Influence of Electrode Spacing on a Symmetrical Washer-Type Electrohydrodynamic Conduction Pump

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Abstract. Electrohydrodynamic (EHD) pumping is an attractive method that can be applied to drive a fluid in mass transport and heat transfer enhancement applications, and more particularly for microfluidic applications. EHD pumps are very interesting because they do not require moving parts. The electric energy is directly converted into kinetic energy via the Coulomb force. Three modes can generate this fluid motion: conduction, induction, and injection. This paper presents the experimental results of a parametric investigation on EHD conduction pumps with washer-type electrode geometry. Only symmetrical electrode configuration is investigated in order to highlight the influence of the positive/negative charge mobility ratio. The working fluid is a dielectric liquid (HFE-7100). The pumping mechanism is examined with several washer-type electrode geometries and different types of spacers. For each configuration, pressure and current time variations are recorded and compared.

1. Introduction

The principle of electrohydrodynamics (EHD) technology is to use electric body forces to act on single phase or two-phase flows. EHD devices have no moving parts, but only an electric field is used to convert electric energy into kinetic energy. Their main advantages are: low power consumption, light weight, remarkably quiet operation, and mainly no vibrations. EHD phenomena may be used to enhance and control mass transport, evaporation and condensation [1].

There are three electric forces capable of acting on dielectric liquids, expressed in this equation:

\[ \hat{F}_e = \rho_e \vec{E} - \frac{1}{2} \vec{E} \cdot \vec{\nabla} \varepsilon + \frac{1}{2} \vec{\nabla} \left( \rho E^2 \frac{\partial \varepsilon}{\partial \rho} \right) \]

where \( \rho_e \) is the electric charge density, \( \vec{E} \) is the electric field, \( \varepsilon \) is the liquid permittivity, \( \rho \) is the mass density, and \( (\partial \varepsilon / \partial \rho) \) is the permittivity variation with density determined at constant temperature \( T \).

The first term on the right hand side represents the Coulomb force, which acts on free charges. The second term is referred to as the dielectrophoretic force [2]. It is related to the gradient of the electric permittivity. The third term is the electrostriction force. This term is only relevant for compressible fluids. All the three forces in Equation (1) can coexist in a liquid when an electric field is applied, but most often one overcomes the others. In homogenous single phase liquids, the gradient of permittivity is negligible even in the presence of thermal gradient then the Coulomb force is the strongest term and dominates when a DC electric field is applied [3]. It can also be noticed that the force magnitude and direction depend on many parameters as: electrode assemblies, working fluids, applied electric field (AC or DC), temperature, impurities.
EHD pumps are one of the most popular EHD devices [4]. They are particularly well adapted to enhance heat and mass transfer for space and microfluidic applications [5]. Three types of EHD pumps mainly exist in literature: ion drag pump [6], [7], induction pump [8], and conduction pump. In a conduction pump, ions are generated in the liquid bulk by an imbalance in the dissociation/recombination process which helps heterocharge layers to develop in the electrodes vicinities when an electric field is applied. These layers are set in motion by the Coulomb force but a net flow is produced only when the force is asymmetrical, which could be obtained by the use of asymmetrical electrode assembly [9]. However, it was demonstrated in some experimental [10] and numerical [11] studies that, even with symmetrical electrodes, a net flow is produced when a difference of mobility exists between positive and negative ions. Unfortunately, only few experimental data are available.

The current work describes the performance of a symmetrical EHD pump designed according to the conduction pumping mechanism. It is composed of two symmetrical washer-type electrodes and a spacer. Conduction is experimentally investigated with four different washer-type electrodes and five different spacers. For each configuration, pressure head and current/time variations are recorded and compared. In this paper, only the effect of electrode spacing on the generated pressure is highlighted.

2. Experimental Setup

An exploded view of the EHD conduction pump setup is shown in Figure 1. It is mainly composed of two stainless-steel flat washer electrodes (2) and (4), each of thickness \( h = 1 \) mm. Their inner diameter \( d_e \) varies from 0.5 to 3 mm and their outer diameter is fixed \( D_e = 12 \) mm. These two electrodes are separated by a dielectric spacer (3) with thickness \( H \) going from 1 to 5 mm, fixed inner diameter \( d_s = 10 \) mm and outer diameter \( D_s = 12 \) mm. All these parts are placed inside the pump body (5) made of PTFE closed from both ends by two perforated caps (1) and (6). These caps are in contact with their respective electrodes and are also used to connect them to the power supply. The PTFE tube (5) is placed inside two Polypropylene caps (7) and (8) equipped with an HCLA 12X5U static pressure sensor via two glass tubes (10) and (11) placed at the top. The left electrode is grounded and the right one is connected to a positive Spellman SL1200 DC high voltage power supply. The applied voltage and the electric current are recorded with an oscilloscope. Note that in conduction pumping, and in order to avoid charge injection at the electrode surface, electrodes should not have sharp edges and the electric field strength between the electrodes should not exceed a certain threshold value [12].

The working fluid used in this study is HydroFluoroEther HFE-7100. Its liquid range of use is between \( -135^\circ C \) and \( 61^\circ C \). Its properties make it well suited for thermal applications such as electronic component cooling and heat transfer enhancement devices. The properties of this liquid at 20°C, which is also the temperature at which experiments were conducted, are presented in Table 1.

| Table 1. Typical characteristics of HFE-7100 at 20°C. |
|-----------------|-----------------|-----------------|
| Mass density \( \rho \) (kg/m\(^3\)) | 1540             |
| Kinematic viscosity \( \nu \) (m\(^2\)/s) | \( 0.4 \times 10^{-6} \) |
| Electric conductivity \( \sigma \) (S/m) | \( 3 \times 10^{-8} \) |
| Dielectric strength \( \kappa \) (kV/mm) | 11               |
| Relative permittivity \( \varepsilon_r \) | 7.39             |

Figure 1. EHD pump exploded view.
3. Experimental Results

All the results presented in this work are intended for storage in database and will be used for numerical benchmark and comparisons. Therefore, a strict experimental protocol is defined to achieve reproducible results. In every experiment, all the parts of pumps are washed with deionized water and cleaned with new HFE-7100 liquid before being assembled. Then the pump is filled with the liquid very slowly to avoid bubble formation. A warm up time of 20 minutes under a voltage of 6 kV is necessary to reach a thermal and electrical equilibrium. During a test, a voltage step is applied and the pressure and current are recorded for 200 seconds. The pressure is assessed during the last 50 seconds of the time step, at steady-state. In order to verify the reproducibility, each measurement was repeated 4 times and a clear agreement was obtained. For better accuracy, a relaxation time of 10 minutes is set after each experiment. Experiments were carried out for 6 applied voltages: 2, 4, 6, 8, 10, and 12 kV.

It was observed that the pump gradient is oriented from the grounded electrode towards the positive one for all tested geometries and voltages. An example of typical experimental results is shown in Figure 2. A voltage step of 8 kV is applied and maintained between \( t_0 = 20 \) s and \( t_1 = 180 \) s (red curve). Then the electric current and pressure are recorded. The time variations of pressure are not shown but the behaviour is similar to the electric current one (blue curve). The pressure attains its maximum a few milliseconds after the voltage activation, and then it decreases exponentially until reaching a steady state, at almost 80 s after the voltage initiation. This decay was observed on all experiments and is not well understood yet. It is a result of a decrease of the Coulomb force which could be caused by the heterocharge layer growth or the flow motion which reduces the heterocharge layer charge density. It could also originate from an electro-purification of the fluid or from a chemical reaction with the electrodes. Additional experiments and analyses must be conducted to understand this phenomenon.

Figure 3 shows the mean values of the generated pressure and the electric current at various applied voltages. The pressure and the electric current vary linearly with the voltage but no clear deductions could be made. As the pressure is produced by a Coulomb force, that is to say voltage and space charge, it is logical to plot the curves based on the electric power, as shown in Figure 4.

Two different behaviours were identified. For a small hole diameter \( (d_h = 0.5 \text{ mm}) \), as in Figure 4), higher pressures are obtained with shorter gaps for the same consumed power. In other words, lower power is required to produce the same pressure for shorter gaps. With larger hole diameters (2 and 3 mm, which are not shown here), the generated pressure does not depend on the electrode spacing but on the electric power. Because a direct relation between the pressure and the spacer gap is not well underlined when data are plotted versus power, it is convenient to study the pressure versus the mean electric field as shown in Figure 5. It can be observed that whatever the hole diameter is, the curves slopes mainly depend on the gap distance. For a given electric field intensity, the higher slope is obtained with the larger gap. It can be assumed that for a given mean electric field and hole diameter, higher pressures are achieved with greater electrode gaps, but require more power.
Figure 4. Pressure versus power ($d_e = 0.5\,\text{mm}$).

Figure 5. Pressure versus electric field ($d_e = 0.5\,\text{mm}$).

4. Conclusion

The symmetrical pump presented in the current work was developed to understand EHD conduction. It is well known that symmetrical conduction pumps are not the most effective but their main advantage is flow reversibility, which can be easily done without power loss by simply inverting the polarity.

It was observed that the pressure and current increase linearly with the voltage. By using pressure versus power representations, it was shown that for shorter gaps, higher pressures were obtained for smaller hole diameters. For larger holes, the pressure is not a function of the gap, but of the power.

Pressure curves versus mean electric field underlined the influence of electrode gap thickness. Higher pressures could be obtained for larger gaps but power is reduced when a short gap is used.

The main goal of the work is to obtain reproducible EHD conduction pumping results, which was achieved experimentally. Some observed behaviours are not perfectly understood yet. Additional experiments will be carried out in order to have a better understanding of these phenomena.

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