A MICROFLUIDIC DEVICE FOR ULTRASONIC SEPARATION

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ABSTRACT

This paper describes a microfabricated device designed to provide continuous flow filtration on a microfluidic scale. It uses ultrasound in the megahertz frequency range to concentrate particles at a single node within the flow. It has the potential to allow either clarified fluid or concentrated particle samples to be prepared and hence offers the possibility of a replacement for a centrifugal separator for microfluidic systems. It is primarily constructed using silicon and Pyrex, making it highly compatible with established microfabrication techniques. The modelling, design, fabrication and initial testing of the device are discussed, along with the potential for future developments in the area.

INTRODUCTION

Ultrasonic standing waves generate forces on particles within that standing wave which act towards nodes or antinodes of the standing wave [1]. This can be used to aggregate particles, to manipulate and fractionate particles, or to separate particles from the carrying fluid.

This paper describes a device which falls into the latter category, being a microfluidic flow through separator, and is an extension of previous work performed by Hawkes and Coakley at Cardiff University into similar devices [2, 3]. These devices were fabricated using traditional techniques, typically from layers of steel and glass. The aim of this work is to fabricate similar devices that are compatible with emerging microfluidic systems, and have the potential to replace conventional centrifugal separation systems for analysis on a microfluidic scale. A separator with the ability to clarify samples or concentrate particles within a sample has important potential applications in integrated microfluidic sensing systems and will be a MEMS device with the ability to concentrate, filter, and harvest particles, cells, and second phases from within a fluid.

DESIGN OF THE MICROFLUIDIC SEPARATOR

In order to ensure compatibility with other microfluidic technologies, the device described is fabricated from silicon and Pyrex, and as such is able to exploit standard silicon processes. Acoustic actuation is achieved via a bonded PZT plate, although future developments will investigate the use of a thick-film PZT actuator [4]. Such a printed actuator would avoid some of the problems currently caused by problems in bonding bulk pzt to a silicon device. Figure 1 shows a schematic cross-section of the prototype.

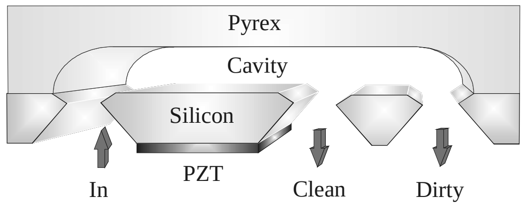


Figure 1 Schematic cross-section of device

As in the Cardiff laminar flow filter [2], a fluid/particle mixture is drawn into the device through the port on the left of the figure. An acoustic standing wave of a half wavelength is maintained within the cavity and as the particles move through the field they migrate to the pressure node at the centre of the cavity. A fraction of the particle-free fluid can then be drawn from the “clean” outlet and the remainder of the fluid/particle mixture can be drawn from the final, dirty outlet. Such a scheme allows for a relatively small quantity of clarified fluid to be produced, but different geometries have the potential to increase the proportion of clarified fluid recovered, or alternatively to increase the concentration of the particles recovered from the “dirty” outlet.

Acoustic Modelling

Previous work [5] has allowed the characterization and validation of a multi-layered resonant structure, constructed in stainless steel, and this work has been extended to include the silicon/Pyrex construction described here.

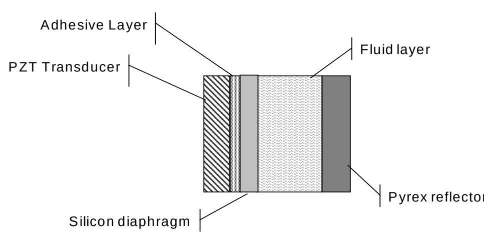


Figure 2 The structural diagram of the layered resonator system

The schematic of Figure 2 shows the structure of the layered resonator system used to model the micromachined ultrasonic separator, and is composed of a piezoelectric transducer, a layer of adhesive, a silicon layer, a filtration chamber filled with fluid, and a Pyrex reflector plate.
Data produced by Hawkes and Coakley [2] has shown the clearance of the stainless steel chamber against frequency. Modelling, using the method described by Hill and Wood [6] demonstrated that a good indication of actual filtration performance could be predicted by the product of the acoustic energy stored in the fluid and the driving frequency (the “energy frequency product”) [5]. The model was used to calculate the energy frequency product against frequency for the Cardiff cell, and this is shown in, together with the experimental clearance data, in Figure 3.

Modelling of the energy frequency product has been used to predict the microfluidic filter’s performance and to select appropriate dimensions for its construction. Dimensions that have been considered include the depth of the cavity, the thickness of the Pyrex layer and the thickness of the silicon layer. A standard silicon wafer thickness of 525µm, along with an overall Pyrex depth of 1.7mm were selected.

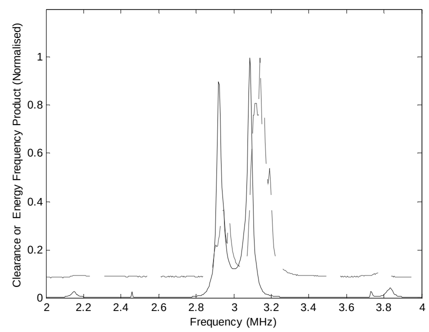


Figure 3. Energy frequency product (solid line) and experimental clearance data (dashed line).

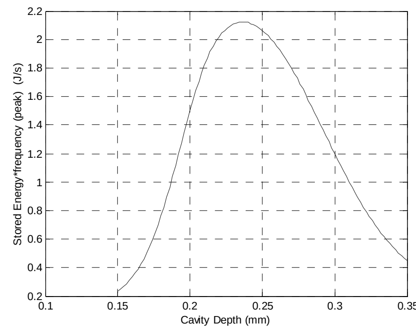
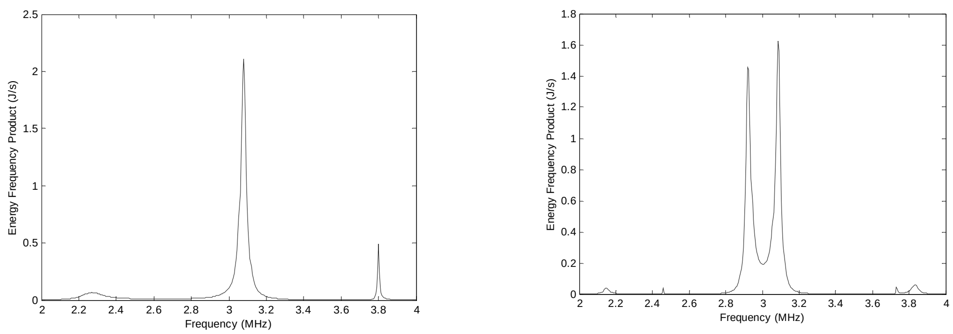


Figure 4 Effect of changing the cavity depth

In order to allow comparison with the performance of the stainless steel filter described in [2], the target cavity depth was in the region of 250μm, to allow a nominal half-wave resonance of about 3MHz. Figure 4 shows the predicted variation in energy frequency product as the depth of the cavity etched into the Pyrex layer is varied. Based on these predictions, a cavity depth of 240μm was selected.



(a) (b)

Figure 5 Predictions of energy frequency product for (a) silicon and (b) steel devices.

If the predicted energy frequency curves for the silicon device are compared with those for the original stainless steel chamber (Figure 5), it can be seen that the curve for the silicon device, has a single dominant peak of slightly higher magnitude. Despite a wide tolerance on peak magnitudes due to uncertainties in material parameters, these simulated results suggest that a silicon-fabricated device has the potential to perform at least as well as the steel chamber.

Fluid Modelling

Computational fluid dynamics (CFD) is being used to investigate the fluid flow through the separator device, principally to highlight flow phenomenon which may be detrimental to the separating performance of the device. The software currently being used for this work is CFX 5.4.1, a commercially available, general purpose CFD package.

The region to be considered for the CFD modelling consists of the silicon/Pyrex section of the device, and excludes the block on which the silicon/Pyrex part is set and contains the relatively large (≤ϕ1mm) inlet and outlet feed channels.

The depth of the flow domain perpendicular to flow typically ranges from 100 to 700μm and the low flow rates being considered in these devices ~0.1 ml/s [2] result in the flow remaining in the laminar region. Also at these scales it is reasonable to assume that the Navier-Stokes set of governing equations and the no-slip condition should be used to describe the fluid flow.[7, 8]

All preliminary CFD simulations have been completed in 2D to reduce computation time. This has the effect of making the flow domain infinitely wide; ignoring the wall effects either side of the flow and making it possible to apply theory pertaining to flow between parallel plates. Initial simulations have been used to optimise the mesh parameters used to create the 2D model and also demonstrate the short distance over which the flow becomes fully developed, typical with the flow rates and micron scale considered for the device.

The entry length, L_e, downstream of which the flow is fully developed and the velocity profile remains constant, is described for laminar flow by [9]

$$\frac{L_e}{d} \approx 0.06\,\mathrm{Re}$$

So for example, where water flows at 0.2m/s between parallel plates 100μm apart the entry length is

$$L_e \approx 0.06\frac{\rho v d^2}{\mu} = 0.06 \times \frac{1000 \times 0.2 \times \left(100 \times 10^{-6}\right)^2}{0.001} = 120\,\mu\mathrm{m}$$

This channel flow example has been modelled in CFD and Figure 6 shows the resulting velocity variation along the centre line and includes the theoretical entry length of 120μm calculated above, clearly correlating excellently with the CFD results where the velocity ceases to change.

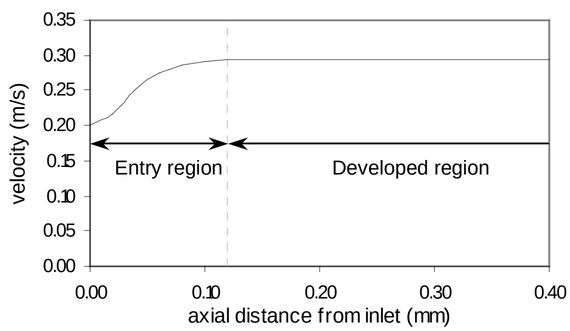


Figure 6 CFD results of centre line velocity over inlet region

Further mesh dependency studies are required to improve the accuracy of the model and as an initial validation will use the above theoretical velocity profile in addition to experimental results. Initial results are good as Figure 7 indicates for the inlet region of the device.

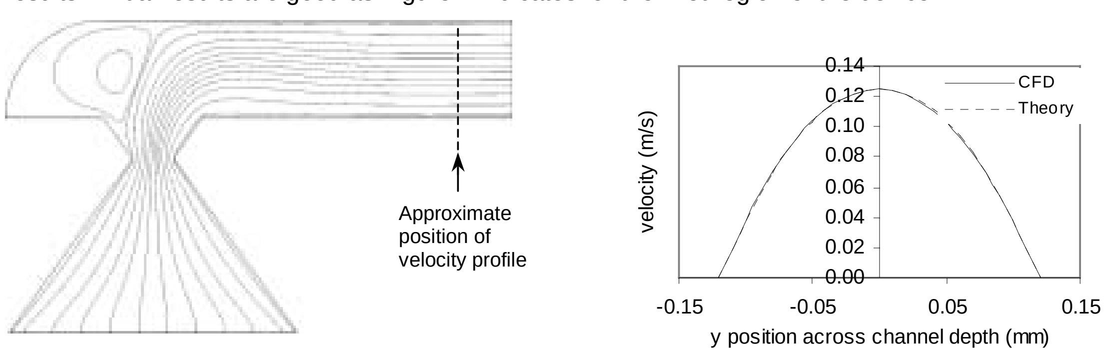


Figure 7 CFD model of inlet section and resulting velocity profile

Initial simulations using the separator geometry have illustrated the extent of separation regions in the flow as shown in Figure 7 for the device inlet region. This suggests a potential for solid particles in the flow to gather in these virtually stagnant regions and presents problems associated with the cleaning of the device between operations and the sudden release of a cluster of particles impeding the separation efficiency of the ultrasonic field and even causing clogging. The influence of these separating regions must be investigated through experiment and could result in recommendations for the inlet and outlet geometry.

CONSTRUCTION

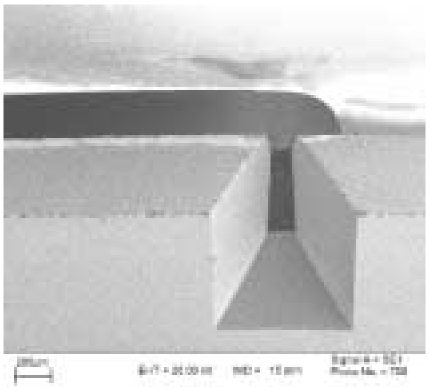


Figure 8 SEM of a single chamfer port

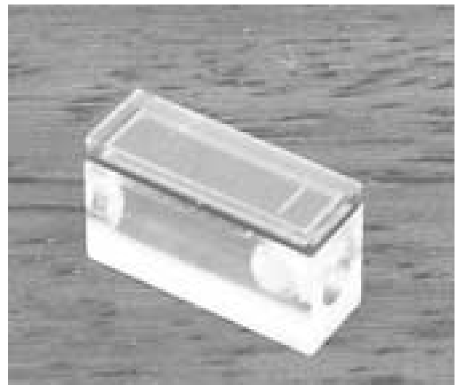


Figure 9 The assembled device

Two types of device have been fabricated, one with double chamfered ports and one with single chamfered ports. In order to achieve this, double sided wafer processing was required. This was achieved using a double sided alignment process and standard wet KOH etching leaving chamfers at the angle of 54.7^{o}. The chamber was then formed by etching a 1.7mm thick Pyrex wafer to the desired depth of 240µm. This was achieved with a 30 minute etch in 48% buffered Hydrofluoric acid using a chrome/gold mask (50nm and 500nm thick respectively) and Shipley S1818 resist in order to minimise pinholes. The silicon and Pyrex wafer were then anodically bonded together.
Figure 8 shows an SEM of a single chamfer port, and a section of the Pyrex cavity, while Figure 9 shows a photograph of the finished separator, mounted on a Perspex manifold, to allow easy connection of pipe work.

INITIAL TESTING

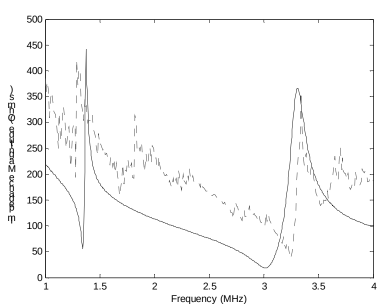


Figure 10 Impedance of empty chamber (Modelled – solid line)

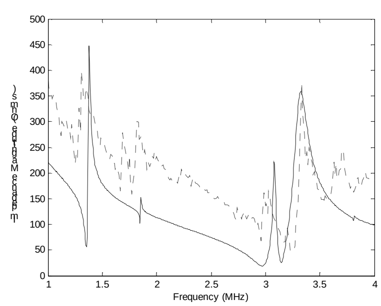


Figure 11 Impedance of full chamber (Modelled – solid line)

In order to test the accuracy of the model, impedance testing has been performed on the assembled prototype. Impedance represents a parameter that is relatively easy to measure experimentally, unlike other parameters such as energy frequency product, allowing partial verification of the model. Impedance measurements were taken using a Hewlett Packard 4192A frequency analyser, under PC control. Initially measurements were taken with both 0.5 and 1V excitation amplitudes, but no measurable difference was noted and so all subsequent measurements were taken at an excitation voltage of 1V.

Figure 10 shows the measured and modelled impedance of the empty chamber, and Figure 11 shows the results for a chamber filled with fluid. The main features to note are that an extra peak appears at 3.1MHz for the full device, which is due to the intensity of the standing wave formed in the cavity. When the device is empty (full of air), the structure shown in Figure 2 effectively has the fluid and the Pyrex layer removed, hence the lack of a trace due to the cavity resonance in Figure 10. It should be noted that the above results have been modelled with an adhesive layer of 60µm. This thickness will be reduced in future prototypes and the elimination of the variability and uncertainty caused by the adhesive is a major motivation for using printed, rather than bulk, PZT in such a design.

CONCLUSIONS

A micromachined microfluidic ultrasonic separator has been modelled, designed and built using standard micromaching processes. The results from the model compare favourably with the results obtained from models of a previous separator built in stainless steel. Further work will test the devices and develop the concept to use a thick-film PZT actuator rather than the bulk PZT currently used.

ACKNOWLEDGMENTS

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