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Sieve-based lateral displacement technology for suspension separation

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ABSTRACT

Sparse lateral displacement arrays are easier to scale up than full deterministic lateral displacement arrays or deterministic ratchets, because they require lower pressure drop and simplify the construction of the device. However, the asymmetry of sparse arrays leads to a non-homogeneous pressure distribution with as a consequence an uneven flow field and limited separation performance. Furthermore, the construction of high throughput displacement sparse ratchet devices that allow separation of small particles is challenging. Therefore, in this study we investigated the use of sieves to replace obstacles in sparse systems. Moreover, we investigated a strategy to optimize the separation performance by adjusting the internal pressure distribution. Our experiments showed in first instance that the introduction of sieves negatively affects separation performance, which was explained by the lower porosity of the sieves. However, via fluid flow calculations and high-speed camera analyses we found that pressure distribution can be optimized by adapting the flow rates of the different outlets preventing high pressure drop across the obstacles arrays near the bottom of the device. Experimental separation data for adjusted outlet flow conditions indeed showed better particle displacement, especially in the bottom region, and as a result improved separation behavior. These findings demonstrate the potential of the scalable sieve-based lateral displacement device to effectively separate particles.

1. Introduction

A deterministic lateral displacement device or deterministic ratchet is a microfluidic device to separate or fractionate particles from suspensions [1]. The separation principle involves arrays of obstacles to displace and separate particles based on their size. Fluid flows through the openings between individual obstacles, which are arranged in rows that are tilted relative to the overall average flow direction of the fluid.

In a laminar flow field, the fluid that will flow through a particular opening is bounded by two flow lines, which comprise the so-called flow lane (dotted lines in Fig. 1). If particles, that are suspended in the fluid, have a diameter that is larger than two times the typical width of the flow lane, (D_{fc}), lateral displacement occurs after steric interaction of the particle with an obstacle (Fig. 1A). When the particle is smaller it stays within its flow lane (dotted lines) and follows the fluid [2]. Thus, larger particles are shifted unidirectionally from their flow lanes, which after many such events results in macroscopic separation. All particles that are smaller than the flow lane width will follow the fluid and therefore will less likely cause obstruction and fouling of the structure, compared to membrane filtration, in which all particles accumulate before a single sieve. This is one of the reasons why the deterministic ratchet separation principle has been considered promising to separate suspensions at a larger scale [3–5].

It is often suggested to scale up microfluidic systems through outscaling or massive parallelization [6–8], but this requires a large number of connected devices, requiring large investment in the peripheral structure, which would also compromise its robustness in operation. It would be economically more interesting to follow the classical laws of scale-up and increase the dimensions of the device [4]. However, increasing the dimensions of deterministic ratchet devices is challenging from a construction perspective. Especially the construction of tall obstacles with enough mechanical strength is difficult and expensive, and therefore the throughput is limited by the cross-section of the channel [6]. A possible solution to increase the throughput of the deterministic ratchet is to use sieves to replace obstacles (sieve frame) and gaps (pores) as shown in Fig. 1C. In contrast to the construction of individual obstacles, there are multiple available manufacturing techniques to create sieves with small and uniform pores (e.g. photolithographic etching [9], electroforming [10], embossing [11] and 3D printing [12]).

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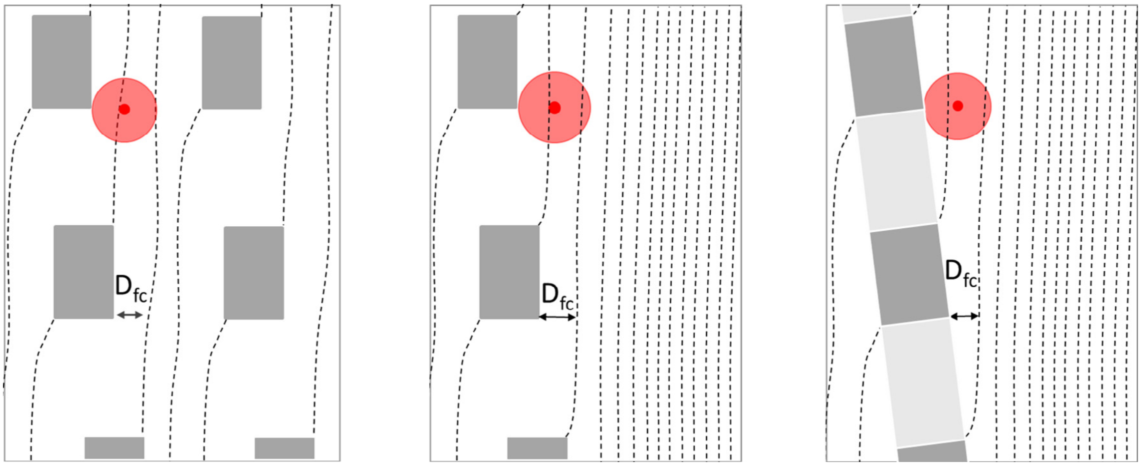

Fig. 1. Schematic diagram of the deterministic lateral displacement separation principle with in (A) the initial obstacle array, in (B) the sparse deterministic ratchet and in (C) the sieve-based deterministic lateral displacement device. The fluid through the system can be divided into flow lanes indicated by the dotted lines. Particles with a diameter $\geqslant 2 * D_{fc}$ are displaced by each obstacle into the adjacent flow lane. Forcing larger particles to follow the direction of the obstacles instead of the flow direction. When particles $<2D_{fc}$, they are not displaced laterally, stay in their flow lanes and follow the flow direction.

Another challenge, besides increasing the single unit throughput, is to apply deterministic ratchets for processing of industrial relevant suspensions. Such suspensions usually consist of deformable and/or irregular-shaped particles which may increase the risk of clogging, even though different properties may be used to enhance separation in deterministic ratchet devices [13]. Recently, Lubbersen et al. introduced the sparse deterministic ratchet concept with a reduced number of obstacles (Fig. 1B). This geometry works, because for dilute suspensions, the separation principle requires only a single obstacle array to displace particles [14]. Fewer obstacles further reduces the risk of particle accumulation, which decreases the pressure drop and lowers the construction costs [14]. However, the asymmetric design of sparse deterministic ratchet creates an inhomogeneous pressure distribution, which negatively affects the separation [14,15]. Nevertheless, a large scale sparse deterministic ratchet design that employs sieves to separate particles is anticipated to be less challenging to produce and to use, compared to mass-parallelized conventional deterministic ratchets.

In this work, we investigate the use of sieves to separate particle suspensions in a sparse deterministic ratchet displacement geometry. Using sieves instead of obstacles will create the possibility to increase the single unit throughput of a deterministic ratchet and thus better facilitates larger scale operation. Here, the effect of sieves on suspension separation and on the fluid flow are described for the sparse deterministic ratchet design. Subsequently, the changes on fluid flow caused by the asymmetric design are examined and optimized to improve suspension separation.

2. Materials and methods

2.1. Device

Experiments were carried out using a flow device (Fig. 2A) as previously described by Lubbersen and co-workers; the flow enters at the top and leaves at the bottom at five different outlets [16–18].

In this device the ratchet designs are placed (top view in Fig. 2B). Three sparse deterministic ratchets with different obstacle designs were used, the original (Fig. 2C) was milled from PEEK. The other two designs consisted of a base plate, which is milled from PEEK and sieve structures which are 3D printed with nylon (Fig. 2D and E). The design of the sparse deterministic ratchet (Fig. 2B) remained the same and only the obstacles were changed (Fig. 2C–E). The obstacle and gap parameters can be found in Table 1. Note that the size of the gaps in the flow direction (gap length) remained unchanged.

2.2. Materials

For concentration experiments, 1 v/v% suspensions of neutrally buoyant particles were prepared using polystyrene particles with a density of 1.05 g/cm^3 (Maxiblast, USA), 79.5% water, 20%/glycerol (VWR BDH Prolabo, France) and 0.5% surfactant (SDS, obtained from VWR BDH Prolabo). The particle size distribution was measured with a Mastersizer 2000 (Malvern, UK) and a D50 of 785 μm was obtained with D10 of 568 μm and a D90 of 1103 μm. For high speed camera imaging a suspension of demi water, Tween-80 (Merck, Germany) and polyethylene particles of 425–500 μm (Cospheric, USA) with a density 0.98–1.00 g/ml were used.

2.3. Experiments

The ratchet sieve designs were positioned in the module (Fig. 2A) and employed by pumping the suspension vertically from the top down to the 5 outlets where the particles can be collected [16]. The inlet flow rate was adjusted in order to obtain a fixed fluid velocity of 0.06 m/s in the channel cross-section before the sieves. The volume concentration at the inlet is calculated using the outlet volume concentrations and respective flow rates of the 5 outlets, which varied slightly per experiment. For ease of comparison between different experiments, the outlet concentrations are normalized using the inlet concentration. Initial experiments were performed with the outflow equally divided over the outlets. At a later stage, experiments were conducted with optimized outflow conditions. For these experiments the volumetric flow rate per outlet was adjusted according the results obtained from the numerical simulations (Table 2). Experiments with different outflows were only performed with design 3, since it shows most resemblance with sieves. The concentration, in case of ideal separation (when all particles are above the critical particle diameter and therefore are displaced) is calculated by assuming a homogeneous distributed suspension at the top of the system.