Modeling of liquid pumping via microchannels

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ABSTRACT

We report numerical finite-element simulation results of acoustic streaming effects in a water droplet, 1-30 μm in diameter, placed on the top of a piezoelectric substrate, induced by surface acoustic waves (SAW), and experimental observations and simulation of flow activation inside a sub-millimeter diameter channel induced by volume acoustic waves.

Keywords: piezoelectric substrate, surface acoustic wave, acoustic streaming

1 INTRODUCTION

Actuation of fluid flow by surface acoustic waves (SAW) propagation on the surfaces and by volume acoustic waves (VAW) in microchannels are important and not well studied phenomena promising numerous practical applications [1,2].

SAWs can be generated by applying an alternating frequency electric field by inter digital transducers (IDT) on the surface of a piezoelectric substrate.

When SAW propagates on a surface of a piezoelectric and encounters a micrometer droplet, the elastic surface energy penetrates into fluid and generates longitudinal waves at a Rayleigh angle [1]. As a result, the absorbed wave energy creates a volume force on the droplet and can move it in the direction of SAW, generates various internal effects, such as vibrating, pumping, stirring, jet formation, and atomization of the droplet.

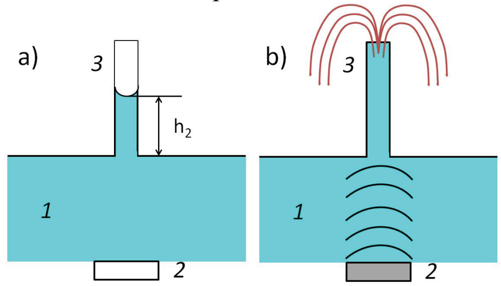

Figure 1. a) Schematics of experimental set-up for water (*1*) pumping via a micron scale tube (*3*); b) Fountain of water through the tube after an ultrasonic transducer (*2*) was turned on.

During the last decades, various simulation models of acoustic streaming within the droplet have been proposed [1].

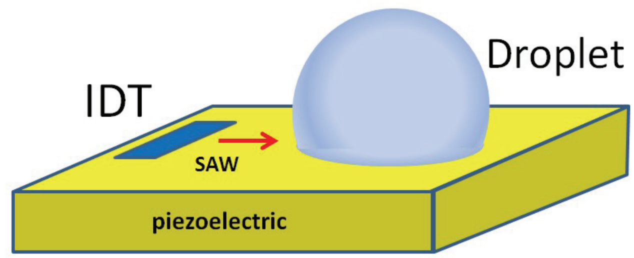

Figure 2. Schematic illustration of SAW propagation from the IDT into a droplet.

Alghane et al. studied the streaming behavior of a liquid droplet as a function of radio-frequency (RF) power and droplet size [1]. The emergence of lab-on-a-chip technology has motivated numerous efforts of replacing optical tweezers [2].

A significant engineering problem exists in the development of a liquid actuation technology that enables high flow fluxes with lower parasitic power losses in micro fuel cell systems. Current fabrication processes are incapable of providing high volumetric liquid fluxes at affordable prices [3]. Today motor-driven air delivery uses about 15% to 20% of the system power available from micro fuel cells. In addition, the costs of such pumps are about ten times higher than the projected market will likely accept [4].

Therefore, a novel nano- and micromechanical pumps (nano- and micro-pumps) are desirable that will be capable of pumping gases and liquids at the nanoscale, through channels with diameters as small as 1–10 nm and 1-100 μm [4,5]. Such pumps will be important devices in cell biology for facilitation, acceleration, and control of the ion exchange into and out of a cell; in medicine, for selective drag delivery in a human body; in energy technology, for hydrogen storage in carbon nanotubes and for hydrogen transport through them.

Here, we present our preliminary experiments on water pumping via micron scale tubes driven by acoustic waves (Fig. 1) and on the surface of a piezoelectric by SAW (Fig. 2) using finite element modeling of this process.

1 EXPERIMENTAL

2.1. Actuation of water flow via a tube

The present work studies the effect of surface acoustic waves with frequency of 37 kHz on the flow rate of water through a tube with the diameter of 0.1-0.6 mm.

Fig. 1a shows the experimental setup. We studied the influence of ultrasound on flow actuation in a tube and the schematic of fontaining is shown in Fig. 1b.

The experiment performed at various values of tube diameter, *d*, and the immersion depth of the capillary tip, *y*, to establish the dependence of the rising the fountain height h on diameter and the depth. Metal tubes with the diameters ranging between 0.3-0.6 mm were used. The results illustrated in Fig.3 indicate the followings:

At the same value of the immersion depth the water level increases with the decreasing of the tube diameter.

For full range of diameter there is a local maximum of water level at the immersion depth of 9-13 *mm*.

The experimental results showed a significant increase of the water flow through the tube after it was placed in water and an ultrasound acoustic transducer at the bottom of the vessel started to generate US signal. Water started to fountain from the open end of the capillary.

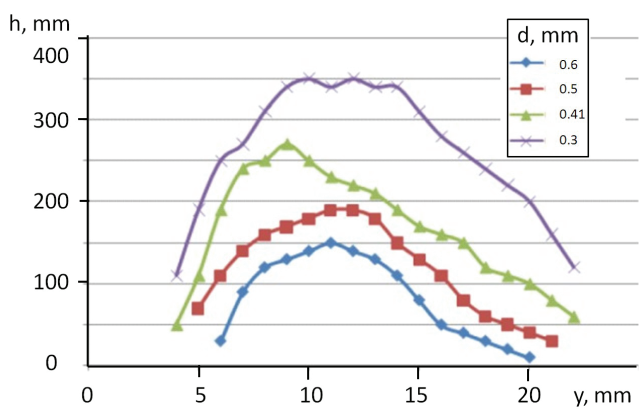

Figure 3. Dependence of the water fontain hight *h* flown via the tube on the depth of tube tip immersion into water and on the tube diameter *d*. (*d* = 0.3-0.6 mm)

2 SIMULATION MODEL

3.1 Modeling of acoustic streaming in a tube

Actuation of water flow in a sub-millimeter tube and the effect of ultra-sound on water droplet was simulated by COMSOL [6]. The Navier-Stokes and acoustic pressure equations were solved simulateneously to determine the hydrodynamic field in the tube.

Our method of solving the hydrodynamic equations for sound propagation in water captures all wave effects, including diffraction.

Figure 4 shows a 2-*d* (*r*, *z*) axisymmetric geometry of simulation which shows two tanks and a cappilary where the blue area indicates water, and the red area - air.

The Laminar Two-Phase Flow, Phase Field (tpf) was used for our simulation, providing the velocity field, the pressure, and the phase field variables [6].

A 3 mm length tube, with various diameters (d=0.3÷0.6mm), has a wetted wall with a contact angle of 70°. Effects of gravity field, of ambient pressure were also included into our simulation. The diameter of the capillary tube was 0.3 mm. The total power of the transducer was 150W. The frequency of the emitted ultrasound was 37kHz.

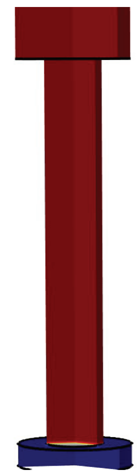

Figure 4. Initial setup of water motion under acoustic pressure, at t = 0. Blue area – water in reservoir, red area – air.

The driving force of water propagation in capillary was periodically alternating pressure governed by equation (1) and (2) applied on inlet with pressure, no viscous stress boundary condition:

$$P = A\sin(kx-\omega t) \quad (1)$$

$$P = P_0,\ [\mu(\nabla u + (\nabla u)^T)]n \quad (2)$$

where P - pressure, A - amplitude, k - wavenumber, x - position, ω - angular frequency, t - time, n - boundary normal pointing out of the domain, u - velocity magnitude, μ - dynamic viscosity, and T – the total stress tensor.

Water flow at the boundary of inlet was governed by the Navier-Stokes equation (3):

$$\rho\frac{\partial u}{\partial t} + \rho(u\cdot\nabla)u = \nabla\cdot[-pI + \mu(\nabla u + \nabla u^T)] + F_g + F_{st} \quad (3)$$
$$+ F_{ext} + F$$

where ρ-density, I - identity matrix, T - total stress tensor, F-body forces.

3.2 Simulation model of droplet actuation

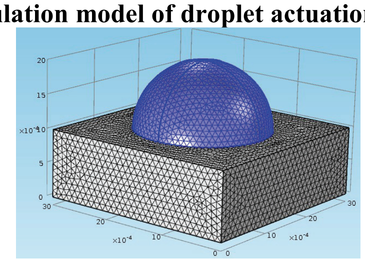

Figure 5. Droplet geometry in COMSOL.

The hydrodynamic behavior of the droplet due to the SAW propagation is assumed to be governed by the laminar incompressible Navier-Stokes continuity equation and momentum equation driven by an external body force F, generated by the SAW-liquid interaction, Ultrasound waves with the frequencies in the range 15-20 kHz were simulated. The characteristic feature of the propagation of ultrasound in gases is the existence of regions of sound dispersion, accompanied by a strong increase in its absorption. But liquids and solid bodies are good conductors of ultrasound, and attenuation of the sound intensity by the medium is almost negligible. Therefore, attenuation was not taken into account in this model.

The propagation of sound waves is governed by two basic relations for the acoustic pressure $p(\boldsymbol{x},t)$ and the acoustic fluid velocity vector $\boldsymbol{v}$ $(\boldsymbol{x},t)$. Pressure p and velocity $\mathbf{v}$ denote small-amplitude acoustic signals, which depend on time t and the space vector $\boldsymbol{x}$. These equations are so called equation of motion and the equation of continuity.

Hard and reflection-free boundary conditions for three spatial dimensions have been treated for the wall of the tank.

The Periodic Flow Condition node is used to prescribe periodicity of the model. Enter one periodic pair in each Periodic Condition node. The node splits its selection in two groups: one source group and one destination group. Fluid that leaves the domain through one of the destination boundaries enters the domain over the corresponding source boundary.

During last decades, numerous attempts to simulate the acoustic streaming excitation within the droplet were reported in the literature.

3 SIMULATION RESULTS

4.1 Streaming Within the Droplet

The diameter of the hemisphere taken to be 1 mm (Fig. 5), that corresponds to the 2.1 μl volume droplet. The platform has a characteristic length of $3\times3\times1$ mm^3. The material is water with a density of 1×10^3 kg/m^3, and with dynamic viscosity of 1×10^{-3} $Pa\cdot s$.

The hydrodynamic behavior of the droplet due to the SAW propagation is assumed to be driven by an external boundary load, $F(x,y,t)$ generated by the SAW-liquid interaction:

$$F(x,y,t) = (A + A\sin(kx - \omega t))\cdot(ax + b) \qquad (4)$$

where a linear factor, $(ax + b)$, describes attenuation of SAW energy by the droplet. The function of SAW force distribution at time point of $t = 0$ is given in Fig. 6.

Fig. 7 illustrates the results of our simulation. We got a significant rotation of fluid in the upper left-hand side of droplet domain that had changing position with time. The center of the rotation moved up and down with SAW propagation.

For comparison the image from the paper was taken into consideration (Fig. 8). There is no good agreement between them, because of the different sizes, geometry and approaches.

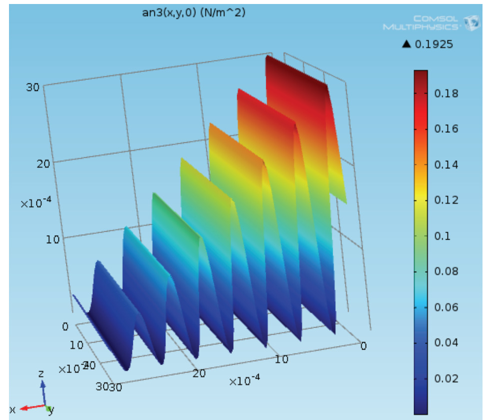

Figure 6. Function of SAW force distribution, $F(x,y,t)$ at t = 0.

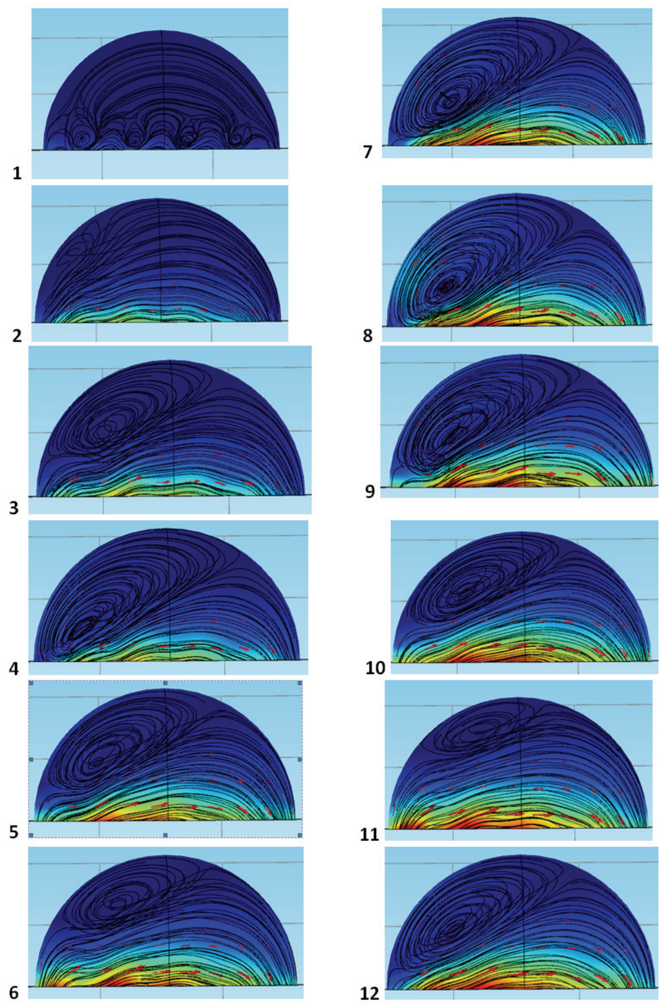

Figure 7. Evolution of SAW streaming patterns.

NSTI-Nanotech 2014, www.nsti.org, ISBN 978-1-4822-5827-1 Vol. 2, 2014

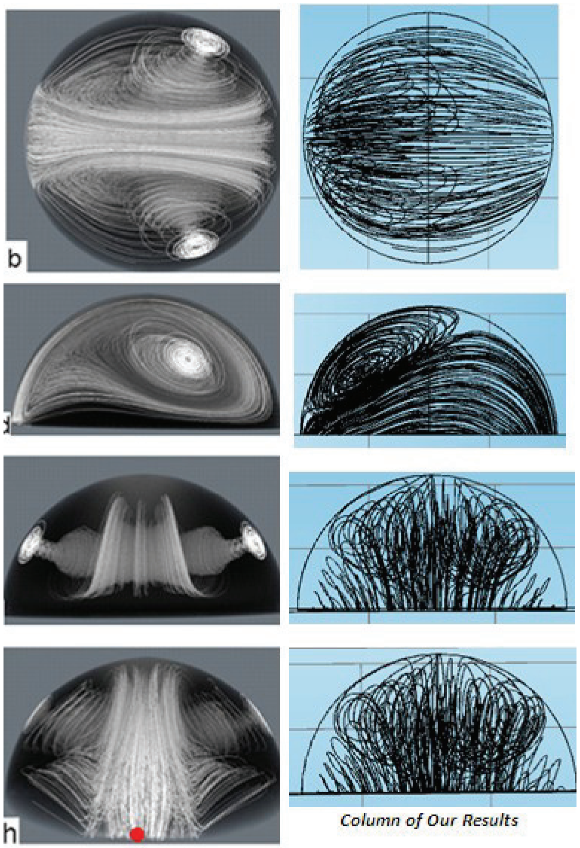

Figure 8. Comparison with the simulation results from Ref.[1]. SAW streaming patterns for 30 μl droplet from top (b), side (d), front (e) and (f), and back view (h). The left column are photos of 6 μm polystyrene particle trajectories, while the right column represents our results.

4.2 Acoustic pumping via a tube

In our case, alternating pressure on inlet will promote oscillating water inflow within capillary and filling of upper reservoir with water. This can be observed on the snapshots illustrated in Fig. 9.

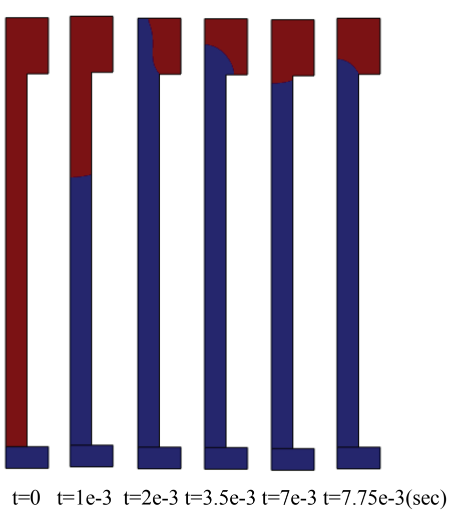

Figure 9. Image sequences of oscillating water inflow within capillary

Fig. 10 (a, b) shows our numerical results regarding pressure distribution and its alternation in capillary system. It can be seen that pressure alternates periodically, and this kind of pressure alternations allow us to simulate ultrasound acoustic radiation pressure impact on subsurface of water.

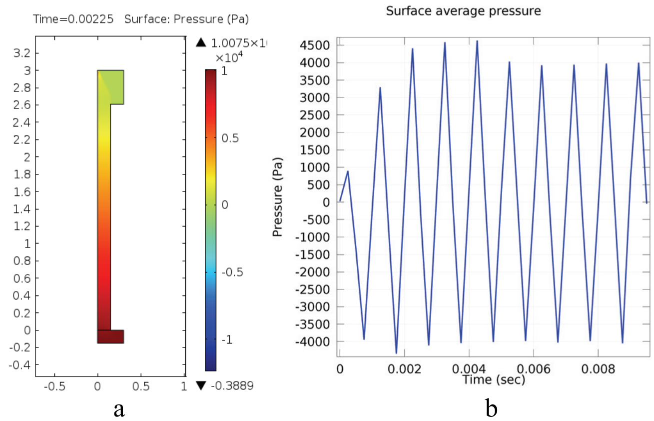

Figure 10. a) Pressure distribution in the capillary system b) Plot of alternating pressure

Variation of velocity magnitude of flow due to interaction with alternating pressure is shown on Fig. 11 (a, b).

According simulation water flow velocity at maximum is 3-4 m/s (higher velocities on graphs corresponds to air flow). In addition, flow velocity alternates as well due to pressure alternation.

The explanation of this phenomenon is the oscillation of fluid inside the tube under the influence of ultrasound source, which causes the sharp growth of capillary effect, and level of water in capillary increases several dozen times. The significant growth in the lifting speed was observed. It was experimentally proved that the flow is activated not because of the radiation pressure or capillary forces, but because of the standing ultrasound waves.

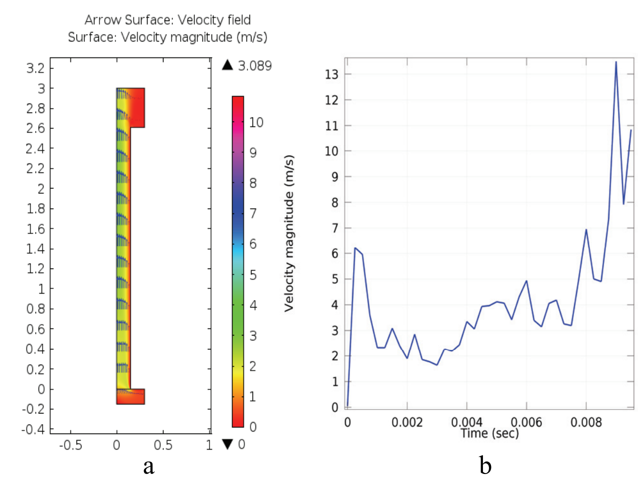

Figure 11. a) Flow velocity variation in the capillary system b) Plot of alternating velocity

The propagation of ultrasound waves in fluids generates the fluid flow, so called acoustic streaming, the velocity of which depends on viscosity of the media, sound intensity and on sound frequency; in general, the magnitude of this stream is low enough and about a percent of ultrasound velocity.

ACKNOWLEDGEMENTS

The authors acknowledge support for this work from the Nazarbayev University Research and Innovative System through the Science World Stars project #031-2013 (3/12/2013).

REFERENCES

[1] M.Alghane, Y.Q.Fu, B.X. Chen, Y. Li, M.P.Y. Desmulliez, and A.J. Walton, J.Appl.Phys. 109,114901 (2011)

[2] Sz-Chin Steven Lin, Xiaole Mao and Tony Jun Huang, Lab Chip, 2012, 12, 2766-2770

[3] RNCOS report, "Fuel Cell Industry Analysis", June 2011.

[4] Z. Insepov, D. Wolf, A. Hassanein, Nano Letters **6** (2006); Z. Insepov, R. Miller, J. Nanotechnology in Eng. and Medicine, 3 (2012) 025201-1..

[5] Z. Insepov, A. Hassanein, US Patent #7,632,482 (Dec. 15, 2009); US Patent # 7,651,673 (Jan. 26, 2010)

[6] Comsol Multiphysics Software (http://www.comsol.com/).

[7] P.W. Carpenter, C. Davies, A.D. Lucey, Current Sci. 79 (2000) 758.