Simulation of a Microfluidic Particle Concentrator and Separator

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ABSTRACT

We present a microfluidic particle concentrator and separator employing a large flow unit array. Each flow unit includes a nozzle, a sharp turn, a diffuser, and a flow dividing segment. After acceleration in the nozzle, the particle starts to separate in the sharp turn due to the inability to follow the fluid flow. By staggering and cascading the flow units, we can acquire concentrated fluid with particles by splitting the downstream outlet. The concept-proving flow and particle dynamics analysis was performed by using the CFD-ACE+ software. Separation of particle sizes ranging from 5 to 20 μm and particles densities ranging from 600 to 2700 kg/m^3 are numerically demonstrated. Denser and larger particles have higher momentum and are easier to be separated. As the particle goes smaller, the fluid drag force becomes more important and suppresses the particle separation. This type of device is promising for applications in a variety of inorganic particles and biological samples.

Keywords: microfluidic, separator, concentrator, micro particles, cell separation

1 INTRODUCTION

Separation of cells, bacteria, or other particles is a critical step in biological, medical, and chemical research. Many technologies have been developed to replace the conventional gradient methods [1] which require bulky centrifuges and separation tubes that are not practical to be implemented in a miniaturized and automated system. Field-flow fractionation (FFF) [2] is a flexible elution technique of simultaneous separation and measurement. It requires outer fields such as gravitation [3-5], electrical field [6], thermal gradient [7], or cross flow [8]. Capillary hydrodynamic fraction (CHDF) [9] was used to analyze the size distribution of particle growth during emulsion polymerization. Hydrodynamic chromatography (HDC) [10] has been tested on separation of fluorescent nano-spheres and macromolecules. CHDF and HDC do not require external fields. The separation processes of the above-mentioned methods are not continuous and require a relatively long separation time and complicated injecting devices. All these attributes are not suitable for large-scale cell or particle preparation. A preparative scale separation technique, pinched inlet split-flow thin fractionation (SPLITT) [11], was applied for the continuous size sorting of airborne particles. However, it requires external fields (gravitation) as in the case with FFF.

In this paper, we present a novel and simple method for particle concentration and separation in a microfluidic device. This method provides continuous processing ability and does not need external fields. Separating of particles with different size and density were demonstrated numerically in this study.

2 PRINCIPLE

The microfluidic particle concentrator and separator are composed of a array of identical flow units, as illustrated in Fig. 1. The flow unit array is arranged in a cascading fashion that each stage has an offset, W_{offset}, to its preceding one. By staggering the flow units with proper offset, we can have fluid equally divided into the two following flow units, as illustrated by the dividing streamline in Fig. 1.

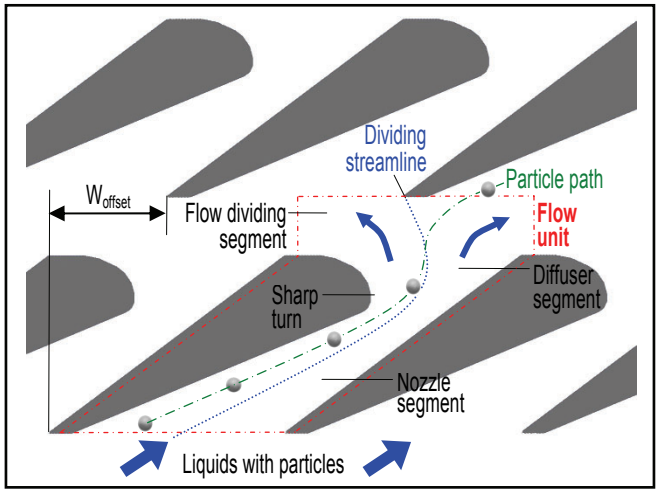

Figure 1: Flow unit of the microfluidic particle concentrator and separator.

Each flow unit includes a contracting nozzle segment, a sharp turn, a sudden-expanding diffuser segment, and a flow dividing segment. The nozzle accelerates the speed of fluid and particles. As result of increased momentum, particles start to resist change in direction near the sharp turn. Due to the inability to follow the fluid flow, the particles from left side of the flow unit cross the dividing streamline to the right side. The diffuser further helps the separation in the flowing dividing segment, as shown in the particle path in Fig. 1.

The microfluidic separator employs a momentum-driven particle separation principle. It possesses the follow advantages:

1. High throughput with the ability of continuous-flow processing
2. No need for external fields for separation
3. Small size suitable for portable device and micro-scale analysis.
4. Inexpensive and easy to be fabricated
5. Ability to be stacked with arrays for large-volume cell separation

3 METHOD OF SIMULATION

The flow dynamics of the microfluidic concentrator and separator is analyzed with the CFD-ACE+ software [12]. The simulation employed transient incompressible flow and the spray models. The spray model tracks a discrete phase (e.g. solid particles) through the calculation domain by solving the governing mass, momentum, and energy conservation equations in a Lagrangian frame of reference. The flow model solves the time dependent continuity equation, the pressure-based Navier-Stokes equations, and the energy balance equation. The particles (discrete phase) can exchange momentum with the surrounding ambient fluid (continuous phase). The governing equation for the particle is:

$$\rho_P V_P \frac{d\vec{U}_P}{dt} = C_D \rho_L (\vec{U}_L - \vec{U}_P)\left|\vec{U}_L - \vec{U}_P\right| \frac{A_P}{2} + \rho_P V_P \vec{G} + S \qquad (1)$$

where ρ_P, V_P, and U_P are the density, volume and velocity of the particle, respectively. C_D is the drag coefficient of particle. ρ_L and U_L are the density and velocity of the surrounding liquid. A_P is the particle projected area. For a spherical particle, $V_P = \pi d_P^3/6$ and $A_P = \pi d_P^2/4$ where d_P is the particle diameter. G is the gravity and S is the additional source term. In incompressible flow, C_D is a function of Reynolds number, $\mathrm{Re} = \rho_L |U_L - U_P|$, and can be evaluated as:

$$\begin{aligned} C_D &= \frac{24}{Re} && for \quad \mathrm{Re} < 1 \\ C_D &= \frac{24}{Re}\left(1 + 0.15 Re^{0.687}\right) && for \quad 1 < \mathrm{Re} < 10^3 \\ C_D &= 0.44 && for \quad \mathrm{Re} > 10^3 \end{aligned} \qquad (2)$$

4 RESULTS AND DISCUSSIONS

4.1 Particle Concentration

Figure 2 shows the design of a microfluidic particle concentrator with a 25×50 flow unit array. Liquids with particles are introduced into the sample inlet. Fluid is split into two outlets downstream of the flow unit array. Most of the liquids without or with much less particles will exit at the Liquid Outlet. The concentrated liquids with particles can be collected at the Particle Outlet.

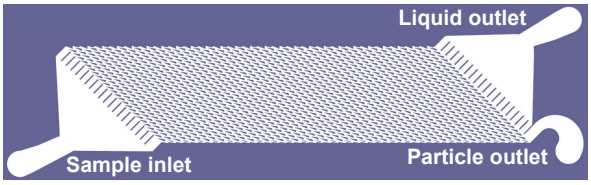

Figure 2: Design of the microfluidic particle concentrator

Because the simulation of the particle-laden flow is computationally intensive, we used simplified geometry with four flow units in a row, as shown in Fig. 3. Figure 3(a) demonstrated the three-dimensional simulation of particle motion in the microfluidic array. The 10 μm particles were introduced into far left side of inlet.

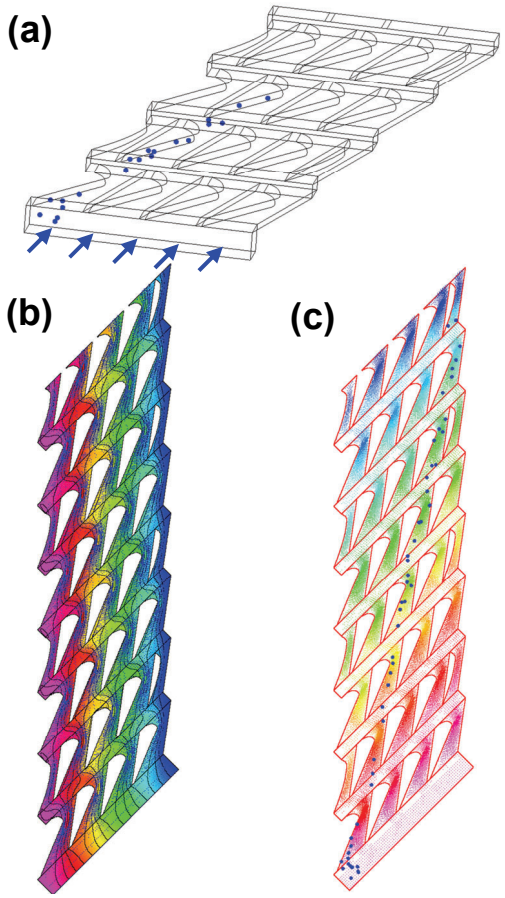

Figure 3: Flow and particle simulation (a) 3-D 4×4 array, (b) Streamline, and (c) pressure and velocity.

Figure 3(b) shows the stream function map of a 4×8 array. One can observe the dividing streamline and equally divided flow as mentioned in Fig. 1 and section 2. The velocity (vectors) and pressure (color) distribution are shown in Fig. 3(c). The particles from the far left side of the inlet were all focused to the far right side of the outlet in the 4×8 array. This promises particles from any locations of the

inlet can be concentrated to one side of the outlet in the microfluidic particle concentrator.

4.2 Density & Size Separation

As traveling through the sharp turn, liquid experiences a centrifugal force because its inertia tends to pull it away from the circular path. A pressure gradient is built to balance the force. Particles experience the same centrifugal force in the sharp turn. However, if the particles have different density from the liquid, there will be a net force that pushes them away from the streamline of liquid. Our microfluidic separator employs this phenomenon to separate different particles with different densities.

On the other hand, as the particle goes smaller, the fluid drag force becomes more important and suppresses the particle separation driven by the momentum. This is because hydrodynamics drag force depends on the particle front projected area while inertia force depends on volume (mass) of the particle. Therefore we can also separate particle with the same density but different sizes, as illustrated in Fig. 4.

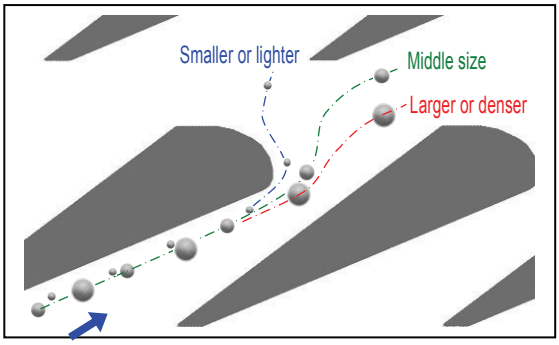

Figure 4: Principle of density and size separation.

Figure 5 shows the design of a microfluidic particle separator with a 25×50 flow unit array. Liquids with particles are introduced into a small portion (top-left) of the inlet. Liquids without particles were fed to the much wider buffer inlet with higher flow rate.

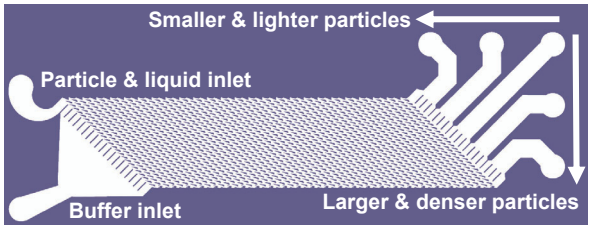

Figure 5: Design of the microfluidic particle concentrator

Separated particles can be collected at different branches (five in Fig. 5) at the end of the flow unit array. Lighter and smaller particles will be moved toward upper and left outlet branches while the denser and larger ones toward lower and right branches. Density and size separation were successfully demonstrated by the microfluidic simulation, as shown in Fig. 6. Figure 6(a) shows 20 μm particles with densities ranging from 600 to 2700 Kg/m^3 were separated. Figure 6(b) shows particle with sizes ranging from 5 to 20 μm were also successfully separated.

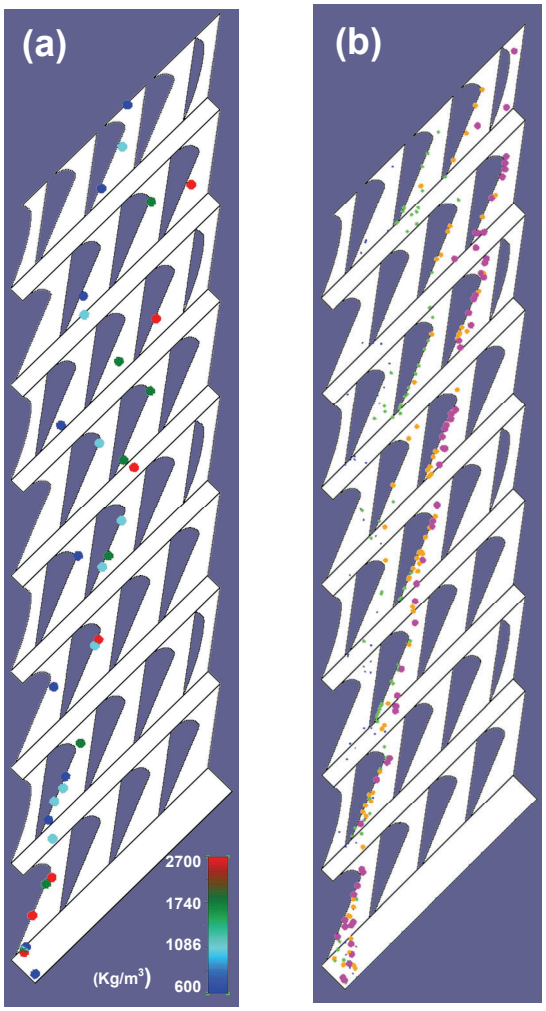

Figure 6: Simulated particle separation (a) by density and (b) by size.

It is worth mentioning that the efficiency of particle separation will be limited when the size becomes very small, say, diameters less than 1 um. It is because the drag force will be much more dominant than the momentum force for the size of particles. Meanwhile, the maximum size of particles is limited by the minimum channel width of the designed device. With a very large array (100 by 200 or higher), a 100 times of concentration increase or much more distinct particle separation can be attained with this particle separation technology. There are many possible applications for this kind of concentrator and separator:

1. Pre-concentration of particulates in water for bacteria detection or quality monitoring.

2. Separating whole blood into red blood cells, platelets, and plasma.
3. Isolation of target cells for disease diagnostics and genomic applications.
4. Particle sizing for the polymer beads, ceramics, and pharmaceutical emulsions.

5 CONCLUSIONS

A momentum-driven particle separation method is presented. The device is composed of a large array of identical flow units arranged in a stagger and cascade fashion. Each flow units includes a nozzle segment, a sharp turn, a diffuser segment, and a flow dividing segment. The nozzle accelerates the speed of liquid and particles. With enough momentum, the particle starts to separate due to the inability to follow the fluid flow in the sharp turn. The diffuser and the flow dividing segment further enhance the separation. By staggering and cascading the flow units, we can acquire concentrated fluid with particles by splitting the downstream outlet. For small particles, the fluid drag force becomes important and suppresses the particle separation. On the other hand, denser and larger particles have higher momentum and are easier to be separated. These distinguishing characteristics are employed to separate particles with different density and size in the microfluidic particle separator.

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