Gas Discharge Induced Electrohydrodynamic Flow in Narrow Channels

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***Abstract*—Electrohydrodynamic (EHD) gas flow generation by gas discharges has been studied as a new technique for inducing a gas flow in narrow channels. Two types of gas discharge, corona and surface barrier discharge, were used to induce the EHD flow. First, a wire rod electrode configuration was used to investigate a corona discharge induced EHD flow. A maximum average flow velocity of 1.7 m/s was achieved with a circular channel having a 20 mm inner diameter. However, it was difficult to obtain a stable corona discharge within a channel having a diameter less than 5 mm. Next, an EHD flow was induced by a surface barrier discharge, which can be stably generated in a narrow channel. EHD flow was successfully generated by a discharge on the inner surface of a circular channel having a 1 mm inner diameter.**

***Index Terms*—Electrohydrodynamics, atmospheric discharge, gas pump, narrow channel**

I. Introduction

THERMAL management of electronics has become significant because highly developed microfabrication technologies have increased the density of electronic circuits. One alternative for cooling of microelectronics is the use of a single phase gas flow for heat transfer [1], however, a new method is required for driving the gas flow in narrow channels, where conventional methods, such as rotary fans have limitations. Gas discharge induced electrohydrodynamic (EHD) flow can realize a micro gas pump because no moving components are required and the driving force of the gas flow may be generated even in the vicinity of a channel wall. Two types of gas discharge have been used to generate the EHD flow: Corona [2] and surface barrier discharge [3]. EHD flow has been applied to various fields, such as aerodynamic control, heat and mass transfer, and gas pumps, as reviewed in [4]. However, there is insufficient research on generating the EHD flow in a narrow channel, and therefore, the suitability of EHD flow for a micro gas pump is still unclear. In this study, gas discharges were generated in circular channels as EHD gas pumps, and the discharge and flow characteristics were investigated.

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II. Corona Discharge Induced EHD Flow

A. Experimental Setup

The schematic of an EHD gas pump driven by a corona discharge is shown in Fig. 1. A wire electrode 60 μm in diameter and a rod electrode 3 mm in diameter were placed in an acrylic pipe with a 13 mm gap between them. The circular channel was 220 mm long, and the inner diameter (i.d.) varied from 3 to 20 mm. The wire electrode was connected to a DC power supply (Matsusada Precision Inc, HB-25N(A)) after passing through a 20 MΩ protection resistor. The rod electrode was grounded through a 1 MΩ resistor for current measurement. Applying a negative DC voltage to the wire electrode produced a negative corona discharge at the wire electrode and an EHD flow was induced from the wire electrode to the rod electrode. Velocity profiles of the EHD flow were measured with a hot-wire anemometer (Kanomax, Anemomaster 6004) in a cross section 5 mm from the exit of the channel.

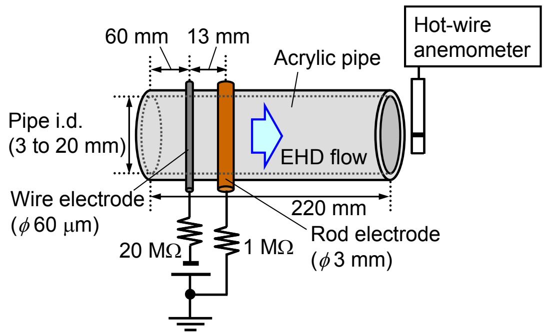

Fig. 1. EHD gas pump driven by a corona discharge.

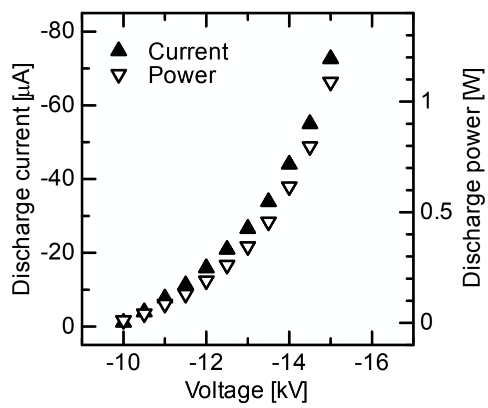

Fig. 2. Time-averaged discharge current and power of the corona discharge as a function of the applied voltage for the channel with an i.d. of 20 mm.

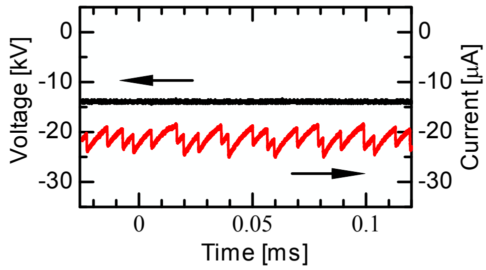

Fig. 3. Voltage and current waveforms of the corona discharge at −13 kV in a channel with an i.d. of 20 mm.

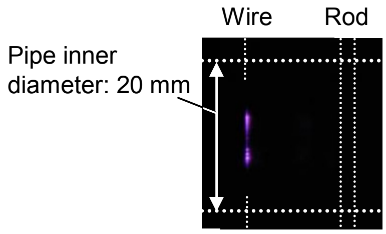

Fig. 4. Discharge image of the corona discharge at −13 kV in the 20 mm i.d. channel taken with an exposure time of 1 s.

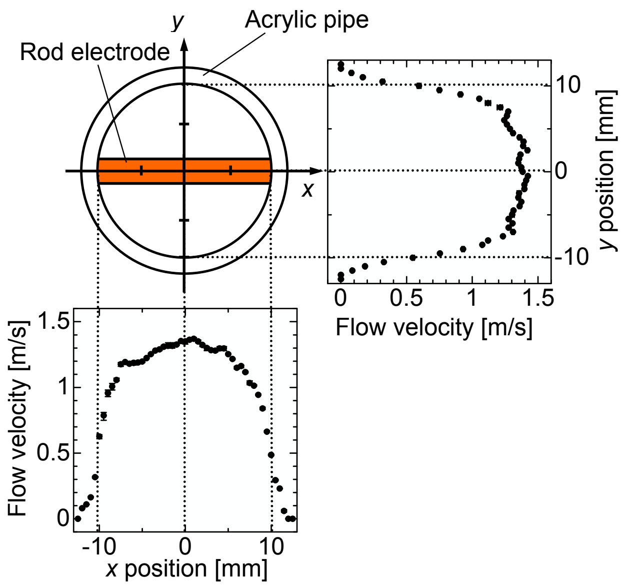

Fig. 5. Flow velocity profiles of the EHD flow at the exit of the 20 mm i.d. channel induced by the corona discharge at −13 kV.

B. *Basic Properties*

The basic properties of the EHD gas pump were obtained with the 20 mm i.d. channel. Fig. 2 shows the time-averaged discharge current and power as a function of the applied voltage. A negative corona discharge began at −10.5 kV, and a transition to a spark discharge appeared at −15.5 kV. The time-averaged current was a quadratic function of the applied voltage. The voltage and current waveforms driven by a voltage of −13 kV are shown in Fig. 3, and the corresponding discharge image is shown in Fig. 4. Several corona tufts were observed along the wire electrode. The number of the tufts increased with an increase in the applied voltage.

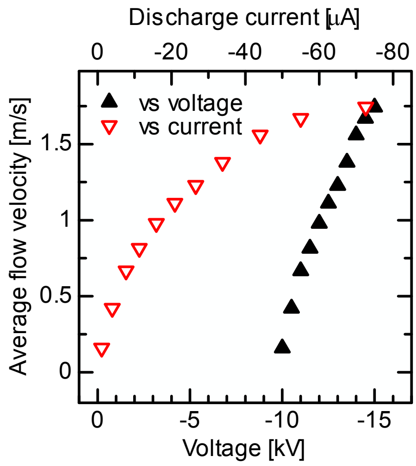

Fig. 6. Average flow velocity of the EHD flow induced by the corona discharge as a function of the applied voltage and the time-averaged discharge current for the channel with an i.d. of 20 mm.

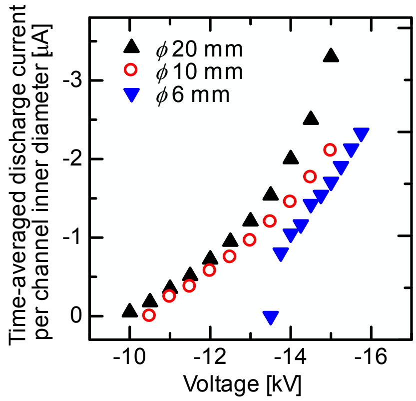

Fig. 7. Time-averaged discharge current divided by channel inner diameter of the corona discharge as a function of the applied voltage for various channel inner diameters.

Fig. 5 shows the velocity profiles for the application of −13 kV. Each point shows the average value and error bar for three measurements within 5 s. Although these profiles are not absolute quadratic curves due to discharge current variations during the measurements, the EHD flow was almost fully developed at the exit of the channel. The average flow velocity, as a function of the applied voltage and the time-averaged discharge current, is shown in Fig. 6. The average flow velocity was proportional to the applied voltage and the square root of the discharge current, which can be explained by a momentum conservation equation [5].

C. *Narrow Channel Operation*

To investigate the characteristics of the EHD gas pump driven by a corona discharge in a narrow channel, the inner diameter of the channel was varied from 3 to 20 mm. In the channel with an i.d. larger than 5 mm, a negative corona discharge was initiated and several tufts were observed, as in the channel with a 20 mm i.d., however, the corona discharge

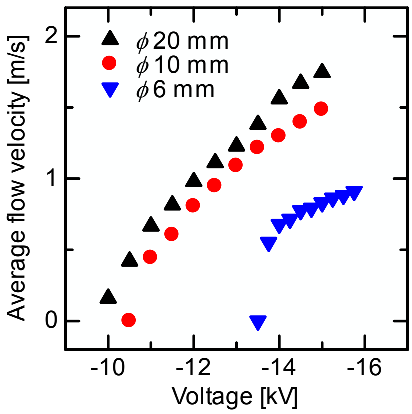

Fig. 8. Average flow velocities induced by the corona discharge as a function of the applied voltage for various channel inner diameters.

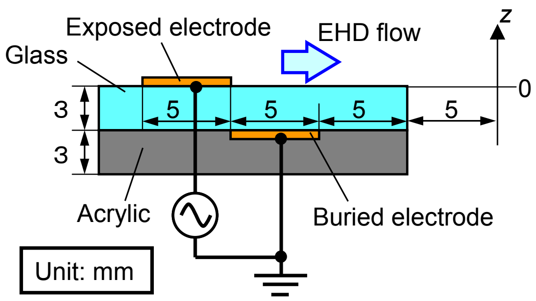

Fig. 9. EHD flow generation by a surface barrier discharge in open space.

could not be observed before spark onset in channels with an i.d. of 5 mm or less. Fig. 7 shows the voltage–discharge current characteristics, showing the time-averaged discharge current divided by the channel inner diameter. Once the corona discharge was initiated, the range of normalized discharge current was almost the same, independent of the channel inner diameter. The corona onset voltage was higher for a smaller channel inner diameter. In addition, the corona discharge was generated in a narrower range of applied voltages, and a transition to a spark discharge occurred easily.

Fig. 8 shows the average flow velocities as a function of the applied voltage. For any given applied voltage, the flow velocity was smaller for a smaller channel inner diameter because the normalized discharge current was smaller, and the pressure loss increased.

D. Concluding Remarks

A wire–rod type EHD gas pump having a circular channel was driven by a negative corona discharge. The following conclusions were obtained:

1) For a channel of i.d. 20 mm, the average velocity of the EHD flow was proportional to the applied voltage and the square root of the discharge current, which can be explained by a momentum conservation equation.
2) In a narrow channel, the corona discharge became unstable. The minimum inner diameter of the channel was 6 mm.

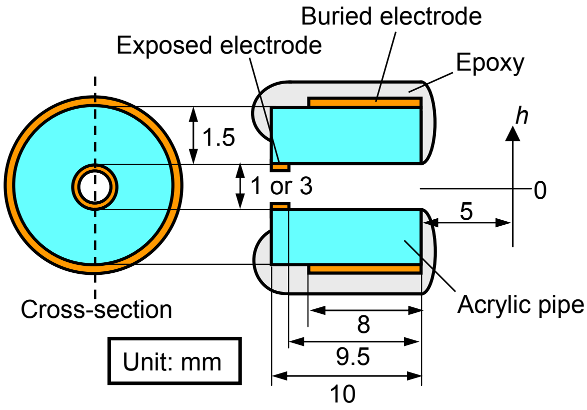

Fig. 10. EHD gas pump driven by a surface barrier discharge.

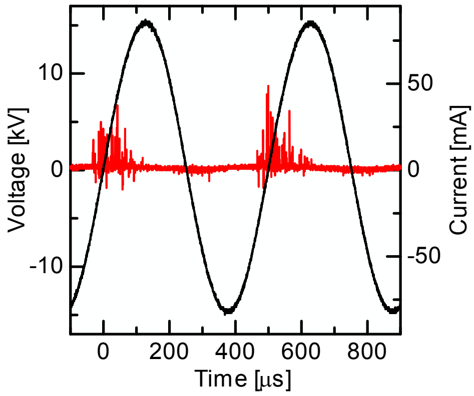

Fig. 11. Voltage and current waveforms of the surface barrier discharge at 15 kV_{peak} in open space.

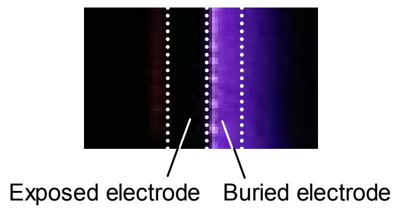

Fig. 12. Discharge image of the surface barrier discharge at 15 kV_{peak} in open space taken with an exposure time of 1 s.

3) For any applied voltage, the flow velocity was smaller for a smaller channel inner diameter because the normalized discharge current was smaller, and the pressure loss increased.

III. Surface Barrier Discharge Induced EHD Flow

A. Experimental Setup

A surface barrier discharge induced EHD flow is usually investigated in an open space. A typical electrode configuration is shown in Fig. 9. One metal electrode was placed on a dielectric barrier and connected to an AC power supply, and the other metal electrode was placed opposite the exposed electrode and buried with dielectrics. The buried electrode was

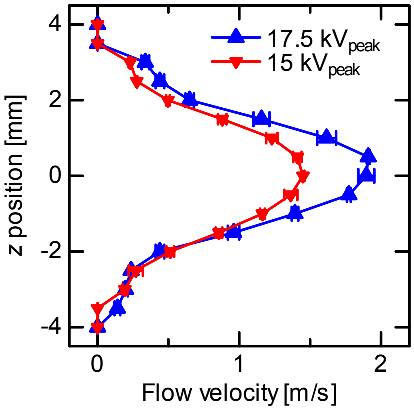

Fig. 13. Flow velocity profiles of the EHD flow along the z-axis induced by the surface barrier discharge.

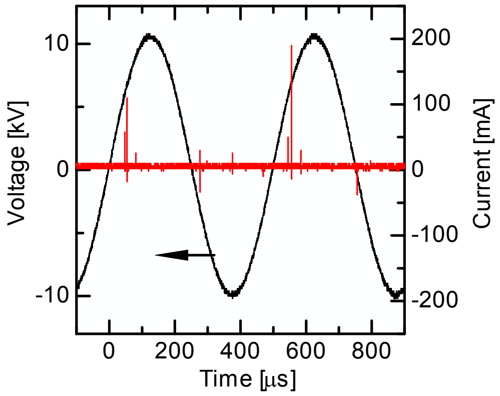

Fig. 14. Voltage and current waveforms of the surface barrier discharge at 10 kV_{peak} in the channel of i.d. 1 mm.

grounded. These electrodes were made of 50 µm thick copper tapes. Applying a sinusoidal voltage generated a surface barrier discharge between the edge of the exposed electrode and the dielectric barrier over the buried electrode, and an EHD flow was induced from the exposed electrode to the buried electrode. The flow velocity was measured with a hot-wire anemometer (Kanomax, Anemomaster 6004) along the z-axis.

To induce the EHD flow in a circular channel, the experimental setup shown in Fig. 10 was used. The exposed electrode, connected to an AC power supply, was placed on the inside wall of an acrylic pipe, while the grounded buried electrode was placed on the outside wall of the pipe and buried with an epoxy resin. The circular channel was 10 mm long, and the inner diameter was varied from 1 to 3 mm. Applying a sinusoidal voltage to the exposed electrode, generated a surface barrier discharge between the exposed electrode and the inside wall of the channel, which served as a dielectric barrier. The induced EHD flow velocity was measured with the hot-wire anemometer along the h-axis 5 mm from the exit of the channel.

B. *Basic Properties in Open Space*

The basic properties of the EHD flow induced by a surface

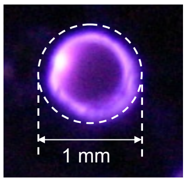

Fig. 15. Discharge image of the surface barrier discharge at 10 kV_{peak} in the channel of i.d. 1 mm taken with an exposure time of 1 s.

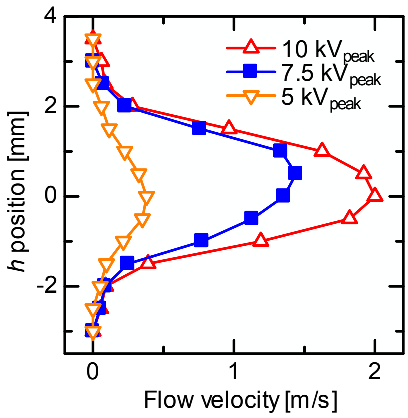

Fig. 16. Flow velocity profiles of the EHD flow along the h-axis induced by the surface barrier discharge in the channel of i.d. 3 mm.

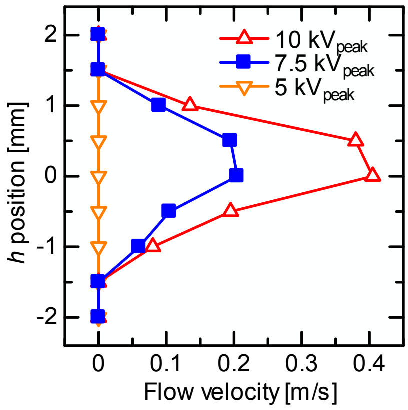

Fig. 17. Flow velocity profiles of the EHD flow along the h-axis induced by the surface barrier discharge in the channel of i.d. 1 mm.

barrier discharge were obtained with the experimental setup shown in Fig. 9 in open space. Increasing the amplitude of the applied voltage at a frequency of 2 kHz initiated a surface barrier discharge at approximately 8 kV_{peak}. The voltage and current waveforms driven by a voltage of 15 kV_{peak} are shown in Fig. 11, and the corresponding discharge image taken from the top of the electrodes is shown in Fig. 12. The surface barrier discharge was uniformly distributed along the dielectric barrier over the buried electrode.

Fig. 13 shows the velocity profiles along the z-axis when the applied voltage was 17.5 and 15 kV_{peak}. The induced flow velocity increased as the applied voltage increased. The maximum applied voltage was restricted by the breakdown voltage of the dielectric barrier.

C. Narrow Channel Operation

The experimental setup shown in Fig. 10 was used to investigate the characteristics of the EHD gas pump driven by a surface barrier discharge in a narrow channel. In this case, a surface barrier discharge initiated at 5 kV_{peak}. Even in for channel i.d. of 1 mm, the surface barrier discharge could be stably generated. The voltage and current waveforms driven by a voltage of 10 kV_{peak} are shown in Fig. 14, and the corresponding discharge image taken from the channel exit is shown in Fig. 15. The discharge was uniformly generated along the inside wall of the circular channel.

Figs. 16 and 17 show the flow velocity profiles along the *h*-axis for channels with i.d.s of 3 and 1 mm, respectively. For a given channel inner diameter, the flow velocity was larger as the applied voltage increased. For a given applied voltage, the flow velocity was smaller for a smaller channel inner diameter because the pressure loss increased.

D. Concluding Remarks

A surface barrier discharge was generated in open space, and in a circular channel as an EHD gas pump. The following conclusions were obtained:

1) The EHD flow velocity increased as the applied voltage increased in both open space and circular channels. The maximum applied voltage was restricted by the breakdown voltage of the dielectric barrier.
2) Even in a narrow channel, with an i.d. of 1 mm, the surface barrier discharge could be stably generated, and EHD flow was successfully induced.
3) For a given applied voltage, the flow velocity was smaller for a smaller channel inner diameter because the pressure loss increased.

IV. Conclusion

Two types of gas discharge were used to induce an EHD flow in circular channels. Although a corona discharge could not be generated in channels with an i.d. of 5 mm or less, a surface barrier discharge could be stably generated even in a channel of i.d. 1 mm, and an EHD flow was successfully induced. Thus, the surface barrier discharge shows potential for realizing a micro gas pump.

Acknowledgment

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