



7th International Conference on Fluid Mechanics, ICFM7

Sheathless separation of particles and cells by viscoelastic effects in straight rectangular microchannels

Chao Liu^a, Chundong Xue^a, Guoqing Hu^{a,*}

^aState Key Laboratory of Nonlinear Mechanics, Institute of Mechanics, Chinese Academy of Sciences, 100190, Beijing, China

Abstract

We demonstrate a label-free and sheathless hydrodynamic approach that successfully separate particles and cells by size in straight microchannels. Particles and cells have size-dependent stable equilibrium positions in 0.1 wt % polyethylene oxide (PEO, $M_w = 4 \times 10^6$ g/mol) solution in a rectangular microchannel: 1 μm particles focus at the channel center while 3 μm particles focus near the channel side walls, which is completely different from the previously observed focusing at the channel center regardless of particle size. The effect of blockage ratio accounts for the deviation of large particles from the center. Utilizing this size-dependent differential migration, we successfully separate *E. coli* bacteria and red blood cells (RBCs) with both components tightly focused at different equilibrium positions in a straight microchannel, which has good parallelizability for higher throughput.

© 2015 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of The Chinese Society of Theoretical and Applied Mechanics (CSTAM)

Keywords: Viscoelasticity, Particle separation, Microfluidics

1. Introduction

Continuous separation of microparticles/cells with high efficiency is a challenging and crucial task for many biological, medical, environmental and industrial applications [1-3]. Recent years, hydrodynamic effects, e.g., fluid inertia [4] and elasticity[5], have been utilized in microfluidic devices to focus and separate particles and cells by driving them laterally migrate towards specific stable equilibrium positions. Elasto-inertial migration of particles in non-Newtonian has attracted much attention since particles in Poiseuille flow of dilute polymer solutions (viscoelastic fluids) will migrate away from walls and towards the channel center when inertia is non-negligible[6]. The reduced stable equilibrium positions (compared with the inertial migration in Newtonian fluids) make elasto-inertial migration desirable for particle manipulation. Several groups have demonstrated sheathless particle

* Corresponding author. Tel.: +86 010-82544298.
E-mail address: guoqing.hu@imech.ac.cn

separation with low efficiency [6,7], where large particles tightly focused at the channel center and small particles remained dispersed (the elastic force F_e is size dependent, $F_e \sim a^3$). Utilizing sheath flow, Nam *et al.* [8] separated 1 μm and 5 μm particles with high efficiency based on the different migration velocities. However, sheath flow is logistically burdensome and may cause flow fluctuation at high flow speed.

2. Design principle

Nomenclature

a	particle diameter
C_e	nondimensional lift coefficient
H	channel height
N	normal stress difference
Q_v	volume flow rate
U_a	average channel velocity
W	channel width
$\dot{\gamma}$	shear rate
η	viscosity
κ	blockage ratio (a/H)
λ	fluid relaxation time

Particles can laterally migrate in a pressure-driven flow of a viscoelastic fluid. The lift force is associated with fluid elasticity: normal stress differences N , i.e., the first (N_1) and second (N_2) normal stress differences. For simplicity, the contribution of N_2 is neglected as $|N_2/N_1| < 0.1$ for most polymer solutions[9]. The lift force on a small sphere arises from the imbalance of N_1 over the sphere surface[5]:

$$F_e = C_e a^3 \nabla N_1 \quad (1)$$

N_1 can be expressed as $N_1 = 2\eta\lambda\dot{\gamma}^2$ using upper convected Maxwell model [9]. By balancing Stokes drag force $F_d = 3\pi\eta aV$, the lateral migration due to the elastic lift is calculated as:

$$V = \frac{2C_e\lambda}{3\pi} a^2 \nabla \dot{\gamma}^2 \quad (2)$$

In rectangular microchannels, particles will migrate towards the centerline and four corners where $\dot{\gamma}$ has minimum. The Weissenberg number ($Wi = \dot{\gamma}\lambda$) characterizes the fluid viscoelasticity. In this work, the characteristic shear rate is defined as $2Q_v/HW^2$. The Reynolds number ($Re = \rho U_a W/\eta$) characterizes the fluid inertia. In a flow with non-negligible inertia, particles are only focused along the channel centerline due to synergetic combination of fluid elasticity and the wall repulsion arising from fluid inertia.

3. Methods

The PEO solution was prepared by adding PEO ($M_w = 4 \times 10^6$ g/mol) powder to 22 wt % glycerin aqueous solution to match the density of the polystyrene (PS) particles (1.05×10^3 kg/m³). The suspensions of 1 μm and 3 μm PS particles were diluted in the PEO solution to 0.005% and 0.01% volume fraction, respectively. To prevent particle aggregation, surfactant Tween 20 was added into the suspensions at 0.1 w/v %. The relaxation time of the PEO solution is estimated as 2.8×10^{-2} s by the empirical formula based on capillary breakup extension rheometry (CaBER) measurement. All the microchannels were 10 μm high and 30 mm long and had one inlet and one outlet.

4. Results

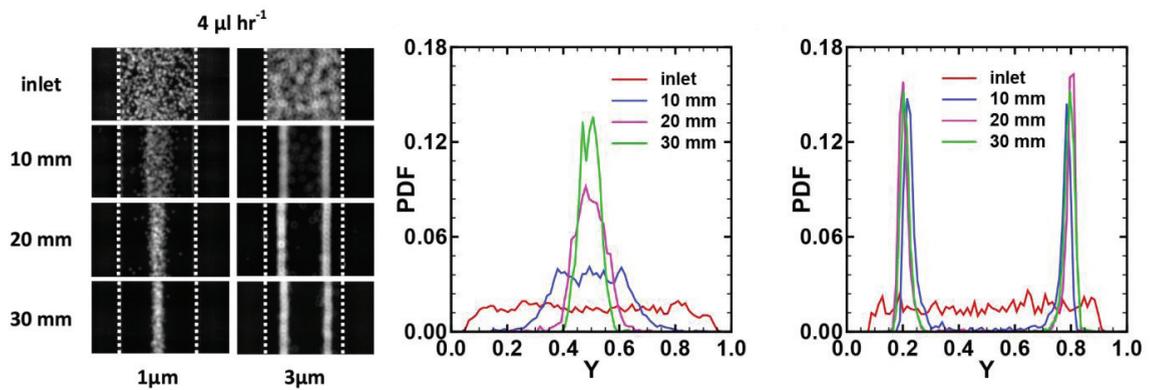


Fig. 1. The size-dependent differential migration of particles with $a = 1 \mu\text{m}$ and $a = 3 \mu\text{m}$.

Figure 1 shows that $1 \mu\text{m}$ particles ($\kappa = 0.1$) are focused at the channel center where the shear rate is vanishing. In contrast, $3 \mu\text{m}$ particles ($\kappa = 0.3$) are focused near the sidewalls. In the limit of small κ , the lift force on a particle arises from the normal stress imbalance due to the curvature of the velocity profile. On the other hand, a particle with large κ tend to migrate closer to the walls, which is associated with intensified normal stresses at the near-center side of the particle[10]. The major portion of fluid chooses to flow through the larger gap between the particle and the channel wall. The streamline around a particle can be intensified at the near-center side of the particle, resulting in enhanced compressive normal stress. As a consequence, large particles will be driven towards the wall. Utilizing this size-dependent differential migration, we successfully separate *E. coli* bacteria and red blood cells with both components tightly focused at different equilibrium positions in a straight microchannel (Fig. 2). This approach has good parallelizability for further throughput improvement.

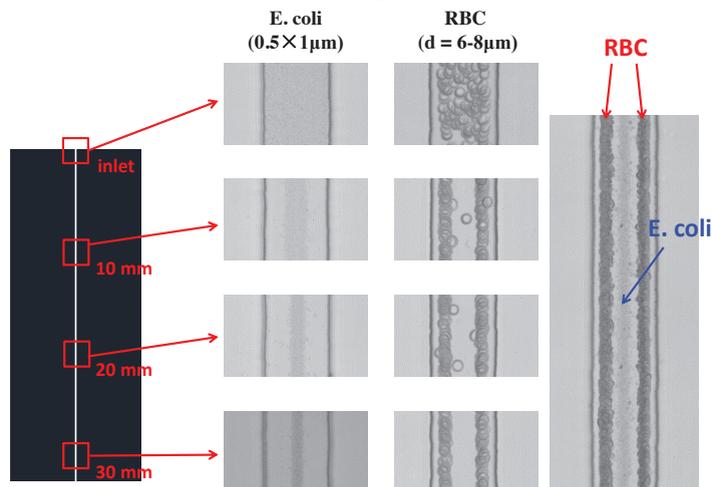


Fig. 2. The separation of *E. coli* bacteria and RBCs in 0.1 wt % PEO solution at flow rate $4 \mu\text{L/hr}$ ($Wi = 3.9$, $Re = 0.028$).

In Fig. 2, the tight focusing of *E. coli* bacteria suggests the potential of obtaining high-quality focusing and separation for sub-micron particles. Using 0.2 wt % PEO solution, we successfully focus particles with $a = 0.5 \mu\text{m}$ into a tight stream (Fig. 3).

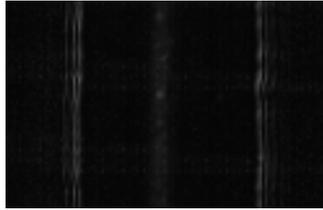


Fig. 3. The focusing of sub-micron particles ($a = 0.5 \mu\text{m}$) in 0.2 wt % PEO solution at flow rate $10 \mu\text{L/hr}$ ($Wi = 15.3$, $Re = 0.07$).

5. Conclusion

Using a size-based differential viscoelastic focusing, we demonstrate a sheathless and label-free separation in strictly straight microchannels. Using 0.1 wt % PEO solution, *E. coli* bacteria and RBCs are completely separated in microchannels with $H = 10 \mu\text{m}$ and $AR = 4$. We further focus sub-micron particles with $a = 0.5 \mu\text{m}$ using 0.2 wt % PEO solution. Due to the straight design, the throughput can be readily amplified by massive parallelization.

Acknowledgements

We thank the Ministry of Science and Technology (2011CB707604) and the National Science Foundation of China (11272321, 11402274) for financial support.

References

- [1] Toner, M.; Irimia, D. Blood-on-a-chip. *Annu. Rev. Biomed. Eng.*, 7(2005) 77.
- [2] Karimi, A.; Yazdi, S.; Ardekani, A. M. Hydrodynamic mechanisms of cell and particle trapping in microfluidics. *Biomicrofluidics*, 7(2013) 23.
- [3] Amini, H.; Lee, W.; Di Carlo, D. Inertial microfluidic physics. *Lab Chip*, 14(2014) 2739-2761.
- [4] Di Carlo, D.; Edd, J.; Humphry, K.; Stone, H.; Toner, M. Particle segregation and dynamics in confined flows. *Phys. Rev. Lett.* 102(2009).
- [5] Leshansky, A. M.; Bransky, A.; Korin, N.; Dinnar, U. Tunable nonlinear viscoelastic "focusing" in a microfluidic device. *Phys. Rev. Lett.*, 98(2007) 4.
- [6] Yang, S.; Kim, J. Y.; Lee, S. J.; Lee, S. S.; Kim, J. M. Sheathless elasto-inertial particle focusing and continuous separation in a straight rectangular microchannel. *Lab Chip*, 11(2011) 266-273.
- [7] Ahn, S. W.; Lee, S. S.; Lee, S. J.; Kim, J. M. Microfluidic particle separator utilizing sheathless elasto-inertial focusing. *Chemical Engineering Science*, 126(2015) 237-243.
- [8] Nam, J.; Lim, H.; Kim, D.; Jung, H.; Shin, S. Continuous separation of microparticles in a microfluidic channel via the elasto-inertial effect of non-Newtonian fluid. *Lab Chip*, 12(2012) 1347-1354.
- [9] Bird, R. B.; Armstrong, R. C.; Hassager, O.; Curtiss, C. F. *Dynamics of polymeric liquids* Vol. 1; Wiley New York.; Vol. 1. (1987)
- [10] Huang, P. Y.; Feng, J.; Hu, H. H.; Joseph, D. D. Direct simulation of the motion of solid particles in Couette and Poiseuille flows of viscoelastic fluids. *J. Fluid Mech.*, 343(1997) 73-94.