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Acoustophoresis on Microfluidic Chips Made of Polymers and Glass: Experimental Comparison

E. De los Reyes[1], *I. González*[1], *L. Díez*[1], *and A. Pinto*[1]
[1]*Consejo Superior de Investigaciones Científicas CSIC, Institute of Physical Technologies and Information ITEFI, Madrid, Spain*
iciar.gonzalez@csic.es

Abstract: We present an experimental study to analyze the influence of the chip material on acoustophoresis processes induced by ultrasounds in microfluidic devices. Two materials with different acoustic properties were used for the chip structutre: glass and PMMA repectively. Different vibrations established in their respective structures give rise to diverse acoustic pressure patterns within the liquid phase of the channels, providing different particle collection efficiencies. Advantages and disadvantages of both types of chips have been tested.

Keywords: Ultrasounds, Microfluidics, Acoustophoresis, Sorting, Micromanipulation.

Background, Motivation and Objective

In last decades, the development of technology in the field of microfluidics has advanced considerably for sorting and separation applications, being Bulk Acoustic Wave actuation (BAW) one of the plattforms that can perform in this field. In these platform, an ultrasonic actuator is mechanically attached to a chip, generating a wave propagation throughout its structure. Different operating mechanisms of BAW actuators depend directly from the materials used in the chips and thus, of its acoustic impedance.

$$Z = \rho c \tag{1}$$

where Z is the material's acoustic impedance, ρ is the density and c is the sound velocity.

In chips made of materials with high acoustic impedance such as glass or silicon, a standing wave is established in the liquid phase between two rigid parallel walls separated by an integer number of half wavelengths. For a half wavelength-channel width, a pressure node is established at the central axis, collecting particles due to the radiation force induced by ultrasound [1]. This type of material presents low acoustic energy loss and high directivity.

In contrast, the polymeric chip materials have a low acoustic impedance, similar to that of the liquids. It is the entire chip structure that is involved in establishing complex three-dimensional vibration modes at any frequency [2, 3]. Acoustic energy is transferred to the liquid phase from the structural vibrations that generates these vibration modes. Due to the low acoustic impedance of these materials, energy loss is greater than that found in acoustically hard materials.

The process of acoustophoresis by which particle collection is achieved is governed by the radiation force, which is due to the nonlinear interaction between the incident and the scatered wave from the particles through the fluid medium. The expression for this radiation force for a one-dimensional standing wave was described by Gorkov [1] as:

$$F_R = \frac{-\pi P_0^2 \cdot V_p \cdot \beta_l}{2\lambda} \cdot \varphi(\rho_p, \beta_p, \rho_l, \beta_l) \cdot \sin\left(\frac{4\pi x}{\lambda}\right) \tag{2}$$

$$\varphi(\rho_\mathrm{p}, \beta_\mathrm{p}, \rho_\mathrm{l}, \beta_\mathrm{l}) = \frac{5\rho_p - 2\rho_l}{2\rho_p + \rho_l} - \frac{\beta_p}{\beta_l} \tag{3}$$

where V_p the volume of the particles, φ, is the acoustic contrast factor with ρ_p, β_p and ρ_l, β_l being the density and adiabatic compressibility of the particles and the fluid, respectively. The distance of the particles from the pressure node is given by *'x'*. The acoustic contrast factor determines whether the movement of the particles occurs toward the pressure nodes ($\varphi > 0$) or toward the antinodes ($\varphi < 0$).

Acoustically rigid materials, such as glass or silicon, have proven to be efficient in particle collection [4, 5, 6, 7] and present stable frequency resonances. However, the still high cost of these devices makes the use of polymer devices an attractive alternative.

In polymer chips, the expression described in Eq. (2) is no longer valid because the field transmitted to the liquid from the chip structure is a fully three-dimensional field. This makes the expressions much

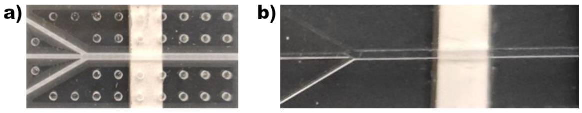

Fig. 1: Pictures of a) Glass Chip, b) PMMA Chip.

more complex, as has been described in recent literature [2]. Previous studies [3], have verified numerical and experimentally this complex behaviours of polymer chips. Results were obtained regarding particle collection along the longitudinal axis of the channel in polymeric-based chips.

However, another parameter is also involved in the particle collection: the flow rate generating drag viscous forces on the particles. The expression that defines these forces, exerted by the fluid on the particles along their trajectory toward the pressure nodes, is given by:

$$F_d = -6\pi\eta R_p(u - v) \tag{4}$$

where η is the dynamic fluid viscosity, R_p is the particle radius u is the particle velocity and v is the fluid velocity.

Laminar flow regime of microfluidics provides flow velocities with parabolic profiles, favouring particle entraintment toward the central axis. According to it, suitable combination of acousto-hydrodymic conditions have been found in this study for optimal particle collection [2, 8, 9, 10].

The objective and motivation of this study is to determine how two materials with very different acoustic impedances affect particle collection in chips and channels with identical cross-dimensions (Fig. 1) at the same frequency. An experimental comparison has been made to show the advantages and disadvantages of both materials.

Experimental setup

Two microfluidic chips were developed to perform the experiments of: i) Borosilicate Glass (Z≈13 MRayls) and ii) Polymethylmethacrylate (PMMA) (Z≈11,9 MRayls). They have the same width and thickness (15x1.5 mm) with identical channel cross-sections (800x500 μm). The channel is centered in both chips.

Piezoelectric PZ26 Ferroperm ceramics were used as ultrasonic actuator, attached underneath the chips, vibrating in Thickness mode at around 1 MHz. They were placed perpendicular to the channel and excited by an Agilent 33500B function generator connected to an E&I 240L amplifier; a continuous sinusoidal wave was used to excite the PZ26.

Polystyrene beads of 20 μm diameter (Dynoseeds TS 20, Microbeads) were used, diluted in deionized water filtered through 0.2 μm pore-size biological grade filters. For the injection of the particle suspension, a 2.5 ml syringe was employed, and the flow rate was regulated using a KDScientific KDS-260-CE syringe pump. Various flow rates were tested, ranging from 50 μl/min to 300 μm/min. Among them, Q = 80 μl/min was selected as the optimal flow rate to enhance particle collection efficiency.

The optical elements used in the laboratory are a ZEISS Axio Scope A1 microscope with a ZEISS EC EPIPLAN 5x/0.13 HD lens, and a Photron FASTCAM SA3 high-speed camera, configured with a frame rate of 2000 frames per second.

Results

The presence of cylindrical-shaped perforations within the glass chip structure, significantly disturbs the propagation of the incident wave from the vibrating surface of the piezoelectric ceramic. Due to the high rigidity of the glass material, wave propagation predominantly occurs along the direction of incidence. The perforations induce highly directed wave guidance toward the channel in the adjacent chip region. In the rest of the chip, these perforations induce acoustic short-circuiting, resulting in wave reflection and significant energy dissipation in areas farther from the channel. Regions in close proximity to the channel, experience more direct wave propagation, which would be equivalent to having a very narrow chip.

Several optimal collection frequencies were found for both chips in the range of 800 kHz to 1200 kHz, with 974 kHz chosen as representative. It is worth noting that, although the glass chip collects over a range that covers the studied interval, with small intervals in which collection is slightly impaired, this is not the case for the polymer chip, where these ranges are very intermittent and in some cases, nonexistent.

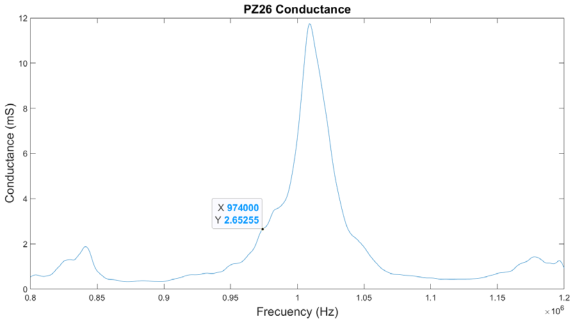

Fig. 2: Graph of the conductance of the PZ26 used in both the glass chip and the PMMA chip.

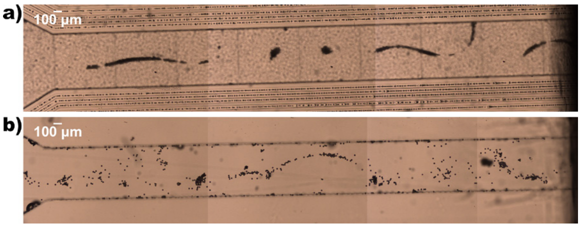

Fig. 3: Particle collection at 974 kHz obtained within the microchannel at stagnant conditions, drawing the pressure node pattern; a) In the glass chip, b) in the PMMA chip.

Under flow stangnant conditions, the acoustic pressure nodes draw a discontinuous line around the central axis of the channel. Instead, they form confined clusters of aggregates at different possitions of the channel width, including small areas beside the walls (Fig. 3). They appear more dispersed in the PMMA chip, showing more irregular and weaker pressure nodes spatially dispersed, due to the establishment of three-dimensional vibration modes within the solid structure of the chips, as described in the introduction.

However, under flow conditions, the parabolic flow velocity profile, with a maximum at the central axis and governed by viscous drag forces, favours circulation of particles along the central area once collected by the radiation force and by viscous drag forces in the same direction. It is, therefore, the acousto-hydrodynamic combination that enables both the collection and maintenance of the particles along the channel axis, even though the pressure nodes are not spatially regular along the channel. This phenomenon has been widely described in the litereature and repeatedly observed in video recordings obtained under flow conditions of our experiments, where circulating particles exhibit a well-defined alignment along this central axis or in its vicinity within small surrounding areas (Fig. 4).

Experiments were conducted with flow rates ranging from 50 to 300 μl/min. It was observed that, in polymer-based chips, flow rates exceeding 80 μl/min result in very poor particle collection, with significant dispersion of particles throughout the channel. On the contrary, particle collection in glass chips tolerate flow rates up to 100 μl/min, although this also leads to a slight reduction in collection efficiency. It is due to times unbalance, the time of circulation is shorter than that required to reach the central axis at these high flow rates, preventing particles circulating near the walls from reaching the center of the channel. Nevertheless, particle collection with efficiency degrees over 70% still occurs at this rate. A flow rate of 80 μl/min allows for particle collection in both types of chips and enables a comparison of their collection efficiency.

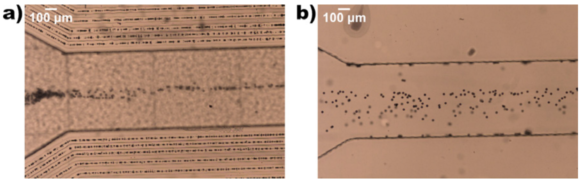

Fig. 4: Particle collection at 974 kHz obtained within the microchannel and a flow rate at the syringe pump of 80 μl/min; a) In the glass chip, b) in the PMMA chip.

Furthermore, particle trapping occurs more slowly in polymer chips, even in stangnant conditions. This suggests that, at a given frequency, the resulting acoustic radiation force is weaker in these materials, which can be explained by the high energy loss and establishment of three-dimensional complex vibrations in this acoustically soft structures described above. Lower flow rates are more favorable for effective collection in these polymer-based chips. In contrast, particle collection in glass chips is nearly instantaneous, both with and without flow.

However, the resulting temperature rise in the ceramic associated to higher voltages supplied, favours formation of bubbles within the channels and aggregation of particles, which adhere to the channel walls and bubble surfaces, thereby altering the acoustic conditions inside. These alterations lead to a significant decrease in collection efficiency.

In our experiments, a collection efficiency of 100% was achieved in the glass chip, whereas in the PMMA chip, the efficiency was approximately 70% although they collected in a wider central area.

Conclusions

In the polymer chip, the acoustophoretic process occurs with lower particle collection efficiency than in glass chips. The greater energy dissipation in acoustically soft materials like PMMA, and complex three-dimensional vibration modes established in this material, results in poorer particle collection in the polymer chips.

However, polymeric chips present the advantages of being lower in cost and are more versatile in establishing pressure nodes at different areas of the channel, they are also more versatile regarding the pressure nodes establishment. It does not occur in glass chips, which provide a wider frequency stability and a very high efficiency in collecting particles at fixed positions within the channels.

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References

[1] L. Gor'kov. "On the forces acting on a small particle in an acoustic field in an ideal fluid". In: *Sov. Phys. Acoust.* 6 (1962), pp. 773–775.

[2] A. Vargas et al. "A 3D analysis of the acoustic radiation force in microfluidic channel with rectangular geometry". In: *Wave Motion* 101 (2021), p. 102701. DOI: 10.1016/j.wavemoti.2020.102701.

[3] E. de los Reyes et al. "Three-dimensional numerical analysis as a tool for optimization of acoustophoretic separation in polymeric chips". In: *The Journal of the Acoustical Society of America* 150 (2021), pp. 646–656. DOI: 10.1121/10.0005629.

[4] C. R. P. Courtney et al. "Manipulation of microparticles using phase-controllable ultrasonic standing waves". In: *The Journal of the Acoustical Society of America* 128 (2010), pp. 195–199. DOI: 10.1121/1.3479976.

[5] M. Evander et al. "Acoustophoresis in Wet-Etched Glass Chips". In: *Analytical Chemistry* 80 (2008), pp. 5178–5185. DOI: 10.1021/ac800572n.

[6] A. Haake and J. Dual. "Micro-manipulation of small particles by node position control of an ultrasonic standing wave". In: *Ultrasonics* 40 (2002), pp. 317–322. DOI: 10.1016/S0041-624X(02)00114-2.

[7] M. A. Şahin, B. Çetin, and M. B. Özer. "Investigation of effect of design and operating parameters on acoustophoretic particle separation via 3D device-level simulations". In: *Microfluidics and Nanofluidics* 24 (2020), 24:8. DOI: 10.1007/s10404-019-2311-1.

[8] Q. Wang, D. Yuan, and W. Li. "Analysis of Hydrodynamic Mechanism on Particles Focusing in Micro-Channel Flows". In: *Micromachines* 8 (2017), p. 197. DOI: 10.3390/mi8070197.

[9] I. González et al. "Influence of Hydrodynamics and Hematocrit on Ultrasound-Induced Blood Plasmapheresis". In: *Micromachines* 11 (2020), p. 751. DOI: 10.3390/mi11080751.

[10] Z. Liu et al. "Effects of fluid medium flow and spatial temperature variation on acoustophoretic motion of microparticles in microfluidic channels". In: *The Journal of the Acoustical Society of America* 139 (2016), pp. 332–349. DOI: 10.1121/1.4939737.