The Sequoia Particle Sorter

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The use of PDMS devices in the sorting of particles allows for easy distribution around the world for a variety of applications. This paper describes a device that shows trends of accurately and efficiently sorting out large particles from smaller ones, despite difficulties faced in the manufacturing and testing of the device. The Sequoia Sorter is among the first of its kind that utilizes airfoils to effectively re-orient streamlines to sort particles that can then be detected in specific reservoirs. As a lab on a chip, this device requires little to no lab instruments in order to test fluid for contaminants, and is the most obvious choice to use in the field of microfluidic particle sorters.

Introduction

Sorting particles has always been an objective much sought after in the world of photolithographic microfluidic systems. The usage of a device that can accurately do so could be used for many applications, ranging from point-of-care antibody testing in blood to in-lab health diagnostics. This device, the Sequoia Sorter, focuses on one main application, de-contaminating fluid, by sorting out large contaminants.

This goal is accomplished in a very unique way, not yet seen in this field. Where other lab teams have used deterministic lateral displacement[1,2] or gravity driven[3] models, Redwood Laboratories decided to incorporate airfoils. By placing these in the middle of our microfluidic channels at certain calculated attack angles, medium to large-sized particles will be deflected into sorting channels, while the smaller particles flow through to the end.

Methods

Design Principles. This device's design is based upon three main aspects: airfoils, multiple sorting paths, and fluid outlet channels, all of which worked towards our objective of detecting contaminants.

Airfoils were chosen for a variety of reasons. For one, airfoils have never been used before in a microfluidic device, and we wanted to study whether or not airfoils were a viable option in terms of sorting particles. Secondly, we took advantage of laminar flow at low Reynolds numbers[4] to separate streamlines with airfoils, making it easy to sort particles that naturally separate into different streamlines. Lastly, by utilizing multiple airfoil angles throughout the device, we can see how to best optimize the use of airfoils in such a system.

The airfoils were modeled to have a specific width and length in order to allow beads to pass by without getting clogged, as well as to properly deflect desired streamlines into the numerous daughter channels. A reasonably shallow angle of attack was used, to insure this sorting tool will deflect streamlines properly and sort particles effectively, without over-sorting. If too many particles are filtered out of the fluid too fast, the device may clog, and thus the airfoils were designed to slowly filter out and sort particles. The airfoils and their respective secondary channels are not too densely packed in our device, to prevent failure due to overexposure during the fabrication process.

The next design decision was to include multiple sorting paths, in essence

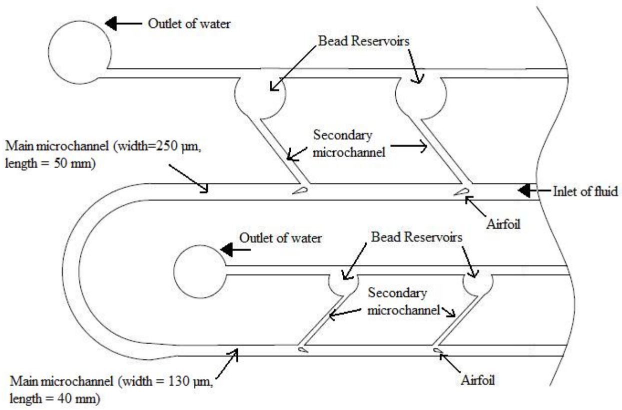

Figure 1: Schematic diagram of the Sequoia Sorter.

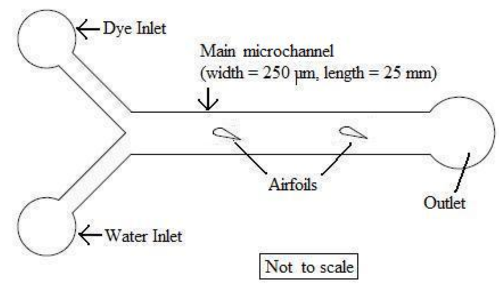

Figure 2: Schematic diagram for secondary device, to test laminar flow around airfoils.

creating a redundant sorting system that will help increase the efficiency with which the medium and large particles are removed from the sample fluid. Over the course of 17 channels, the particles are sorted out, eventually outputting a sample without medium or large particles (Figure 1).

The last design principle involved incorporating exit channels for the fluid, to prevent clogging or backflow. Each collecting bin had a small channel at the end to allow for fluid to escape to an outlet pore, while the model particles stayed in the receptacles.

For this device and the method of fabrication used, the estimated margin of error that the device can withstand was calculated to be around 10%, based on our critical airfoil parameters. Any errors greater than 10% may cause the airfoils to act undesirably and not achieve the desired sorting efficiency.

The Sequoia Sorter was fabricated out of polydimethylsiloxane (PDMS) using standard soft lithography procedures. A mask was printed from a CAD file, which was then used in contact lithography. This mask was used to create a negative master out of SU-8 2100 photoresist on a silicon wafer. Once finished, PDMS was molded against this negative master. After baking, the PDMS device was cut out from the mold and plasma bonded to a glass substrate, thereby creating the microfluidic channels. The inlet and outlet ports were cored with syringes, to allow for tubing at the inlets and for fluid to escape at the designated outputs.

A number of steps were taken to ensure that minimal errors occurred during fabrication. To avoid complications in the exposure and resist-processing step, we placed the vital parts of our device away from the edges, sidestepping the problem of outgassing, overexposure, and natural beading at the edges caused by SU8 resist. Precautions were also taken with the plasma treating of the device by running the PDMS structure and glass substrate multiple times through the machine to ensure complete bonding.

Experiment. The experimentation on this design started with an initial check of the fluid flow around the airfoils. In order to test their effectiveness, a separate device was created, with a design consisting of one main channel with airfoils at similar angles to the original device (Figure 2).

Prior research showed that the flow would be laminar, based on experiments done with fluid on the microscale (at low Reynolds numbers)[4]. Green dye was mixed with a phosphate buffered saline solution (PBS) and injected into the system using a syringe pump. The flow proved to be

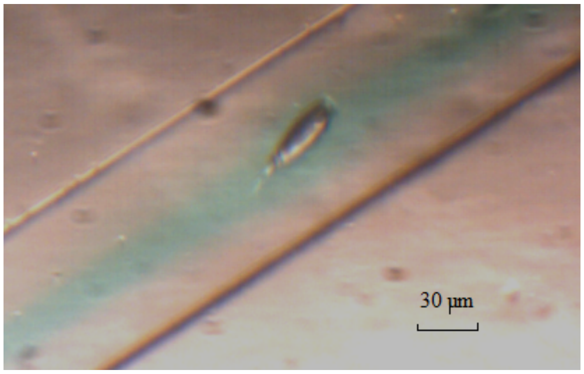

Figure 3: Photo of dye-infusion test, where fluid characterized by laminar flow can be seen before and after encountering the airfoil.

laminar, and the airfoils indeed did separate streamlines, as was initially expected[5]. After the PBS solution flowed around the airfoils, the streamlines collapsed again into one distinct flow. Turbulence was neither expected nor accounted for, and thus seeing the laminar flow before and after the airfoils was an initial success for this design[6] (Figure 3).

After the initial experiments to test the fluid flow were completed, the next step was to test the efficiency of the actual devices. Microspheres of diameters 10, 25, 50 µm were used as model particles. These colloids were suspended in a PBS solution that was injected through the inlet port with a syringe pump. Initially, a slower flow rate was used, but the velocity was not enough to create the desired streamlines. The optimal velocity was found to occur at approximately 300 μl per minute, and thus this flow rate was used for the entirety of the experiment.

From past research, all particles in a streamline travel at the same velocity[6]. Because the colloids that were used in this experiment were made of the same material (constant density), the different sized particles have different masses, and thus different velocities. This ensures that the different sizes of beads will flow in separate streamlines[6] (See Figure 4). We took advantage of this laminar fluid-flow

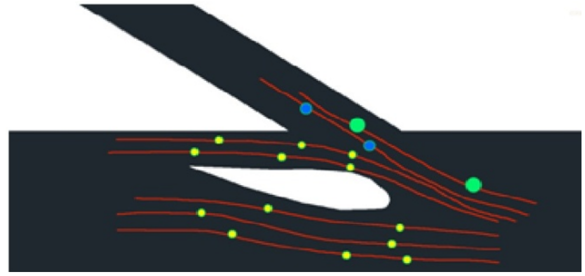

Figure 4: Cartoon of the way beads are expected to behave when approaching the airfoil. The larger beads (green and blue) will separate off, while the smaller beads (yellow) will pass around the airfoil.

phenomenon and used it to create airfoils that would further separate and deflect streamlines, in order to collect the particles in reservoirs.

As the fluid serpentines through the device, the channel width decreases, to increase velocity. This was implemented to ensure that the fluid would continue to flow through the entire device, without any disrupting backflow.

Assessing the performance of this device involves ensuring that there is a minimal amount of small particles in the side channels, relative to the number of larger beads. Eighty percent of the beads in the final reservoir are expected to be small beads to be truly efficient. Based off this data, the device may be modified to increase efficiency either by changing the size of the airfoils or their angle of attack, or by modifying the channel widths.

Results

The final devices had some major failures, and thus the results are limited, although they do show some promise. As can be seen in Figure 5, the first few channels did show a general decline of large and medium particles. The largest irregularity however, is the bead count in the final reservoir, and under the PDMS in that region. Because the channel serpentines and winds back, the leak from one of the earlier channels ran into the exit port, thus

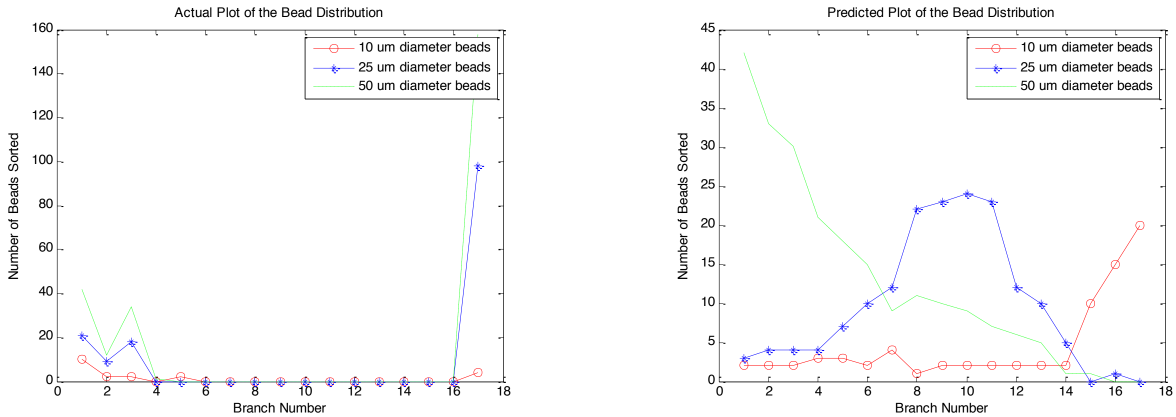

Figure 5: Plots of bead distribution. Shown are plots of number of test colloids found in each collecting bin, as a function of reservoir number. Reservoir 1 is the first reservoir from the entrance, and reservoir 14 is at the exit. Left is the actual bead distribution, resulting from initial lab tests. Right is predicted bead distribution, based on preliminary research and design principles.

producing a large and unexpected pool of fluid containing a majority of the model particles.

Due to problems with sealing and contaminants in the Sequoia Sorter, beads ended up in many places that they should not have. Some particles clogged outlet ports (Figure 6) and the flow around airfoils, but the most significant failure was due to leaks that allowed the colloids to escape the channels and get trapped between the PDMS structure and the glass substrate. There were some substantial leaks at many different sections of the device, resulting in distorted results. For preliminary testing, two devices were fabricated, identical except for the attack angle of the airfoils. However, one device had a leak at the inlet port, so the entire device was rendered unusable (Figure 7). The other device had a leak around the fourth reservoir, so channels 5-17 were also unusable.

To obtain more definitive results, more lab time is needed, although from our preliminary testing, we did see some success in the airfoils. The separation of streamlines is the key to the success of this device, and that was demonstrated by pumping dyed fluid through the device. This phenomenon is shown in Figure 8[7].

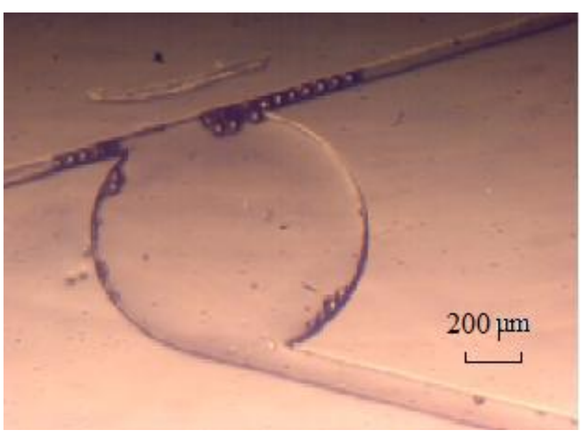

Figure 6: Photo of one reservoir, where fluid outlet port was blocked by large colloids.

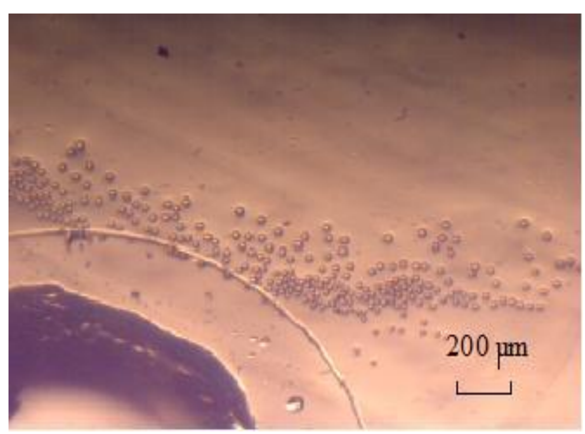

Figure 7: Photo showing sealing failure at inlet port, resulting in the leaking of sample fluid.

Discussion

From the start, the Sequoia Sorter was designed to sort out particles in stages, by forcing fluid to flow around airfoils, which can be used to redirect streamlines. Some streamlines are forced into daughter channels that lead to small bead reservoirs. The sorting begins with the largest beads, then those of medium size, while the smallest beads are contained in the final reservoir.

Unfortunately, this goal was not achieved. When first pumping solution through our device, we noticed that the PDMS was not bonded completely, causing multiple leaks. Upon closer inspection of the device, we also discovered that approximately %40 of the airfoils were not present. This can be explained by overdevelopment of the negative relief structure. Acetone was used to speed up the development process during fabrication of the master; however, many of the airfoils found the acetone to be fatal, and the final device was missing almost half of the total amount of airfoils. This left our device without many of its sorting apparatuses. A small portion of one of the main channels also fell victim to overdevelopment. This did not affect the success of this particular device, however, because sealing failure already rendered almost 80% of the device unusable. However, had the PDMS structure successfully bonded to the glass wafer, the malfabricated channel would have destroyed the integrity of that single device. Along with the dramatic PDMS failures, some sections of PDMS encapsulated hair and dust contaminants during the fabrication process. These manufacturing defects resulted in a dramatic decrease in the efficiency of this device's sorting capabilities.

The parameter that varied between our two prototypes was the attack angle of the airfoil. However, the second device had a massive leak at the inlet port, resulting in almost all beads escaping at the beginning of the main channel. Because of this, Redwood Labs was not able to effectively test what a change in attack angle would have accomplished. However, this design change would predictably allow for more effective deflection and sorting, because a steeper angle would cause the streamlines to be deflected farther out, and thus force more particles into the sorting channels[8].

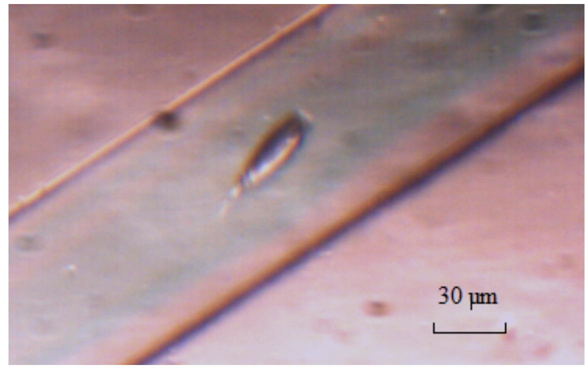

Figure 8: Initial test showing the separation of streamlines as fluid flows over airfoil.

If given the time, there are many improvements that could be implemented to improve this device. Better bonding between the PDMS and the glass will avoid the sealing and leaking problems faced in the experimentation phase, providing a better opportunity to fully test our devices. Another way to allow for a more forgiving substrate is to shrink the device to keep it away from all edges, in order to give the PDMS more of a chance to seal to the substrate. The current design does not allow for this extra space near the edges of the substrate, and thus an improvement here has the possibility to reduce a large majority of the errors we faced during this initial round of experimentation and testing.

Also, the Sequoia Sorter was designed with relatively large differences in bead sizes (between 15-25 µms difference) in mind. The airfoils, as well as the length and width of the channels can be changed to accommodate sets of particles that are closer in size to one another than the colloids that were used during testing, while not losing efficiency.

Also, a decrease in width of the fluid flow exit channels would help prevent the clogging that was experienced while testing the device. Making these channels smaller would allow a faster outflow of excess fluid without slowing down the device.

Other improvements can be made to increase throughput, in order to make this device viable for commercial uses. By adding dozens of parallel arrays to our device, gallons of contaminated fluid can be processed within a reasonable time, versus just milliliters, as was done in the lab.

A viable application for the Sequoia Sorter is as a point of care device for detecting contaminants in drinking water. Easily portable and with no extra accessories or power supplies, this device can be taken almost anywhere. Even though a syringe pump was used in testing, a hand-driven syringe is also compatible with this device. In addition, the fabrication process for the average consumer is simple, requiring only PDMS and a negative master, which can be fabricated anywhere and marketed as a small disposable diagnostic tool: in essence, a lab on a slide.

Despite this ease of use, Redwood Laboratories has been working on a front end to the device, to make it even simpler to operate. Instead of having the consumer having to insert tubes and pumps, possibly misusing, or worse, breaking the device, the Sequoia Sorter will be pre-packaged, where using it is as simple as injecting a syringe of sample fluid into a hole. Then, place it under a microscope and observe the results. Each sorter will be packaged with a detailed instruction manual so that anybody can operate it without fear of misuse.

In terms of restrictions on sample fluids, the fluid should not contain another polymer, because the PDMS (being a polymer) will absorb other polymers. There is also a restriction on the viscosity of the fluid. Testing has only been done on low viscosity fluids, so caution should be taken when using very viscous fluids, as the performance of the device has not been tested and cannot be predicted. The Sequoia Sorter is designed to sort out fairly dissimilar sized particles, so there are some restrictions onto the limits within which the sorter will be able to separate different particle streamlines. The airfoil attack angle is the parameter that will change the deflection of the streamlines, so larger angles of attack will induce larger deflections, which will allow for separation of more similar sized particles.

Are airfoils the key to particle sorting success? This design demands more testing to make any definitive statements, although initial testing shows that the airfoils can separate and deflect streamlines, a major milestone on the way to achieving near perfect particle sorting on the microscale.

Conclusion

We looked at possible uses for airfoils on the microscale. The small scale allows us to utilize laminar flow characteristics, and thus take advantage of fluid flow over aerodynamic shapes. The data shows general trends leading us to the conclusion that this device, although currently requiring more tests, can successfully sort out particles on the order of 25-50 μm in diameter. This can be used in rural or undeveloped areas to filter out unwanted fluid contaminants. The Sequoia Sorter can be used almost anywhere, to effectively detect and sort out contaminants in fluids. It can be fabricated anywhere, without needing a clean room or expensive lab equipment. PDMS and a negative master, which can be purchased prefabricated, are the only materials needed. Further work will involve optimizing the attack angle and size of the airfoils, the critical number of sorting channels, and increasing the throughput to allow this device to efficiently separate out contaminants in drinking fluid to allow a reasonable flow rate on the macro scale.

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References

1. K.. Loutherback, et al. "Deterministic Microfluidic Ratchet." Physical Review Letters (Jan. 2009): 045301-1 - 4. Print.

2. D. W. Inglis, et al. "Critical Particle Size for Fractionation by Determinisitic Lateral Displacement." Lab on a Chip (Mar. 2006): 655-658. Print.

3. D. Huh, et al. "Gravity-Driven Microfluidic Particle Sorting Device with Hydrodynamic Separation Amplification." Analytical Chemistry 79.4 (2007): 1369-1376. Print.

4. B. Munson, et al. *Fundamentals of Fluid Mechanics*. 6th ed. N.p.: Wiley, 2009. Print.

5. J. Bertin and M. L. Smith, *Aerodynamics for Engineers, Third Edition*, Upper Saddle River, NJ: Prentice-Hall, Inc., 1998. Print.

6. R. A. Granger. *Fluid Mechanics*. pp. 422-425: Dover Publications, 1995. Print.

7. M. Nakamura. "Air Foil." *Massachusetts Institute of Technology*. Martin L. Culpepper, 1999. Web. 5 Dec. 2010. <http://web.mit.edu/2.972/www/reports/airfoil/airfoil.html>.

8. R. H. Barnard and D.R. Philpott. *Aircraft Flight: a description of the physical principles of aircraft flight*, Essex, England: Longman Group Limited, 1995. Print