Serpentine Fluidic Structures for Particle Separation

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ABSTRACT

The abstract proposes size and mass based separation and concentration of particles including biological agents suspended in fluidic media in a serpentine channel structure. On the curved sections of the serpentine channel, the interplay between the outward directed centrifugal force and the inward directed transverse pressure field from fluid shear allows for separation of particles. Methods currently employed for particle separation include: mechanical sieving, sedimentation, hydrodynamic chromatography, and electrophoresis. These techniques are batch processes and require large investments in equipment and set-up time for each run. This present study details a filter-less continuous process which employs flow velocity and tailored channel geometry to achieve separation and segregation of particles over a large dynamic size range which can span micro-scale to macro-scale fluid capacities.

Keywords: serpentine channel, centrifugal force, pressure field, particle separation

Nomenclature:

V	=	Flow Velocity
P	=	Pressure
F_{cf}	=	Centrifugal Force on the Particle
F_{id}	=	Inward directed dynamic forces
F_{vd}	=	Force due to viscous drag
R	=	Radius of curvature of the channel
η	=	Dynamic Viscosity of the fluid
m	=	Mass of the particle
a	=	Radius of the particle assuming it to be spherical

1 BACKGROUND

Particle separation and sorting represents an important requirement especially in biological and chemical processes for both macro-scale and miniaturized lab-on-chip applications. The techniques used today for this purpose fall into two broad categories – mechanical sieving and external force field. Mechanical sieving involves the use of filters as a physical barrier and has its own disadvantages such as clogging, reduction in performance with time and high cost for filters designed for smaller size particles.

Sedimentation, chromatography, electrophoresis and Field Flow Fractionation (FFF) are techniques based on external force. More recent developments in microfluidics based filter-less particle separation system include work based on the *Zweifach–Fung* effect [1], Pinched Flow Fractionation (PFF) [2, 3], SPLITT Fractionation [4], Ultrasonic particle separation [5].

Microfluidics based centrifugal separation has been reported by Brenner [6] which is essentially a miniature centrifuge constructed on a rotating disk with polymer microstructures to carry the fluid. Centrifugal separation in a curved microchannel is also presented in [7], which is based on generation of secondary flow called Dean's vortices in the transverse plane, owing to the curvature. These vortices push the particles towards the outer side of the curved channel, which are collected through the bifurcation.

Though most of these techniques have seen exponential growth, it should be noted that all the above work in this field has a variety of shortcomings. For example, most of them require an additional external force. Moreover, many of these techniques are limited to batch processing and are scaled to handle only minute volumes of samples. Further, many of these processes are typically designed for only a centrifugal mode of operation. The current demand is for continuous flow, high throughput and low cost processes.

2 PROPOSED TECHNIQUE

Here we present a filter-less technique and a system for size and mass based separation of particles. The technique utilizes only channel geometry, radius of curvature and flow velocity within the channel to exert the required force on particles within the fluid to separate out either to the inside or to the outside channel walls. Strategically located collection chambers help in collection of particles from the flowing fluid. The technique is a continuous process which separates particles over a large dynamic size range and which can span from micro-scale to macro-scale fluid capacities.

2.1 Analytical consideration for flow in a curved channel

Particles within a flowing fluid experience a combination of forces acting on them. In the scenario of laminar fluid flow in a curved channel, particles have to face a competition between the outward directed centrifugal force and the inward directed hydro-dynamic forces, which result from pressure variation, channel geometry and flow conditions. Along with these forces there is also the viscous drag, which transports the particles forward in the flow direction. The resultant of these forces causes a net force in one direction, which affects particle motion with respect to the channel axis. Fig 1 shows the different forces acting on a particle of a spherical shape.

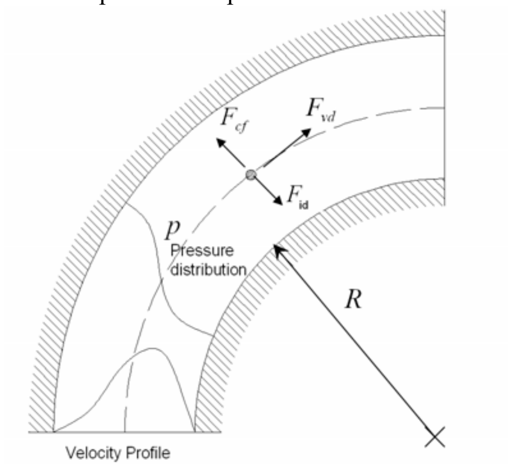


Figure 1: Segment of a curved channel showing various forces acting on the particle along with the velocity profile and the pressure distribution

The expressions for the centrifugal, transverse pressure driven, and viscous drag forces acting on the levitated particle can be expressed as follows:

$$F_{cf} = \frac{mV^2}{R(r)} = \frac{4}{3}\pi a^3 \frac{V^2}{R(r)} \quad (1)$$

$$F_{id} = p\pi a^2 \quad (2)$$

$$F_{vd} = 6\pi\eta a V \quad (3)$$

The particles will move outwards if $F_{cf} > F_{id}$, or

$$\frac{4}{3}\pi a^3 \frac{V^2}{R(r)} > p\pi a^2 \quad (4)$$

Or, $a > p\frac{R(r)}{V^2}\frac{3}{4}$ (5)

Equation (5) can be used to determine the lower bound for levitated particle size that will move outwards for any given geometry, pressure and velocity of flow. Particles smaller than this lower bound will move inwards, or

$$a < p\frac{R(r)}{V^2}\frac{3}{4} \quad (6)$$

The distance of travel before the particle migrates across the flow channel (transverse direction) is dependent on the relative magnitudes of F_{vd} and F_{id}

Also since $F_{id} \propto a^2$ and $F_{vd} \propto a$, larger particles will be more affected by the flow induced transverse pressure drop directed towards the inner surface. The transverse pressure may be derived by considering peripheral flow in a concentric cavity where the parabolic profile fits:

$$V_\theta = V_0(r - r_1)(r_2 - r) \quad (7)$$

And r_1 and r_2 are the inner and outer radii, respectively. The radial pressure drop, *p*, is given by (for R>>r):

$$p = \int_{r_1}^{r_2} \frac{\rho V_\theta^{\ 2}}{R(r)} dr$$
$$= V_0^{\ 2}\frac{\rho}{R}\left[\frac{r^5}{5} - \frac{(r_1 + r_2)r^4}{2} + \frac{(r_1^{\ 2} + 4r_1r_2 + r_2^{\ 2})r^3}{3} - r_1r_2(r_1 + r_2)r^2 + r_1^{\ 2}r_2^{\ 2}r\right] \quad (8)$$

It can be seen from the equation (8) that the pressure is a function of the velocity of flow, density of particles and the radius of curvature of the curved channel.

At a higher velocity the centrifugal force, directed away from the centroid of the curvature, is dominant on the particles, pushing the particles towards the outside wall [7, 8]. At a lower velocity, the centrifugal force is not strong enough to push particles towards the outside and to trap them near the outside wall. The particles can settle at the base of the channel in the slow flow and migrate toward the inner wall by the hydrodynamic pressure induced by the secondary flow or Dean's vortex. The Dean's number can be calculated by equation (9),

$$De = \mathrm{Re}\sqrt{\frac{D_{eq}}{2R}} \quad (9)$$

where, Re is the respective Reynolds number and D_{eq} is the hydraulic diameter. Placing a collection chamber strategically towards the outer wall will capture the particles from the flow with high efficiency. The collection chamber should be designed in such a way that the flow pattern within the collection chamber is decoupled from the flow within the channel adjacent to it. A strategically located collection chamber at the inner wall of the channel will capture these particles in a similar fashion as that in the higher velocity case.

3 EXPERIMENTS

3.1 Prototype

Experimental prototypes were built to prove the concept. The schematic of the experimental prototype is shown in Fig. 2. The width of the channel used is 5 mm. The radius of curvature of both the curved sections is 28 mm. The thickness of the whole structure is 500 µm (0.05 cm). The collection chambers are located strategically so that the particles will move into them as soon as they encounter a resultant directional force. Collection chambers A & D lay on the out side of the curved channel profile while chambers B & C lay on the inside of the curved channel profile. The fluid containing particles enters through the inlet, which is connected to a peristaltic pump.

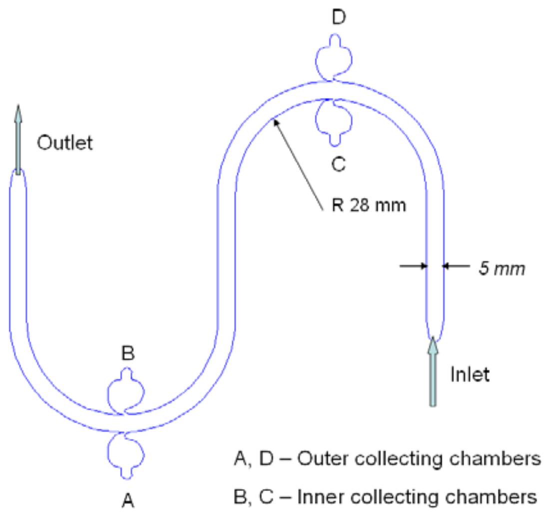


Figure 2: Schematic of the experimental prototype to prove the concept.

The fluid passes through the two curvatures of the serpentine channel and comes out through the outlet. Two different flow rates were used for the experimental purpose *viz.* 5 ml/min and 14 ml/min.

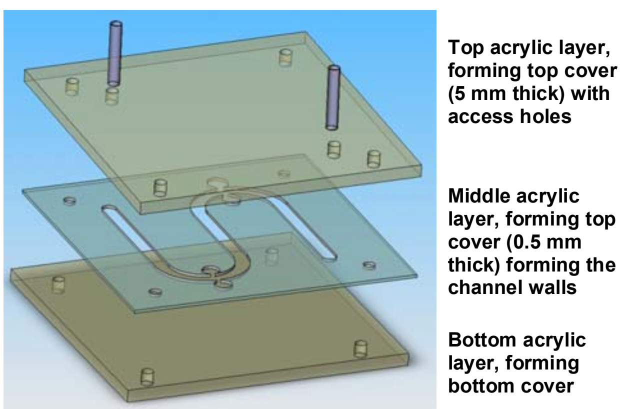
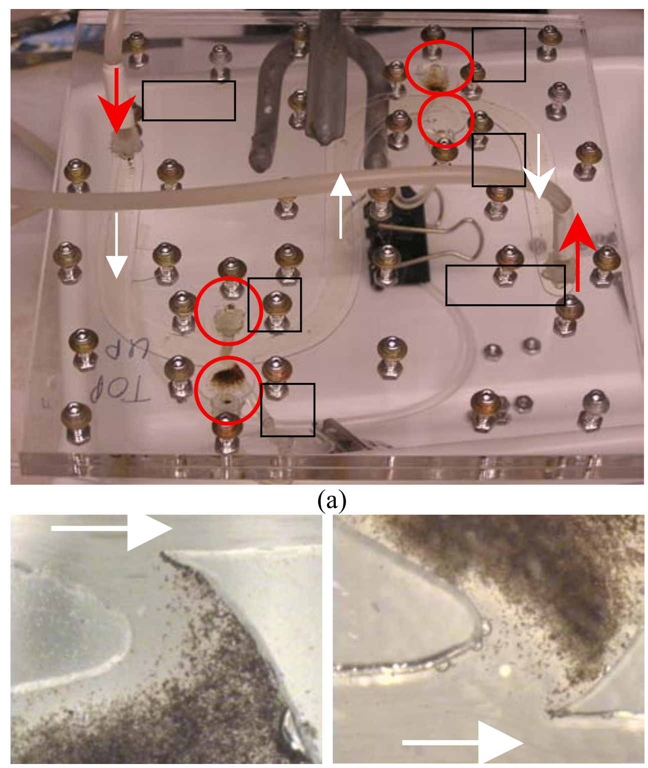


Figure 3: Three component layers of a serpentine cell.

The channels were formed by cutting silicone sheets to the required dimensions using a laser cutter. The acrylic sheet formed top and bottom covers and also provided holes for the inlet and outlet. The different layers were bonded together with the help of screws. The channel was primed with DI water to remove bubbles and then a solution containing particles was flowed at two different flow rates forming the parts of two different experiments. Figure 3 shows a schematic of the flow cell that was used for the experiments.

3.2 Experimental results and discussion

Two different results were observed at the two different inlet flow rates. At a flow rate of 14 ml/min, the centrifugal force on the particle dominates over the force due to the hydrodynamic pressure gradient experienced by the particles. This force is directed outwards away from the centroid of the radius of curvature. The Reynolds number for the flow is 85 and Dean's number is 10 in this case. The Dean's vortices keep the particles re-suspended within the channel and prevent them from settling down. Thus, due to the centrifugal force encountered by them, the particles move away from this center of the curvature when they come across the curved section. This outward force acting on the particle pushes them into the collecting chambers A and D which are situated outwards of the curvature. Fig. 4 shows particle laden fluid flowing through the channel from the inlet to the outlet along a serpentine path at an inlet flow rate of 14 ml/min. It can be seen that the particles get diverted into the outer collection chambers A and D and not in the chambers B and C which are situated inwards of the curvature just opposite of the outer collection chambers. Fig. 4 (a) and (b) shows enlarged views of the collection chambers which are also shaped to de-couple fluidics but allow particle capture.

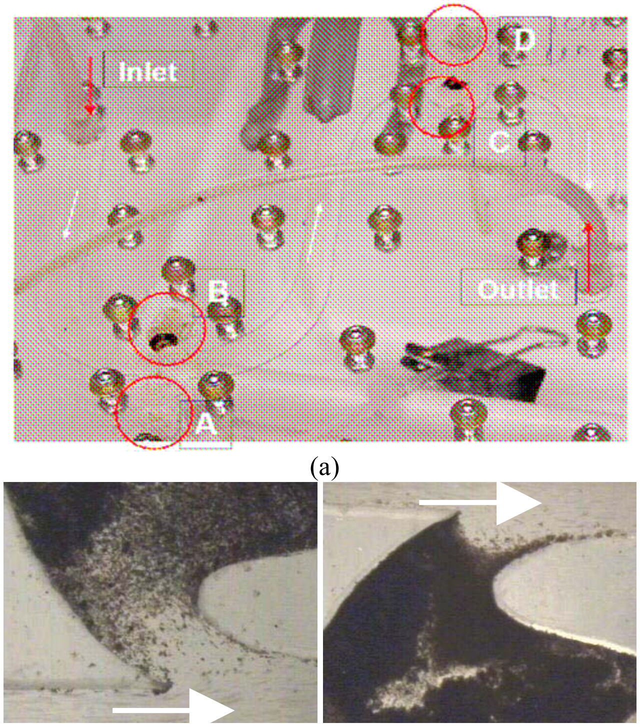


(a)

(b) (c)

Figure 4: (a) Experimental set-up showing that the particles being collected in the outer collection chambers A and D at a flow rate of 14 ml/min and showing an expanded view of the collection chambers A (a) and D (b). The arrow indicates the direction of flow.

At a flow rate of 5 ml/min, the hydrodynamic forces on the particle due to the pressure difference across the channel were dominant compared to the centrifugal force experienced by the particles. These forces are directed inwards towards the centroid of the radius of curvature. The Reynolds number for the flow is 30 and Dean's number is 3 [7, 8]. Due to the slow velocity, the particles settle down and the velocities of the Dean's vortices are not sufficient to get them re-suspended. The centrifugal force is not large enough to push them towards the outer wall. Thus particles move towards the center of the curvature when they come across the curved section. This inward force acting on the particle pushes them to the collecting chambers B and C which are situated inwards of the curvature. Fig. 5 shows particle laden fluid flowing through the channel from the inlet to the outlet along a serpentine path at an inlet flow rate of 5 ml/min. It can be seen that the particles get diverted into the inner collection chambers B and C and not in the chambers A and D which are situated outwards of the curvature just opposite of the inner collection chambers. Fig. 5 (a) and (b) shows enlarged views of the collection chambers which are shaped to decouple fluidics but allow particle capture.



(a)

(b) (c)

Figure 5: (a) Experimental set-up showing that the particles being collected in the inner collection chambers B and C at a flow rate of 5 ml/min and showing an expanded view of the collection chambers B (a) and C (b). The arrow indicates the direction of flow.

4 DISCUSSION AND CONCLUSION

This method solves the issue of an external field required for manipulating particles in the fluid. In the proposed design, geometric controls are only required on the channel width, height and the radius of curvatures of the curved sections. Another advantage of this method is that continuous particle separation of a wide range of liquid volumes can be achieved when compared to techniques such as centrifugation or chromatography. As compared to other continuous particle separation processes, the advantage is the simplicity in geometric control of the device. The channel widths need not be comparable with the size of the particle under question. The magnitude and the direction of the force on the particle can be manipulated just by changing these geometric parameters and the flow rate.

By easily altering the channel widths and the radius of curvatures of the curved sections, particles of decreasing size can be collected at discrete collection chambers placed along the length of the serpentine channel. The correct selection of dimensions can limit the device for a particles size separation range below 10 µm. This is the typical range of biological cell size. The collection efficiency can be improved by, along with dimensional changes, the strategic placement of collection chambers. A microscale version of such a device can be easily fabricated with simple techniques and can be easily integrated inline with other components in a Lab-on-a-chip type environment. The simplicity comes with the fact that a use of external field is eliminated. This makes the whole micro-scale analysis device much simple and reliable.

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