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Scaling-up ultrasound standing wave enhanced sedimentation filters

Jeff E. Prest [b], Bernard J. Treves Brown [a], Peter R. Fielden [b], Stephen J. Wilkinson [c], Jeremy J. Hawkes [a,*]

[a] Manchester Institute of Biotechnology, The University of Manchester, Oxford Road, Manchester M13 9PL, UK
[b] Department of Chemistry Faraday Building, Lancaster University, Bailrigg, Lancaster LA1 4YB, UK
[c] University of Chester Faculty of Science and Engineering, Thornton Science Park, CH2 4NU, UK

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ABSTRACT

Particle concentration and filtration is a key stage in a wide range of processing industries and also one that can be present challenges for high throughput, continuous operation. Here we demonstrate some features which increase the efficiency of ultrasound enhanced sedimentation and could enable the technology the potential to be scaled up. In this work, 20 mm piezoelectric plates were used to drive 100 mm high chambers formed from single structural elements. The coherent structural resonances were able to drive particles (yeast cells) in the water to nodes throughout the chamber. Ultrasound enhanced sedimentation was used to demonstrate the efficiency of the system (>99% particle clearance). Sub-wavelength pin protrusions were used for the contacts between the resonant chamber and other elements. The pins provided support and transferred power, replacing glue which is inefficient for power transfer. Filtration energies of ~4 J/ml of suspension were measured. A calculation of thermal convection indicates that the circulation could disrupt cell alignment in ducts >35 mm high when a 1 K temperature gradient is present; we predict higher efficiencies when this maximum height is observed. For the acoustic design, although modelling was minimal before construction, the very simple construction allowed us to form 3D models of the nodal patterns in the fluid and the duct structure. The models were compared with visual observations of particle movement, Chladni figures and scanning laser vibrometer mapping. This demonstrates that nodal planes in the fluid can be controlled by the position of clamping points and that the contacts could be positioned to increase the efficiency and reliability of particle manipulations in standing waves.

1. Introduction

1.1. Physical particle filtration and concentration

Particle concentration and filtration stages are used by almost every laboratory and industry that processes particle suspensions. These stages could be accomplished by a wide variety of devices but are usually performed by centrifuges, settling devices, filtration screens or chemical flocculation. These few devices are very successful for handling fluid volumes scales from cm^3 to m^3 but when very small scale, very large scale, high flow rates or continuous flow are needed these standard devices have limited development potential. At the sub-millilitre scale there are several particle manipulation processes based on physical characteristics which promise to increase the scope of microfluidic applications, for example electrostatic [1] and magnetic attraction [2], thermophoresis [3], microthermal field-flow fractionation (micro-TFFF), shear-induced particle migration [4], sedimentation based field-flow-fractionation [5], dean-flow inertial-focusing [6], electrowetting [7,8], optical traps [9], dielectrophoresis [10] and ultrasound-standing-wave particle filtration [11–13]. This last process, the subject of this paper, can in principle also be scaled up and it can also operate with: gas or liquid suspension phases; high or low media conductivity; and opaque or transparent samples. Its channels can be more than 10 mm across for filtering 5 μm diameter particles (therefore contaminating debris is unlikely to cause blockages). Despite its seemingly huge potential ultrasound filtration is currently not widely used, although commercial devices have existed for nearly 20 years. An inability to achieve significant scale-up and reliability have been two factors holding back development. Both challenges are addressed by the system described in this paper.

1.2. Scale-up limited by heating

The largest commercial ultrasound-enhanced-sedimentation-filter (from AppliSens [14]) has a processing volume of just 290 ml and its ultrasonic path length is <0.055 m. Current ultrasound

* Corresponding author. Tel.: +44 151 2818068.
E-mail address: JeremyJHawkes@gmail.com (J.J. Hawkes).

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filtration systems operate in the low MHz region and a quick calculation shows that sound absorption by the fluid is not limiting scale-up for most current chambers: At 1 MHz, 50% of sound wave energy is absorbed over a distance of 27 m in deionised water and, 0.4 m in whole blood. These distances are calculated from $d = \ln(A_0/A_1)/\alpha$, where A_0 and A_1 are the initial and transmitted sound amplitudes, and their ratio, A_0/A_1, is equal to 2 for 50% absorption. The absorption coefficients α are 0.03 Np m^{-1} for water [15] and 1.4 Np m^{-1} for blood [16]. However although sound absorption within the fluid is low, device heating is a problem and therefore for almost every apparatus with more than 1 ml of fluid in the resonant chamber; air, water or Peltier cooling is used [13,17–20]. In one exception to this, heating is permitted and a thermal equalization period is introduced [21]. We assume a significant amount of the heat comes from destructive interference arising from the geometries and interfaces of the PZT and chamber. The 36 ml chamber described here does not have a cooling system. Instead minimally-damped-coherent-waves are encouraged throughout the duct. This is achieved through by directly coupling the PZT to the chamber rather than using a glue interlayer; minimizing contact points, so damping at suboptimal contacts is reduced, and by using a duct formed from a single element as the resonant chamber, so reducing losses at joints. We give some proof-of-principle experiments which show that in the current system, filtration is possible with only a low level of heat production and we discuss ways to further reduce heat production. Heat disrupts ultrasound filtration because it changes the resonant frequency [22] and in addition thermal convection disrupts the acoustic organisation of particles [11]. While resonant frequencies can be tracked, in large systems thermal convection presents the greatest problem, we quantify the problems and suggest a reduced chamber height as an amelioration method.

1.3. Advantages of ultrasound enhanced sedimentation for scale-up

There are two main approaches used for ultrasound filtration: ultrasound enhanced sedimentation, (UES) [11,17,18,23–25] and hydrodynamic acoustic filtration (HAF) [22,26,27]. UES filters are usually multi-wavelength devices with a channel 10–60 mm wide and do not require high precision in their construction. HAF devices require much higher manufacturing precision: they are usually half wavelength devices, the acoustic path length is <1 mm and downstream from the sound the channel is divided to direct each band of focused particles to a separate outlet. Scale-up of HAF devices is complex, as multi-wavelength sound paths require additional outlet-ducts. By contrast, UES systems can be scaled up in any dimension without adding more ducts. Therefore we selected UES filtration to demonstrate our scale-up of the resonant section. The approaches described such as glue free contacts and control of the nodal plane direction could however also be introduced to HAF and small-scale devices.

1.4. Wave interference between surfaces

The wave-shape on the surface of the PZT and the duct wall (or any two parts consisting of different materials or geometries) are not usually the same at any frequency (as in Fig. 1), therefore any interface with face-to-face contact will have some out of phase regions (marked 180° in Fig. 1) where interference is destructive, and even regions moving in phase will move with different magnitudes when impedances differ. Therefore transferring vibrations from one structure to another is always accompanied by some conversion of ordered vibration into thermal energy.

1.5. Introducing point contacts to give vibrational freedom

In traditional UES filter design the wave shape on interacting surfaces is not considered, they are constructed with a fluid separating a driven wall and a reflecting wall; the driven wall is either a PZT or a wall with a PZT glued behind it; the side walls and watertight seal are not designed to couple structural vibrations to the reflector [17,24,27]. Models are usually one dimensional [28–32], this means they only consider the compression waves along the axis, from the transducer, through any glue and coupling layer, into the fluid and the reflector. These 1D models suggest maximum energy in the water layer is achieved when the whole sound path acts as a coupled resonant unit and like travelling wave systems [33], matching layers increase the coupling efficiency between layers. However in resonant systems with out of phase connections face-to-face as shown in Fig. 1 matching layers increase both constructive and destructive interference between the layers, and are therefore unhelpful [27]. The design in this paper is based on the concept of allowing individual parts to vibrate freely where possible by using sub-wavelength contact points as shown in Fig. 2b. Multiple small contacts are used to give more structural stability than a single contact. These contacts are not aligned at points of matched displacement on two surfaces, because alignment is currently not practical due to the large number of potential resonances at MHz frequencies. However our 3D models indicate that making contact only at in-phase regions is a feasible aim.

2. Materials and methods

2.1. Chambers and sound transmission from the PZT to the resonance chambers

Four springs placed at the corners of a 100 × 20 × 3 mm aluminium clamping plate pressed it onto the back face of the 2 mm thick (1 MHz nominal resonance thickness) 20 × 20 mm PZT (Pz26, Meggitt A/S, Kvistgård, Denmark). The PZT is pressed with a force of ~10 N against the resonant duct (see Fig. 2a and c). For the reasons given in Section 1.4, the contact face of the aluminium plate is milled with an array of pin protrusions 0.2 × 0.2 × 0.2 mm at 2.5 mm spacing in a square grid, (the same pin-grid is used for all face-to-face contacts with vibrating parts). In addition to mechanical support for the PZT, the aluminium plate carries the live electrical signal to the outer PZT face. A second aluminium plate, with the pin-grid restrains the opposite face of the chamber. One of these plates has a BNC connector fitted at one end, and acts as a ground plate, the other plate is live with the signal transferred by a long spring-loaded-screw to the central BNC pin. When a glass (non-conducting) chamber is used, a second long spring loaded screw makes the ground connection to the chamber side of the PZT.

Three types of chamber were used, each cut to 100 mm length from extruded duct: Chamber I was a rectangular borosilicate glass duct with an internal section 30 × 3 mm, wall thickness 1.5 mm (Vitrocom, Mountain Lakes, NJ, USA) volume 9 ml (Fig. 2a and c). Chamber II was a square section aluminium duct internal section 19 × 19 mm, wall thickness 3.25 mm (RS Components, Corby, UK) (Fig. 2b) volume 36.1 ml. Chamber III was an aluminium duct similar to chamber II but with a wall thickness reduced (milled) uniformly to 1.5 mm. The PZT was pressed against the lower sections of all ducts, 20 mm above the lower end. To increase vibration freedom of the aluminium duct and PZT, the grid of pin protrusions was cut into the duct at the contact area.

Chamber I, the glass duct, was used in two configurations: (a) The PZT was pressed against the 30 mm wide flat wall; (b) The PZT was pressed against the 6 mm curved wall.