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Microfluidic particle separator utilizing sheathless elasto-inertial focusing

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HIGHLIGHTS

- We demonstrated particle separation by size under microfluidic viscoelastic flow.
- Performance evaluation of a separator based on sheathless elasto-inertial focusing.
- Polymer and particle concentrations, as well as flow rate affect the separation.
- Existence of upper limit for polymer concentration and optimal flow rates.

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ABSTRACT

Microfluidics-based particle separation has attracted much attention in a wide range of chemical, environmental, and biological applications. However, most of the existing methods require complex channel designs to generate inertial flows or external forces such as electric fields. In this work, we demonstrate a facile particle separation technology with extremely simple straight channel geometry not relying on any external force. In viscoelastic flow, larger particles are enriched downstream of a straight channel in a self-modulated manner by sheathless elasto-inertial focusing mechanism (Yang et al., Lab Chip, 2011, 11, 266-273). We evaluated the performance of a microfluidic separator based on this mechanism, and found significant effects for polymer and particle concentrations, as well as flow rate. In particular, we determined an upper limit for the polymer concentration, which was attributed to the occurrence of shear-thinning behavior, and we found optimal flow rates for the separation. In addition, we found that particle-particle interaction plays an important role in the separation process and the purity of separated particles is gradually degraded with increasing particle concentration. This work will contribute to the design of microfluidic particle separators and the fundamental understanding of particle dynamics in polymer solutions flowing through confined geometries.

1. Introduction

Particle separation is a key technology in a wide range of industrial, environmental, and biological processes that involve particulate systems (Giddings, 1993). Recently, microfluidics-based separation has attracted significant attention since it inherently demands small volumes of samples, and the flow conditions can be precisely controlled to achieve high-performance separation (Lenshof and Laurell, 2010; Pamme, 2007). It is expected that procedures from sample preparation to separation will be performed on a single chip in an automated manner (Pamme, 2007). In such microfluidic approaches, it is a prerequisite to spatially focus particles in a narrow stream prior to particle separation (Xuan et al., 2010).

A conventional approach to particle focusing utilizes sheath flows; these usually direct flows through two coaxially aligned cylindrical tubes comprising an inner stream for sample flow and an outer stream for sheath flow (Lenshof and Laurell, 2010). However, the miniaturization of such traditional flow focusing techniques into planar microchannels is highly challenging due to the difficulty in implementing the coaxial structure (Mao et al., 2007). Thus, particle focusing techniques that do not rely on sheath flows (sheathless particle focusing) have been actively pursued by many researchers (Gossett et al., 2010; Lenshof and Laurell, 2010; Xuan et al., 2010). Currently, sheathless particle focusing relies on two types of principle: active and

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passive methods (Xuan et al., 2010). In the active methods, external forces such as the electric force drive the particles laterally into focused streams. It requires a multi-layered channel structure composed of several materials in order to generate external force fields, which requires complicated fabrication procedures (Xuan et al., 2010).

In contrast, in the passive methods, the particles laterally migrate toward equilibrium positions in a self-modulated manner by nonlinear flow effects such as inertial or viscoelastic forces (Karimi et al., 2013). Among the passive methods, viscoelastic-based particle focusing has recently attracted much attention because a single focused particle stream can be achieved by simply flowing particles in extremely simple straight channels (D'Avino et al., 2012; Del Giudice et al., 2013; Kang et al., 2013; Leshansky et al., 2007; Nam et al., 2012; Romeo et al., 2013; Yang et al., 2011, 2012). Under viscoelastic Poiseuille flows, the particles are laterally driven toward equilibrium positions by gradient of normal stress differences (Ho and Leal, 1976). The equilibrium position is the low first normal stress difference region, e.g., mid-plane in a slit geometry (Leshansky et al., 2007) or the channel centerline in a circular channel (D'Avino et al., 2012). On the other hand, in planar rectangular channels, Yang et al. demonstrated that the multiple particle equilibrium positions in elasticity-dominant flow reduce to a single particle stream along the channel centerline when the elastic and inertial forces are synergistically balanced, which was termed as elasto-inertial particle focusing (Yang et al., 2011). They also demonstrated the possibility of separating particles by size, which accommodates the difference in particle size-dependent migration speeds under viscoelastic flow (D'Avino et al., 2012; Leshansky et al., 2007; Romeo et al., 2013; Tehrani, 1996; Yang et al., 2011). Later, Nam et al. (2012) utilized the elasto-inertial particle focusing mechanism to separate both particle and platelet from whole blood in high purity (Nam et al., 2012).

In this study, we examined the effects of polymer and particle concentrations, in addition to flow rate, on the separation performance of a microfluidic particle separator based on sheathless elasto-inertial particle focusing. The particle separation herein was achieved by simply flowing mixtures of particles with different sizes through a straight channel from a single inlet. Thus, the channel structure and operation were very simple, and the sample flow rate was higher, as compared with the previous work that used the sheath flow-based approach (Nam et al., 2012). We expect that the current method can be applied to a wide range of applications such as cell sorting.

2. Background theory

We designed a microfluidic device for the size-based separation of micron-range particles, which was based on lateral particle migration under viscoelastic flow (Ho and Leal, 1976; Leshansky et al., 2007; Nam et al., 2012; Tehrani, 1996; Yang et al., 2011, 2012). This phenomenon was reported in the 1960s (Karnis et al., 1963), but it has been only recently applied to microfluidic technologies such as particle/cell counting and sorting (D'Avino et al., 2012; Kang et al., 2013; Karimi et al., 2013; Leshansky et al., 2007; Nam et al., 2012; Yang et al., 2011, 2012). Theoretical modeling to explain the viscoelastic particle migration has been rigorously investigated (D'Avino et al., 2012; Del Giudice et al., 2013; Kang et al., 2013; Leshansky et al., 2007; Romeo et al., 2013; Yang et al., 2011, 2012). Here, we briefly introduce the theoretical background for predicting lateral particle migration under viscoelastic Poiseuille flow (refer to D'Avino et al., 2012 and Yang et al., 2012 for more detailed discussion).

When polymer molecules are added to a solvent, the solution exhibits non-Newtonian viscoelastic properties resulting in a wide range of intriguing phenomena, such as rod climbing. Non-vanishing normal stress differences are responsible for such non-Newtonian flow behaviors (Bird et al., 1987). On the other hand, it was theoretically predicted that a particle laterally migrates under non-homogeneous flow by the gradient of the first or second normal stress differences (N_1 or N_2) (Ho and Leal, 1976). Hence, a non-uniform normal stress difference distribution under viscoelastic Poiseuille flow causes lateral particle migration (Ho and Leal, 1976; Leshansky et al., 2007; Tehrani, 1996). The particle migration by the second normal stress difference is usually negligible since it is one order of magnitude less than the first normal stress difference (Leshansky et al., 2007; Tehrani, 1996; Yang et al., 2011). The elastic force exerted on a sphere ($\boldsymbol{F}_e$) was modeled with $\boldsymbol{F}_e \sim a^3 \nabla N_1$ (Leshansky et al., 2007; Tehrani, 1996), where a is the particle radius. Under elasticity-dominant inertialess flows, the lateral particle migration velocity ($\boldsymbol{V}/U$) normalized with the average streamwise velocity (U) was predicted as follows (Leshansky et al., 2007; Tehrani, 1996; Yang et al., 2011, 2012):

$$\frac{\mathbf{V}}{U} \sim Wi\left(\frac{a}{h}\right)^2 \hat{\nabla}\hat{\dot{\gamma}}^2 \tag{1}$$

where h denotes the channel height and $\hat{\dot{\gamma}}$ corresponds to the non-dimensionalized shear rate (normalized with the characteristic shear rate, $\dot{\gamma}_c$). Wi is the Weissenberg number, which denotes the relative ratio of elastic to viscous properties for viscoelastic flows, and is defined by $\lambda\dot{\gamma}_c$ (λ: relaxation time). The characteristic shear rate ($\dot{\gamma}_c$) is defined by $2U/h$, and the length scale is non-dimensionalized with $h/2$. The Reynolds number, Re, represents the relative ratio of inertial to viscous forces, which is defined by $hU\rho/\mu_0$ (in the current work, the channel width and height are equal to h). ρ and μ_0 are the density and the zero-shear viscosity of the polymer solution, respectively, where the zero-shear viscosity corresponds to the shear viscosity for Newtonian fluid and Boger fluid (viscoelastic fluid with constant shear viscosity). The elasticity number El denotes the relative ratio of elastic to inertial forces, and is defined by $Wi/Re \equiv 2\mu_0\lambda/\rho h^2$. Hence, Eq. (1) can be applied to high El number flows ($El > > 1$; elasticity-dominant flow).

Eq. (1) clearly demonstrates that the lateral migration speed strongly depends upon particle size, which was experimentally observed in previous works (D'Avino et al., 2012; Leshansky et al., 2007; Romeo et al., 2013). In the current study, this size-dependent migration speed plays an essential role in separation by size: larger particles accumulate more around equilibrium positions as compared to smaller ones. On the other hand, Eq. (1) predicts that the particles migrate toward low shear rate regions (or low first normal stress difference regions), which correspond to the channel centerline in a cylindrical tube (D'Avino et al., 2012). For rectangular channels which are relevant for most microfluidic devices, it was predicted that the particles would migrate toward the channel centerline or the four corners, which have the minimum first normal stress differences (Yang et al., 2011, 2012). For practical particle separation by size, multiple particle equilibrium positions complicate the design of a device to collect the separated particles.

The multiple particle equilibrium positions at the channel centerline and four corners are reduced to a single particle stream along the channel centerline when both Wi and $Re > 0$, i.e., $El \sim O(10^0)$ (elasto-inertial focusing) (Yang et al., 2011). In Fig. 1(a), the schematics denote that the inertial force (wall lift force; F_i) selectively pushes the particles away from the walls, whereas the particles along the channel centerline are still focused by elastic force (F_e) (Yang et al., 2011). We also mentioned that the particle dynamics in shear thinning viscoelastic fluids notably deviates from the above theory. With holography technique, Seo et al. (2014) very recently observed particle distribution under viscoelastic fluid flows with constant or shear-thinning viscosity in the cross-section of microchannels. They demonstrated that particle focusing is gradually strengthened under a viscoelastic flow with a constant shear viscosity according to increase of flow rate. However, the increase of the flow rate attenuates the particle focusing in case of a shear-thinning viscoelastic fluid.