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Particle Trajectories and Transverse Dispersion in Acoustic Microfluidic Devices

Gergely Simon†, Gergely B. Hantos*, Matěj Hejda‡, Anne L. Bernassau* and Marc P. Y. Desmulliez*
Email: gergely.simon@edinst.com gbh1@hw.ac.uk matej.hejda@strath.ac.uk {a.bernassau, m.desmulliez} @hw.ac.uk
†Edinburgh Instruments Ltd, Livingston, UK
*School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, UK
‡Department of Physics, University of Strathclyde, Glasgow, UK

***Abstract*—The difference in residence time spent by particles in acoustic separator devices correlates to the values of the efficiency and purity coefficients. Although the particle trajectories and the required flow speeds have been investigated in theoretical and numerical studies, most of the existing studies overlook the effect of transverse flow profiles. More complex sorter methods, such as tilted-angle or frequency-modulated methods however can be better understood by applying analysis based on flow profiles. A numerical integration scheme is used here to obtain axial particle trajectories for arbitrary flow profiles with residence time differences of up to 20% for simple time-of-flight sorting. For more complex phase modulated techniques, a non-monotonous dependence of residence time on particle size is observed, with differences up to 27%.**

Keywords—microfluidics, acoustic radiation force, particle separation, stochastic, numerical techniques

I. Introduction

Various acoustic sorting methods aim to achieve the separation of target entities from a mixed population. Usually when these methods are investigated numerically and theoretically, the effect of flow profile is neglected and flow is assumed uniform on any channel cross section plane. In this paper we demonstrate that the effect of flow profile can be significant on particle trajectories resulting in different residence times. The variability in residence times is shown to have a potentially significant effect on the efficiency and purity coefficients, even in microfluidic devices with microvalves and switches.

II. Acoustic Separation Methods

Two acoustic separation methods have been investigated in this study: a commonly used free-flow or time-of-flight [1] method and a frequency modulated method [2-4], both utilizing a form of acoustic standing wave. Other approaches, such as travelling wave methods [5], or geometry-based methods, such as a tilted-angle separator [6], could be analyzed in a similar fashion.

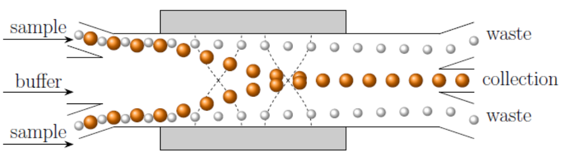

Fig. 1. The free-flow acoustic sorting method. The two types of particles (white/grey and orange) are subjected to different acoustic radiation forces and settle to the pressure node with different speeds, achieving sorting. Figure from [7].

A. Free-flow (time-of-flight) separation method

In this method illustrated in Fig. 1, the acoustic standing wave is formed using either a bulk or surface acoustic wave transducer pair. The field exerts an acoustic radiation force on the particles, whose movement is inhibited by the viscous drag force. A balance of the forces results in separate trajectories for the different kinds of particles:

$$y_A(t) = \frac{1}{k_y}\tan^{-1}\left[\tan\left(k_y y_0\right)\exp(\gamma t)\right] \tag{1}$$

where k_y is the wavenumber, y_0 the initial particle position and γ the ratio of acoustic and viscous forces:

$$\gamma = \frac{2k_y^2 V_\mathrm{p} E_\mathrm{ac}\Phi_\mathrm{AC}}{6\eta\pi a} \tag{2}$$

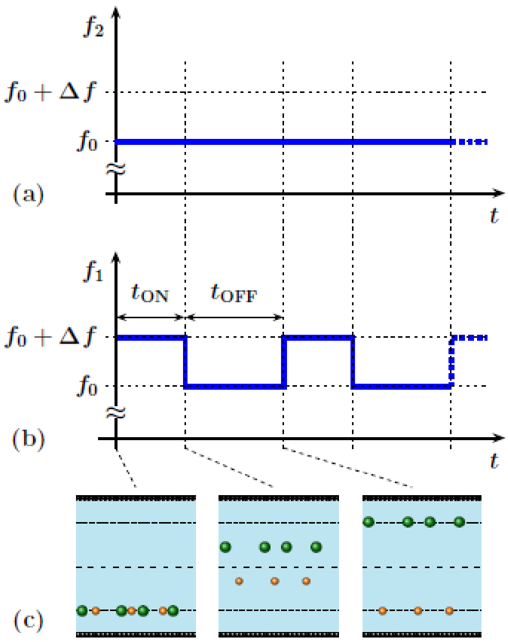

Fig. 2. The frequency modulated sorting method. The sorting can be divided into two parts: first, a slight frequency difference between the two transducers is set (usually 6 orders of magnitude smaller than the main excitation), creating a standing wave that shifts in space, dragging particles with different speeds. Next a stage, where the same frequency is used for both transducers, lets particles settle at the nearest presure nodes. (a) Frequency of transducer 1, (b) frequency of transducer 2, (c) the resulting particle movement and achieved separation. Figure from [7].

where V_p is the (spherical) particle volume, E_{ac} the acoustic energy density, Φ_{AC} the acoustic contrast factor, η the viscosity of the fluid and a the particle radius.

B. *Frequency (phase) modulated separation method*

The frequency (or phase) modulated separation method utilizes an acoustic standing wave that is slowly shifted in space; the latter therefore drags with different speeds particles that are initially trapped at the acoustic pressure nodes [2-3,7]. The particles are also periodically trapped for stability when the shift is switched off. Fig. 2 illustrates the principle of the separation method. The trajectories can be described as

$$y_B(t) = \frac{\Delta\omega t}{2k_y} - \frac{1}{k_y}\tan^{-1}\left[\frac{\gamma - Q\tan\left(Q/2(c_1 - t)\right)}{\Delta\omega}\right] \quad (3)$$

where $\Delta\omega$ is the angular frequency difference between transducers and $Q = \sqrt{(\Delta\omega)^2 - \gamma^2}$, for other parameters refer to (1) and (2).

III. Numerical Modelling

In all cases, a two-step numerical framework was utilized. First, transverse particle trajectories were generated using (1) and (2). Afterwards, these were used in a numerical integration scheme to obtain axial trajectories:

$$x[i+1] = x[i] + f(y[i]) \cdot dt \quad (4)$$

where x[i] is the axial position, y[i] is the transverse position and f(y) the flow profile. Two flow profiles were investigated: a uniform flow for validation of the method, and a parabolic flow profile, following the distribution $f(\bar{y}) = \bar{y}(1 - \bar{y})$ with $\bar{y}$ the normalized transverse position on the (0, 1) interval. Any scaling for the flow speed was neglected, i.e. the peak flow rate at the channel center is taken as unity.

IV. Results

A. *Validation of the numerical method*

First an arbitrary sorting method with a uniform flow was selected, as shown in Fig. 3, to validate the numerical method. Both particles are in synchronicity, i.e. have the same x position at the end of the simulation, validating thereby the numerical method.

B. *Time-of-flight sorting*

This sorting method was investigated with the following parameters: polystyrene particles suspended in water, with 105 kPa pressure amplitude with channel width of 200 microns. Particles between 6 and 15 microns in diameter were analysed and the length of simulation was 0.5 sec to allow for a good particle spread across the channel. The results are summarized in Figs. 4 and 5. Final particle position differs by up to 20%.

The reasons for this difference are the parabolic flow profile and the different extent the different particles propagate into higher velocity regions within the channel. To illustrate this, the channel width was doubled to 400 microns, and the results show minimal spread as shown in Fig. 6.

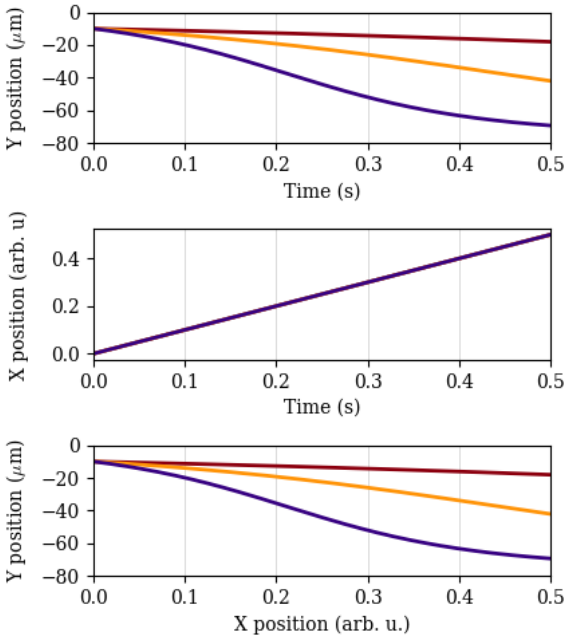

Fig. 3. Validation of the numerical method. (a) Transverse y vs t trajectories of 6 (red), 10 (yellow) and 15 (purple) micron diameter particles. (b) Axial x vs t trajectories of the particles, the slope for both particles is unity, as expected. (c) y vs x position trajectories for the particles, both particles are in synchronicity, i.e. have the same x position at the end of the simulation.

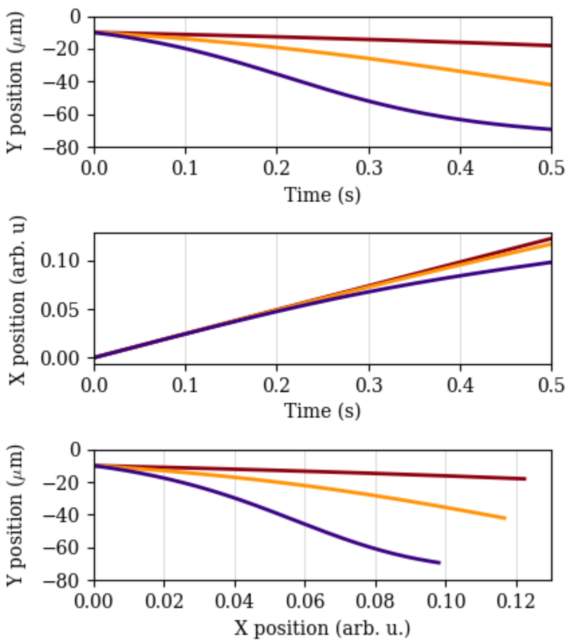

Fig. 4. Time-of-flight sorting method with parabolic flow profile. The red, yellow, and purple colours correspond to 6, 10 and 15 micron diameter particles. (a) y vs t trajectories (b) x vs t trajectories (c) y vs x trajectories. The final position of particles in x differs up to 20%.

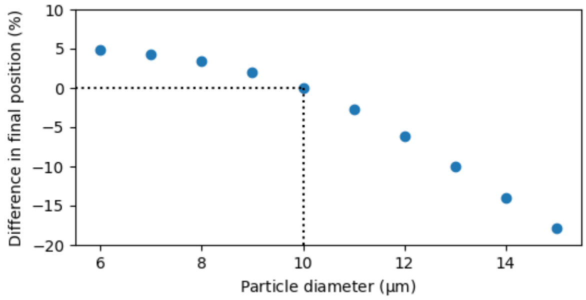

Fig. 5. Difference in final particle position vs particle size. The y-axis refers to the precentage difference in final position of particles, referenced to the 10 micron diameter particle.

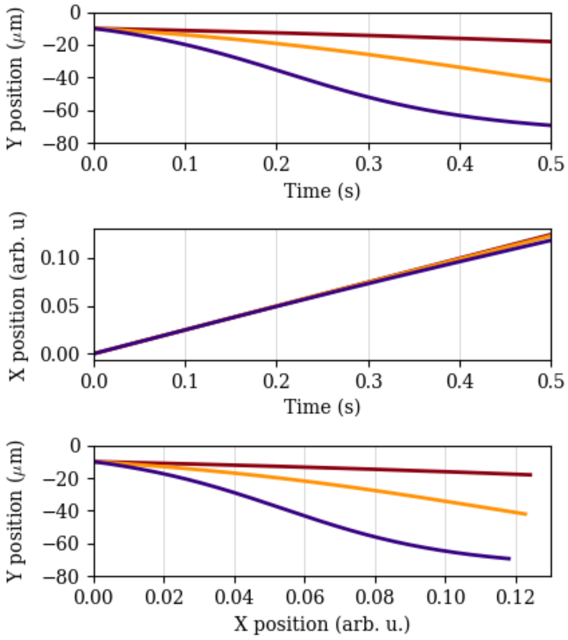

Fig. 6. Doubling the width of the channel decreases the difference in final particle positions to 5% as the particles propagate through regions with smaller fluid velocity differences.

C. Frequency-modulated sorting, single stage

The frequency modulated sorting setup in a similar fashion was then studied with parameters in Table I. The usual water and polystyrene values [7] resulted in acoustic contrast of 0.57.

TABLE I. SIMULATION VALUES FOR THE FREQUENCY-MODULATED METHOD

Base frequency	Modulation frequency	Rest time	Pressure amplitude	Acoustic contrast
13.3 MHz	0.75 Hz	2.7 s	105 kPa	0.57

The results are summarized in Figs. 7 and 8. In this case the difference in the final position of the particle depends on particle size and does not follow a monotonous graph. The fastest moving particle is approximately 10 micron in diameter.

To examine of the effect of channel width on particle spread, the width of the channel was doubled resulting in a minimal spread of up to 5%, as shown in Fig. 9.

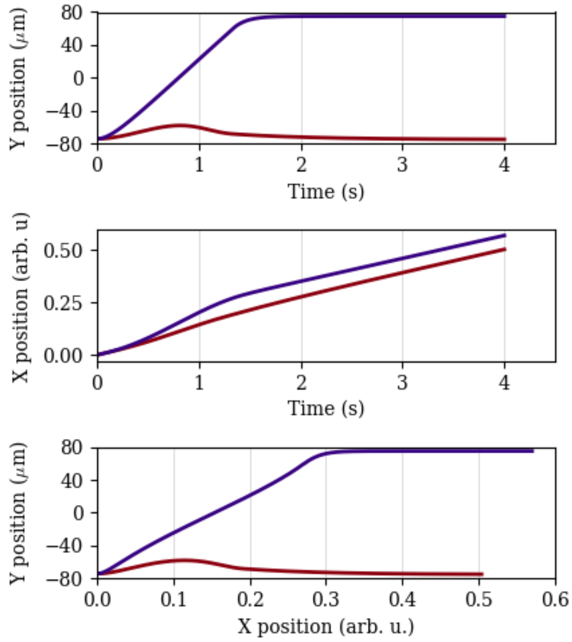

Fig. 7. Frequency modulated sorting scenario for separating 6 (red) and 15 (purple) micron polystyrene particles. (a) y vs t trajectories (b) x vs t trajectories (c) y vs x trajectories. The final position of particles in x differs 12%.

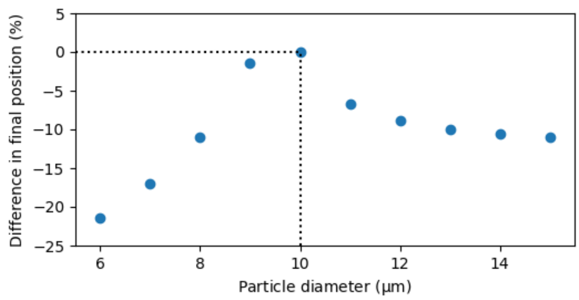

Fig. 8. Difference in final particle position vs particle size. All results are referenced to the 10 micron diameter particle. Coincidentally around the 10 micron particle size the particles move through the channel the fastest. Below this value, they do not cross the channel axis and stay in the low flow speed side of the channel; above the 10 micron size they cross the channel axis so quickly that they are less and less affected by the fastest mid section within the device.

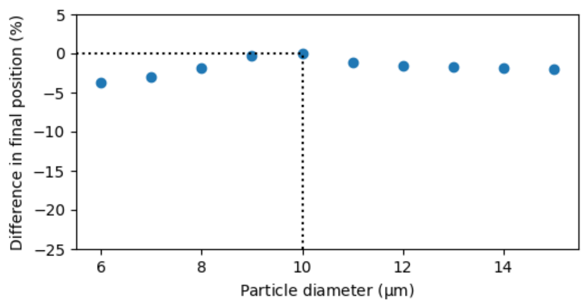

Fig. 9. The effect of double channel width decreases the difference in final particle positions (up to 5%) as the particles propagate through regions with smaller fluid velocity differences. The peculiar non-monotonous shape pertains.

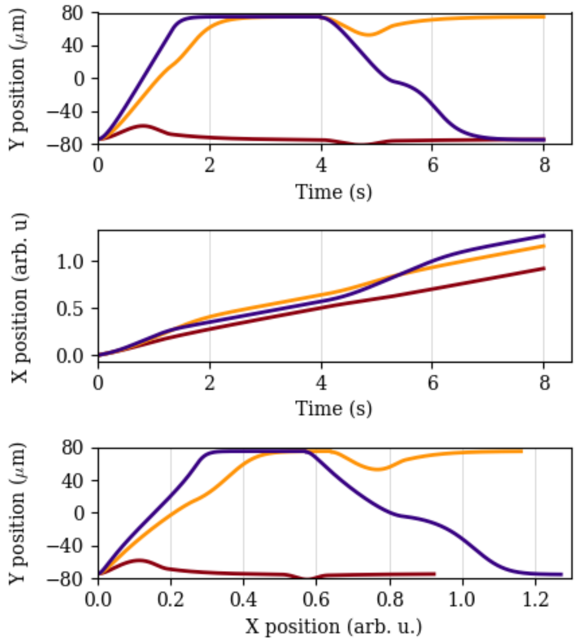

Fig. 10. Bandpass sorting setup for 6 (blue), 10 (orange) and 15 (green) micron diameter polystyrene particles. (a) y vs t trajectories (b) x vs t trajectories (c) y vs x trajectories. The final position of particles in x differs 27%.

D. *Frequency-modulated sorting, bandpass*

Finally a frequency modulated bandpass sorting setup was studied. This is achieved by adding another sorting stage to the frequency modulated method, with different frequency difference polarity and pressure amplitude [3]. In this case, the pressure amplitude has been dropped to 70 kPa, to achieve bandpass sorting of 6, 10 and 15 micron diameter particles as shown in Fig. 10. Due to the double shifting of the largest entities, the target particles have now medium residence time. The multitude of potential parameters would result in an extensive investigation that is beyond the scope of this paper.

V. Conclusions and Future Work

In this paper we investigated particle trajectories along the channel axis during acoustic sorting scenarios and noticed different residence times depending on the length of time spent by the particle in the vicinity of the channel axis with high flow speeds. This can be detrimental for counting or collecting entities. This phenomenon can also be used beneficially for example by the use of microvalves at the outlets and or by blocking slower non-target particles. This work is intended to be extended by using more realistic flow profiles obtained from finite element simulations, and compare them the simulated with trajectories from experimental videos.

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