Advances in Machinery, Materials Science and Engineering Application
M. Chen et al. (Eds.)

doi:10.3233/ATDE220510

Design of a Fishbone-Shaped Micron Particle Sorting Device Based on Dielectrophoresis

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Abstract. Micron particle sorting has an important role in biomedicine, renewable energy, and micro-manufacturing. In this study, a fishbone-shaped micron particle sorting device was designed based on the dielectrophoretic manipulation of micron particles technique. Firstly, the simulation model of multi-physics field coupling is established using experimental data, and the results are calculated and analyzed using the method of finite element analysis. Finally, according to the simulation results, the factors affecting particle manipulation are particle dimensions, number of electrodes, voltage magnitude, and sheath flow rate. Studies have shown that when the sorting particle diameter is different, increasing the sheath flow speed, voltage strength, and the number of electrodes can improve the sorting effect. By modifying the factors affecting the dielectrophoretic manipulation of micron particle sorting, it can make the present design applicable to the sorting of different micron-size particles and provide a significant reference value for the subsequent particle sorting method.

Keywords. Micron particle sorting, dielectrophoresis, finite element analysis, influencing factors

1. Introduction

The development of micro-size particle manipulation technology, it will replace the original traditional micro-size particle sorting technology such as centrifugation and filtration. The main existing techniques for sorting micro-sized particles are dielectrophoretic sorting [1-3], acoustic sorting [4], magnetophoretic sorting [5], and inertial flow sorting [6]. Dielectrophoresis sorting does not need to mark the particles before manipulation [7], and there is no contact with the particles during the manipulation process, simple equipment, flexible manipulation, and has the advantages of more minor damage to biological particles [8]. In this study, we designed a fishbone-shaped device that can sort different micron-size particles after applying AC electric field based on dielectrophoresis manipulable micron-size particle technology [9]. Analyze the electric and flow fields in the simulation results, and optimize the design of the sorting device by adjusting the model and changing the factors that affect the sorting results of the sorting device. Finally, a fishbone-shaped particle sorting device

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is designed, which has the advantages of simple structure, easy manipulation, short sorting time, wide applicability, high throughput and high resolution.

2. Mathematical Models

In this study, a fishbone-shaped micron particle sorting device with three inlets and three outlets was designed. Fourteen electrode positions are set in the sorting area, and the two-dimensional geometry of the fishbone-shaped particle sorting device is shown in figure 1. The two inlets A and D are the inlets for the particles to be mixed, and the other inlet C is the sheath inflow port. Exit E and G are the same kind of particle outflow channel after sorting, and exit F is another kind of particle outflow channel. In this study, three inlet channels and three outlet channels were designed to increase the particle flux to be sorted, thus improving the sorting efficiency. The sorted particles flow out from the E, F and G exit channels respectively. AC current is applied to all electrodes so that the fluid in the sorting area is within the range of action of the electric field. The entrance channels of A, C, D, and E, F, and G are 40μm wide. The electrode width is 40μm, the distance between the upper and lower symmetrical electrodes is 120μm, and the electrodes are evenly distributed in the sorting area. The sorting area length is 520 μm.

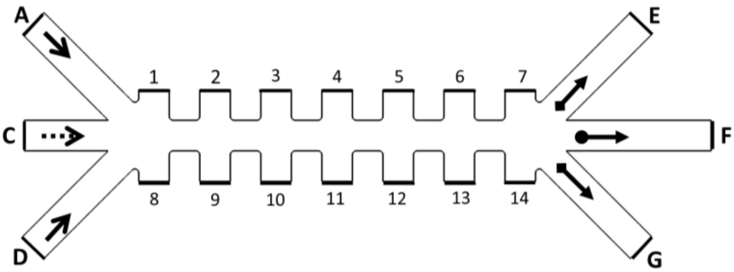


Figure 1. Schematic diagram of the two-dimensional structure of the fishbone-shaped particle sorting device.

The particles in the solution are subjected to a dielectrophoretic force:

$$F_{dep} = 2\pi r_p^3 \varepsilon_0 \mathrm{real}(\varepsilon_r^*)\mathrm{real}\left(\frac{\varepsilon_{r,p}^* - \varepsilon_r^*}{\varepsilon_{r,p}^* + 2\varepsilon_r^*}\right) \nabla |E_{rms}|^2 \tag{1}$$

r_p is the size radius of the particle. ε_0 is the vacuum dielectric constant and takes the value of $8.85\times10^{-12}\mathrm{F/m}$. ε_r^* is the dimensionless complex permittivity of the solution. $\varepsilon_{r,p}^*$ is the dimensionless complex permittivity of the particle. $\mathbf{E}_{rms}(\mathrm{V/m})$ is the effective electric field. In the present study the complex permittivity is $\varepsilon^* = \varepsilon - \frac{i\sigma}{\omega}$. ε（F/m）is the dielectric constant. σ（S/m）is the electrical conductivity. ω (Hz) is the electric field frequency. In this study the electric field frequency is 100 kHz. The dielectric constant and conductivity of the particles need to be considered in equation (1). Considering that the sorting device has the possibility of sorting biological particles, the target particles of this study were selected as biological particles. Bioparticles have a cell wall structure, and the cell wall does not have the same electrical conductivity and dielectric constant as the interior of the cell. Therefore, in this study, the conductivity and permittivity of the particle wall and the particle interior are defined separately, and the particle complex permittivity in equation (1) is replaced by the complex relative permittivity of the particle cell wall and the particle cell interior, as shown in equation (2).

$$\varepsilon_{eq}^{*} = \varepsilon_{s}^{*} \frac{\left(\frac{r_0}{r_i}\right)^3 + 2\left(\frac{\varepsilon_{r,p}^{*} - \varepsilon_{r,s}^{*}}{\varepsilon_{r,p}^{*} + 2\varepsilon_{r,s}^{*}}\right)}{\left(\frac{r_0}{r_i}\right)^3 - \left(\frac{\varepsilon_{r,p}^{*} - \varepsilon_{r,s}^{*}}{\varepsilon_{r,p}^{*} + 2\varepsilon_{r,s}^{*}}\right)} \tag{2}$$

r_0 and r_i are the outer and inner diameters of the particle walls, respectively. $\varepsilon_{r,p}^{*}$ is the dimensionless complex permittivity inside the particle. $\varepsilon_{r,s}^{*}$ is the dimensionless complex permittivity of the granular cell wall. For the convenience of the later discussion, the two types of granular cells are referred to as red-round granules and blue-round granules, respectively. Concerning the existing studies [10], the internal conductivity of red and blue circular particles was chosen as $10^{-4}(\mathrm{mS/m})$ and $10^{-5}(\mathrm{mS/m})$, and the dielectric constants were chosen as $3\varepsilon_0$ and $60\varepsilon_0$, respectively. The outer wall conductivity of red and blue circular particles was chosen as $10^{-8}(\mathrm{mS/m})$ and $10^{-7}(\mathrm{mS/m})$, and the dielectric constants were chosen as $5\varepsilon_0$ and $40\varepsilon_0$, respectively. The red round particles have an outer diameter of 2(μm) and a wall thickness of 8(nm), and the blue round particles have an outer diameter of 5(μm) and a wall thickness of 9(nm). The solution conductivity is defined as 55(mS/m) and the dielectric constant is defined as $80\varepsilon_0$. The density and viscosity of the solution are classified as $\rho = 1000\mathrm{k \cdot gm^{-3}}$, $\eta = 0.001\mathrm{Pa \cdot s}$. Considering that the length and width dimensions of the studied particle sorting device are much larger than the height dimensions and that different planes are subjected to the same dielectrophoretic force [11], a two-dimensional model was used to model this study to simplify the computational volume. This study uses open source finite element software for modeling and analysis, and the model is studied and analyzed by coupling electric field, flow field, and multi-particle tracking.

3. Results and Analysis

3.1. Sorting Theory

Figure 2 shows the trajectory of the particles when the sorting device is not energized, with red dots corresponding to red round particles and blue dots corresponding to blue round particles. A solution with two different types of particles mixed at a flow rate of 800um/s enters the sorting device from the A and D inlet channels. The sheath flow enters the sorting device from the C inlet channel at a flow rate of 1500um/s. The sheath flow dilutes the mixed solution of particles to be sorted and acts as a facilitator of sorting. Because the electrodes of the sorting device are not energized, there is no electric field generated in the sorting area and no dielectrophoretic effect. From figure 2, it can be observed that after the particles are sorted enter from the entrance channels of A and D, the trajectories of the particles do not change .They are not subject to dielectrophoresis, and the mixed particles flow out from the exit channels of E and G. No particles flow out from the exit channel of F. This phenomenon indicates that when the sorting device is not energized, the particles to be sorted do not flow out through the F exit channel. The darker color in figure 2 represents the higher flow rate. It can be observed that the flow rate in the sorting area is larger than that in the inlet channel, indicating that the three inlet channels can increase the flow rate in the sorting area and thus improve the sorting efficiency. In the sorting area, the flow rate below the electrodes is smaller than the flow rate below no electrodes. The lower flow rate below the electrode facilitates the increase of the dielectrophoretic action time of the particles. Below the absence of electrodes, a larger flow rate is beneficial to increase the particle motion and thus the flux.

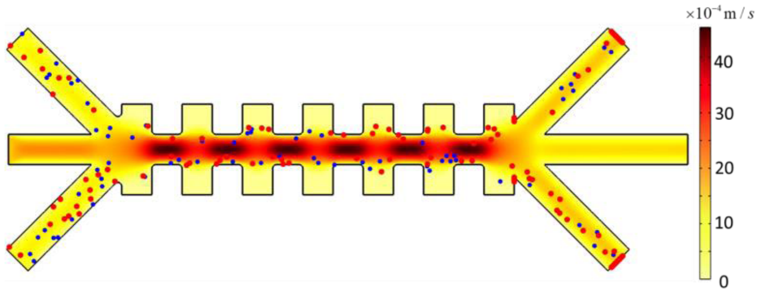


Figure 2. Sorting device not working diagram.

The potential is set to V_0 at electrodes 1, 2, 3, 4, 5, 6, and 7 and $-V_0$ at electrodes 8, 9, 10, 11, 12, 13, and 14. Figure 3 shows the trajectory of the particles when the applied voltage is 7 V. The lighter colors represent the places with higher potential, and the darker colors represent the places with lower potential. Equation (1) shows that the particles are subjected to maximum dielectrophoresis in light-colored places and minimum dielectrophoresis in dark-colored places. The solution is mixed with two kinds of particles from A, D entrance channel into the sorting device, flowing through the electrode position by the electrode generated by the electric field, to be sorted particles by the action of dielectrophoresis after the change in the trajectory. The denser the line in figure 3, the higher the flow rate. The flow lines are sparser near below the electrode, and the longer the particles are subjected to dielectrophoretic action, the greater the effect on the change in particle trajectory. The red round particles are close to the electrode and the blue round particles are far away from the electrode. Finally, the red round particles flow out from the E and G exit channels, and the blue round particles flow out from the F exit channel to realize the sorting of particles to be sorted.

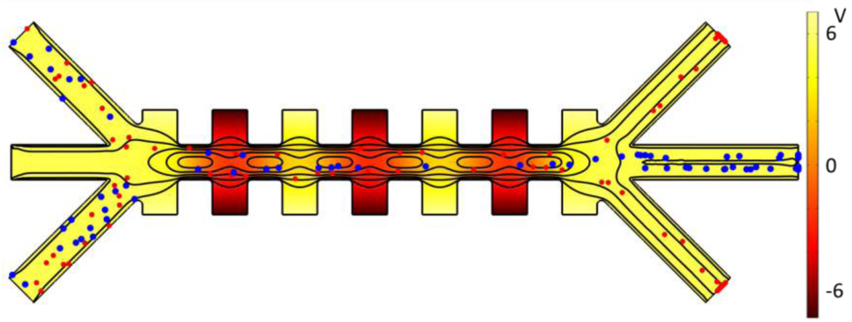


Figure 3. Sorting device working results graph.

3.2. Factors affecting the sorting effect

To investigate whether the position of the energized electrodes has an effect on particle sorting, the potential is set to V_0 at electrodes 1, 3, 5, 7, 9, 11, and 13, and $-V_0$ at electrodes 2, 4, 6, 8, 10, 12, and 14. As shown in figure 4, it was found that the particles could be sorted, and the electric field intensity in the sorting channel was stronger than that of the electrode arrangement in figure 3. The results show that asymmetrically arranged energized electrodes can increase the potential intensity of the sorting area in the sorting device, indicating that the sorting effect of the sorting device can be improved based on the optimized design of electrode positions. A smaller applied voltage enables the electric field to generate a smaller Joule heat, preventing the deactivation of the particles from being sorted. The voltage intensity designed in this study was compared with the experimental data [11] and it was found that the voltage intensity designed in this study did not affect the activity of the bioparticles.

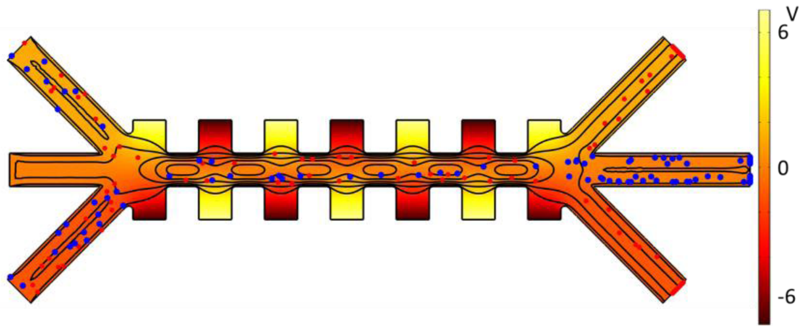
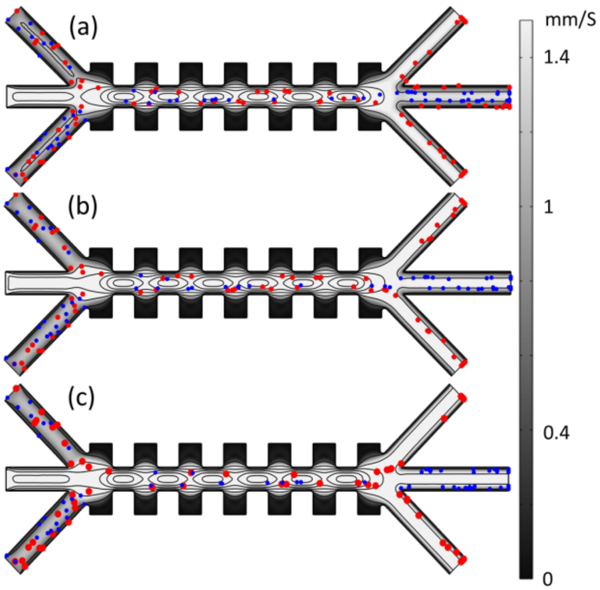


Figure 4. Sorting device potential distribution and flow line diagram.



(a) C inlet channel flow rate of 1500 [μm/s]; (b) C inlet channel flow rate of 2000 [μm/s]; (c) C inlet channel flow rate of 3000 [μm/s].

Figure 5. Changing the size ratio of the particles to be sorted.

Figure 5 shows the working result of the sorting device. The gray scale represents the flow velocity of the flow field, and the lighter the color represents, the larger the flow velocity. The line is the equivalence line of the velocity. With the other parameters unchanged, the radius of the red circle particles was changed from the original 2 μm to 3 μm. It was observed that the particles were not completely sorted at the exit channel, as shown in figure 5(a). To investigate the effect of sheath flow velocity on sorting, the sheath flow velocity in the C inlet channel was changed from the original 1500 um/s to 2000 um/s, as shown in figure 5(b), and it was observed that the particles were sorted achieved sorting at the outlet channel. Comparing figures 5(a) and (b), it is found that the contour sparsity is different at the three inlet channels, and the increased flow rate of the sheath flow can bring the particles closer to the vicinity of the electrodes. With no change in the voltage value, the dielectrophoretic effect on the particles is increased and the flux in the sorting device is increased, ultimately improving the effectiveness of the sorting device. This phenomenon indicates that the flow rate of the sheath flow impacts the sorting of the sorting device, and the particle sorting efficiency can be improved by optimizing the sheath flow rate. In order to further verify the results, the radius of red round particles was changed from 3 μm to 4 μm, and the sheath flow rate in the C inlet channel was changed from 2000 um/s to 3000 um/s. The particles shown in figure 5(c) could be sorted.

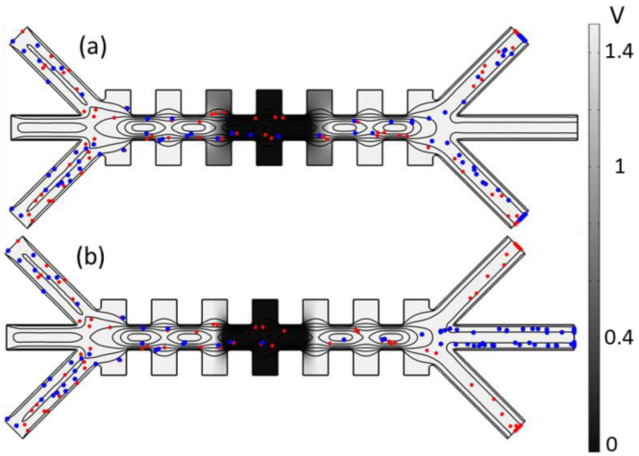


Figure 6. Working diagram of sorting device under different voltage.

The potential intensity distribution of the sorting device is shown in figure 6. To study the effect of the number of electrodes on the sorting results, V_0 electrodes are set at positions 2 and 6 in figure 6(a), and $-V_0$ electrodes are set at position 4. Without changing the particle size and inlet velocity as well as the voltage magnitude, the particles, as shown in figure 6(a) cannot be sorted. When increasing V_0 to 15 V, the particles are shown in figure 6(b) can be sorted. Combining with equation (1), it can be seen that increasing the voltage can make the dielectrophoretic effect on the particles larger and the change of particle motion trajectory more obvious. This phenomenon shows that increasing the voltage can achieve particle sorting under the limited structure size and the limited number of electrodes.

4. Summary

In this study, based on the principle of particle manipulation by dielectrophoresis, a fishbone-shaped particle sorting device is designed in which the particles are subjected to dielectrophoresis when flowing through the electrode position and the trajectory changes, and the device can achieve sorting of particles of different sizes. The numerical analysis of the designed sorting device by finite element analysis method leads to the following conclusions: the size of the particles affects the sorting effect, and the larger the difference between two particle sizes, the more obvious the sorting effect. Increasing the electric field strength, increasing the sheath flow rate, and increasing the number of electrodes can help improve the sorting effect. The fishbone-shaped particle sorting device designed by this research is simple in structure, convenient in operation, high in sorting efficiency, and low in cost. By adjusting the parameters of the sorting device, it can be applied to the sorting of particles of different sizes.

Acknowledgement

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported in part by the Dongguan Science and Technology of Social Development Program (No.20211800905482) and in part by the Innovation Research Team of Mechanical Engineering in Guangdong University of Science and Technology, grant number (GKY-2020CQTD-1)and in part by the College Student Innovation and Entrepreneurship Training Program of Guangdong University of Science and Technology (No.202113719002; No.202113719005) and the Project of Characteristic Innovation of Guangdong Province (No.2021KTSCX148).

References

[1] Rajeshwari T, Kalyana K, et al. 2D dielectrophoretic signature of Coscinodiscus wailesii algae in non-uniform electric fields. Algal Research. 2017; 27: 109-114.
[2] Huang ZW, Wu ZH, Zhou T, Shi LY, et al. Multi-particle interaction in AC electric field driven by dielectrophoresis force. Electrophoresis. 2021; 42(21-22): 2189-2196.
[3] Galicia MCM, Vázquez PM, Alemán NGS, et al. Rapid lipid content screening in neochloris oleoabundans utilizing carbon-based dielectrophoresis. Micromachines. 2021; 12(9).
[4] Park JW, Kim SH, Takuro I, Teruo F, Kim SY, et al. Acoustofluidic harvesting of microalgae on a single chip. Biomicrofluidics. 2016; 10(3).
[5] Chu FJ, Wan TJ, Chen H, Wu CH, Kao PM. Magnetophoretic harvesting of nannochloropsis oculata using iron oxide immobilized beads. Water. 2020; 12(1).
[6] Wang YJ, Wang JS, Zhou C, et al. A microfluidic prototype system towards microalgae cell separation, treatment and viability characterization. Sensors. 2019; 19(22).
[7] Coralie S, Velev OD, Slaveykova VI, Caputo D. Alternating current-dielectrophoresis collection and chaining of phytoplankton on chip: Comparison of individual species and artificial communities. Biosensors. 2017; 7(1).
[8] Cetin B, Li DQ. Dielectrophoresis in microfluidics technology. Electrophoresis. 2011; 32(18).
[9] Suscillon C, Velev OD, Slaveykova VI. Alternating current-dielectrophoresis driven on-chip collection and chaining of green microalgae in freshwaters. Biomicrofluidics. 2013; 7(2).
[10] Deng YL, Kuo MY and Juang YJ. Development of flow through dielectrophoresis microfluidic chips for biofuel production: Sorting and detection of microalgae with different lipid contents. Biomicrofluidics. 2014; 8(6): 064120(1-10).
[11] Wang YJ, et al. Dielectrophoretic separation of microalgae cells in ballast water in a microfluidic chip. Electrophoresis. 2019; 40(6): 969-978.