EFFECT OF ELECTRICAL CONDUCTIVITY AND PERMITTIVITY OF LIQUIDS AND THE FREQUENCY OF THE APPLIED VOLTAGE ON DROPLETS ACTUATION ON DIGITAL MICROFLUIDIC DEVICES

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ABSTRACT

We study, experimentally and numerically, the effect of liquid electrical properties (conductivity and permittivity) and frequency of the applied potential on the electrodynamic forces generated on droplets in digital microfluidic (DMF) devices. Electrodynamic forces were found to increase with increasing the electrical conductivity in the range between 10^{-5} S/m to 10^{-3} S/m. Moreover, forces decreased significantly with increasing frequency of the applied voltage beyond a certain threshold, which increases with the increase of droplet conductivity. These results enable one to choose optimum voltage and frequency required to generate highest actuation forces and, consequently, highest droplet speed and actuation reliability.

KEYWORDS: Digital microfluidics, Conductivity, Permittivity, Electrodynamics forces, Electrowetting, Actuation frequency

INTRODUCTION

Digital microfluidics (DMF) technology enables manipulation of micro droplets from any conductive or polar liquid on an array of microelectrodes [1] and has found its way to many biomedical and applications such as PCR[2], cell culture[3], and proteomics. Although, electrodynamic forces generated on droplets were concluded by many studies to be the cause of droplet motion[4], finding best operation parameters (applied voltage and its frequency) that produce highest actuation forces for each liquid has not yet been fully examined in this scope. Unlike previous studies which calculate forces using the simplified lumped capacitance modeling [5], we simulated the electric field in the entire device and calculated forces using Maxwell stress tensor which gives more detailed and more accurate prediction of actual forces.

THEORY

The finite-element package COMSOL Multiphysics was used to model the electric field in a two-plate (closed) DMF device, figure 1(a). We used the Electric Currents module to solve current conservation equations in the entire device.

\[ \nabla \cdot J = Q_j, \quad J = \sigma E + j \omega D + J_e, \quad E = -\nabla V \]

Where \( Q_j \) represent current source, \( J \) electric current density, \( \sigma \) electrical conductivity, \( \omega \) natural frequency, \( D \) the displacement current, \( E \) the electric field and \( V \) the electric potential. Mesh sizes were tested first to make sure simulation results are mesh independent. In addition, we also made sure the size of the model we created is large enough to capture the phenomenon as it happens in borderless environment in reality. This was done by increasing the model size in both x and y directions and recalculating the force to make sure it does not depend on model size.

EXPERIMENTAL

Experimentally, we measured the generated forces using a technique similar to Quincke’s bubble method [6] to measure the resulting forces through the vacuum it generates in a trapped air volume, Figure 2-a. The applied electrodynamic force can be measured from the following equation:

\[ F_e = \Delta p * A + \rho g A (H_1 - H_2) \]
Where, $F_e$ is the electrodynamic force, $\Delta p$ is the pressure difference between air pocket and atmospheric pressure (measured by the pressure sensor), $A$ is the cross sectional area of the tube, $\rho$ is the liquid density, $g$ is the gravitational acceleration, and $H_1$ and $H_2$ are the initial and final height of the liquid inside the tube, respectively.

![Figure 1](image1.png)

**Figure 1**: (a) The modeled 2-plate (closed) microfluidic device. Red color represents the actuated electrode. (b) Distribution of electric potential inside the device. Arrows represent force vectors on droplet surface, concentrated near three phase contact line, (c) Effect of electrical conductivity and permittivity on calculated forces at a constant frequency (18 kHz).

DMF device for experimental testing were fabricated by rapid prototyping on PCB substrate as described by Abdelgawad and Wheeler [7]. Electrodes were in the form of long stripes 2 mm wide spin-coated with a 10 µm thick dielectric layer of PDMS (5500 rpm, 30 sec). A hydrophobic by of Fluoropel 1607 (Cytonix, Beltsville, MD) was applied by spin coating (3000 rpm, 30 sec) followed by baking on a hot plate (200 °C, 30 min).

![Figure 2](image2.png)

**Figure 2**: (a) Schematic of the principle behind force measurement in the current study. Applied forces are balanced by vacuum created in the tube behind the liquid arm. (b) Schematic of the setup used to measure actuation forces on the liquid interface. Actuation forces are determined by measuring the vacuum generated in the air trapped behind the moving liquid column (valves closed). Stripe electrodes were used to apply a continuous force on the advancing liquid front.

**RESULTS AND DISCUSSION**

Overall, forces increased with increasing liquid conductivity in the range between $10^{-5}$ S/m and $10^{-3}$ S/m. Outside this range, forces became independent of the conductivity, Figure 1-c. Droplet permittivity had an effect on generated forces only at low conductivities (less than $10^{-4}$ S/m), where the liquid becomes more like an insulator.

Frequency of the applied potential had an effect opposite to that of conductivity on the generated forces, Figure 3. At very high frequencies, free charges in the liquid cannot follow the rapid changes in field polarity resulting in a pseudo low conductivity behavior resulting in reducing generated forces. This occurs after a threshold frequency that increases with increasing liquid conductivity, Figure 3-a, which explains why
researchers found experimental limitation in finding this high threshold frequency when using highly conductive liquids [8]. This is clear in Figure 3-c, where the force on a water droplet (at a 2 mS/m conductivity) was not found to decrease with increasing the applied frequency up to the maximum frequency manageable by our amplifier (~40 kHz at 200 V).

Figure 3: (a) Increasing applied frequency beyond a certain threshold reduces the generated electrodynamic forces on the droplet. Increasing the electrical conductivity, increases the threshold frequency above which forces start to decrease. (b) When using DI water the force started to decrease at low threshold frequency (100 Hz) but with higher conductivity (2 mS/m), (c) the measured force did not decrease up to frequency of 40 KHz (voltage amplifier limitation) which correlates with the simulation results.

CONCLUSION
The results presented here help one choose proper actuation frequency depending on electrical properties of the actuated liquid. Low conductivity liquids should be actuated at low frequencies whereas high conductivity liquids can be manipulated at much larger frequencies without sacrifice in actuation forces. This study presents one step forward in understanding the physics behind droplet motion in digital microfluidics.

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