Separating Particles Using Tangential Flow Filtration and Inertial Microfluidics

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Abstract

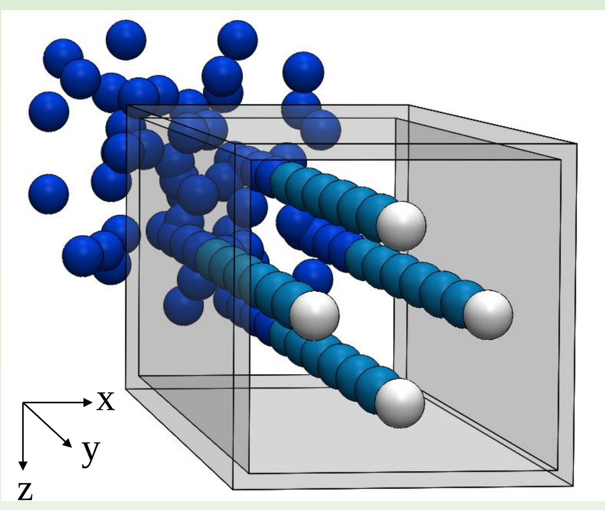
Separation of particles is a crucial component in a myriad of bioanalytical and chemical processing applications. Recently researchers have exploited the phenomenon of inertial microfluidics by focusing known particles sizes into static equilibrium positions to separate the micron-sized particles because the technique requires smaller sample volume, has a high throughput, and is inherently robust. Unfortunately, inertial microfluidics lacks versatility: the extent of achievable separation is limited, since particle equilibrium positions are determined by the geometry only. To overcome this limitation, we experimentally investigate the effect of adding permeate flow in an inertial microfluidic system to refocus particles into tunable equilibrium locations, thus creating dynamic separations. Specifically, we experimentally investigate the effect of permeate flow on the equilibrium location of 5, 10, and 15 µm polystyrene particles in a MEMS fabricated inertial flow system with permeate channels (i.e. a tangential flow filtration device). We observe that smaller particles focus closer to the channel walls than larger particles. Furthermore, the particle equilibrium location is a function of streamwise distance, and equilibrium location at the exit is a function of the ratio of outlet to inlet flow. Taking advantage of this data, we aim to create in-situ control of particle equilibrium locations resulting in real time separations of particles of unknown size distribution. This method can be combined with on-chip devices for diagnostic applications, benefitting the fluids and separations community.

Background

The Reynolds number (Re) of a flow describes the relative importance of inertial forces and viscous forces.

$$Re = \frac{\rho U H}{\mu}$$

where ρ is the fluid density, U is the velocity, H is the characteristic length, and µ is the viscosity.



For Re values much less than one, viscous forces dominate; for Re values much greater than one hundred, inertial forces dominate. In the Reynold's regime between one and one hundred, where neither forces dominate, inertial focusing occurs.

Figure 1: A random distribution of particles gathering in four equilibrium positions as a result of inertial focusing.

Inertial focusing is caused by two main forces that push on the particles from either side (Fig 2).[1]

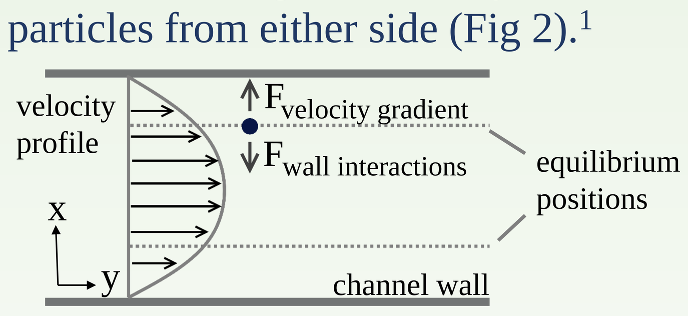


Figure 2: The force arising from interactions between the particle and the wall pushes the particle closer to the center. The force from the velocity gradient pushes the particle toward the wall.

In addition to Reynolds number there is particle Reynolds number Re_p, used to understand particles and the nature of the surrounding flow.

$$Re_p = Re\left(\frac{a}{H}\right)^2$$

where Re is the Reynolds number, α is the particle diameter, and H is the characteristic length.

We added Tangential Flow Filtration (TFF) to our inertial microfluidic device, allowing manipulation of the permeate flow. We define β as the ratio of retentate flow to feed flow to show the relationship between the permeate and the equilibrium positions.

$$\beta = \frac{retentate}{feed}$$

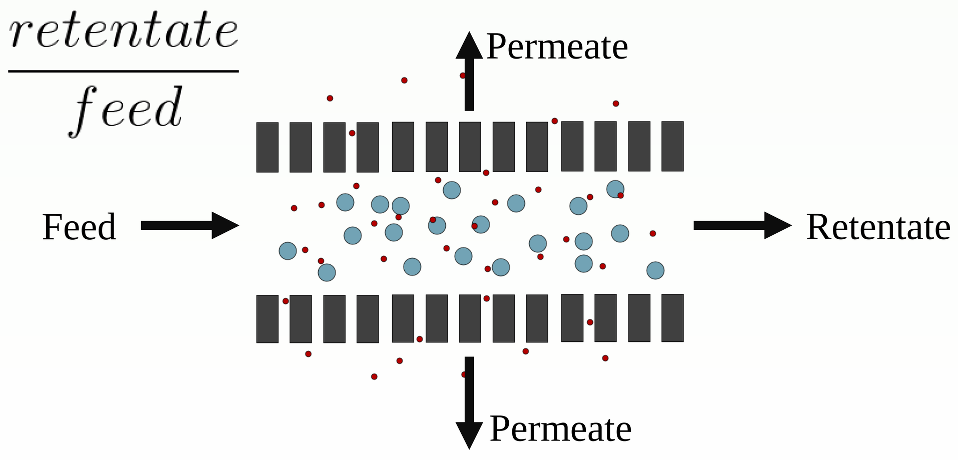


Figure 3: TFF is a method of purification where fluid enters the main channel and is tangentially filtered through the porous channel walls (permeate). The remainder of the fluid that exits the channel is the retentate.

Goals

Through experimentation, we wanted to understand how manipulations in the permeate force changed equilibrium position, and if there was a size dependence with this force. If there was a size dependence, we wanted to determine what parameters lead to the best separation.

Methods

We fabricated our microfluidic chip by etching channels into a silicon wafer and bonding it to a borosilicate wafer. This process is repeatable with the ability to make channels that can withstand high pressures without deforming or leaking. The main channel is 100µm wide and the permeate channels are 5µm wide.

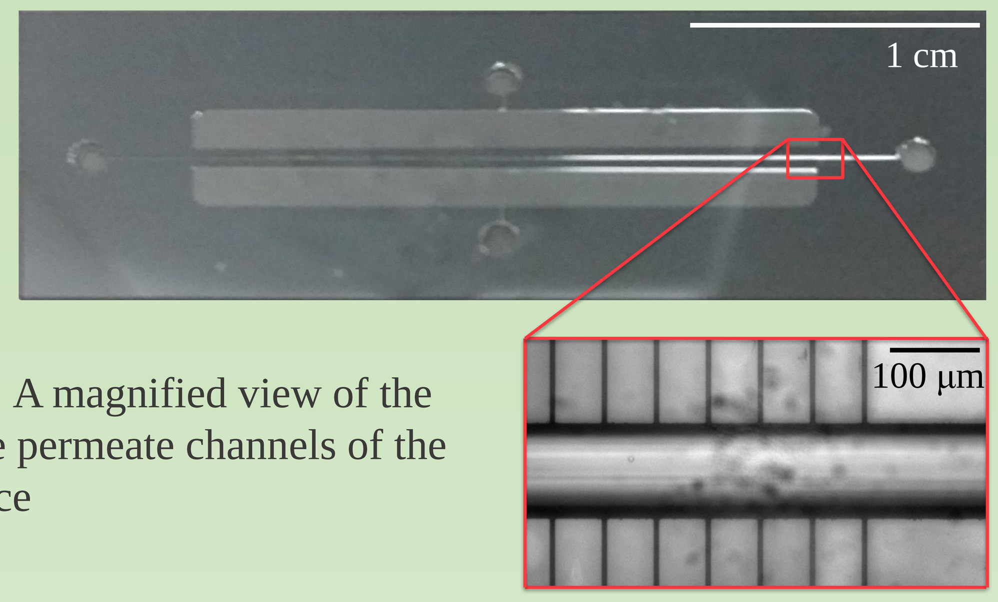


Figure 4: A magnified view of the end of the permeate channels of the TFF device

To run our experiments, we designed a setup where we could manipulate the feed flow and permeate flow independently, as well as observe particles in the flow directly. We used syringe pumps to control the flow rate in (Feed) and flow rate out (Retentate). Modulation of the second pump allowed control over the volume of fluid exiting through the permeate channels through the difference between pump rates.

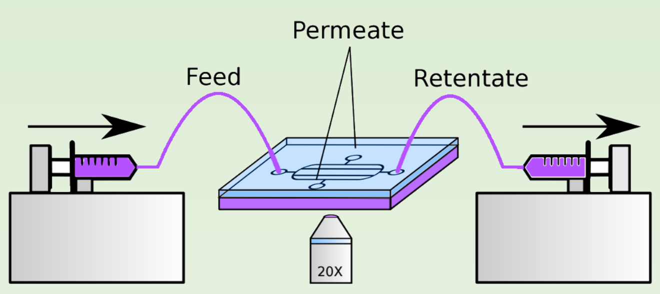


Figure 5: The experimental setup depicting the two syringe system to control permeate flow through the microfluidic TFF device.

Using fluorescent microscopy, we captured long exposure images of the particles. This method was used to show the probability of the particles density and to capture the location of the densities for an accumulation of many particles. We used MatLab to analyze the images and find the distance between the peaks. The distance between the channel center and an equilibrium location is half of the peak-to-peak distance since the equilibrium positions are symmetrical about the channel center. We recorded equilibrium position data for polystyrene particles that were 5, 10 and 15µm in diameter.

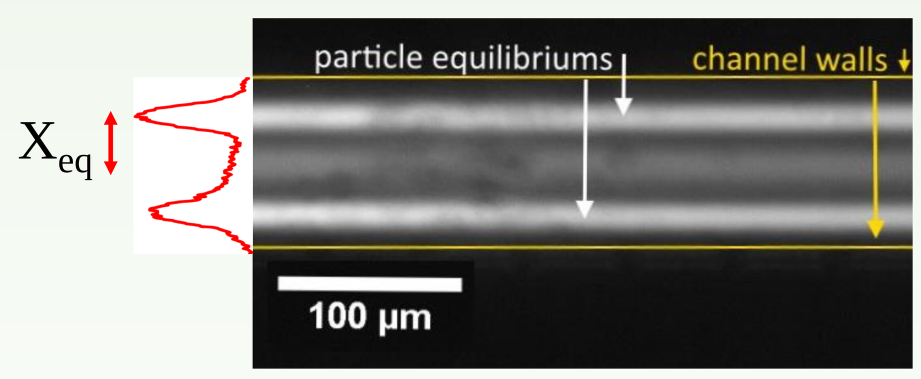


Figure 6: An example of a long exposure image, where the white streaks are the particle equilibriums and the yellow lines represent the channel walls.

Results

For each particle diameter, we recorded data for a combination of different Reynolds numbers and different β. In the first set of experiments, we recorded data for the different sizes of particles separately.

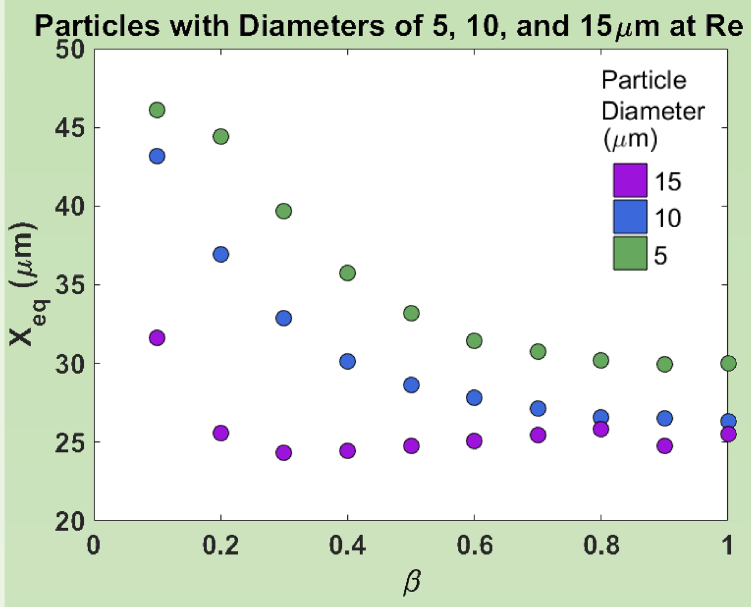


Figure 7: As β increases, the particles equilibrate closer to the channel center. As particle diameter increases, the particles equilibrate closer to the channel center.

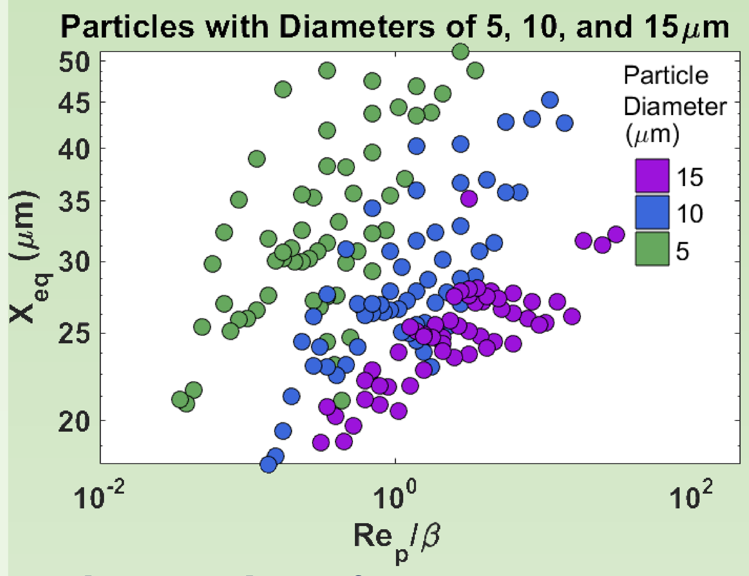


Figure 8: A summary of for all Re, plotted against Rep/B to linearize the data.

In the second set of experiments we created a solution of 15 and 5µm particles to see if our method of separation was viable for particles that are in the same solution.

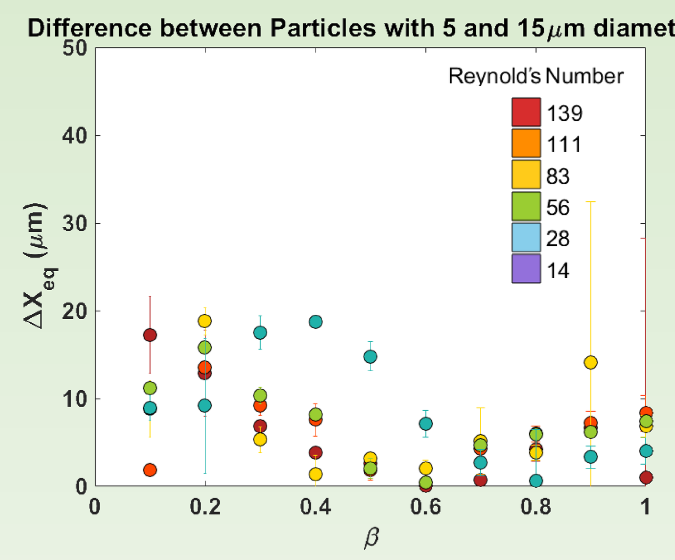


Figure 9: The difference in equilibrium position between particles of 15 and 5µm diameters (15µm X_{eq} – 5µm X_{eq}).

Discussion

Figure 7 suggests that separation is possible for low values of β, where the difference between the equilibrium positions of different sized particles is largest. Figure 9 suggests that β values that are relatively low (0.2) and relatively high (0.9) are ideal for separating 15 and 5µm particles. We believe smaller particles have more variance in X_{eq} because they are more susceptible to changes in flow rates due to having less mass, whereas larger particles have more inertia and are more difficult to move.

Conclusion

Thus far, we have observed that our TFF device meets the standard in inertial microfluidic particle separation, and exceeds it in distance between particle equilibrium locations.[2]

By comparing the data in Figures 7 and 9, we can conclude that, with a single device, we can separate given particle sizes for a given flow rate and change the flow rate in real time to separate a different set of particle sizes. For example, we can separate 5 and 15µm particles at Re28 β0.4, and then change the flow rates to Re139 β0.2 to separate 5 and 10µm particles.

Future Work

To further explore the inertial interactions that occur in our microfluidic TFF device, we will observe how the equilibrium location changes over the length of the channel. We believe this occurs based on recirculation of the permeate flow in the permeate reservoir channels. We hope to design a chip geometry such that there is no permeate recirculation, but rather a constant permeate flow.

References

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