Performance Characteristics of Partially Covered Wire-Parallel Plate Electrodes Type Electrohydrodynamic Gas Pumps

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Abstract—In recent years, a variety of EHD gas pumps have been experimentally and analytically investigated and developed for heat and fluid transportation. As one of the effective EHD gas pumps concepts, a partially covered wireparallel plate type EHD gas pump has been suggested. In this study, the experimental investigations were conducted for the effects of the flow channel width, the number of wire electrodes (from 1 to 3 wires) and distance between wire electrodes on the pump characteristics for the EHD gas pumps under dc positive applied voltage. Furthermore, a method on the partial insulation cover of the corona wire was tested in order to miniaturize the EHD gas pump. These experimental results on discharge and flow characteristics for 7 kinds of partially covered wire-parallel plate type EHD gas pump configurations are shown and discussed in detail in this paper.

Keywords-EHD gas pump, partially covered wire-parallel plate, multistage, velocity, volume flow rate

I. INTRODUCTION

In recent years, the heat and/or fluid transportation has been more important for cooling system of electronics equipment. Especially, the notebook computer is the overwhelming candidate to remove the heat from printed-circuit board and is becoming increasingly important year by year. So far, multiple heat pipes and gas fans have achieved the major role in the electronics equipment for computers. In this study, an EHD gas pump has been investigated in order to replace the gas fan and/or liquid pump in the thermal management system [1-4].

The studies on electrohydrodynamic (EHD) applications resulted from corona discharge have been conducted for a variety of fields, such as aerodynamics, heat and mass transfer, and dust particle collection [5-8]. EHD gas flow is induced from the exchange momentum due to collisions between gas molecules and ions which travel between a high voltage electrode and a grounded electrode (GND) due to the applied electric fields. When compared to the traditional gas pumping system containing moving parts such as a diaphragm or fan, one advantage point of the EHD gas pump is to contain no moving components. Therefore, the EHD gas pumps have a potential for simple design, lower noise, longer life, higher energy efficiency and faster control of gas flow.

Recently, a variety of EHD gas pumps have been experimentally and analytically investigated and developed for heat and fluid transport [9-20]. The authors have suggested a partially covered wire-parallel plate type EHD gas pump as one technique.Particularly, this

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type of EHD gas pump has some characteristics such as stable corona discharge, high free design and small multistage gas pump.

In this study, the experimental investigations were conducted for the effects of the flow channel width, the number of wire electrodes (from 1 to 3 wires) and the distance between the wire electrodes on the discharge and pump characteristics for the EHD gas pumps under dc positive applied voltage. Furthermore, the corona wire partially covered by insulation spray was tested in order to miniaturize the EHD gas pump. These experimental results for 7 configurations of partially covered wireparallel plate type EHD gas pumps are shown and discussed in detail in this paper.

II. EXPERIMENTAL APPARATUS

The schematic of the experimental set-up used in this study is shown in Fig. 1. In the experiment, air at atmospheric pressure and room temperature was used as a working fluid. The corona discharge was obtained by applications of high positive voltage at the wire electrode of 0.25 mm o.d with a dc power supply (Glassman, model PS/ER20R15.0-10). The applied voltage at the corona wire electrode and the discharge current between the GND electrodes were measured with a high voltage probe (Tektronix, model P6015A, \pm 3%) and a digital ammeter (IWATSU, model VOAC86A, \pm 0.5%). A hotwire anemometer (FUSO, model YK-2005AH, \pm 5%) was used to measure gas velocity profiles in the axial direction 5 mm downstream from the channel exit.

The measurement of the local gas velocity at the exit cross section were conducted about 5 times at each location with 2 mm and 1 mm intervals on the horizontal and vertical axes, respectively. Volumetric flow rates were determined by integrating gas velocity profiles at



Fig. 1. Schematic of the experimental set-up.



Fig. 2. Detail configuration of EHD gas pumps.

the exit cross sectional area. The standard deviation of the local velocity measurement was about \pm 15 % and decreased with increasing velocity.

Fig. 2 and Table I shows the detailed configuration and classification of the wire-parallel plate electrode type EHD gas pumps used in this study. The flow channel was made of transparent acrylic resin except for the GND electrodes. The configuration of the flow channel was rectangular, and its height and width were 5 mm and 10 mm, and the total length was 100 mm. Two GND electrode plates made of brass were placed above and below the corona wire electrode as a part of the flow channel. A corona wire electrode of 0.25 mm in diameter, made of stainless steel, was placed at the center of the flow channel parallel to the GND electrodes. In order to induce the net unidirectional gas flow, part of the corona wire was covered by insulating material. As a tube Polyetheretherketone insulation method. (PEEK) insulating material of 0.25 mm inside diameter and 1.59 mm outside diameter having covered angles of 135° were used for types A to F. In addition, for the purpose of further miniaturization of the EHD gas pump, a spray insulation method was used. The EHD gas pumps with wire electrodes partially sprayed with an insulation material of Polyurethane having about 0.03 mm in thickness was tested as type G. The electrical properties of the insulation materials were shown in Table II.

 TABLE I

 CLASSIFICATION OF THE EHD GAS PUMPS USED IN THIS STUDY

Type of EHD Gas Pumps	The number of wire electrodes, N	Insulating material and thickness, <i>r</i> [mm]	Distance between wire electrodes, <i>b</i> [mm]	Channel width, <i>L</i> [mm]
А	1	PEEK, 0.85	-	10
В	1	PEEK, 0.85	-	30
С	2	PEEK, 0.85	5	10
D	2	PEEK, 0.85	10	10
Е	2	PEEK, 0.85	15	10
F	3	PEEK, 0.85	10	10
G	1	Polyurethane 0.03	-	10

 TABLE II

 ELECTRICAL PROPERTIES OF INSULATION MATERIALS

Materials	Relative	Dielectric Breakdown
	Permittivity, E_r	Strength, E_C [kV/mm]
PEEK	3.2	19
Polyurethane	6.5 - 7.1	16 - 20

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Tube Insulation Method EHD Gas Pump

1) Time averaged discharge current

The time averaged discharge current per unit length of the corona wire (I/L) as a function of the positive applied voltage (V) for types A to F of the EHD gas pumps is shown in Fig. 3. Corona on-sets occurred at an applied voltage of about 6.0 kV. Independent of EHD gas pump type, the time averaged discharge currents per unit length of corona wire increased with increasing applied voltage. For the single wire electrode EHD gas pumps, the maximum currents before on-sets of spark discharge were 25.6 mA/m at 7.8 kV for Type A, 10 mA/m at 7.25 kV for Type B, respectively. For the double wire electrodes EHD gas pumps, the maximum currents before on-sets of spark discharge were 22.6 mA/m at 8.25 kV for Type C, 17.8 mA/m at 8.0 kV for Type D, 20.9 mA/m at 8.0 kV for Type E. For the triple wire electrodes EHD gas pump, the maximum currents before on-sets of spark discharge were 15.8 mA/m at 8.0 kV for Type F. A glow corona discharge was observed for all positive applied voltages.

For the effect of channel width, the type B EHD gas pump had lower discharge current and has a narrower range of corona discharge than that for type A. One of the reasons may be due to different parallelism of the wire electrode to GND electrodes causing by different length of the wires. This effect needs further investigation.

For the effect of the number of wire electrodes, the discharge currents decreased with increasing number of wire electrodes because of the less area of GND electrodes per a wire electrode and the change of the electric field due to interference between the wire electrodes. Further detail is shown in Appendix A.

For the effect of the distance between the wire electrodes, there was no clear difference of the discharge current. This shows that the discharge between the wire and the GND electrodes has little change in the range from 5 mm to 15 mm of the distance between the wire electrodes.

2) Mean velocity and volumetric flow rate

Figs. 4 and 5 show the experimental results of the mean velocity (U_{mean}) and the corresponding volumetric flow rate (Q) at the exit section as a function of the discharge power (W) for types A to F of the EHD gas pumps. For all types of the EHD gas pumps, the mean velocities sharply increased with increasing discharge power up to the maximum values of 1.5 m/s at 1.0 W (=7.2 kV) for type A, 2.0 m/s at 2.2 W (=7.3 kV) for type B, 2.4 m/s at 1.4 W (=7.5 kV) for type D and 3.2 m/s at 1.3 W (=7.4 kV) for type F, respectively. The volumetric flow rates, corresponding to each maximum mean velocity, are 4.6 l/min, 17.6 l/min, 7.2 l/min and 9.7 l/min for type A, type B, type D and type F, respectively.



Fig. 3. Time averaged discharge current per unit length of corona wire as a function of the applied voltage for types A to F of the EHD gas pumps.



Fig. 4. Mean velocity at the exit section as a function of the discharge power for types A to F of the EHD gas pumps.



Fig. 5. Volumetric flow rate at the exit section as a function of the discharge power for types A to F of the EHD gas pumps.

Except for type B, beyond the maximum values, the mean velocities decreased with increasing applied voltage. This effect may be related to the discharge current downstream to upstream ratio I_d/I_u , as this ratio decreases with increasing applied voltage. The peaks of mean velocity and volumetric flow rate, furthermore, were observed at about 1~2 W except for type B of the EHD gas pump.

For the effect of channel width, the mean velocity for type B was higher than that for type A, when the applied voltage was more than 1 W. One of the reasons is that frictional pressure drop for type B was less than that for type A because of bigger cross sectional area of the flow channel.

For the effect of the number of wire electrodes, the maximum mean velocities increased with increasing number of wire electrodes. Especially, the maximum mean velocities for double wire electrodes EHD gas pump (Type D) and triple wire electrodes EHD gas pump (Type F) were about 52% and 104% higher than that for a single wire electrode EHD gas pump (Type A). Fig. 6 shows Reynolds numbers, $Re (=U_{mean, max}*d_h/v)$ for types A, D and F against the number of the wire electrodes, where $U_{mean, max}$ is the maximum mean velocity at the exit section, d_h the hydraulic diameter and v the kinematic viscosity. The *Re* number electrodes as per Eq. (1).

$$Re = 662.68N^{0.6883}$$
(1)

For the effect of the distance between the wire electrodes for a double wire electrode type EHD gas pump, there was little difference between the mean velocities for type D and type E. The mean velocity for type C was about 20% lower than that for types D and E. As can be observed in Figs. A (b), (c) and (d) of the appendix, the electric potential around each wire electrode for type C is mutually affected by the other one. Particularly, the gradient of the electric field in the direction of the z axis around the first wire electrode for type C becomes smaller than that for types D and E. Therefore, we think that the first wire electrode could not fully contribute to induce the net gas flow because of small EHD forces ($F = eN_iE$, where e is the elementary charge, N_i the ion number density and E the electric field) by the first wire electrode due to the electric field around the second wire electrode. Moreover, it is very importance to attempt to understand the net gas flow from the viewpoint of the flow field between wire electrodes. We expect that accelerated gas flow by EHD force from the region near the wire electrode to the GND electrodes sharply changes to the direction of the channel axis near the GND electrodes. In fact, it is generally known that there are symmetrical two vortices at up and down in the downstream region of the wire electrode for the gas flow in the channel with a wire electrode between the plate electrodes as shown by Mizeraczyk et al. [19]. We think that the strength and/or location of the vortices between wire electrodes have a strong effect on the net gas flow for the multi wire electrodes EHD gas pump



Fig. 6. Reynolds numbers for types A, D and F as a function of the number of the wire electrodes.



Fig. 7. The pump efficiency as a function of the discharge power for types A to F of the EHD gas pumps.

aiming at compatibility with high performance and miniaturization. The experimental result on the distance between the wire electrodes means that when the multi wire type EHD gas pump is designed, the distance between wire electrodes should be at least more than 5 mm for wire - parallel plate type EHD gas pump of 5 mm channel height.

3) Efficiency

The input electrical power to kinetic energy conversion efficiency (η) for types A to F of the EHD gas pumps as a function of the discharge power (*W*) is shown in Fig. 7 for types A to F of the EHD gas pumps. The efficiencies of the EHD gas pumps sharply increased with discharge power up to maximum values, and then gradually fall off with increasing discharge power. The maximum efficiencies (Output gas kinematic energy / Input power = $MU_{mean}^{2}/2W$) for the EHD gas pumps are 0.015% for type A, 0.034% for type B, 0.016% for type C, 0.043% for type D, 0.034% for type E, and

0.107% for type F, respectively. Here, M, U_{mean} and W are the mass flow rate, the mean velocity at the exit section and the discharge power. The effects of the channel width, the number of the wire electrodes and distance between wire electrodes on the pump efficiency are attributed to the combined effects among the applied voltage, the discharge current and the gas velocity. Though the magnitudes of these efficiencies appear poor, it is noted that the values of efficiency are a similar order of magnitude of a conventional fan driven flow in open air and higher compared with fan driven flow in narrow channels [20]. In the case of the narrow channel, we believe that most of the energy is mainly transformed to frictional loss and increased enthalpy (temperature) of the gas. In addition, in spite of narrow channel, the efficiencies of the partially covered wire-parallel plate electrodes type EHD gas pump are approximately equal to or more than other types of EHD gas pumps having needle-ring electrodes or wire tips-plate electrodes in references [18, 21].

For the effect of channel width, for example, the efficiency for type B was twice higher than that for type A at 6.5 kV. The reasons are higher mean velocity and lower averaged discharged current for type B than that for type A.

For the effect of the number of wire electrodes, the maximum pump efficiencies increased with increasing of the number of wire electrodes. Especially, the maximum pump efficiency for double wire electrodes EHD gas pump (Type D) and triple wire electrode EHD gas pump (Type F) were about 2.9 times and 7.1 times higher than that for a single wire electrode EHD gas pump (Type A). The cause of this trend is the combination between the mean velocity and the discharge current. As mentioned before, the higher number of wire electrodes, the higher the mean velocity and the lower discharge current per unit length of the wire electrode will be.

For the effect of the distance between the wire electrodes, the pump efficiency for type D was higher than type C and type E. The main reasons are lower discharge current and higher mean velocity for type D at 7.0 kV or below than that for types C and E.

B. Spray Insulation Method EHD Gas Pump

1) Time averaged discharge current

The time averaged discharge current per unit length of the corona wire (I/L) as a function of the positive applied voltage (V) for type G of the EHD gas pump is shown in Fig. 8. Corona on-sets occurred at an applied voltage of about 5.3 kV. The time averaged discharge currents per unit length of corona wire increased with increasing applied voltage. The maximum current before on-sets of spark discharge was 35.6 mA/m at 7.3 kV. In addition, the time averaged discharge current for type G was about twice higher than that for type A. The reasons are probably the reduced insulated area of the wire electrode by the insulation material as shown in Fig. 9 and insufficient insulation due to the minimal thickness.



Fig. 8. Time averaged discharge current per unit length of corona wire as a function of the applied voltage for type G of the EHD gas pump.



Fig. 9. The condition of the insulation materials on the wire electrodes for type G of the EHD gas pump.



Fig. 10. Center velocity on the channel axis at the exit section as a function of the applied voltage for type G of the EHD gas pump.

2) Center velocity

Fig. 10 shows the experimental result of the center velocity (U_c) on the channel axis at the exit section as a function of the positive applied voltage (V) for the type G EHD gas pump. Along with corona on-sets occurred at applied voltage of about 5.0 kV, the center velocities increased with increasing applied voltage up to the maximum values of 0.5 m/s at 7.2 kV. Compared with type A, the wire electrode type G was inadequately covered by Polyurethane at the downstream side. This cover condition caused a higher discharge current ratio of downstream to upstream (I_d/I_u) . However, the result means that if the wire electrode surface at only upstream the side is insulated, the net gas flow can be generated by

using insulation spray similar as the cases using the tube insulation method.

IV. CONCLUDING REMARKS

In this study, experimental investigations were conducted to clear the effect of the channel width, the number of the wire electrodes and distance between wire electrodes on discharge and flow characteristics under dc positive applied voltage for partially covered wireparallel plate EHD gas pump with air as the working gas. Furthermore, a partially sprayed wire-parallel plate EHD gas pump was tested. The results show that:

- (1) Maximum average gas velocity of 3.2 m/s for type F of the EHD gas pump was observed and the corresponding volumetric flow rate was 7.4 l/min;
- (2) For the effect of the channel width, the mean velocity and pump efficiency for type B was higher than that for type A, and the volumetric flow rate for type B more than the cross-sectional area ratio of 3 times for type A;
- (3) For the effect of the number of wire electrodes, the higher number of the wire electrodes, the higher mean velocity, volumetric flow rate and pump efficiency;
- (4) For the effect of the distance between wire electrodes, the best pump characteristics for type D was shown among the double wire electrode type EHD gas pumps.
- (5) A potential for partially sprayed wire electrode EHD gas pump with insulation material to generate the net gas flow was demonstrated.

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APPENDIX A.

In order to obtain a better understanding of the effects of the number of wire electrodes and the pitch of wire electrodes on the net gas flow, numerical modeling was conducted for the tube insulation method EHD gas pumps. Five types of EHD gas pumps classified in Table I as Types A, C, D, E and F were simulated. The finite difference approximation was used to solve the partial differential equation, where Poisson's equation was used to obtain the electric field distribution in a 2 D cross section perpendicular to the wire electrode on the center line of the channel assuming a uniform spatial discretization corresponding to 1000×100 grid numbers. With respect to the boundary conditions at the discharge electrode surface, the uniform ion density distribution along the perimeter of the discharge electrode was used. At grounded electrodes the ion density was set to zero. The gradient of the ion density in the direction normal to the inlet and outlet boundaries of the pipe channel was set to zero. In order to know the tendencies of effects of the wire number and distance between wire electrodes on electrical potential, the applied voltage at the wire electrode for all types was assumed to be 7 kV in this numerical modeling.

Figs. A (a)-(e) show typical numerical results of the electric potential distribution for the five wire electrode configurations: (a) Type A (Single wire electrode), (b) Type C (Double wire electrodes with 5 mm space), (c) Type D (Double wire electrodes with 10 mm space), (d) Type E (Double wire electrodes with 15 mm space) and (d) Type F (Triple wire electrodes with 10 mm space). The electric potential equipotential lines and electric field vectors in the section from z=0.34 to z=0.66 are shown for all types. For the effect of the wire number, it can be observed that there is little difference of the electric potential distribution for types A, D and F. On the other hand, for the effect of the distance between wire electrodes, the gradient of the electric field in the direction of z axis around first wire electrode for type C becomes smaller than that for types D and E.



Fig. A. The electrical potentials of the partially covered wire – parallel plate electrodes type EHD gas pumps at 7 kV; (a) type A, (b) type C, (c) type D, (d) type E and (e) type F.