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Travelling Surface Acoustic Waves Microfluidics

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Abstract

In this paper, we demonstrate the working principle of travelling surface acoustic waves (TSAWs) in a microfluidic system. The TSAWs were incorporated to separate polystyrene (PS) particles of variable diameters and perform controlled mixing of different chemicals for concentration gradient generation, both inside a polydimethylsiloxane (PDMS) microfluidic channel. The TSAWs generated an acoustic streaming flow (ASF) upon coupling with a liquid and exerted an acoustic radiation force (ARF) on the suspended particles. The ARF was theoretically estimated for PS microspheres suspended in water, and conditions for ARF dominance over ASF or vice versa were identified. Recently reported TSAW-based PS particles separation and gradient generation results by our group are summarized here.

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1. Introduction

In a microfluidic system, standing surface acoustic waves (SSAWs) have been used to manipulate micro-objects. A pair of interdigitated transducers (IDTs) is usually used to generate SSAWs, however, a single IDT has also been reported to produce a similar affect. In a parallel domain, traveling surface acoustic waves (TSAWs) produced by a single IDT as shown in Fig. 1a have been used to efficiently actuate (mix, pump, nebulize, jet) fluid on a microfluidic platform. Recently, TSAWs have shown promising potential in dexterous handling (separation, sorting, trapping) of micro-objects in a micro-sessile droplet or inside a microfluidic channel (Destgeer et al., 2015b). The present study is focused on the use of TSAWs for micro-object manipulation and micro-fluid actuation. The actuation of micro-fluids via TSAWs is dependent on the acoustic streaming flow (ASF) generated by the dissipation

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of acoustic waves in the fluid, whereas the manipulation of micro-objects depends on the acoustic radiation force (ARF) derived from TSAWs' frequency, particles' diameters and relative densities of the fluid and particles. The ASF is produced in conjunction with the ARF. A κ factor ($= \pi d f / c_f$), directly proportional to the diameter of the particle (d) and TSAWs' frequency (f), is used to characterize the different behaviors of the particles under the effect of TSAWs, where c_f is the speed of sound in the fluid. For $\kappa > 1$, the ARF on the particles dominates the drag force induced to the particles via ASF. The ARF can derive the suspended microsphere of adequate diameters in the direction of acoustic wave propagation (see Fig. 1b). For $\kappa < 1$, the particles are so small to be effected by the ARF and the effect of ASF dominates. The smaller particles move with the ASF vortices as the ARF is unable to drive them along the acoustic wave (see Fig. 1c). We have taken advantage of these promising effects to separate polystyrene (PS) microparticles (see Fig. 1d) and controllably actuate fluids for concentration gradient generation (see Fig. 1e) inside the polydimethylsiloxane (PDMS) microchannel.

2. Theoretical models

The ARF (F) acting on a rigid microsphere as proposed by King (1934) is defined as:

$$F = \left(\pi d^2/4\right) \cdot \overline{E} \cdot F_F \quad for \quad \overline{E} = \frac{1}{2}\rho_f k |A|^2, \tag{1}$$

$\overline{E}$ is the sound energy density in the fluid (density ρ_f), k is the wavenumber, and A is the complex amplitude of velocity potential function related with the amplitude of sound wave. The acoustic radiation force factor (ARFF) for a plane travelling wave and a rigid microsphere (density ρ_s) is defined as:

$$F_F = \frac{4}{\kappa^4}\left[\frac{1}{l_0 l_1} + \frac{2\left\{\kappa^2 - 3(1-r)\right\}^2}{\kappa^8 l_1 l_2} + \sum_{n=2}^{\infty} \frac{(n+1)}{\kappa^{4(n+1)}} \times \frac{\left(\kappa^2 - n(n+2)\right)^2}{l_n l_{n+1}}\right] \quad for \quad r = \frac{\rho_f}{\rho_s}, \tag{3}$$

$$l_1 = \frac{\pi}{2\kappa^3}\left[(1-r)^2 \cdot \left(j_{1.5}^2 + j_{-1.5}^2\right) + 2\kappa \cdot (1-r) \cdot \left(j_{-1.5} j_{-2.5} - j_{1.5} j_{2.5}\right) + \kappa^2 \cdot \left(j_{2.5}^2 + j_{-2.5}^2\right)\right] \tag{4a}$$

$$l_n = \frac{\pi}{2\kappa^{2n+1}}\left[n^2 \cdot \left(j_{n+0.5}^2 + j_{-n-0.5}^2\right) + 2n\kappa \cdot \left(j_{-n-0.5} j_{-n-1.5} - j_{n+0.5} j_{n+1.5}\right) + \kappa^2 \cdot \left(j_{n+1.5}^2 + j_{-n-1.5}^2\right)\right] \quad for \quad n \neq 1. \tag{4b}$$

The ARFF (F_F) for a plane travelling wave interacting with an elastic microsphere includes the effects of the compressibility and the elasticity of a particle. The F_F is defined by Hasegawa and Yosioka (1969) as:

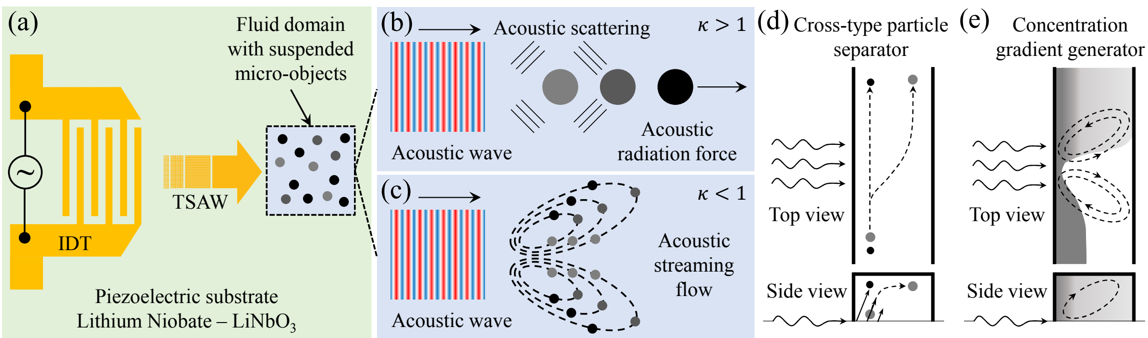

Fig. 1. (a) Device schematic. (b) A travelling acoustic wave imposed an ARF on the microparticles if $\kappa > 1$. (c) For $\kappa < 1$, the ASF forces the particles to move with the vortices. (d) A particle separation device based on ARF. (e) A concentration gradient generator based on ASF.

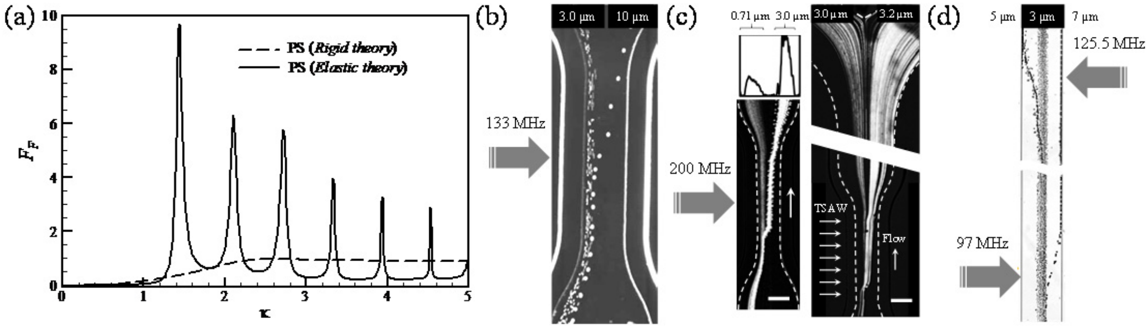

Fig. 2 (a) F_F calculated for PS microspheres using rigid and elastic theories is plotted against κ. (b) Continuous separation of PS particles (Destgeer et al., 2013). (c) Submicron separation of particles (Destgeer et al., 2014b). (d) Tri-separation of particles (Destgeer et al., 2015a).

$$F_F = \frac{4}{\kappa^2}\sum_{n=0}^{\infty}\left[\begin{array}{c}(n+1)\cdot\left(p'_{n+1}\cdot q'_n - p'_n\cdot q'_{n+1}\right)\cdot\kappa^2 - n\cdot(n+1)\cdot(n+2)\cdot\left(p_{n+1}\cdot q_n - p_n\cdot q_{n+1}\right)\\ +\left(n\cdot(n+1)\cdot\left(p'_{n+1}\cdot q'_{n+1} - p'_{n+1}\cdot q_n\right) - (n+1)\cdot(n+2)\cdot\left(p'_n\cdot q_{n+1} - p_{n+1}\cdot q'_n\right)\right)\cdot\kappa\\ +(n+1)\cdot\left(p_{n+1}\cdot q_n - p_n\cdot q_{n+1}\right)\cdot\kappa^2\end{array}\right], \quad (5)$$

$$p_n = (1+m_n)\cdot j_n + n_n\cdot y_n, \quad q_n = n_n\cdot j_n - m_n\cdot y_n, \quad (6)$$

$$m_n = -\frac{\left[h_n\cdot j_n - \kappa\cdot j'_n\right]^2}{\left[h_n\cdot j_n - \kappa\cdot j'_n\right]^2 + \left[h_n\cdot y_n - \kappa\cdot y'_n\right]^2}, \quad n_n = -\frac{\left[h_n\cdot j_n - \kappa\cdot j'_n\right]\cdot\left[h_n\cdot y_n - \kappa\cdot y'_n\right]}{\left[h_n\cdot j_n - \kappa\cdot j'_n\right]^2 + \left[h_n\cdot y_n - \kappa\cdot y'_n\right]^2}, \quad (7)$$

$$h_n = \frac{r\cdot\kappa_2^2}{2}\,\frac{\dfrac{\kappa_1\cdot j'_n(\kappa_1)}{\kappa_1\cdot j'_n(\kappa_1) - j_n(\kappa_1)} - \dfrac{2\cdot n\cdot(n+1)\cdot j_n(\kappa_2)}{(n+2)\cdot(n-1)\cdot j_n(\kappa_2) + \kappa_2^2\cdot j''_n(\kappa_2)}}{\dfrac{\kappa_1^2\cdot\left[(\sigma/(1-2\sigma))\cdot j_n(\kappa_1) - j''_n(\kappa_1)\right]}{\kappa_1\cdot j'_n(\kappa_1) - j_n(\kappa_1)} - \dfrac{2\cdot n\cdot(n+1)\cdot\left[j_n(\kappa_2) - \kappa_2\cdot j'_n(\kappa_2)\right]}{(n+2)\cdot(n-1)\cdot j_n(\kappa_2) + \kappa_2^2\cdot j''_n(\kappa_2)}}, \quad (8)$$

$$\kappa_1 = k_1\cdot d/2 = \pi\cdot f\cdot d/c_1, \quad \kappa_2 = k_2\cdot d/2 = \pi\cdot f\cdot d/c_2. \quad (9)$$

The wavenumbers k_1 and k_2 and sound velocities in elastic sphere c_1 and c_2 correspond to longitudinal (or compressional) waves and shear waves propagating inside the particle, respectively. j_n and y_n are the spherical Bessel functions of the first and second kind of order n, respectively. σ is the Poisson ratio. The ARFF estimated by using both the rigid and elastic theories for PS particles suspended in water is plotted in Fig. 2a.

3. Applications

3.1. Particle separation

The fundamental understanding of the TSAW interaction with the PS particles reveals the conditions for which the ARF dominates the ASF and the particles are deflected as a results. The separation of 3 and 10 μm PS particles was achieved in a continuous flow inside a single layered PDMS microfluidic channel using 133 MHz TSAWs (see Fig. 2b). The TSAWs were produced by a focused unidirectional transducer that ensures maximum acoustic energy radiation towards the fluid carrying particles. A separation efficiency of ~100 % was realized (Destgeer et al., 2013). A similar cross-type acoustic particle separator was used to perform submicron separation of PS particles (Destgeer et al., 2014b). The ARF rapidly increases for $\kappa > 1$, which means a pair of particles with a small difference (less than one micron) in diameters will experience significantly different force leading to submicron separation of particles. As a result, the TSAWs (200 MHz) were used to separate PS particles pairs: 0.71 and 3µm, and 3 and 3.2 µm (see Fig. 2c). Recently, we have demonstrated a novel separation mechanism based on microchannel anechoic corner for tri-separation of PS particles (3, 5 and 7 µm) using two separate counter propagating TSAWs (97 and 125.5 MHz) as shown in Fig. 2d (Destgeer et al. 2015a). It is important to note here that the theoretical prediction of ARF and the separation behaviors observed here are strongly dependent on the particle material viz. PS. A different material may show different acoustic properties and the corresponding ARF estimation may vary (Destgeer et al., 2015b).

3.2. Chemical concentration gradient generation

The interaction of the acoustic waves with fluid produces a chaotic streaming flow that strongly depends on the dimensions of the microchannel (width and height). In the particle separation device, a narrow microchannel (200 µm) helps in preventing the formation of strong ASF. However, a wider microchannel (500 µm) producing a reasonable high velocity ASF that is harnessed for controlled and continuous mixing of fluids inside the microchannel. A focused unidirectional IDT is used to produce focused TSAWs that form symmetrical ARF vortices (see Fig. 3a). Two different fluids (green and white in Fig. 3a) can be effectively mixed in a continuous flow resulting in a concentration gradient profiles modulated by changing the input power (see Fig. 3b). The gradient profiles measured downstream of the microchannel are plotted in Fig. 3c (Destgeer et al., 2014a).

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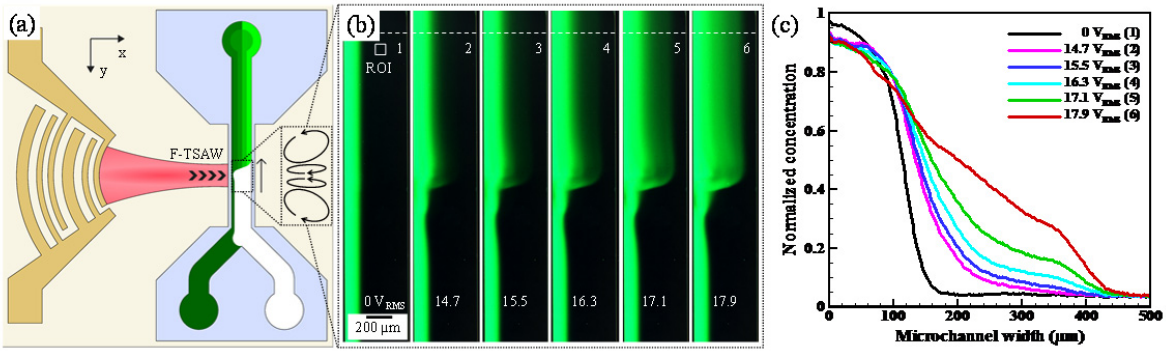

Fig. 3. (a) The microfluidic chemical concentration gradient generator. (b) The ASF vortices mix two fluids to form a controlled concentration gradient. (c) The concentration profiles across the microchannel width corresponding to positions 1-6 in (b). (Destgeer et al., 2014a)