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Particle separation in a microchannel using tilted focusing standing surface acoustic wave

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Abstract

Acoustic particle separation is a promising active bioparticle separation with various functionalities. The importance of particle isolation and separation in chemotherapy and diagnoses tends scientists to conduct vast research on this subject. Irrespective of all efforts there are two major drawbacks to acoustic separators. The first one is the particle separation distance and the latter is minor throughput. In this article, we proposed a tilted angled focused standing acoustic wave that enhanced both parameters. The particle separation lateral displacement in our approach is improved and got more than two-fold from 23 µm to 46 µm at a 0.6 m/s flow rate. In this work, we proved our concept through numerical simulation of experimental research. The numerical simulation in COMSOL Multiphysics software provides better insight into the functionality of acoustic separators and it is helpful in the cost reduction of lab-on-chip devices. So by validation of our simulation, a new particle separator is presented.

Keywords: Acoustic separation; Acoustophoresis; Particle separation; Cell separation.

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1. Introduction

Particle separation is a crucial technology for a wide range of applications, agriculture, diagnosis, chemotherapy, etc [1]. Active particle separation is one of the major approaches to particle separation besides the passive method. Active methods usually use external force fields like electrical, magnetic, optic, and acoustic [1]. Engaging a force field to affect particles enhances purity and selectivity but it results in major deficiencies like minor throughput and damage to biological cells [2]. Among all active methods acoustic field shows great potential in biocompatibility despite of lower input rate [2]. To resolve the mentioned downside of acoustic separation several researches have been conducted. Ai et al proposed the double side inputs with one large sheath flow in the middle to increase the throughput rate of an acoustic separator [3]. Ref 2 proposed a simple side sheath flow to linearize particles, then, a narrow streamline passed through a highly intense acoustic field. This work demonstrated a high throughput particle separator. Ding et al introduced a tilted angled surface acoustic wave-particle separator that enhanced the limitation of particle separation distance of normal acoustic separators [4]. Shamloo et al illustrated that a trapezoidal channel configuration with two tangential inputs and one middle sheath can improve separation throughput [5]. Despite all the efforts acoustic separators still suffer from low input throughput and limited separation distance [2].

In this article, we proposed a high throughput tilted angled standing surface acoustic wave bioparticle separator. Our novel approach combined both tilted angled configuration and intense acoustic filed divide particles in the further distance and higher flow rate besides improvement of size selection capability. In our device, two focused interdigital transducers were deposited in front of each other. The wavelength of 200 micrometers with 30 fingers was considered for acoustic field generation. We proved the efficiency of our approach in both separation distance and increase in input using a 3-dimensional simulation in COMSOL Multiphysics software. The simulation provides an informative insight into the function of acoustic separators.

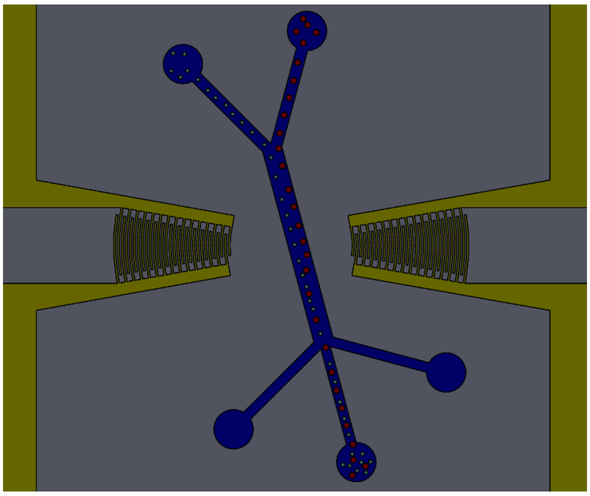

Figure 1- primary design

2. Governing equation and working principle

Acoustic particle separation through standing surface acoustic waves needs two interdigital transducers on a Lithium Niobate piezoelectric ceramic. By applying an electric field to the comb drives, reverse piezoelectric influence converts electric fields to mechanical waves. By interference generated waves with the same phase and amplitude low-pressure and high-pressure regions will be created. The Low and high-pressure zones are known as nodes and anti-nodes. When biological particles that commonly have positive acoustic factors cross through an acoustic field particles are prone toward pressure nodes. The generated force that affects particles in acoustic fields is acoustic radiation force and it can be measured by the following equation [3]:

$$F_R = -\left(\frac{\pi p_0^2 V_c \beta_f}{2\lambda}\right)\varphi(\rho,\beta)\sin(2kx) \qquad (1)$$

In Equation 1 the term V_c is particle volume, p_0 is acoustic pressure, λ is wavelength, k is wave number and x is particle distance from node. The term $\varphi(\rho,\beta)$ refer to the acoustic factor of the particle that can be calculated from the following equation:

$$\varphi(\rho,\beta)=\frac{5\rho_p-2\rho_f}{2\rho_p-\rho_f}-\frac{\beta_p}{\beta_f} \tag{2}$$

In equation 2, β_p and β_f are compressibility of particles and fluid, ρ_p and ρ_f are the density of particles and fluid. In acoustic separators when a narrow stream line of particles that consists of cancerous cells and blood cells is exposed to an acoustic field cancerous cells due to the larger size tend to node faster than ordinary blood cells. This phenomenon results in the separation of cancerous cells from blood cells [3]. In this article, a tilted angled standing surface acoustic wave generated from two focused interdigital transducers had been used to separate particles. At the primary stage, particles had been focused by sheath flow. Then, the tight particle stream line passes through a tilted angled standing acoustic field. The tilted-angled FIDTs can separate particles in higher throughputs and further distances compared to simple IDT and even FIDT arrangements.

3. Numerical simulation and validation

A finite element method (FEM) based numerical simulation (using COMSOL Multiphysics 6.1, www.comsol.com) was developed to study acoustic-piezoelectric interaction problems. a 3D modelling of device is considered in a frequency analysis. So, the acoustic-piezoelectric interaction module in the frequency domain was chosen to model the developed SSAW-based device. A PDMS layer was located on the top of the piezoelectric substrate, for simplification of the model, acoustic impedance is applied as a boundary condition of channel walls instead of PDMS modeling. The propagation of SAW in a piezoelectric substrate is obtained by Maxwell’s equation for the electric field and the stress−strain equations for mechanical motion. The linear piezoelectric constitutive equations are expressed as [3]

$$T=C_E.S-e^{tr}.E \tag{3}$$

$$D=e.S+\varepsilon.E \tag{4}$$

where **T** is the mechanical stress vector, **C_E** is the elasticity matrix, **S** is the strain vector, **e** is the piezoelectric stress matrix, **E** is the electric field vector, **D** is the electric displacement vector, and **ε** is the dielectric matrix. The superscript "tr" denotes the transpose of the matrix.

As a validation of simulation, a high-throughput SSAW cell/particle separator presented by Ren et al [2] is simulated and it was proved that the results of Ren’s article agree with our simulation results. According to Ren’s work, a sinusoidal AC signal with a peak-to-peak magnitude of 30 V and frequency of 38.8 M Hz was applied to the interdigital electrodes on the piezoelectric substrate to generate the electric field within it. Also, the velocity of the fluid is set at 0.4 m/s. The remaining boundaries of the piezoelectric substrate were assumed to be zero-charge surfaces. The low reflecting boundary condition is applied to the bottom and side of the substrate to prevent any wave reflection [6]. Also, the particle with the size of 10 μm must be separated from 3μm particles.

The standing acoustic wave field in the fluid across the channel was created by the SAWs emitted into the fluid from the piezoelectric substrate. The outer surface of the PDMS domain was defined as a sound hard boundary [3].

$$n\cdot\left(-\frac{\nabla p}{\rho_i'}\right) = 0. \tag{5}$$

In equation 5, n is a normal vector. Simulations with varying mesh sizes were conducted to confirm that the numerical results were both converged and independent of the mesh size. A coarse mesh was generated near the bottom of the piezoelectric substrate. Element size in the top surface of piezoelectric and domain of microchannel must be less than λ/6 [7]. So, a fine mesh with a size of 16 μm was employed in the microchannel to precisely capture the pressure nodes of the SSAW field. The result of the simulation of particle separation is illustrated in Figure 2.

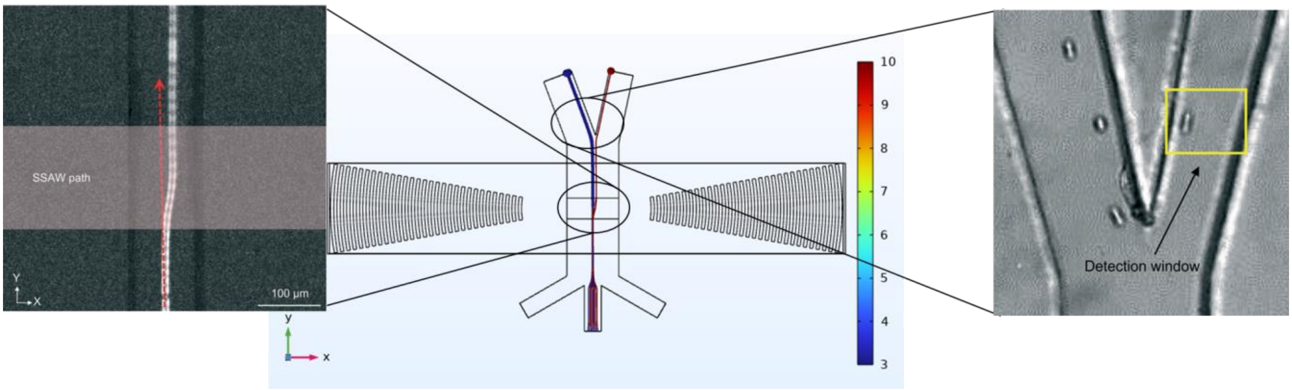

Figure 2- showing particle separation in the validation of simulation in comparison with Ren's work [2]: as shown in the acoustic zone the acoustic force on particles, make separation on them and each particle size, exited from the related outlet.

As shown in Figure 2, 10 μm particles are separated from 3 μm particles. The lateral displacement in this case is 23 micrometers and as expected the maximum displacement is equal to λ/4 and the lateral displacement in this simulation is about that. To solve this problem that restricts the maximum displacement of particles, we applied a tilting angle to the microchannel.

4. Result and Discussion

To increase the separation purity and range of throughput, a tilted angle microchannel on a focusing interdigital transducer (FIDT) is simulated. The input voltage and frequency of the FIDT are the same values of Ren's separator. 5, 10, 15, 20, and 25 degrees is applied as tilting angle. The lateral displacement of particles was obtained for each angle. 15 degrees is the optimum angle that is chosen as the tilting angle of the microchannel. The result of the particle separation simulation is shown in Figure 2.

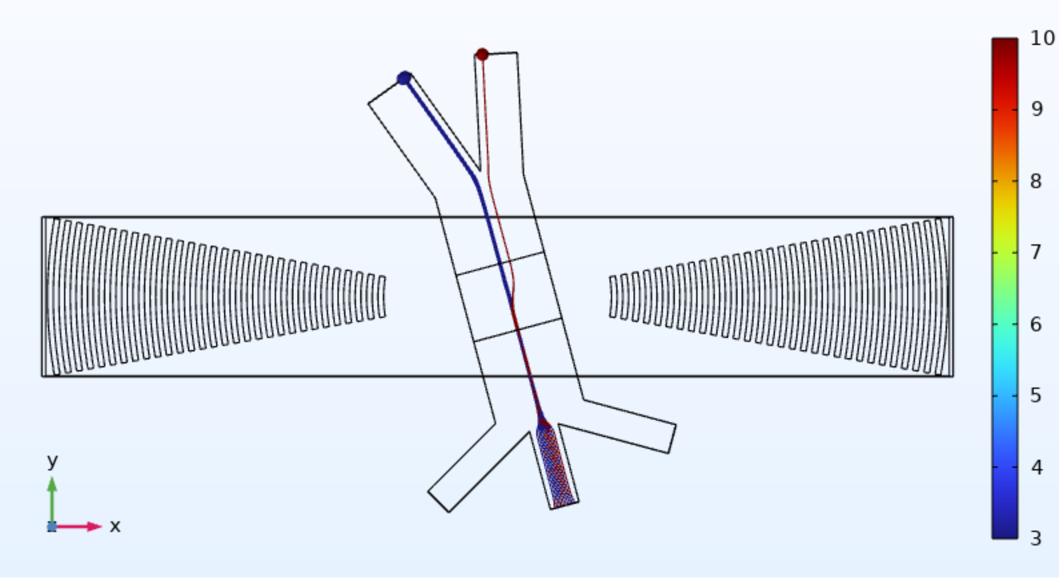

Figure 3- Simulation of particle separation in a tilted angle microchannel on FIDT

As shown in Figure 3, with the same input velocity, the lateral displacement of particles increased from 23 μm to 46 μm. This lateral displacement between large and small particles causes an increase in better separation of particles by increasing the probability of exiting the particles with different sizes from separated outlets, therefore, the purity increases according to this concept. Also, the maximum velocity of the fluid increased up to 0.6 m/s. So, this simulation proves that this model improved the throughput range and purity of particle separation.

5. Conclusion

Acoustic particle separation is one of the major research approaches in the field of biocompatible cell isolation. In this research, we offered a new device formed by the combination of both tilted angled standing waves and an intense acoustic field that was generated from two focused interdigital transducers. Our device could separate particles in the 0.6 m/s flow rate from conventional 23 μm to 46 μm with a 15-degree tilt angle. Besides the promising result, we offered a 3-D numerical simulation from experimental research that provides insight into device functionality and could help design viable acoustic lab-on-chip devices.

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