Modeling and Comparison with Experiment of SAW Induced Water Droplet Motion

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Abstract. A water droplet motion on a piezoelectric substrate, which is actuated using Surface Acoustic Waves (SAW), is presented toward water desalination purposes. The processes of fluid flow motion under different RF powers and SAW frequencies, induced by internal streaming, has been observed both experimentally and numerically. A free droplet dynamics in the volume of 2 and 5 μl interacted with intensive SAW on the piezoelectric substrate surface for 34 and 58 MHz frequencies, and power output between 0 - 4 dBm observed. In the paper a three-dimensional (3D) finite element model using computational fluid dynamics approach of the free water droplet motion was developed. The different dependences of microfluidic performance such as locally streaming lines, slip length and droplet motion velocity have been studied.

1. Introduction

Recently, there has been an increased interest in SAW-based devices for microfluidic applications using high-performance piezoelectric materials. Nanopumping effect [1-3] can be used as a new energy-saving method for the development of the water purification and desalination. When SAW propagates on a surface of a piezoelectric device, it encounters to the droplet and generates longitudinal waves at a Rayleigh angle [4], as a result, the wave energy creates a volume force and can move a droplet in the direction of SAW. Depending on conditions, various effects could be observed, such as vibrating, pumping, streaming, jetting formation, and atomization of the droplet. A lot of papers has been investigated on the effect of liquid interaction with SAW [5-10].

A linear relationship on microfluidic performance such as streaming, pumping and jetting between the SAW power, frequency and streaming velocity has been obtained in the paper Y. J. Guo et al. [8] based on 128⁰ YX LiNbO₃ and ZnO/Si substrates. Alghane et al. studied the streaming behavior of a liquid droplet, simulated numerically and verified experimentally SAW-driven mixing process of the dye particles inside microdroplets [10]. Alvarez et al. has described the fabrication of SAW atomizer and shown its ability to generate monodisperse aerosols for drug delivery applications [11]. Kurosawa et. al. [12] has proposed a novel way to produce dry fog using SAW based ultrasonic atomizer. Analytical theory of the droplet streaming by the Rayleigh wave on solid substrate was developed in [13, 14].

Our work differs in that we describe own experimental data of the shape formation of the liquid motion under the action of SAW, and have calculated different dependences by using video camera and advanced computational fluid dynamics (CFD) approaches.
In this paper, simulation and investigation of water droplet moving under the influence of SAW was performed numerically using Comsol Multiphysics [15] software by attracting 3D visualisation tools, compared with the experiments and build droplet motion speed dependence graphs. Experimentally observed the free water droplets of 2 and 5 μl volumes induced by frequencies 34 and 58 MHz, then numerically simulated the free water droplet motion under influence of SAW on the piezoelectric substrate [16].

2. Mathematical and Numerical Modeling
The numerical modeling of free water droplet moving under influence of SAW is carried out. These results are important for clarifying the mechanism of SAW interaction with a water droplet and for designing laboratory devices on chips. We have used the finite element method (FEM) of Comsol Multiphysics software. In the figure 1. shown a three-dimensional mathematical model of SAW propagation on a piezoelectric substrate and its influence on water droplet.

![Figure 1](image)

Figure 1. a) the appearance of the SAW device with IDT. 1 - interdigital transducer (IDT); 2 – piezoelectric substrate; 3 – liquid droplet. b) Cross section of the SAW propagation into the droplet.

This model allows us to consider SAW motion processes on the surface of the substrate and calculate dependences of internal fluid streaming flows and droplet velocity. The piezoelectric effect connects mechanical and electrical components in the wave equation. From the SAW basics, it is known that SAW propagation in a piezoelectric substrate is controlled through both stress and strain equation (electromechanical) of motion.

In this section a dynamic three-dimensional (3D) mathematical model of the water droplet motion was developed. Modeling consists of two parts. Initially, a piezoelectric substrate with IDT was simulated to determine the eigenfrequencies of SAW, then these frequencies were used to excite a signal at IDT with time-dependent analyse coupled with the fluid motion. It should be noted that the lower part of the substrate assumed was fixed and absorbed vibrations and did not reflect the waves. In order to capture the interfacial movement with a high resolution, Two Phase Flow Moving Mesh (TPFMM) module of the COMSOL Multiphysics software was selected to accurately mark the exact position of the interface with a time-dependent study which solves the Navier-Stokes equation (1) for incompressible fluid flow:

\[
\rho \frac{\partial u}{\partial t} + (u \cdot \nabla) u = -\rho \nabla p + \mu (\nabla u + (\nabla u)^T) + F
\]

(1)

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \ u) = 0
\]

(2)

where \(\rho\) - the density (kg/m\(^3\)); \(u\) - the velocity vector (m/s); \(p\) - pressure (Pa); \(F\) - the volume force vector (N/m\(^3\)); \(I\) – Identity matrix; \(\mu\) – dynamic viscosity (Pa*s).
Equation (1) is the momentum equation and (2) is the continuity equation. Here \( u \) denotes the mesh velocity and arises from the definition of time derivatives in the coordinate system of the deformed mesh. Poisson’s equation is solved for mesh displacement.

The Navier Slip boundary condition used for the surface of the fluid and solid contacts, also gravity force taken into account. The mesh Model Builder with Swept Distribution calibrated to fluid dynamics. The volume force vector components obtained according to [10, 14]:

\[
F_x = \rho \left( 1 + \alpha_i^2 \right) A^2 \xi x \cdot \exp \left( 2 \left( k_x + \alpha_i k_z \right) \right) \\
F_z = \rho \left( 1 + \alpha_i^2 \right) A^2 \xi z \cdot \exp \left( 2 \left( k_x + \alpha_i k_z \right) \right)
\]

where \( \alpha_i = j\alpha, k = k_x + jk_z \). Total SAW streaming force \( F^2 = F_x^2 + F_z^2 \). \( F_x \) and \( F_z \) are \( x \) and \( z \) component of the volume force \( F \), respectively. \( A \) is the SAW amplitude.

The model was shown that due to the difference in the elastic wave propagation velocities under Rayleigh angle of acoustic radiation of the energy is transferred by acoustic radiation into the liquid, called leaky waves. These data were useful for calculating the components of the total volume force, which acts on the droplet and falls down in an exponential relationship as the acoustic absorption into the water droplet.

3. Experiment

The SAW devices were made on the basis of the 128° YX-cut of a LiNbO₃ crystal with interdigital transducer (IDT) structure for forming SAW with a wavelength of \( \lambda = 60 \mu\text{m} \) at the frequency of \( f = 58 \text{ MHz} \) and \( \lambda = 100 \mu\text{m} \); \( f = 34 \text{ MHz} \) using the photolithography method. That excites SAW propagations along the Z-axis at the velocity of \( V = 3488 \text{ m/s} \). For the generation of SAW signals were used a high-frequency generator APH 2140 with regulated power 0–5 dBm (1-2.5 mW). The registration of the process of water liquid motion under the influence of SAW was performed by using a Sony FHD video camera with 0.5 mm bars.

Time indicators show the fragments of a liquid droplet moving under the action of SAW. The first fragments show the initial droplet following frames when HF signal is applied on the IDT, until the droplet reaches the end of the substrate (Figure 2).

The results of testing the basic characteristics of the SAW device have shown the necessity of comparison experiment with modeling.

![Figure 2. Fragments of the 2 µl and 5 µl water droplet movement under influence of SAW.](image)
Based on the collected experimental data of droplet actuating induces by SAW, the analysis of interdependencies between the supplied power (W), volumes of droplet (μl), frequencies (MHz), types of liquids (water, 50% ethanol solution in water), the speed of movement of the droplet was carried out. In the experiment, the droplet speed was from 0.5 cm/s to 4.5 cm/s, depending on the volume of the droplet and the SAW power. The speed of movement of a water droplet in the experiment has good correlation with modeling, results shown in Figure 3.

![Figure 3. Applied frequency and water droplet speeds, mm/s.](image)

4. Results and Discussions
The streaming effect for water droplet was experimentally observed and modeled for standard laboratory conditions. An advanced three-dimensional Moving Mesh Finite Element Method applied for the dynamic modeling the liquid-solid-gas interface combined with acoustic streaming. Further, using the laminar flow module in conjunction with a moving-variable grid, the components of the volume force acting on the water droplet were applied.

![Figure 4. The simulation results (a- moving mesh, b-streamlines) of water droplet motion under the influence of SAW compared with (c) experimental observation.](image)
Corresponding parameters of dynamic viscosity, contact angle, and surface tension force were set. The simulation results show that the water droplet motion under the influence of SAW is consistent with the experimental observations in Figure 4c.

The simulation is calculated about 40 minutes. As a result, it is clear that, despite the physics of laminar flow, turbulence is used and internal high speed streaming is observed (see Figure 4b). This is because the volume force is non-uniform and varies in-depth and in height of the drop, as in eq.3, it decays exponentially with distance from the source of the SAW.

5. Summary
In summary, the water flow was actuated with surface acoustic waves. Water droplet motion was experimentally observed for a water droplet in the volume of 2 and 5 μl, SAW frequencies 34 and 58 MHz. The influence of frequency on microfluidic characteristics, such as the speed of the movement, slip length dependence was studied by modeling and observed experimentally in the power range 0–5 dBm. Next these obtained results and the simulation of water movement will be applied for a water filtration through nanomembranes and will be published elsewhere. The numerical modeling of free water droplet motion under the influence of SAW was carried out. As a result, a three-dimensional (3D) dynamic mathematical model of the water droplet motion induced by SAW was developed using COMSOL Multiphysics software. Water motion such as streaming and droplet formation has been observed numerically, and the simulation shape of droplet looks the same as in experimental observation. The simulation results gives same average value and in good agreement with the experiment.

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5