Particle focusing in a microfluidic channel with acoustic metamaterial

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ABSTRACT

Particle focusing has been numerically studied in a microchannel filled by an acoustic metamaterial fluid that possesses negative density, and under a pair of ultrasound incidences from the lateral boundaries. Acoustic metamaterial with negative density exponentially damps the ultrasound field along its propagation direction that forms a very low field at the center of the microchannel. Driven by the acoustic radiation force and dissipated by the fluid, the particles laterally vibrate in the microchannel and gradually aggregated in the vicinity of the channel center. A structural microchannel with acoustic resonant elements that generates equivalent negative density property for the fluid in the microchannel has been designed, which decays the ultrasound field in a similar way. Particle movement in the structural microchannel has also been investigated and particle focusing is also achieved. The merit of the proposed particle focusing method by metamaterial concept lies in its independence on the type of the incident wave and width or size of the microchannel.

Keywords: Particle focusing, acoustic metamaterial, evanescent wave, acoustic radiation force, lab-on-a-chip.

1. INTRODUCTION

Manipulation of particles into a limited region is significant for lab-on-a-chip devices. A variety of particle focusing methods have been proposed, ranging from hydrodynamic focusing[1-3] to methods based on electroosmosis[4-7], dielectrophoresis[8-10], magnetophoresis[11], acoustophoresis[12-14] and etc. Hydrodynamic focusing needs shealth resolution for three-dimensional (3D) focusing[15], while electroosmosis, dielectrophoresis and magnetophoresis methods could cause possible damage to the particles likes cells. Among these techniques, acoustophoresis approach is considered as an ideally non-invasive method for particle focusing. The acoustophoresis approach usually depends on the standing waves building in the microchannel. The nodal points of the standing wave are the stable regions where particles tend to be trapped in. Inherently, the wave length of the standing wave has a close relation with the size of the microchannel. If the microchannel is broad and there exists many nodal points in the microchannel, the particles will be spread into multiple nodal vicinities.

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The nodal point of a standing wave is principally a region with very small field amplitude, which could be easily realized by adopting the excellent properties of metamaterials[16-19]. A distinct characteristic of metamaterial with single negative parameter (e.g. negative density) is that it supports evanescent waves[16]. The evanescent wave exponentially decreases its amplitude after penetrating into the single negative metamaterial. If both lateral boundaries of the metamaterial fluid are excited by acoustic wave with the same magnitude, then a small field can be achieved at the central of the fluid, thus the particles will be trapped in the center. This is the principal of the particle focusing in an acoustic metamaterial fluid.

In this work, two models of particle movement driven by acoustophoresis force are simulated by Comsol Multiphysical software. These two models are illustrated in Figure 1. First model (Figure 1 (a)) is particles randomly distributed in a fluid with homogeneous acoustic negative density. In this case, the evanescent field distribution of a microchannel filled by acoustic metamaterial fluid was calculated first. After that, particles were released in the fluid and driven by acoustic radiation force into the center of the channel. The other model (Figure 1b) is a structural microchannel designed with acoustic resonant elements, which is an experimental realization of the first model. Again particles are released in the structureal microchannel and driven by radiation force. Finally particle focusing is achieved in the structural microchannel.

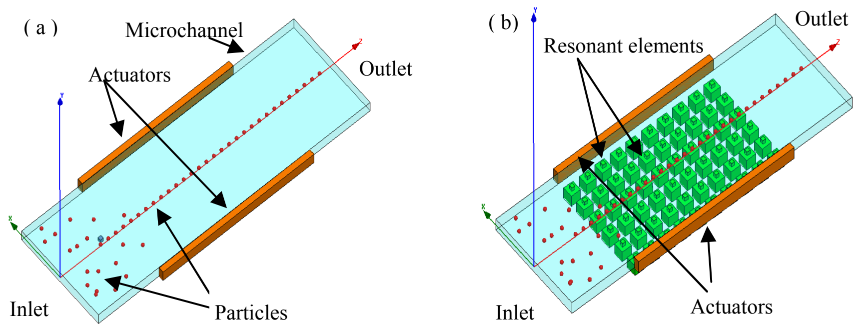

Figure 1. (a) The sketch of particle focusing in a microchannel with effective fluid of both negative density and negative modulus. (b) The sketch of particle focusing in a microchannel with acoustic resonant elements.

2. MODEL DESCRIPTION

Figure 1 (a) shows the microchannel with a pair of actuators at its lateral sides, which generates vibration and transits pressure wave in the fluid of the microchannel. Particles are injected into the channel from the inlet with a dispersive pattern, and expected to be confined in the center during traveling in the channel. The fluid in the microchannel is assumed to be of negative density that transforms the pressure wave into evanescent field.

The field distribution of the evanescent wave in the microchannel is shown in figure 3. Considering the incident pressure wave frequency to be 38.2 KHz, the width of the microchanel to be $L_m = 0.055\text{m}$, height to be $H_m = 0.006\text{mm}$, density of the fluid to be -1000 kg/m^3, bulk modulus to be 2.2×10^9 Pa, the pressure incidence is induced by the actuators at the boundaries, and the up and down boundaries are acoustic hard wall. As demonstrated in figure 3, the wave amplitude at the lateral boundaries is about 2.0×10^6 Pa, and it decreases exponentially while propagating towards the center, reduces to a level of 2.0×10^3 Pa at the middle of the channel.

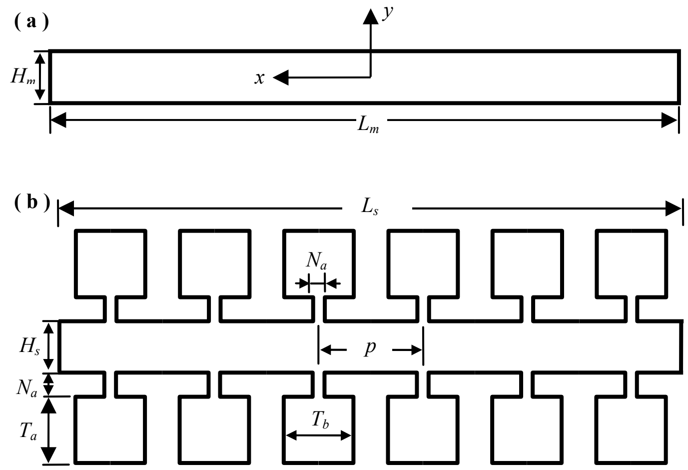

Figure 2. (a) The section plane of the effective fluid microchannel. (b) The section plane of the microfluid channel with acoustic resnonant elements.

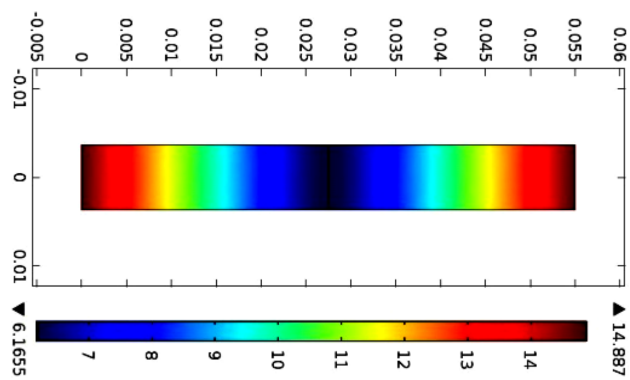

Figure 3. Pressure amplitude distribution of the acoustic wave in the microfluid with metamaterial fluid by a pair of the actuators from the channel sides.

Using the Comsol Multiphysics softwave , particle movement driven by time-averaged radiation force in the acoustic field is simulated and displayed in figure 4. Particles are supposed to be released at the nodes of the meshes among any location of the fluid in the beginning (in figure 4, a dot means the position of a particle, not represents a real particle, so they will not collide). The radius of the particles is assumed to be 1/20 of the wavelength (about 0.0018 m), with density of 1050 kg/m^3. The viscosity of fluid is assumed to be 0.001002 Pa·s, both the acoustophoretic force (radiation force) and drag force are taken into account for the particle movement, while the gravitiy is ignored.

From figure 4 (a), one can find that, at the start moment, the particles sit furthest from the center are exerted with the largest radiation force, about ±0.29 N. These forces cause the particle move with large acceleration, however, the speed of the particles is slow, as the fluid drag force will significantly comsume the kinetic energy of the particle. After several rounds of traveling back and forth, 5 seconds later, the particles finally gather at the center of the channel.

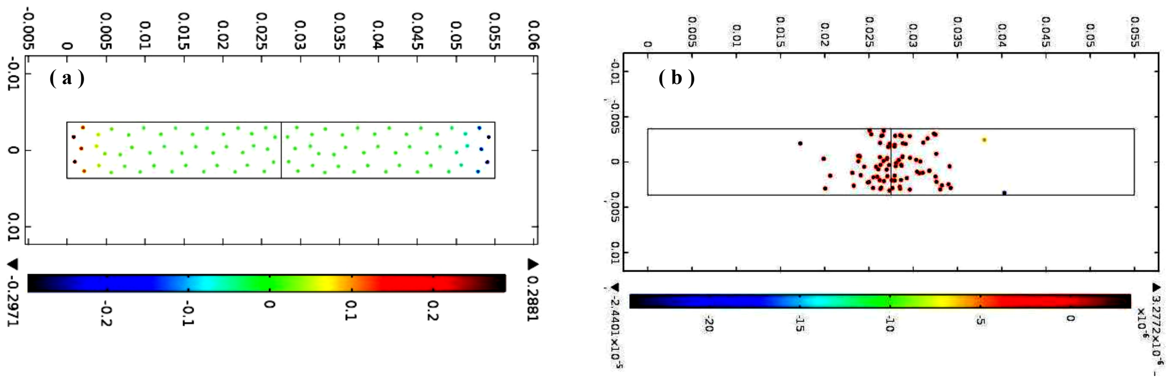

Figure 4. Partilces focusing in the center of the microchannel with metamaterial fluid after 5 seconds of the acoustic wave incidence.

To realize the metamaterial fluid and evanescent field, we employs the Helmholtz resonators to tune the reaction of the fluid in the channel to acoustic wave pressure[19] the same way as in a homogeneous liquid with negative density. The setup of the microchannel with Helmholtz resonators is shown by figure 1 (b), while the section of it is given in figure 2 (b). Given the values of the variable $L_s = 0.058\text{m}$, $H_s = 0.007\text{m}$, $N_a = 0.0007\text{m}$, $N_b = 0.0022\text{mm}$, $T_a = 0.0066\text{m}$, $T_b = 0.0066\text{m}$, $p = 0.007\text{m}$, figure 5 shows the pressure distribution in the mcirochannel while under illumination of a pair of actuators at the lateral boundaries. The frequency of the wave is the same as that in figure 3. The field is also decays exponentially towards the center of the channel and reduces to level of $10^{-3} p_0$, although the gradient is not so smooth, because the sharp variation at the necks of the Helmholtz resonators.

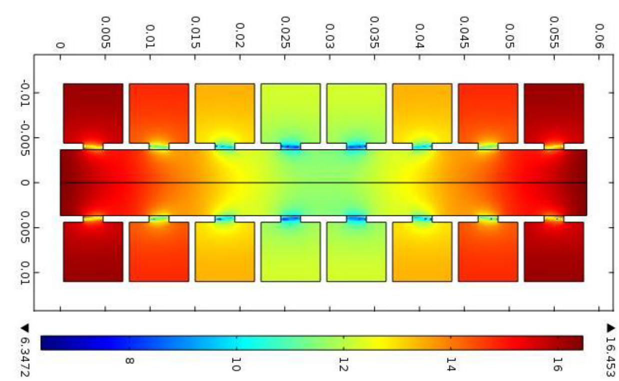

Figure 5. Pressure amplitude distribution of the acoustic wave in the microfluid with resonant elements by a pair of the actuators from the channel sides.

Based on the field distribution in the resonant channel, particle movement driven by the time-averaged radiation force is simulated and illustrated in figure 6. Noting the particle diameter is larger than the width of neck of the resonant element, particles would never penetrate into the resonant elements. Again large initial radiation force is observed to be acted on the particles near the lateral sides, about 0.15 N. Particles located close to the neck of the resonator have relative small force. After one second, the majorities of the particles have already moved to the center region, only a small part of them were still trapped in the vicinities of the necks. At the end of 5 seconds, most of the particles were finally aggregated in the center region of the channel.

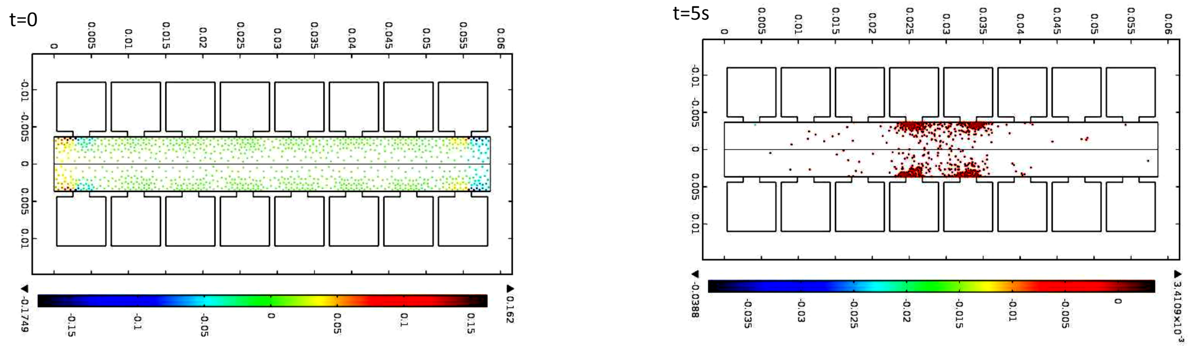

Figure 6. Partilces focusing process in the microfluid channel with resonant elements. After 5 seconds of the acoustic wave incidence, obvious particle aggregation can be observed.

CONCLUSION

A particle focusing microchannel model was designed based on the acoustic radiation force of particle experienced in evanescent field. The field distribution of evanescent wave in an acoustic fluid with negative density is studied, and the time-averaged radiation force acting on the particles has been investigated. Using Comsol Multiphysical software, particle movement in the metamaterial fluid is simulated, in which particle focusing process is demonstrated. By adding the Helmholtz resonators under a traditional microchannel, a structural microchannel is proposed and simulated, and the evanesent acoustic field is also found in the channel. After calculating the particle movement in the structural channel, particle focusing phenomenon is also observed. A experimental design was also illustrated. The theoriotical analysis and simulation results show that acoustic metamaterial can serve as a good alternative for particle focusing application.

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