Particle Continuous Separation by Evaporation Force on Microfluidic System

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Abstract—We propose a novel microfluidic system for continuous particles separation by using capillary force and evaporating force. Typically, the microfluidic system needs external force or extra pumps to drive fluids, which were caused system complexity. It is a kind of the simple method to utilize evaporation force and capillary force on driving liquid. The particles can be continuously separated according to their diameter. The microfluidic system was fabricated under room temperature processes, which was also performed particle separation by using micro beads. Because it does not need other accessory systems like micropump or power supplying device, so separation by using micro beads. Because it does not need other accessory systems like micropump or power supplying device, so that it can reduce cost. This method can be used widely for accessory systems like micropump or power supplying device, so that it can reduce cost. This method can be used widely for continuous and precise separation on various kinds of particles, and can be functioned as an important part of disposable biochips in the future.

Index Terms — evaporating force, evaporation region, particles separation.

I. INTRODUCTION

In the recent years, lots of studies on microfluidic systems have been reported with the advance of MEMs technologies. Microfluidic systems can achieve a reduction in the required sample volumes, a highly effective reaction, and high portability. They are especially effective in fields related to chemical analysis or biomedical applications. Micro total analysis system (\(\mu\)-TAS), a concept of integrating microfluidic components into one automated system has been constructed in this regard. It has also been recognized that using a small structure to separate small particles is very effective, especially for particles size was comparable with the size of microchannels. A number of particle separation technologies using nano or micro structures and many kinds of material have been reported by using for fabricating microfluidic devices, such as silicone, glass, quartz and polymers in past years.

Several particle separation techniques were reported before. Hydrodynamic chromatography (HDC) \cite{1-3} requires a relatively long time for particle separation, even with a high separation speed in a microchip. Field flow fractionation (FFF) \cite{4-6} requires outer field controls such as centrifugal, gravitational, or thermal field. In the case of Dielectrophoresis (DEP)\cite{7-9}, an electric field application is needed and precise separation cannot be achieved by this method. Also, it is hard to separate and collect particles continuously in almost all these methods, therefore making them insufficient for preparative applications. We proposed a method with advantages of continuing particle separation and of driving microfluidic system without extra pumping devices. Also, no outer field control is needed, which are essential for the most of the methods described above. In this method, particles can be separated according to different sizes of their diameter simply by introducing liquid flows with and without particles into a microchannel. The most essential characteristic of evaporating pinched flow (EPF) method is that it integrated all components of a total system. In EPF system, micro particles can be continuously sorted using multiple branch channels connected to pinched channel entrance. By the way, the evaporating regions were settled in the end of each branch channel of the EPF system to create the driving force by evaporating force.

II. EXPERIENCE

Working principle

In fluid mechanics, the Reynolds number is the ratio of inertial forces (\(v_0L\)) to viscous forces (\(\mu L\)) and consequently it quantifies the relative importance of these two types of forces for given flow conditions. Thus, it is used to identify different flow regimes, such as laminar or turbulent flow.

Reynolds number is one of the most important dimensionless numbers in fluid dynamics and is used, usually along with other dimensionless numbers to provide a criterion for determining dynamic similitude. When two geometrically similar flow patterns, in perhaps different fluids with possibly different flow rates, have the same values for the relevant dimensionless numbers, so called dynamically similar.

\[
Re = \frac{\rho v_0 L}{\mu} = \frac{v_0 L}{\nu} = \frac{Inertial forces}{Viscous forces}
\]

where \(v_0\) is mean fluid velocity, \(L\) is characteristic length, \(\mu\) is (absolute) dynamic fluid viscosity, \(v\) is kinematic fluid viscosity ( \(\mu / \rho\), \(\rho\) is fluid density). The transition between laminar and turbulent flow is often indicated by a critical Reynolds number, which depends on the exact flow configuration and must be determined experimentally. For example, within circular pipes the critical Reynolds number is around 2300, where the Reynolds number is based on the pipe diameter and the mean velocity \(v_0\) within the pipe.

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Reynolds number always falls onto laminar flow region if the channel was around micorscale. With this character, it is key factor to design principle of particles separation shown in Fig. 1. It assumes that particles will move with streamline which cross center of its diameter. Particles are compressed onto one sidewall with aid of flow without particles. Thus, differences in the center positions from the sidewall arise according to the particle size. Different sizes of particle will be guided into different branch of system.

In the other way, the driving force was generated by liquid evaporation at the exit of microchannels controlled under room temperature. The force could be estimated by using following equations:

\[
\text{Re}_{\text{evaporation}} = \left(3.52 \times 10^{-22}\cdot \frac{1}{\text{cm}^2 \cdot \text{sec}}\right) \cdot \frac{P_v}{\sqrt{MT}}
\]  

\[
P_v = P_{vo}e^{-\frac{\Delta H_v}{RT}} \quad \text{with} \quad \Delta H_v = \text{heat of vaporization}
\]

It has a completed relation between temperature and evaporation rate. It is hard to control velocity of flow, thus, area of evaporating region would become essential designed factor.

In order to realize evaporating rate under room temperature, simply experiments to verify correlation between evaporating area and velocity of flow was designed shown on Fig. 2. DI water was put in, then driven by the evaporating force created by the hot plate on comb structures.

After processing, evaporating region of chips was fixed on silicon bulk which connected to hot plate to keep on the same temperature shown on Fig. 2. At the results, velocity of flow probably was proportion to area of evaporating region. It was linear relation since operating on fixed width of main channel with different area of evaporating region. The slope of velocity/evaporating-area ratio will decrease with increasing width of main channel.

**Simulations**

By applying the estimated force at the exits of microfluidic system, particle separation phenomena could be found by using CFDRC simulator, which was useful for the design of separation region. While flow with particles was compressed to one sidewall of microchannel, moving distance of particles from pinched segment is proportion to particle diameter as predicting, as shown on Fig. 4. Due to laminar flow phenomena in microchannel, differences in the center positions from the sidewall arise according to the particle size so that particles were separated in the designed region with proper branch channel design.
In the result of simulation, particles were systematic distributed on branched channels in low velocity situation. It supposes that particles’ movement will cause variation of stream function, is shown on Fig. 5. The stream function \( \psi \) for a two dimensional flow is defined such that the flow velocity can be expressed as:

\[
\mathbf{u} = \nabla \times \psi
\]  

\( (3) \)

No flow can exist normal to a streamline; thus, selected \( \psi \) lines can be interpreted as solid boundaries of the flow.

Module simulated on steady state without particles is shown as Fig. 5(a). When pinched channel flowed with multiple particles, streamline would swing from one branch to another branch, is shown on Fig. 5(b)(c), so that the liquid flow is not equally distributed to multiple branch channels, especially on high flow rate. As assumption that particles will move with streamline cross center of its diameter. Therefore, it has gray region to precisely collect target particles. The suitable operating velocity range is located on 200-400 \( \mu \text{m/sec} \). The flow rate is controlled by area of evaporating region.

\section*{Microdevice fabrication and design}

The microfluidic system was designed as shown in Fig. 6(a), including inlets for sample and buffer, separation region, and evaporation region. When sample and buffer were dropped into the entrance of microchannel, particles were flown into microchannel by capillary force. Thus, by designing the proper outlet size of microchannels, particles would be separated in the designed region. Different size of evaporate region has an effect on the influence of particles separation in the separation region.

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Deep UV which wavelength is about 173nm, at this wavelength is effective in producing ozone, which dissociates polymers into smaller polar oxidation products. Then, 20 μg/ml of BSA (Bovine Serum Albumin) was used as buffer to pre-flow into microchannel. When BSA is dropped onto surface of PDMS channel, the protein could be trended to hydrophilic surface. The charge on surface will co-affect to each other, so as that BSA will be adsorbed steadily on surface. The BSA thin film has excellent hydrophilic, anti-adhesive and stable properties. It is nice for experiments repeatability.

Observation system

The operating process is observed by optical microscope (Optem125, QIOPTIQ IMAGING SOLUTIONS, US) with color video camera (ExwaveHAD, SONY, Japan).

III. RESULTS AND DISCUSSION

The evaporation force, which would be also used for particle separation, will drive the liquid, and velocity of particles could be gone up to 3000μm per second under room temperature. Polystyrene with diameter about 1 μm ± 10%, and QD (quantum dot) with diameter about 2.8 μm ± 10%, were used as samples for particle separation test. Fig. 8(a) was shown that polystyrene throw across microchannel due to its smaller size compared with QD that was shown on Fig. 8(b). Comparing with HPLC (high-pressure liquid chromatography) method, it is needless to have high pressure and high pumping force for liquid flowing in microchannel structure. It can sort sample continually, and you don’t worry about sample inject problem under micro scale.

IV. CONCLUSION

By using this microfluidic system, separation range of sample can be predicted by structural design and CFDRC simulator. The sorting process could be completed in very short period, which is better than the one from HPLC column method. Furthermore, the high speed camera may be applied on observing samples to enhance quantity measurement in the future.

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