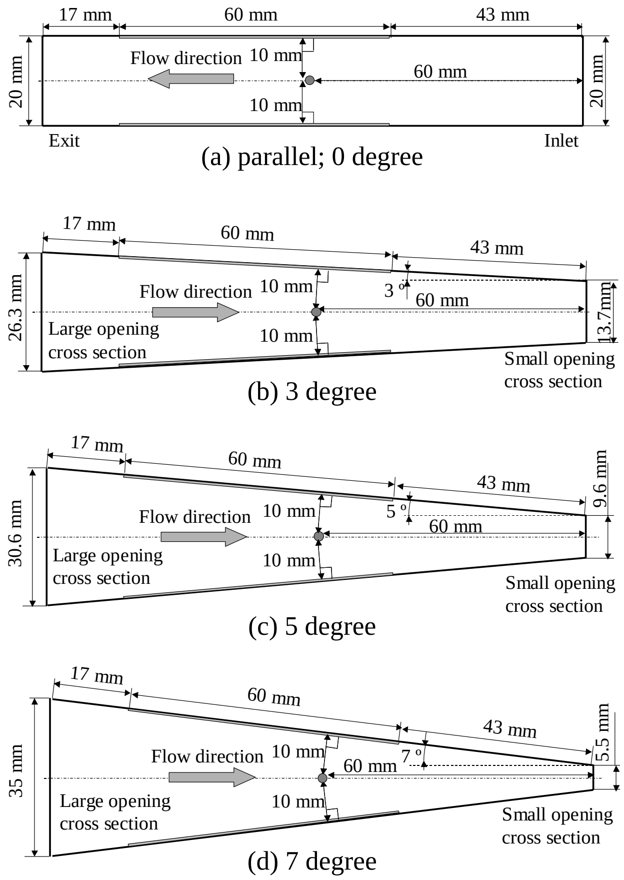

Figure 2 Details of the EHD gas pump geometry for various convergent angles; (a) parallel, (b) 3 degree, (c) 5 degree and (d) 7 degree.

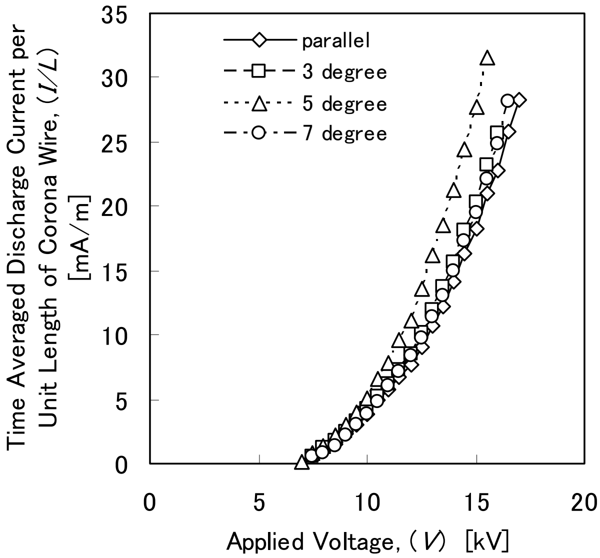

Figure 3 Time averaged discharge current per unit length of corona wire as a function of applied voltage for various convergent angles.

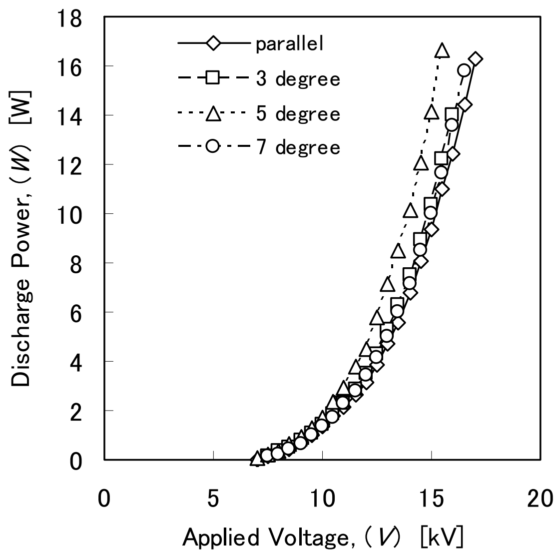

Figure 4 Discharge power as a function of applied voltage for various convergent angles.

model P6015A) and a digital ammeter (BK Precision, model 2831C), respectively. A hot-wire anemometer probe (Extech, model 407119A) was used to measure gas velocity along the channel axis, on its axis. The probe was located 5 mm away from either the inlet cross section (large opening) or exit cross section (small opening) of the EHD gas pumps. Volumetric flow rate at the exit (the small opening) was estimated by multiplying the gas velocity by the cross section area.

Details of the EHD gas pump geometry are shown in Figure 2 (a)-(d). The flow channel of the EHD gas pump was made of transparent acrylic plates. The length of the EHD gas pump was about 120 mm. The geometry of both ends of the channel was rectangular with a width of 34 mm. A corona wire electrode made of high-carbon steel with 0.23 mm outside diameter was horizontally placed perpendicular to the channel axis. Two GND electrodes made of aluminum plates of 0.15 mm thickness were flush mounted on the channel wall as shown in Figure 2. The vertical distance from GND electrode to corona wire electrode was 10 mm.

3. Experimental results and discussions

3.1. Time averaged discharge current and power

Figures 3 and 4 show experimental results of the time averaged discharge current per unit length of corona wire (*I/L*) and power (*W*) as a function of negative applied voltage (*V*) for various convergent angles.

Corona on-sets occurred at an applied voltage of about 7 kV for all convergent angles since vertical distances between the corona wire and GND plate was fixed constant. The time averaged discharge current increases with increasing negative applied

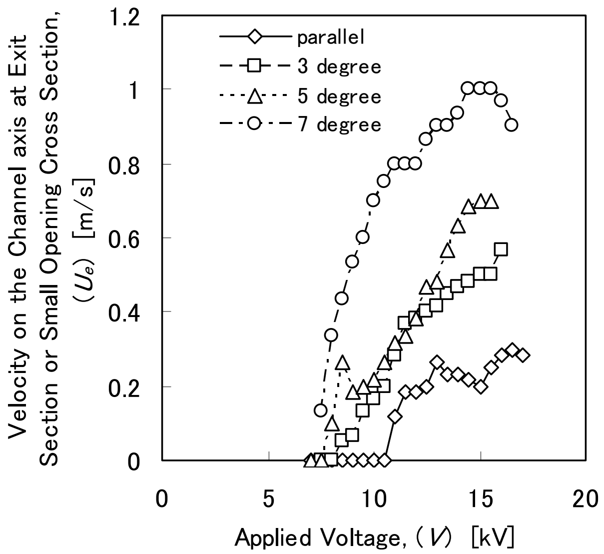

Figure 5 Velocity on the channel axis at exit section or small opening cross section as a function of applied voltage for various convergent angles.

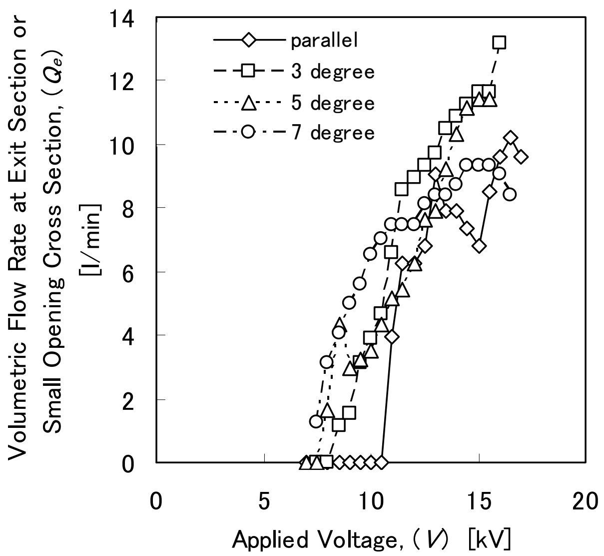

Figure 6 Volumetric flow rate at exit section or small opening cross section as a function of applied voltage for various convergent angles.

voltage. The maximum operating voltage, current and power before on-sets of the spark discharge were around 16 kV, 28 mA/m, and 16 W, respectively. In addition, the tuft corona discharge was observed for all convergent angles of EHD gas pumps [6].

3.2. Gas flow direction, velocity and volumetric flow rate

Figures 5 and 6 show the exit gas velocity on the channel axis (U_e) and the volumetric flow rate (Q_e) as function of negative applied voltage.

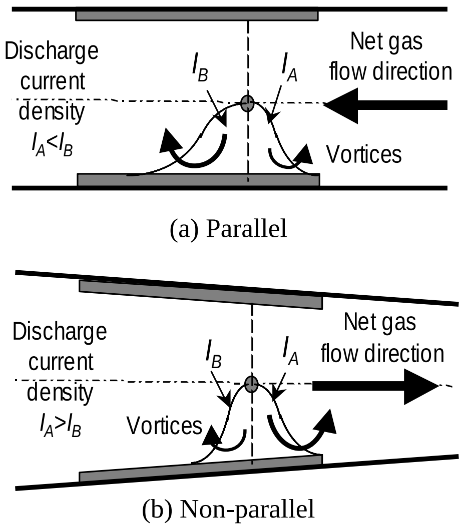

Figure 7 The principle for net gas flow generation and change of gas flow direction by convergent angle of GND electrodes.

The gas flow direction for angles of 3, 5 and 7 degree is from the large opening cross section to the small one, and this direction is opposite to that of the 0 degree as shown in Figure 2. The reason for the different gas flow direction in the case of 0 degree is due to the length of the ground plate for up-stream and downstream of corona wire since no net unidirectional flow can be generated for perfectly symmetrical electrode arrangement. The net gas flow direction depends on the total EHD force relative to the differential discharge current at the front and rear of the corona wire position as shown in Figure 7. Here, the net discharge current at the left side of the corona wire position is smaller than that at the right side due to the convergent angle of the GND electrodes.

The exit gas velocity for each type of EHD gas pump increases with increasing applied voltage. The maximum values of the exit mean velocities are 0.3 m/s, 0.57 m/s, 0.7 m/s and 1.0 m/s for 0, 3, 5 and 7 degree, respectively. These values correspond to the exit volumetric flow rates of 10.2 l/min, 13.2 l/min, 11.4 l/min, and 9.4 l/min for 0, 3, 5 and 7 degree, respectively. In the range of the experimental conditions, the optimum convergent angle of GND electrodes is 3° from the view point of maximum volumetric flow rate.

4. Relationships with dimensionless numbers

4.1 Definition equations of Reynolds number and EHD numbers

Reynolds number and EHD numbers are often used for analyses of EHD flow [3, 4]. The Reynolds number is defined by Eq. (1), while the EHD numbers can be defined for the wire electrode (Ehd_w) and the GND electrode (Ehd_g), as shown by Eqs. (2) and (3), respectively.

$$Re = \frac{U_w \times L}{\nu_g} \quad (1)$$

$$Ehd_w = \frac{Id^3}{\rho_g \nu_g^2 \mu_c A_w} \quad (2)$$

, and

$$Ehd_g = \frac{IL^3}{\rho_g \nu_g^2 \mu_c A_g} \quad (3)$$

Here, U_w is the gas velocity at corona wire position as estimated from exit gas velocity, L is the perpendicular distance between two GND electrodes at the corona wire position, and ν_g is kinematic viscosity of air. I, d, ρ_g, μ_c, A_w and A_g are the time averaged discharge current, diameter of corona wire, density of air, ion mobility of air, surface area of corona wire and GND electrodes, respectively.

4.2 Relationships between Reynolds number and the two kinds of EHD numbers

Figure 8 shows the relationships between Reynolds number (Re) and the two kinds of EHD numbers (Ehd_w) and (Ehd_g), based on wire or GND electrodes, obtained from the experimental results. Reynolds number for all types of EHD gas pumps increases with increasing EHD numbers. Maximum values of Reynolds numbers are about 400, 520, 450 and 370 for 0, 3, 5 and 7 degree, respectively. These occur at Ehd_w about 1×10^4 and Ehd_g about 4×10^7.

The convergent angle of the GND electrodes shows a qualitative effect on the relationships between the Reynolds number and the EHD numbers.

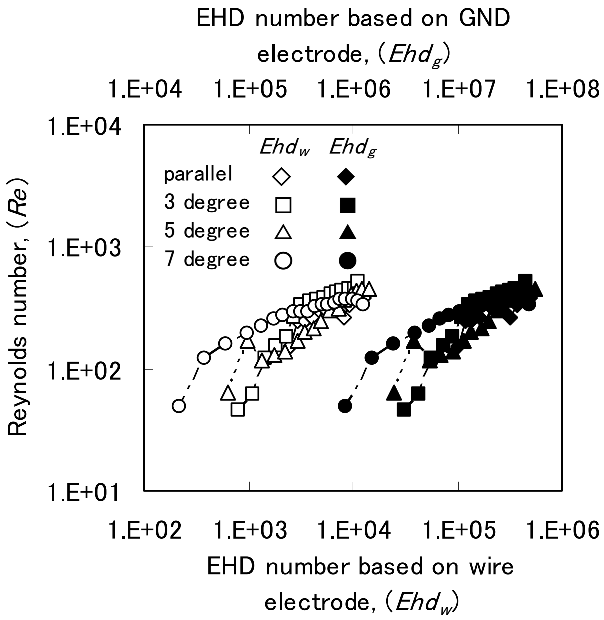

Figure 8 Relation ships between Reynolds number and EHD numbers based on wire and GND electrodes under negative applied voltage for each type of EHD gas pump.

5. Conclusions

In this paper, the results of the experimental investigation of the effect of GND electrode convergent angle on the flow characteristics under dc negative applied voltage for a wire-plate type EHD gas pump in a rectangular flow channel are presented. The results show that:

(1) The change of the gas flow direction caused by the angle of the GND electrodes was experimentally demonstrated;

(2) The effects of the angle of the GND electrodes on the flow characteristics, such as gas velocity and volumetric flow rate, were experimentally obtained; and

(3) The relationships between Reynolds number and EHD numbers based on experimental results were shown.

6. Acknowledge

The authors wish to thank D. Ewing, C.Y.Ching and M. Kocik for valuable discussions and comments. This work is supported by NSERC of Canada.

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