Particle separation in microfluidics using different modal ultrasonic standing waves

Yaolong Zhang a,b, Xueye Chen a,*

a College of Transportation, Ludong University, Yantai, Shandong 264025, China
b Faculty of Mechanical Engineering and Automation, Liaoning University of Technology, Jinzhou, Liaoning 121001, China

ARTICLE INFO

Keywords:
Microfluidic technology
Ultrasonic standing wave
Acoustic radiation
Hydrodynamic focusing

ABSTRACT

Microfluidic technology has great advantages in the precise manipulation of micro and nano particles, and the separation of micro and nano particles based on ultrasonic standing waves has attracted much attention for its high efficiency and simplicity of structure. This paper proposes a device that uses three modes of ultrasonic standing waves to continuously separate particles with positive acoustic contrast factor in microfluidics. Three modes of acoustic standing waves are used simultaneously in different parts of the microchannel. According to the different acoustic radiation force received by the particles, the particles are finally separated to the pressure node lines on both sides and the center of the microchannel. In this separation method, initial hydrodynamic focusing and satisfying various equilibrium constraints during the separation process are the key. Through numerical simulation, the resonance frequency of the interdigital transducer, the distribution of sound pressure in the liquid, and the relationship between the interdigital electrode voltage and the output sound pressure are obtained. Finally, the entire separation process in the microchannel was simulated, and the separation of the two particles was successfully achieved. This work has laid a certain theoretical foundation for the rapid diagnosis of diseases in practical applications.

1. Introduction

In recent years, due to its advantages of high efficiency, low consumption, and easy integration, microfluidic technology has developed rapidly in the fields of biology [1,2], chemistry [3,4] and medicine [5,6]. It gradually began to replace the various functions of the traditional -conventional biochemical medical laboratory, and has a wide range of application prospects [7–10]. Especially in the fight against COVID-19 this year, various detection methods and vaccine development technologies developed based on microfluidic technology have played a key role [11–12]. Microsomal chips can realize many functions including sorting [13,14], mixing [15,16], reaction [17], cell culture [18], etc, among which sorting is one of the most core functions. The sorting method using microfluidics can be divided into active method and passive method. Passive sorting techniques include microstructure filtration, field flow and hydraulic sorting, deterministic lateral migration, inertial sorting, bionic sorting and other methods. They generally have the advantages of high flux and no additional force field. Active sorting techniques include methods such as dielectrophoresis sorting, magnetic sorting, acoustic sorting, and light sorting, which generally have the advantage of high sorting accuracy. Among them, acoustic sorting has obvious advantages in various sorting techniques due to its good biocompatibility and label-free characteristics. At the same time, the surface acoustic wave standing wave devices have low propagation loss, easy integration, relatively simple requirements for the properties of the sorted particles, and relatively easy realization conditions. Therefore, the particle sorting technology based on acoustic waves has been more widely used [19].

Acoustic sorting is to apply an ultrasonic field around the microfluidic chip, so that the suspended particles are subjected to acoustic radiation. When the ultrasonic field forms a surface acoustic wave standing wave on the cross section of the flow channel, the acoustic radiation force will drive the particles to migrate to the pressure node or pressure anti-node. The speed and direction of the particle movement depend on the particle diameter and the acoustic contrast factor (Φ). Therefore, the use of surface acoustic wave standing wave principle to separate particles can generally be studied from two aspects. The first is to use standing waves to separate particles with opposite acoustic contrast factors in the suspension. When there is a standing wave, the particles with positive and negative acoustic contrast factors...
will move to the pressure node and pressure anti-node, respectively. Gupta et al. [20] found that in the glycerin solution, high-density polyethylene and polystyrene particles have a positive $\Phi$, while low-density polyethylene particles have a negative $\Phi$, and successfully separated them to the pressure node and pressure antinode respectively. Petersson et al. [21] applied a standing ultrasonic wave on the cross section of the flow channel to focus the dense red blood cells (positive $\Phi$) to the node in the center of the flow channel. Petersson et al. [21] applied a standing ultrasonic wave on the cross section of the flow channel to focus the dense red blood cells (positive $\Phi$) to the node in the center of the flow channel, and focus the low-density lipid globules (negative $\Phi$) to the antinodes on both sides of the flow channel, the separation efficiency is greater than 70%. Carl Grenval et al. [22] used a similar device to separate somatic cells and fat particles in milk.

The second is to use standing waves to separate particles with the same sign of acoustic contrast factor in the suspension. In this case, the separation should be carried out according to the size of the acoustic radiation force caused by different particle sizes or acoustic contrast factors. Most cells and particles show positive acoustic contrast factors in aqueous solutions. When there is a standing wave, these particles will move to the pressure node. Therefore, the method of separating particles with a positive acoustic contrast factor using standing wave surface acoustic waves has attracted widespread attention. Shi et al. [23] proposed a sorting device based on particle size, which uses standing waves to form a pressure node line in the center of the microchannel. The particles on both sides of the channel move to the nodal line at different speeds due to different particle sizes, thus realizing the separation of two different sizes of particles. Kumar et al. [24] used the difference of acoustic radiation force and the laminar flow characteristics of micro-fluid to sort hybridoma cells and Lactobacillus rhamnosus cells. Kapishnikov et al. [25] used a similar design to achieve the separation of mixed microspheres with diameters of 2.5 $\mu$m and 10 $\mu$m. Petersson et al. [26] used acoustic methods to realize the sorting of four different sizes of microspheres (2 $\mu$m, 5 $\mu$m, 8 $\mu$m and 10 $\mu$m), as well as the sorting of red blood cells, platelets and white blood cells. Li et al. [27] arranged the interdigital transducer and the micro flow channel at a certain angle to produce multiple pressure nodule lines and pressure anti-nodal lines in the sorting flow channel, so that the particles in the flow channel can have a greater offset distance, which solves the problem that the migration distance of ordinary structures is limited by the distance between the pressure nodes during the sorting process, and the white blood cell sorting experiment shows that the sorting efficiency of the device is greater than 97%. Harris et al. [28] proposed to use standing waves of three different acoustic modes with frequency switches to separate particles. The first mode sound wave is used to pre-focus the particles, and the second and third mode sound fields are switched to separate cells with different sizes or contrast factors. This design reduces the restriction on the residence time of target particles in the microchannel in ordinary devices.

This paper proposes a continuous separation device using three modes of ultrasonic standing waves to separate particles with positive acoustic contrast factor in microfluidics. Using hydrodynamic focusing to control the initial position of the particles. And the acoustic standing waves working in three modes are simultaneously used in different parts of the microchannel, the particles with different volumes are separated by using the different speeds of the particles moving to the nodal lines of different positions. The width of the microchannel is an integral multiple of half the wavelength of the acoustic waves–3 in the three modes at the same time. The feature of this device is that particles can be separated at fixed points, and different particles will move to different nodal lines, which greatly improves the separation efficiency. At the same time, the second and third mode sound waves have a common nodal line at the center of the channel, so that the particles always move towards it, and once the particles reach the nodal line, they will always remain stable. This device is especially suitable for particles with little difference in the intensity of the sound force received in the sound field. At the same time, the second and the third mode sound waves have a common nodal line at the center of the channel, so that the particles can always move towards it, and once the particles reach the nodal line, they will always remain stable. This device is especially suitable for particles with little difference in the intensity of the sound force received in the sound field.

2. Methodology

This paper uses the finite element software COMSOL Multiphysics5.0 to simulate the separation of particles in the microchannel. In order to reduce the amount of simulation calculation and ensure the accuracy of the simulation, we can adopt the following assumptions:

1. The surface acoustic wave only propagates on the surface of the substrate and shows a geometric attenuation in the thickness direction. Therefore, only 1–3 times the wavelength depth can be simulated to reflect its surface wave characteristics well.
2. The propagation direction of the surface acoustic wave is perpendicular to the direction of the acoustic aperture of the electrode, and the displacement in the direction of the acoustic aperture is not coupled to the wave equation, and the amount of field remains unchanged along the length of the electrode, so the three-dimensional structure model can be simplified into a two-dimensional structure model.
3. Ignore the gravitational influence of fluids and particles on the microscopic scale.

2.1. Surface acoustic wave device

Surface acoustic wave refers to the elastic wave generated on the solid surface and propagated along the surface or interface. The device that uses surface acoustic wave to propagate and process the signal is the surface acoustic wave device, which is composed of piezoelectric material and two sets of interdigital transducers on its surface, and its basic structure and principle are shown in Fig. 1. As this article mainly studies the application of surface acoustic wave energy, two sets of interdigital transducers will be used as input at the same time.

In the interdigital transducer, $W$ is the acoustic aperture of the transducer, $d$ is the distance between the interdigital fingers, $b$ is the width of the interdigital fingers, and $M$ is the length of the periodic section. In addition, the number of interdigital pairs $N$ determines the intensity of the excitation surface acoustic wave. When $a = b = M/4$, it is called uniform interdigital transducer, which is also the type of interdigital transducer used in this article. The device designed in this paper contains two pairs of IDTs, and the two pairs of IDTs simultaneously generate surface acoustic waves to act on the fluid in the microchannel. After the two waves are superimposed, a standing wave field will be generated, which will form a periodically distributed and stable pressure nodes and anti-pressure nodes will be formed inside the fluid. The pressure node and the pressure anti-node, different suspended particles in the fluid will move towards the pressure node or the pressure anti-node. According to the principle of wave interference, when the following conditions are met, the intensity of the surface acoustic wave generated by the uniform transducer excitation is the largest:

$$b = \frac{M}{4}$$
force acting direction is orthogonal to the sound force and drives the particles out of the microchannel along the liquid flow direction. Since the fluid flow in the microchannel is laminar and the particle volume is relatively small, the hydrostatic force can be approximated by the Stokes formula:

\[ F_{\text{stokes}} = -6\pi r \eta (v_p - v_f) \]  

where \( \eta \) represents the dynamic viscosity of the fluid, \( r \) represents the radius of the particle, \( v_p \) represents the velocity of the particle, and \( v_f \) represents the flow velocity of the flow field where the particle is located.

### 2.3. Working mechanism

Most of the particles used in the experiment have a positive acoustic contrast factor. Driven by the acoustic radiation force, these particles will move toward the pressure node. This paper uses polystyrene microspheres of corresponding sizes to simulate the separation process of red blood cells and platelets in the microchannel. The specific parameters are shown in Table 1. The device uses three kinds of standing waves across the entire channel width, and their corresponding wavelengths are respectively 2 times, 2/3 times and 1 times the width of the microchannel. They are called the first mode standing wave, the third mode standing wave, and the second mode standing wave. The three kinds of standing waves establish two, three and three nodal lines in the microchannel respectively, as shown in Fig. 2. In this case, the acoustic standing waves working in the three modes are simultaneously used in different parts of the microchannel to separate particles of different sizes according to the speed of the particles moving to the nodal line. In this case, the acoustic standing waves working in the three modes are simultaneously used in different parts of the microchannel to separate particles of different sizes according to the different speeds at which the particles move to the nodal line. The wavelength of the acoustic wave in the first mode is twice the channel width, and its standing wave forms two pressure node lines on both sides of the channel. The sound waves of the third mode and the second mode both form three nodal lines, and their central nodal lines coincide with each other.

At the entrance of the microchannel, the target stream is used to pre-focus the particles in the center of the channel, so as to make the most of the channel space and prepare for the particle stream to enter the sound field separation zone. According to the force formula of the particles in the fluid in the sound field, the larger microsphere \((5.0 \mu m)\) receives a larger acoustic radiation force and moves to the node faster, while smaller particles \((1.8 \mu m)\) are slower. When \(1.8 \mu m\) particles that experience a small sound force have not crossed the pressure anti-node \([B-B]\) between the two nodal lines, and \(5.0 \mu m\) particles have crossed \([B-B]\), the particles enter the third mode acoustic wave region. At this time, because the two kinds of particles are on both sides of the pressure anti-node \([B-B]\), they move to different nodes. The \(5.0 \mu m\) particle moves to the nodal line \([M-M]\) under the action of the acoustic radiation force, and the \(1.8 \mu m\) particle moves to the nodal line \([O-O]\). Since the nodal line \([M-M]\) is farther from the center line than the inverse nodal line \([D-D]\), the \(5.0 \mu m\) particles will eventually cross the nodal line \([D-D]\), and the \(1.8 \mu m\) particles will gather towards the central nodal line \([O-O]\). At this time, the particles enter the second mode acoustic wave area. Since the nodal line \([M-M]\) is farther from the center line than the inverse

---

### Table 1

| Material   | Density \((kg/m^3)\) | Speed of sound \((m/s)\) | Compressibility \((T/Pa)\) | Dynamic viscosity \((mPa s)\) | Particle diameter \((\mu m)\) |
|------------|----------------------|--------------------------|-----------------------------|-------------------------------|-------------------------------|
| Water      | 997                  | 1497                     | 448                         | 0.890                         | 5,1.8                         |
| Polystyrene| 1050                 | 2350                     | 249                         |                               |                               |
nodal line [D-D], the 5.0 μm particles will eventually cross the nodal line [D-D], and the 1.8 μm particles will always gather toward the central node line [O-O] where the third mode and the second mode overlap each other. After finally passing through the second mode acoustic wave area, the two kinds of particles are effectively separated on two sets of nodal lines, 5.0 μm particles are gathered on the nodal lines (N-N) on both sides, and 1.8 μm particles are gathered on the central nodal line (O-O).

As long as it is two kinds of particles that experience different sound intensity due to size or acoustic contrast coefficient in the fluid, the separation process involved in this device can be carried out. It can be widely used for the separation of various cells or particles, and is especially suitable for particles with similar sound force in the sound field. The application of three modal acoustic standing waves in the microchannel makes the particles gather to different nodes, which can greatly improve the sorting efficiency.

2.4. Two-dimensional model

This article models the device designed based on the above working principle. Through analysis, it can be found that the study of a complete physical model based on surface acoustic standing wave particle separation needs to consider the influence of static electricity, solid elasticity and fluid dynamics on the system. To simulate a complete three-dimensional system model requires considerable computational cost. At the same time, since the displacement in the direction of the acoustic aperture of the surface acoustic wave device is not coupled to the wave equation, and the field quantity is constant along the length of the electrode, we can simplify the three-dimensional structure model into a two-dimensional structure model, as shown in Fig. 3.

As shown in Fig. 3, a two-dimensional modeling of the required device is carried out, which is composed of a surface acoustic wave device and a microchannel. On the 128°YX-LiNbO3 substrate, 15 pairs of interdigital electrodes made of metal aluminum are distributed on the left and right sides, with a thickness of 0.2 μm, the electrode width is a, and the distance between the electrodes is b. The distance between the interdigital transducers on both sides is L, and the base thickness is h. The specific parameters are shown in Table 2. The microfluidic separation channel has a height of 100 μm and a width of 320 μm, which is larger than the theoretical width of 300 μm. On the one hand, it allows possible errors in the device, and on the other hand, it reduces the adhesion of particles to the channel wall. There are three inlets in the microchannel, the length and width of which are respectively 200 μm and 130 μm. The left and right sides are the sheath flow inlets, and the middle is the particle inlet, which aims to perform initial hydrodynamic
Table 2
Surface acoustic wave device parameters.

| Standing wave mode | The first mode | The third mode | The second mode |
|--------------------|----------------|----------------|-----------------|
| Wavelength(μm)     | 600 μm         | 200 μm         | 300 μm          |
| a                  | 150 μm         | 50 μm          | 75 μm           |
| b                  | 150 μm         | 50 μm          | 75 μm           |
| L                  | 11850 μm       | 12050 μm       | 12075 μm        |
| h                  | 750 μm         |                |                 |

The focusing of the particle stream so that the particles are concentrated to the center of the channel before entering the sound field. After the two kinds of particles pass through the microchannels where the standing waves of the three modes with lengths of 600 μm, 200 μm and 300 μm act together, the 5.0 μm particles will eventually flow out from the outlets on both sides of the channel end, while the 1.8 μm particles can be collected from the middle outlet.

3. Results and discussion

3.1. Simulation analysis of surface acoustic wave devices

The uniform interdigital transducer is the most basic and simple transducer. When the interdigital transducer excites sound waves, the sound waves excited by each pair of electrodes will be superimposed on each other. According to the principle of wave interference, only when the period length M is equal to an integer multiple of the surface acoustic wave half-wavelength λ/2, the acoustic waves are superimposed in phase, and the surface acoustic wave excited by the interdigital transducer is the strongest [29]. Therefore, it is very important to find the resonance frequency of the interdigital transducer under various modal acoustic waves.

We use periodic boundary conditions to simplify the interdigital transducer model, the simplified two-dimensional unit model is shown in Fig. 4(a). In order to maximize the intensity of the excited surface acoustic wave, the three modal acoustic waves correspond to three different uniform transducers. The specific parameters are shown in Table 2. Fig. 4(b) shows the grid division of the model. Since the surface acoustic wave only propagates within the range of 1–2 wavelengths on the substrate surface, in order to reduce the amount of calculation, the mesh on the surface of the base can be divided more densely, and the grid on the bottom can be divided more sparsely. At the same time, it should be ensured that one wavelength is divided into at least 5 grids to ensure that the vibration information of the sound wave in one period is completely recorded.

A modal analysis was performed on the model, and the result is shown in Fig. 5. Among them, (a), (b), (c) are the mode diagrams when uniform interdigital transducers are used and equations 1–3 are satisfied, and the sound wave wavelengths are 200 μm, 300 μm, and 600 μm, respectively. It can be found that when the resonance frequencies of 19.512 MHz, 13.009 MHz and 6.509 MHz are applied respectively, the model vibration shape is a sine wave waveform, and the surface node displacement is the largest. Then (a), (d), (e) are the mode diagrams when the same transducer is used and the excitation frequency is changed to generate sound waves with wavelengths of 200 μm, 300 μm and 600 μm. It can be found that the mode diagrams in (d) and (e) are also sinusoidal, but compared to (b) and (c), the mode shapes are not smooth enough, and the maximum displacement of the nodes is also reduced, and the surface acoustic wave excited by it is also weakened.

3.2. Numerical simulation of sound wave propagation in liquid

In order to study the mechanism of surface acoustic waves in liquids, the physical field changes inside the liquid when the sound waves radiate into the liquid are simulated. We use the two-dimensional model shown in Fig. 3, in which the water area in the middle of the device is set to 1000 μm × 600 μm, and the result is shown in Fig. 6. Before t = 1.5033e-6 s, because the surface acoustic wave has not reached the liquid domain or has arrived but the sound wave energy is very small, there is no sound pressure distribution inside the liquid. When t = 1.5033e-6 s, the sound pressure distribution began to be seen on both sides of the liquid domain, until t = 1.7425e-6 s, the sound pressure distribution inside the liquid was very obvious. At t = 1.9561e-6 s, most of the liquid domain has sound pressure distribution, and it can be found that the sound pressure is distributed in diagonal stripes inside the liquid. At the same time, sound waves are refracted into the liquid domain at a certain Rayleigh angle. At t = 2.1354e-6 s, the sound pressure has been steadily distributed in the liquid domain. It can be found that during the entire process of sound wave propagation in the liquid domain, the magnitude and direction of the sound pressure at the same position in the liquid domain may change, but the positions of the sound pressure node and the sound pressure anti-nodal point have remained unchanged, which also shows that the separation system we used is very stable.

Fig. 4. The simplified diagram of the two-dimensional model of a surface acoustic wave device. (a) Simplified model (b) Schematic diagram of grid.
Fig. 5. Mode shape diagram. (A) Vibration diagram when $\lambda = 200 \mu m$ (b) Vibration diagram when $\lambda = 300 \mu m$ (c) Vibration diagram when $\lambda = 600 \mu m$ (d) Vibration diagram when $a = b = 50 \mu m$, $f = 13.009$ MHz (e) Vibration diagram when $a = b = 50 \mu m$, $f = 6.509$ MHz.

Fig. 6. Propagation of sound waves in liquid.

Fig. 7. The distribution of sound pressure in the liquid of the microchannel.
3.3. The distribution of sound waves in the liquid of the microchannel

In the two-dimensional model of the system used in this paper, the corresponding boundary conditions are set to simulate the distribution of sound pressure in the microchannel during particle separation, the result is shown in Fig. 7. Similarly, (a), (b), (c) are the distribution of sound pressure in the microchannel liquid when the sound wave wavelength is 200 μm, 300 μm and 600 μm, respectively. At this time, a uniform interdigital transducer is used and equations 1–3 are satisfied. It can be found that when the third mode acoustic wave is used, three pressure nodes and three pressure anti-nodes are generated inside the microchannel liquid, which are symmetrically distributed in the microchannel. In the second mode acoustic wave area, there are three pressure nodes and two pressure anti-nodes in the liquid, and the center node coincides with the third mode acoustic wave, and the other two nodes are distributed on the two side walls. For the first mode acoustic wave, there are two pressure nodes and a back pressure node in the liquid, and particles will be pushed to both sides of the channel when passing through this area. The sound pressure distribution in the microchannel liquid under the three modes of acoustic waves is consistent with the design requirements. Then (a) (d), (e) are the distribution of sound pressure in the liquid when the same transducer is used and the excitation frequency is changed to generate sound waves with wavelengths of 200 μm, 300 μm and 600 μm. Although the sound pressure distribution shown in (d) and (e) can also meet the design requirements, the sound pressure intensity is much smaller than in (b) and (c).

The interdigital electrode voltage is a very important parameter of the transducer, which will affect the energy output of the surface acoustic wave device. It is necessary to find a suitable terminal voltage so that the microchannel can generate sound pressure conditions that meet the smooth separation of particles. Fig. 8 shows the relationship between the absolute value of the maximum sound pressure in the microchannel and the interdigital electrode voltage under three modal acoustic waves. It can be found that the sound pressure intensity has a linear relationship with the electrode voltage, the greater the voltage, the greater the sound pressure intensity in the liquid. Through simulation analysis, the sound pressure in the microchannel liquid that meets the separation conditions in the three modal sound waves is 1.9e5Pa, 2.15e5Pa and 4.24e5Pa, respectively, and the corresponding electrode voltages are 2.6 V, 3.8 V and 15.8 V, respectively.

3.4. The separation process of particles

In order to meet the various equilibrium constraints of the separation of particles in the microchannel, we designed and selected various structural parameters of the microchannel, liquid flow rate, and parameters of the interdigital transducer, and finally successfully separated the two kinds of particles, the specific process is shown in Fig. 9. Fig. 9(a) is the flow field distribution diagram in the microchannel. The channel has three inlets, the middle is the target particles inlet, and the left and right sides are the sheath flow inlets. It can be found that the flow velocity of the inlets on both sides is greater than the middle inlet, which can make all particles are concentrated to an initial known central node before entering the sound field to facilitate subsequent separation. The acting direction of the fluid power in the channel is orthogonal to the sound force, and the particles are mainly driven out of the microchannel along the length of the channel.

Fig. 9(b) shows the specific separation process of two kinds of particles of different sizes under the combined action of hydrodynamic and
acoustic forces. At $t = 0$ s, the particle flow has not yet entered the channel, and only the flow field shown in Fig. 9(a) exists in the channel. At $t = 0.35$ s, the particle stream enters the channel and focuses on the center of the microchannel due to the action of the sheath flows on both sides, which provides convenient conditions for better separation of the particle stream after entering the sound field area. When $t = 0.75$ s, the particle flow has passed the first mode standing wave zone. Since the first mode standing wave generates two pressure nodes on both sides of the microchannel width direction, both particles move to the nodes. The larger 5.0 μm particles move faster in the width direction and cross the

Fig. 9. Flow field and particles in the microchannel. (a) Flow field distribution diagram (b) Particle separation process.
pressure anti-node [B-B] of the third mode standing wave, while 1.8 μm particles have only a small displacement in the width direction. In the third mode standing wave zone, since the 5.0 μm particles and 1.8 μm particles are on both sides of the pressure anti-node [B-B], they move to the node [M–M] and node [O–O] respectively. At t = 1.35 s, the particles have passed through the third mode standing wave zone and entered the second mode standing wave zone. At this time, the 5.0 μm particles have passed the pressure anti-node [D–D] of the second mode standing wave and move towards the pressure node [O–O]. Since the second and third mode standing waves have coincident central pressure nodes, the 1.8 μm particles continue to move towards the pressure node [O–O]. When t = 2.50 s, 5.0 μm and 1.8 μm particles are effectively separated on the two sets of nodal lines (N–N) and (O–O) after passing through the action of the microchannel, and flow out from the outlets on both sides and the middle of the channel respectively, and successfully separated the two kinds of particles by using acoustic properties.

4. Conclusion

We demonstrated a device that uses three different modal standing waves across the entire width of the microfluidic channel to achieve particle separation. The separation process is completed under the combined action of acoustic radiation force and fluid power. Particles subjected to different acoustic radiation forces move to different nodal lines to achieve separation. The following conclusions can be drawn from the research in this article:

- When uniform interdigital transducers are used to generate sound waves with wavelengths of 200 μm, 300 μm and 600 μm, the corresponding resonance frequencies are 19.512 MHz, 13.009 MHz and 6.509 MHz respectively.
- When the period length M = λ and the frequency of the external excitation voltage is equal to the resonance frequency of the transducer, the surface acoustic wave excited by the uniform interdigital transducer is the strongest.
- In a surface acoustic wave device, the electrode voltage has a linear relationship with the output intensity of the surface acoustic wave, and the output intensity of the acoustic wave increases as the voltage increases. Different sound pressures can be obtained by changing the electrode voltage. The electrode voltages corresponding to the first, the second and the third modal standing waves in this article are 15.8 V, 2.6 V and 3.8 V respectively.
- In the selection of various parameters of the microfluidic channel particle separation device, it is the key to satisfy a variety of equilibrium constraint conditions. In this paper, the key is to control 5.0 μm particles to cross the back pressure nodes [B–B] and [D–D] when entering the third and the second mode acoustic wave regions of the microchannel, and to ensure that the 1.8 μm particles continue to move to the central pressure node [O–O].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work was supported by Young Taishan Scholar’s Program of Shandong Province of China (tsqs202013091), Shandong Provincial Natural Science Foundation (ZR2021JQ01).

Data availability

The data that supports the findings of this study are available within the article [and its supplementary material].

References

[1] X. Feng, W. Du, Q. Luo, B.-F. Liu, Microfluidic chip: next-generation platform for systems biology, Anal. Chem. Arts 650 (1) (2009) 83–97.
[2] Y.-Z. Shi, S. Xiong, Y. Zhang, L.K. Chin, Y.-Y. Chen, J.B. Zhang, T.H. Zhang, W. Ser, A. Larsson, S.H. Lim, J.H. Wu, T.N. Chen, Z.C. Yang, Y.L. Hao, B. Liedberg, P. H. Yap, K. Wang, D.P. Tsai, C.-W. Qiu, A.Q. Liu, Sculpting nanoparticle dynamics for single-bacteria level screening and direct binding efficiency measurement, Nat. Commun. 9 (1) (2018), https://doi.org/10.1038/s41467-018-03156-5.
[3] M. Rahimi, B. Agheb, M. Alizahab, A. Sepahvand, H.R. Ghasempour, Optimization of biodiesel production from soybean oil in a microreactor, Energy Convers. Manage. 79 (2014) 599–605.
[4] S. Mashbaghi, A. Abbaspourrad, D.A. Weitz, A.M. van Oijen, Droplet microfluidics: A tool for biology, chemistry and nanotechnology, TRACS Anal. Chem. 82 (2016) 118–125.
[5] Hultcrantz, Jessica, et al. “Proliferation and viability of adherent cells manipulated by standing-wave ultrasound in a microfluidic chip.” Ultrasound in medicine & biology 33.1 (2007): 145-151.
[6] C.D. Chin, T. Laksmannopin, Y.K. Cheung, D. Steinmillier, V. Linder, H. Parsa, J. Wang, H. Moore, R. Rousse, G. Umvughozou, E. Karia, L. Mwambazange, S. L. Braunstein, J. van de Wijgert, R. Sahabo, J.E. Justman, W. El-Sadr, S.K.A. Sia, Microfluidics-based diagnostics of infectious diseases in the developing world, Nat. Med. 17 (8) (2011) 1015–1019.
[7] Z. Yin, W. Wang, Structure-Induced Method for Circular Cross-Sectional Nanochannel Fabrication, J. Nanosci. Nanotechnol. 19 (9) (2019) 5750–5754.
[8] T. Zhou, Z. Song, X. Zhang, R. Gani, K. Sundmacher, Optimal Solvent Design for Extractive Distillation Processes A Multiobjective Optimization Hierarchical-Based Framework, Ind. Eng. Chem. Res. 58 (15) (2019) 5777–5786.
[9] D. Jing, J. Song, Comparison on the hydraulic and thermal performances of two tree-like channel networks with different size constraints, Int. J. Heat Mass Transf. 150 (2019) 1070–1074.
[10] E. Cheng, H. Zou, Y. Yin, Juriček, X.i. Zhang, Fabrication of 2D polymer nanochannels by sidewall lithography and hot embossing, J. Micromech. Microeng. 23 (7) (2013) 075022, https://doi.org/10.1088/0960-1317/23/7/075022.
[11] S. Bose, et al., “A retrievable implant for the long-term encapsulation and survival of therapeutic xenogenic cells.” Nature, Biomed. Eng. (2020) 1–13.
[12] Kim, Eun, et al. “Microencapsulated drug delivered reconstituent coronavirus vaccines: Immunogenicity and rapid translational development.” ElbisMedicine (2020): 102743.
[13] Y. Zhang, X. Chen, Dielectrophoretic microfluidic device for separation of red blood cells and platelets: a model-based study, J. Braz. Soc. Mech. Sci. Eng. 42 (2) (2020) 89.
[14] Y. Zhang, X. Chen, Blood cells separation microfluidic chip based on dielectrophoretic force, J. Braz. Soc. Mech. Sci. Eng. 42 (2020) 1–11.
[15] R.R. Golde, P.M. Pawar, B.P. Ronge, N.D. Misal, R.B. Kapurkar, A.P. Parkhe, Evaluation of the mixing performance in a planar passive micromixer with circular and square mixing chambers, Microsyst. Technol. 24 (6) (2018) 2599–2610.
[16] M. Bayareh, A. Usefian, N.A. Ahmadi, Rapid mixing of Newtonian and non-Newtonian fluids in a three-dimensional micro-mixer using non-uniform magnetic field, J. Heat Mass Transfer Res. 6 (1) (2019) 55–61.
[17] Y.-H. Chang, G.-B. Lee, F.-C. Huang, Y.-Y. Chen, J.-L. Lin, Integrated polymerase chain reaction chips utilizing digital microfluidics, Biomed. Microdevices 8 (3) (2006) 215–225.
[18] M. Mehlings, S. Tay, Microfluidic cell culture, Curr. Opin. Biotechnol. 25 (2014) 95–102.
[19] S. Li, X. Ding, F. Guo, Y. Chen, M.I. Lapsley, S.-C. Lin, L. Wang, J.P. McCoy, C. E. Cameron, T.J. Huang, An on-chip, multichannel droplet sorting system for standing surface acoustic waves, Anal. Chem. 85 (11) (2013) 5468–5474.
[20] S. Gupta, D.L. Feke, I. Manas-Zloczower, Fractionation of mixed particulate solids according to compressibility using ultrasonic standing wave fields, Chem. Eng. Sci. 50 (2005) 3275–3284.
[21] F. Petersson, A. Nilsson, C. Holm, H. Jonsson, T. Laurell, Separation of lipids from blood utilizing ultrasonic standing waves in microfluidic channels, Analyst 129 (10) (2004) 938–942.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work was supported by Young Taishan Scholar’s Program of Shandong Province of China (tsqs202013091), Shandong Provincial Natural Science Foundation (ZR2021JQ).

Data availability

The data that supports the findings of this study are available within the article [and its supplementary material].

9

Y. Zhang and X. Chen

Ultrasonics Sonochemistry 75 (2021) 105603