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A Fundamental Characteristic and Image Analysis of Liquid Flow in an AW Type EHD Pump

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Abstract : Non-intrusive two-phase fluid pumping based on an electrohydrodynamically (EHD) induced flow phenomenon with free liquid surface exposed to gas-phase corona discharges is experimentally investigated. Dielectric liquid flow generated near a corona discharge electrode progresses toward an inclined plate electrode, and then climbs up the surface against the gravitational force for an air-wave (AW) type EHD pump. The AW type EHD pump is operated on ionic wind field along the inclined plate electrode. The pumping performance of time-averaged liquid flow rate and the liquid-phase flow motion are characterized. The liquid flow characteristics related to a dimensionless parameter of corona discharge fields are presented.

Keywords : EHD pump, Image analysis, PIV, Liquid flow, Corona discharge field.

1. Introduction

An application of electric tension to dielectric gas or liquid often presents EHD induced flow phenomena. The EHD effect on fluids has been used in dielectric fluid pumping (Stuetzer, 1959), a heat transfer enhancement (Yabe et al., 1988), and an electrostatic precipitator analysis (Ohkubo et al., 1990, Mizeraczyk et al., 2003). Especially, the EHD pump has the advantage of not using moving mechanical components in the flow stream and can be operated with high efficiency in terms of electrical power (Chang, 1989, Bryan and Yagobi, 1991).

The EHD flow system on the single-phase dielectric fluid has been applied to ion drag pumps (Pickard, 1963, Sharbaugh et al., 1985) and traveling wave induction pumps (Melcher et al., 1969, Crowley et al., 1990). These EHD pumps are intrusive types with a fully immersed electrode to working fluids. The EHD forces can be distinguished in the Coulomb's force with an injected space charge and the dielectric force with a permittivity gradient (Davidson, 1986, Chang et al., 1994, Atten, 1996). For two-phase flow with gas-liquid interfaces, the EHD forces are complicated by additional interfacial momentum transfer effects (Change, 1989). The operation under gas-liquid two-phase flow has not been experimentally investigated fully (Wawzyniak, 1999, Ohyama et al., 2001 and 2003). The EHD research has been conducted by electrical, mechanical and chemical engineers as well as by chemists and physicists. In most engineering and science fields, the dimensionless parameters have been derived from the fundamental governing conservation equations, and based on many experiments. More recently the dimensionless parameters used for single-phase EHD analyses have been unified (Chang J. S., Touchard G., 2003). For the gas-liquid two-phase EHD pumping phenomena, derivation of the unifiable dimensionless parameters from fundamental investigations has been required. Therefore, at present day a fundamental study trends to understand the EHD phenomena included multi-phase flow.

In this work, a non-intrusive two-phase EHD pump (an air-wave type EHD pump, Ohyama et al., 2001) with a wire electrode in gas-phase and a partially immersed plate electrode inclined to a gas-liquid interface was further experimentally investigated by particle image velocimetry (PIV). An operation of corona discharge induced the gas-liquid two-phase flow and pumped up the dielectric liquid of reservoir through the plate electrode surface. Based on the experimental investigations, the wire location in gas-phase above the liquid presented more higher flow rate than the wire inside liquid. Besides this observation, this type of non-intrusive/non-moving component pump is normally used for the transport of hazardous liquid from containers or for the cleanup of spilled hazardous liquid. The fundamental characteristic of time-averaged liquid pumping flow rate was evaluated in terms of dimensionless parameters. For purposes of physical applications, a properly detailed analysis for EHD induced liquid flow motion in the reservoir has been required. In this experiment, the visualized characteristic of liquid-phase flow motion in the reservoir was investigated by an image analysis.

2. Experimental Model and Setup

The explanatory schematic of a non-intrusive two-phase EHD pump originally proposed in this work is shown in Fig.1, which shows a side plane view of a liquid reservoir with a wire electrode and a grounded plate electrode inclined at angle θ to the free liquid surface. This EHD induced dielectric liquid pumping was generated on the inclined plate electrode surface near the gas-liquid interface exposed to gas-phase corona discharges in the atmosphere. The rectangular based liquid reservoir had a horizontal bottom cross section of 150×200 mm^2 with 150 mm height made of acrylic plates. A pumping section consisted of an aluminum ground plate electrode of 200×200 mm^2 with a stainless steel wire of 0.5 mm diameter and 200 mm length over the gas-liquid interface. The wire electrode was connected to a DC high voltage source. To specify the wire electrode location (x, y), the contact point between the reservoir floor and the plate electrode was used as a reference (0, 0).

For this work, a mineral oil (Fisher Sci. Co., brand #19) of low electrical conductivity was used as a working dielectric liquid with a depth of L_d. Although the inclination angle θ and the liquid level L_d are variable factors, θ was fixed at 30 degrees and L_d was the range of 50 ~ 70 mm, where the L_d was almost invariant throughout experiments since only the maximum of 50 mL of the liquid volume was pumped over a fixed time period in each measurement test. The wire electrode location (x, y) was varied among x = -60 ~ +100 mm and y = 60 ~ 100 mm above the free liquid surface. The DC high voltage V of +15 kV ~ +35 kV was applied to the wire electrode and the inception voltage of corona discharge generation was 15 kV. The pumped liquid over the top of the plate electrode was collected on a measuring tray and the time-averaged flow rate Q_{ave} was calculated from the liquid volume accumulated over the fixed time period. The time-averaged current I_{ave} from the DC power source was measured by an electrometer (Keithley Ins., Model 486).

The liquid-phase flow motion on a vertical section along the reservoir center was analyzed by a particle image velocimetry (PIV) with cross correlation tracking algorithms (Kaga, 1993, Hu et al., 1998, Fayolle et al., 2000). The experimental arrangement consisted of a mask pattern projector (Mikasa Co., MA-10) with a slit of 1 mm, which is a 250 W Hg parallel light source using in semiconductor integrated circuit products, a progressive CCD camera (Photoron Co., PhotoCam 120) attached a camera lens (Nikon F1.8) and a personal computer with an image frame grabber. The camera captured sequential visualized images of 2-dimensional liquid flow fields illuminated by the light sheet. The illuminated tracer particles contaminated in the working liquid were glass powder of average particle diameter of 6 μm with the adjusted specific gravity. The selection of tracer particles on the optical characterization of EHD fields was an important factor for the fluid flow measurement.

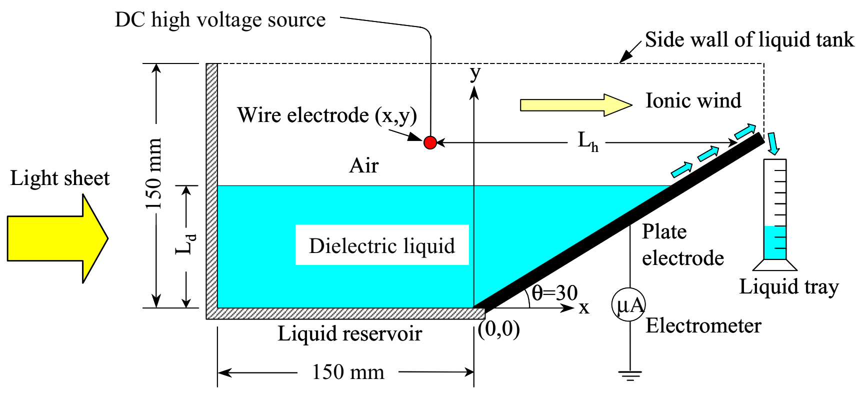

Fig. 1. Schematic of non-intrusive two-phase EHD pump used in present work.

It was desirable that the tracer material suitable for EHD liquid flow measurement was based on differing permittivity and resistivity between tracer and liquid. If the EHD induced liquid motion is the electrophoresis type from the tracer particles charged by ionic wind, the liquid flow rate would be emphasized. In previous work, the liquid flow rate without tracer particles has been evaluated in the same experimental EHD pump (Ohyama et al., 2001). As the result, the liquid flow rate was almost same with or without tracer particles of the experimentally used glass powder. In the present system, the spatial and time resolving power was 13.5 pixel/mm and 120 s^{-1}, respectively. The flow velocity measurements on PIV were conducted for the liquid reservoir region divided into 14 sections and each section was an area of 35×35 mm^2. The liquid flow velocity was estimated as the average of 30 measurements for each section.

3. Experimental Results and Discussions

An EHD liquid pumping phenomenon occurred simultaneously with corona discharge at the wire electrode after applying voltage. The liquid along the gas-liquid interface was flowing toward the inclined plate electrode from the liquid reservoir, and climbed to the top of plate electrode against the gravitational force. The flowing liquid layer over the plate electrode was very thin less than a few millimeter and significant surface waves appeared due to EHD instability with an electrostatic tensile force (Pérez, 1997). The wavy surface was about 10 mm away from the junction of the free liquid surface and the plate electrode. Other surface waves were not formed in the region of the reservoir. The EHD liquid pumping depended on the electrical current, the applied voltage and the wire electrode location. The time-averaged flow rate Q_{ave} and the time-averaged current I_{ave} obtained in the present experimental condition was the range of 0.03 ~ 2.7 mL/s, 1.3 ~ 7.8 μA, respectively.

3.1 Fundamental Characteristic of EHD Effect on Liquid Pumping

In the corona discharge fields of pumping section, it was expected that ionic wind as gas-phase EHD flow was blown along the gas-liquid interface from the wire electrode toward the plate electrode. It seemed that the ionic wind improved the liquid pumping due to an interfacial momentum transfer effect along the gas-liquid interface. In order to scale experimental results of the time-averaged flow rate Q_{ave} and the time-averaged current I_{ave} depended on the applied voltage V and the wire electrode location, a dimensionless parameter Σ_E on the time-averaged current I_{ave} was introduced (Ohyama et al., 2001). The EHD parameter Σ_E which depends on previously defined non-dimensional numbers, i.e. EHD number E_{hd} and Masuda number M_d (formally conductive and dielectric electric EHD Rayleigh number $E_{l\sigma}$, $E_{l\varepsilon}$) in ionic flow fields (Chang et al, 1994, Chang, 1989), Froude number Fr and Reynolds number Re based on force balances, was given by

$$\Sigma_E = \frac{E_{hd} \cdot M_d \cdot Fr^2}{\mathrm{Re}^2} = \frac{\varepsilon_g \cdot I_{ave} \cdot V^2}{\mu_{ig} \cdot \rho_g{}^2 \cdot \nu_g{}^2 \cdot A \cdot g}, \quad (1)$$

where

$$R_e = \frac{u_0 \cdot L_h}{\nu_g}, \quad Fr = \frac{u_0}{\sqrt{g \cdot L_h}}, \quad E_{hd} = \frac{I_{ave} \cdot L_h^{\ 3}}{\rho_g \cdot \nu_g^{\ 2} \cdot \mu_{ig} \cdot A}, \quad M_d = \frac{\varepsilon_g \cdot V^2}{\rho_g \cdot \nu_g^{\ 2}}.$$

Here ε_g is the dielectric constant of gas (= 8.854×10^{-12} F/m), μ_{ig} is the ion mobility of gas (= 0.21×10^3 m^2/V·s), ρ_g is the density of gas (= 1.205 kg/m^3), ν_g is the kinematic viscosity of gas (= 18.2×10^6 m^2/s), g [m/s^2] is the gravitational acceleration, A is the effective collector surface area of plate electrode (= 0.04 m^2), u_0 [m/s] is the characteristic velocity and L_h [m] is the characteristic length (see Fig. 1). The equation (1) shows that the EHD forces E_{hd} and M_d driven by corona discharge are balanced by viscous force (Re^2) and gravitational force (Fr^2) in fluid motion up an inclined surface as a stratified two-phase flow. On the other hand, the Reynolds number Re_l in flowing liquid on the time-averaged flow rate Q_{ave} was expressed by

$$\mathrm{Re}_l = \frac{Q_{ave}}{\nu_l \cdot L_h}, \tag{2}$$

where ν_l is the kinematic viscosity of working liquid (= 0.115 m^2/s). Figure 2 shows a characteristic of Re_l as a function of Σ_E. In spite of this simple evaluation, an adequate power law correlation between Re_l and Σ_E was founded. The experimental results suggested that the performance of the present EHD pump could be approximately characterized by corona discharge driven EHD, fluid viscous and gravity forces.

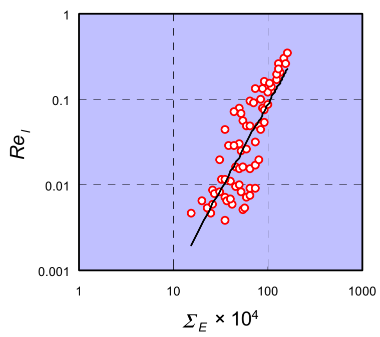

Fig. 2. Liquid-phase Reynolds number Re_l as a function of dimensionless parameter Σ_E for wire electrode locations x = -60 to 90 mm, y = 80 to 100 mm.

3.2 Visualization Characteristic of Liquid-Phase Flow Pattern

Under the corona discharges at wire electrode, the liquid flow was expected that the charged liquid in reservoir was moving to the plate electrode. Figure 3 shows a typical distribution of time-averaged liquid flow velocity in the reservoir, where the applied voltage V was +25 kV and the wire electrode location was (30, 60) mm. The flow velocity was accelerated at the free liquid surface near the wire electrode. The liquid moved to the junction of the surface and the plate electrode and then the main flow moved toward the reservoir floor along the plate electrode. A strong vortex appeared in the local

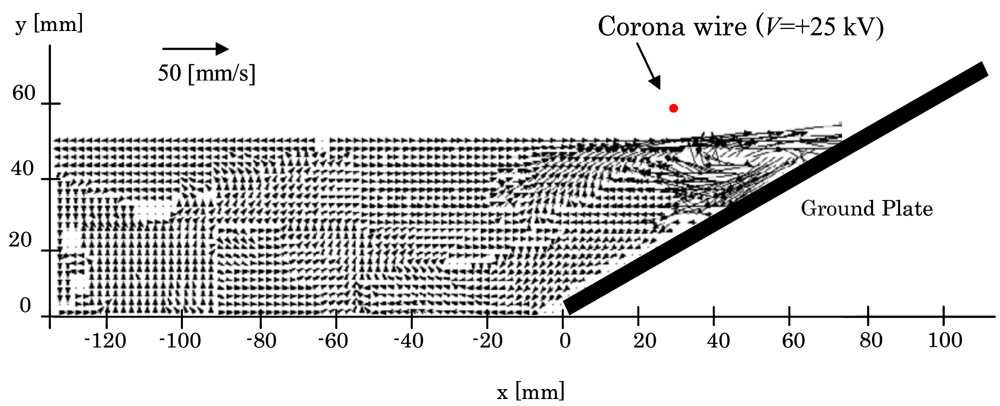

Fig. 3. Typical flow velocity distribution inside liquid reservoir for liquid level L_d = 50 mm.

wedge-shaped flow field as shown in Fig. 3. It was known that the amount of climbing liquid up the plate electrode was a small part of liquid flow accelerated near the wire electrode.

Figure 4 shows typical image reconstruction based on the liquid flow velocity distribution obtained from PIV measurements in case of applied voltage V = +20 kV and the wire electrode locations (60, 80), (0,80) and (-60,80) mm, where a 2nd-order spline functional approximation to the space supplementation was applied. The EHD induced liquid flow was a certain appearance at the free liquid surface near the wire electrode to the plate electrode. The liquid flow accelerated toward the plate electrode and its velocity near halfway indicated a maximum. Figure 5 shows the maximum flow velocity u_{max} as a function of the dimensionless parameter Σ_E. The result suggested an adequate power law correlation between u_{max} and Σ_E. This result was an expected phenomenon that the direction of ionic wind was taken the liquid flow as the interfacial momentum transfer effect.

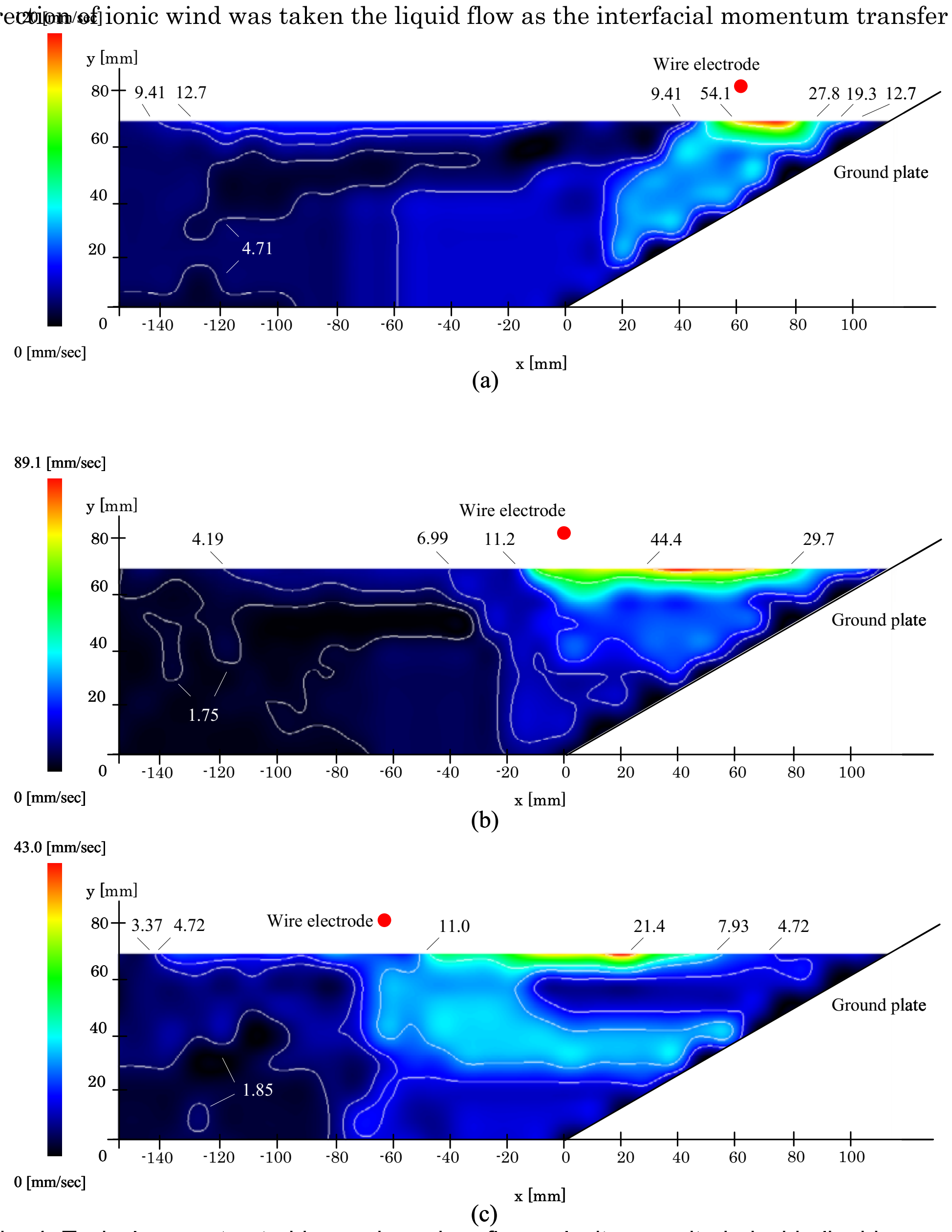

Fig. 4. Typical reconstructed image based on flow velocity magnitude inside liquid reservoir for liquid level L_d = 70 mm, applied voltage V = +20 kV. Wire electrode location (x, y) = a, (60, 80) mm; b, (0, 80) mm; c, (-60, 80) mm.

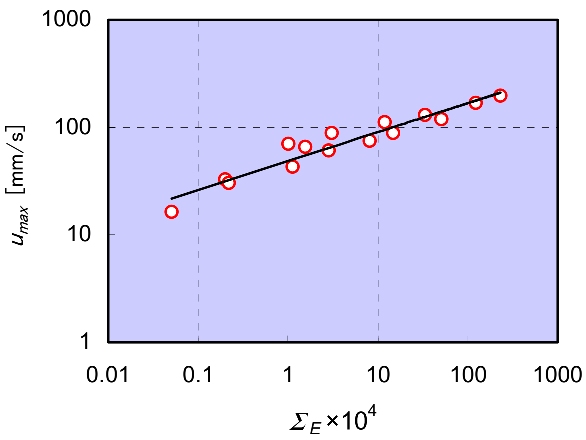

Fig. 5. Maximum liquid flow velocity u_{max} as a function of dimensionless parameter Σ_E for wire electrode locations x = -60 to 60 mm, y = 80 mm, L_d = 70 mm, and V = +15 to +25 kV.

4. Conclusion

Flow profiles in a non-intrusive two-phase EHD pump consisted of a gas-phase wire electrode and a plate electrode inclined to the gas-liquid interface were imaging by PIV techniques. The dielectric liquid pumping operated on gas-liquid two-phase EHD flow in corona discharge fields. The pumping performance was characterized by corona discharge induced dielectric EHD and conductive EHD, fluid viscous and gravity forces in terms of dimensionless parameters. The liquid flow measurement in reservoir was conducted by PIV method with image analysis and the quantified flow distribution was visualized. As the results, an interfacial momentum transfer effect on the liquid flow motion could be characterized by an EHD dimensionless parameter of corona discharge fields. Although a computational procedure for the EHD analysis and its engineering design is a very important tool, at the present day we must wait for developments of the required quantitative charge profile estimation. This work is useful to progress in further investigations concerning the interfacial momentum transfer effect on charged liquid flow.

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