Supplementary information

Continuous sheath-less microfluidic separation of nonmagnetic microparticles in a novel viscoelastic-based ferrofluid

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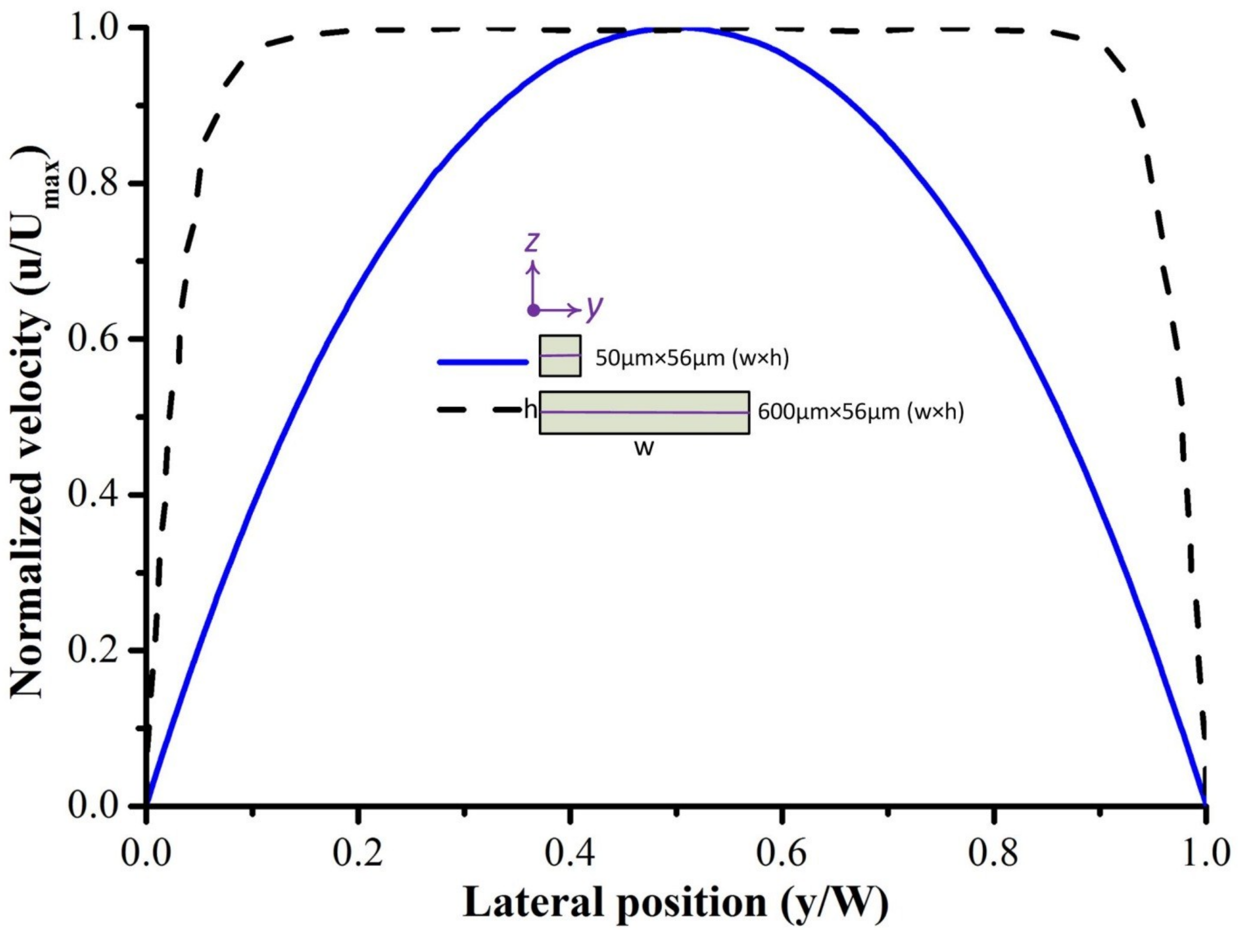
(1) Figure S1 Fluid velocity profile along channel width for two different cross-sections (50μm×56μm & 600μm×56μm).



(2) Numerical Simulation

Physics:

(I) Magnetic Fields, no Currents

$$H = -\nabla V_m \tag{S1}$$

$$\nabla \cdot B = 0 \tag{S2}$$

V_m: Magnetic scalar potential

B: Magnetic flux density

H: Magnetic field

Magnetic field: Constitutive relation: Magnetization

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}) \tag{S3}$$

(II) Laminar flow

Steady, incompressible Newtonian laminar flow

$$\rho(u \cdot \nabla)u = \nabla \cdot \left[-pI + \mu\left(\nabla u + (\nabla u)^T\right)\right] \tag{S4}$$

$$\rho\nabla \cdot (u) = 0 \tag{S5}$$

where $\boldsymbol{u}$ is velocity vector of fluid, P is fluid pressure, and ρ is fluid density. Noted here, the Newtonian flow with constant viscosity is used for simplicity, and the average dynamic viscosity was obtained from the rotational rheometer (Anton-Paar MCR 301, AU) at room temperature.

(III) Particle tracing for Fluid Flow

Magnetophoretic force

$$F_t = 2\pi r_p^3 \mu_0 K \nabla H^2 \tag{S6}$$

$$K = \frac{\mu_{r,p} - \mu_r}{\mu_{r,p} + 2\mu_r} \tag{S7}$$

where μ_r is relative permeability, which is related to susceptibility χ as μ_r=1+χ.

Drag force:

$$F_D = 3\pi\mu d_p(u_f - u_p) \tag{S8}$$

Meshing:

Mapped mesh for microchannel and the permanent magnet

The rest space is meshed using Free Triangular

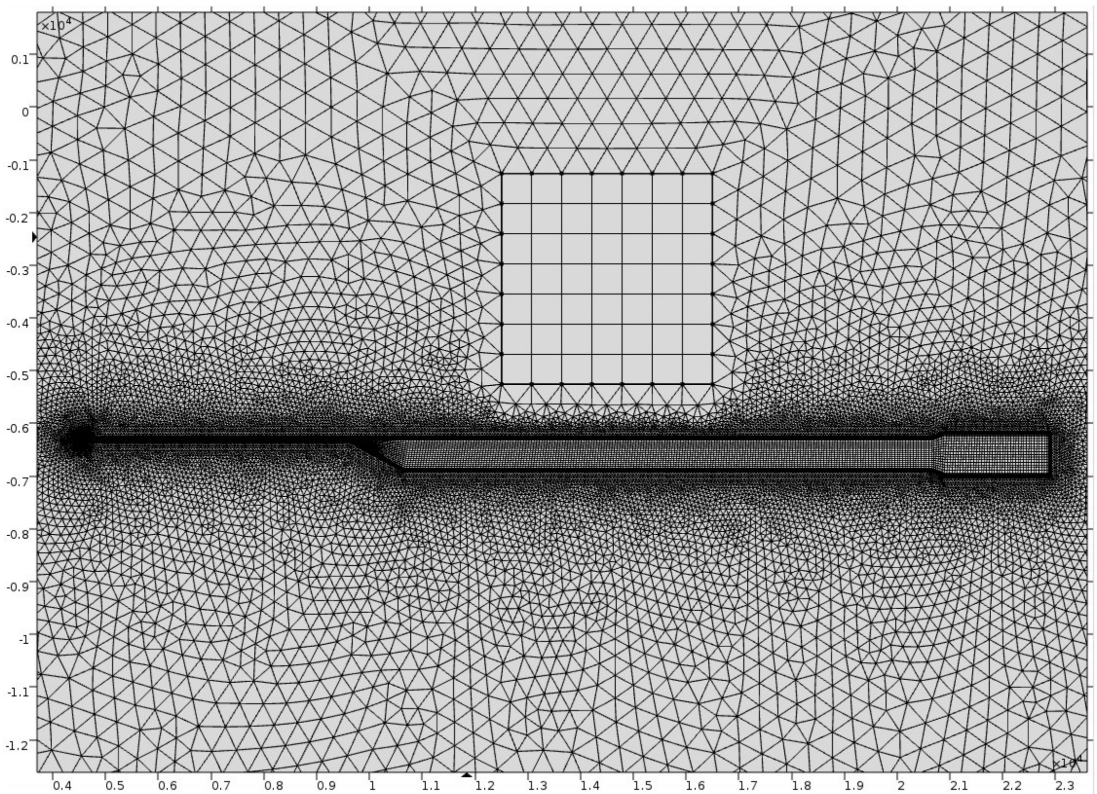


Figure S2 Meshing of geometry.

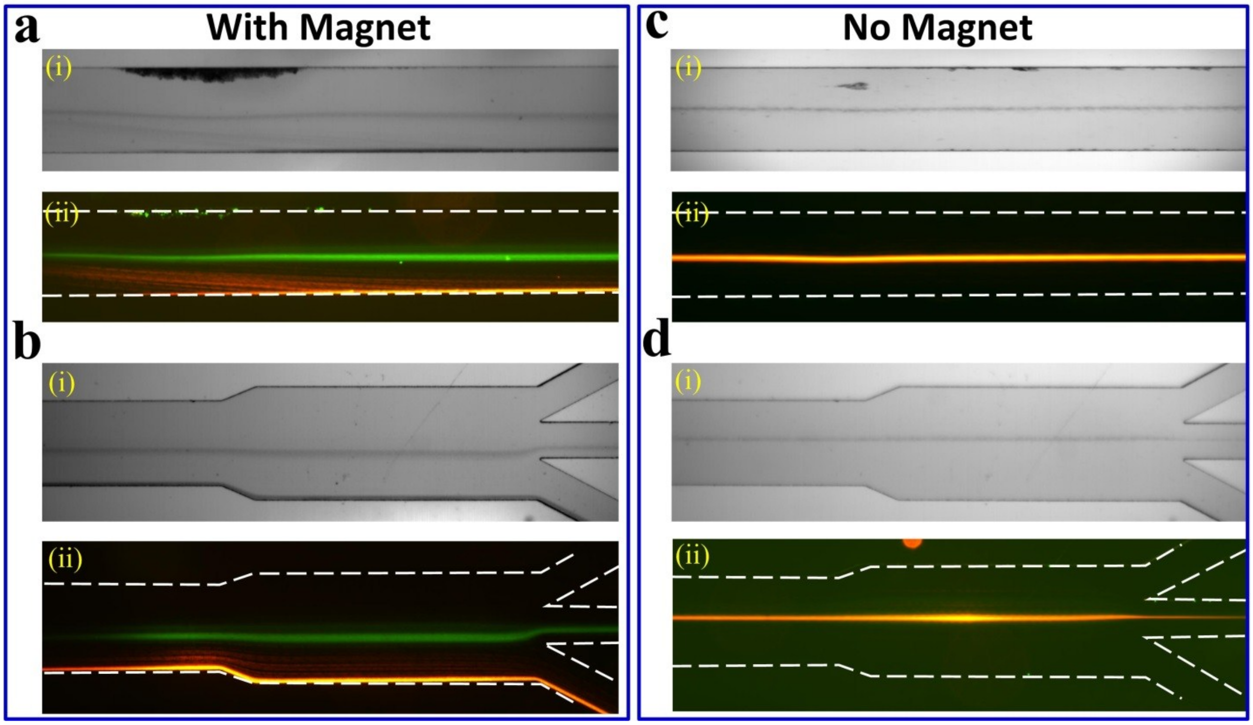
Parameters

The values of parameters used in the simulation are listed in the following table.

Table S1 Parameter values in the numerical simulation

Properties	**value**
Permanent magnet relative permeability	1.05
Air and PDMS relative permeability	1
Polystyrene particles relative permeability	1
PEO-based ferrofluid relative permeability	1.026
Fluid density (kg/m^3)	1007
Fluid dynamic viscosity (mPa•s)	8
Polystyrene particle diameters (μm)	5 and 13
Polystyrene particle density (kg/m^3)	1050

(3) Figure S3 Particle size-dependent magnetophoretic deflection with and without magnetic field in the PEO-based ferrofluid. (a) and (b) particles magnetophoretic deflection within magnet region and outlet when the magnet exists. (c) and (d) when the magnet is absent, particles focus at centreline without magnetophoretic deflection within magnet region and outlet.



(4) Supplementary video 1: Numerical results of negative magnetophoresis

(5) Supplementary video 2: Separation of non-magnetic particles in PEO-based ferrofluid at the outlet

(6) The reason why we applied the flow rate of 15 μl/min for particle separation tests

It is based on our experimental results of viscoelastic focusing and negative magnetophoresis in Figure 2 and Figure 3. In Figure 3b, we found that the optimal flow rate for particle viscoelastic focusing is 15 μl/min. Therefore, in order to confine particles in a narrow area in the downstream, particles need to be well focused by the viscoelastic effects. Meanwhile, from Figure 2, we found that the negative magnetophoretic deflection of 5-μm particles becomes insignificant when the flow rate is 15 μl/min, but magnetophoresis of 13-μm particles at the flow rate of 15 μl/min will be similar to that of 5-μm particles at a flow rate around 2.2 μl/min by a simple analytical analysis.

$$\left(V_y/V_x\right)_{13\mu m,\ 15\mu l/min} = \left(F_m/3\pi\mu a V_x\right)_{13\mu m,\ 15\mu l/min}$$
$$= A\left(a^2/V_x\right)_{13\mu m,\ 15\mu l/min}$$
$$= 6.76A\left(a^2/V_x\right)_{5\mu m,\ 15\mu l/min}$$
$$= A\left(a^2/V_x\right)_{5\mu m,\ 2.2\mu l/min}$$
$$= \left(V_y/V_x\right)_{5\mu m,\ 2.2\mu l/min}$$

where A is a constant independent of particle size and flow speed.

If the flow rate is too high, not only the viscoelastic focusing becomes worse, causing a wide particle streak, but also the magnetophoretic deflection of large particles may become less distinct with smaller particles, therefore hindering particle separation performance. If the flow rate is too low, the magnetophoretic force may repel both small and large particles to the opposite wall, and it will deteriorate particle separation too.

(7) Rheology of the PEO-based ferrofluid