MAGNETIC PARTICLES AS MULTIFUNCTIONAL TRANSPORT CARRIERS AND FLUID DRIVERS IN MICRO SYSTEMS

Roy J.S. Derks and Arjan J.H. Frijns
Eindhoven University of Technology, Mechanical Engineering, 5600 MB Eindhoven, The Netherlands
r.j.s.derks@tue.nl and a.j.h.frijns@tue.nl

Menno W.J. Prins
Eindhoven University of Technology, Applied Physics, 5600 MB Eindhoven, The Netherlands
Philips Research Europe, 5656 AE Eindhoven, The Netherlands
menno.prins@philips.com

Andreas Dietzel
Eindhoven University of Technology, Mechanical Engineering, 5600 MB Eindhoven, The Netherlands
Holst Centre, 5605 KN Eindhoven, The Netherlands
a.h.dietzel@tue.nl

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ABSTRACT
Magnetic actuation principles using superparamagnetic particles suspended in a fluid are studied in this paper. Two experimental setups for different magnetic field settings are designed and fabricated. On the basis of optical velocity measurements, the induced behavior of single and ordered chains was analyzed and compared to theoretical models. Interactions between the particles, fluid and nearby walls induce self-organization phenomena, that can be used for performance enhancement of particles as transport carriers and fluid drivers in micro systems.
1. INTRODUCTION

Miniaturization and integration are the key aspects of future biomedical diagnostics technologies and are driven by the need for speed, reliability, sensitivity, and to minimize human intervention [1]. The challenge in these micro systems is to generate effective catching of analyte, mixing with fluids and transportation towards a sensor surface, because molecular diffusion alone leads to unacceptably long reaction times. For a typical protein of DNA molecule with a diffusion value of $D = 10^{-11} \text{m}^2/\text{s}$, Einstein’s Law of diffusion shows that a travel of only 1 mm can take up more than half a day. Especially high surface area systems as micro porous membranes that are used to enhance sensitivity, the confined and quiescent fluidic micro volumes are the bottleneck for acquiring fast results [2]. Active manipulation of analyte and fluids in lab-on-a-chip systems is therefore one of the most important challenges for the microfluidic engineer.

New miniaturized sensing technologies based on superparamagnetic particles are currently under investigation in many research groups [3]. Because biological matter is barely magnetic, these techniques can be used in complex biological samples without any interference. The superparamagnetic nature of the particles gives a very strong magnetizability in combination with a disappearance of a magnetic moment after switching off external magnetic fields. Another important aspect is observed when the magnetic field is switched on: the particles may form chains aligned with the field lines. The properties of non-contact manipulation, non-interference and controllability in velocity and direction, indicates that application of magnetic particles as multifunctional objects in microfluidic systems seems to be very promising [4,5,6]. In this paper, we study particle dynamics in unbounded and confined fluid volumes with the focus on magnetic and hydrodynamic interactions. Subsequently, we discuss potential magnetic particle applications in microfluidic systems as analyte carriers and fluid drivers.

2. PARTICLE DYNAMICS

The magnetic force $F_m$ acting on a single particle, approximated by a magnetic dipole with a magnetic moment $m_b$, is proportional to the gradient of the field $B$ and given by [7]:

$$ F_m = \left(\vec{m}_b \cdot \nabla\right)\vec{B} \quad (1) $$

The magnetic moment of a superparamagnetic particle is again induced by the field $B$. Because the magnetic susceptibility of the surrounding medium is assumed to be zero and there are no time varying fields or currents in the medium, we can adapt equation (1) to the case of a superparamagnetic particle as [4]:

$$ F_m = \frac{V_b}{2} \cdot \frac{\chi_{b,\text{eff}}}{\mu_0} \cdot \nabla \vec{B}^2 \quad (2) $$

Parameter $V_b$ is the volume of the particle and $\chi_{b,\text{eff}}$ the effective magnetic susceptibility of the particle including demagnetization effects. In case of very large fields, the particle magnetization is no longer dependent on the applied field and is constant, as shown in figure 1 where the saturation value $M_{\text{sat}}$ is indicated. For this case, the magnetic force on a single particle can be expressed as [4]:

$$ F_m = V_b \cdot M_{\text{sat}} \cdot \vec{B} \quad (3) $$

The magnetic attraction forces given in equation (2) and (3) generate particle motion in a fluid, which causes a counteracting hydrodynamic drag force. For a single particle without surface roughness, the drag force in open volumes can be calculated with Stokes law [8]:

$$ F_d = -6 \cdot \pi \cdot \eta_f \cdot r_b \cdot \vec{v}_b \quad (4) $$

The dynamic viscosity of the surrounding fluid is given by $\eta_f$. The hydrodynamic radius of the particle is assumed to be equal to the material radius $r_b$ of the particle. Equations (2) and (4) can now be combined to calculate the particle velocity $v_b$, as the time to reach terminal velocity is negligible [4]:

$$ \vec{v}_b = \frac{\chi_{b,\text{eff}} \cdot r_b^2}{9 \cdot \mu_0 \cdot \eta_f} \cdot \nabla \vec{B}^2 \quad (5) $$
Figure 1: Magnetic particles consist of iron oxide grains (8-15 nm), embedded in a highly cross-linked matrix of polystyrene. A vibrating sample magnetometer (VSM) measurement of a high concentrated bulk solution of these particles shows a superparamagnetic behavior, with a high magnetic saturation and no remanent magnetization after removal of external fields.

In case of a particle in magnetic saturation, equation (4) has to be combined with (3), giving [4]:

\[ \tilde{v}_b = \frac{2 \cdot \dot{M}_{sat} \cdot r_b^2 \cdot \nabla \cdot \vec{B}}{9 \cdot \eta_f} \]  \hspace{1cm} (6)

These equations are valid if the induced motion is perpendicular to gravitation and if Brownian motion does not play a significant role. For micron sized particles, Brownian motion lead to superimposed velocities in random directions below 100 nm/s and can therefore be neglected. On the other hand, the hydrodynamic drag forces assume a regime of pure laminar flow, indicated by a Reynolds number \( \ll 1 \) [8].

Figure 2: A Comsol Multiphysics model is created to investigate the magnetization enhancement by chain formation of the particles. A homogenous magnetic field intensity is applied on the particles. The magnetic field lines concentrate in the chain, creating a higher magnetization on the points of contact. The demagnetization factor is decreased by the increasing number of particles in the chain.

Magnetic particles that aggregate in chains require a different analysis due to the large transformation in shape. Dipole interactions between neighboring particles induce a change in the demagnetization fields, whereby the effective susceptibility will change. We performed numerical simulations in Comsol Multiphysics to study the influence of the chain shape on resulting magnetization (figure 2). The chain is modeled as a row of spheres each of 1 µm in diameter and with the same intrinsic susceptibility as the single particles. The spacing of 50 nm represents twice the non-magnetic shell of the particles. The simulations show that the demagnetization factor is reduced by increasing the number of particles in the chain. We defined a magnetization enhancement as \( \alpha_{mag} = \frac{\chi_{c,eff}}{\chi_{b,eff}} \), where \( \chi_{c,eff} \) is the effective susceptibility of a chain. This magnetization enhancement approaches a maximum already to a factor 1.2 in the case of 5
particles in a chain. By defining the chain length as \( l_c \), the magnetic force on a long chain can now be expressed as:

\[
\vec{F}_m = \frac{\pi \cdot l_c \cdot r_b^2 \cdot \alpha_{mag} \cdot \chi_{b,eff}}{3 \cdot \mu_0} \vec{B}^2
\]  

(7)

The hydrodynamic drag on a chain also highly depends on its shape and orientation [8]. This counteracting force for elongated bodies axially dragged in a viscous fluid can be approximated by:

\[
\vec{F}_d = \frac{C_1 \cdot \pi \cdot \eta_f \cdot \frac{1}{6} l_c \cdot \bar{v}_c}{\ln(l_c/r_b) + C_2} \cdot \bar{v}_c
\]  

(8)

In this approximation, \( C_1 \) and \( C_2 \) are dimensionless constants that describe the hydrodynamic shape of the body, which have to be determined experimentally. If we now combine equation (7) and (8), the velocity of a chain relative to the medium can be derived:

\[
\bar{v}_c = \left( \frac{\ln(l_c/r_b) + C_2}{\frac{1}{6} C_1} \right) \cdot \left( \frac{r_b^2 \cdot \chi_{b,eff} \cdot \vec{B}^2}{9 \cdot \mu_0 \cdot \eta_f} \right) = \left( \frac{\ln(l_c/r_b) + C_2}{\frac{1}{6} C_1} \right) \cdot \bar{v}_b
\]  

(9)

The above equation shows that the chain velocity \( \bar{v}_c \) is proportional to the velocity of a single particle \( \bar{v}_b \). The proportionality - or in this case enhancement - factor that is shown in brackets on the right in equation (9), depends only on the aspect ratio \( l_c/r_b \), the hydrodynamic constants \( C_1 \) and \( C_2 \) and the magnetic enhancement factor \( \alpha_{mag} \).

As shown by the formation of chains, superparamagnetic particles obviously interact magnetism; a strong but short-range interaction which falls off very strongly as a function of \( (s^{-1}) \) [9]. These magnetic interaction forces can be calculated using a dipole approximation:

\[
\vec{F}_{m,\text{int}} = \frac{\mu_0}{4 \cdot \pi} \frac{m_b^2}{s^3} = \frac{4 \cdot \pi \cdot r_b^6 \cdot \chi_{b,eff} \cdot \vec{B}^2}{9 \cdot \mu_0 \cdot s^3}
\]  

(10)

However, particles also influence each other by means of hydrodynamic interactions. The motion of magnetic particles transfers momentum to the fluid and subsequently back to the nearby particles. In order to explain this interaction, we consider the 1-D flow profile of the fluid on an imaginary travel axis [8]:

\[
\bar{v}_{f,\text{int}} = \bar{v}_b - \chi_2 \cdot \bar{v}_b \cdot \left( \frac{r_b}{s + r_b} \right)^3 - 3 \cdot \left( \frac{r_b}{s + r_b} \right) + 2
\]  

(11)

If two particles are interacting by hydrodynamics, the resulting axis velocity profile can be calculated by a superposition of the two single particle profiles. By using the method of reflections based on a dipole approximation, the hydrodynamic interaction force can be expressed as [8,9]:

\[
\vec{F}_{f,\text{int}} = \frac{\pi \cdot r_b^4 \cdot \chi_{b,eff} \cdot \vec{B}^2 \cdot \left( 3 \cdot s^2 + 6 \cdot s \cdot r + 2 \cdot r^2 \right)}{3 \cdot \mu_0 \cdot (s + r)^3}
\]  

(12)

Surprisingly, many publications in this field of research only take into account magnetic interactions [9]. The hydrodynamic interactions are near not as strong as magnetic interactions, but will already dominate a couple of particle diameters away because of the weak \( (s^{-1}) \) fall off. Therefore, hydrodynamic interactions between micron sized particles are at least as important as the magnetic interactions, as shown in figure 3.

Next to the two particle interactions, more particles can generate surprising self assembled structures by the interplay of magnetic and hydrodynamic interactions [4,5,6]. If three particles are placed in a row, superposition of the single particle profiles reveals that the middle particle reaches a higher velocity than the outer particles as a result of contributions from both neighbors, as shown in figure 4. Over time, the middle particle will therefore approach the heading particle until a stable twin is formed and will travel away from the left particle. The described mechanisms also occur on a longer row of \( n \) particles, where a released twin successively creates space for the subsequent particles to twin as observed in the experiments. The resulting poly twin system is able to regulate and stabilize its interspacing: a twin that approaches a second twin in
front will enlarge its intraspaning and thereby reduce velocity. Conversely, the twin in the leading position will reduce its intraspaning (if present) and thereby accelerate to travel away from the following twin [6].

**Figure 3:** A calculation of the magnetic and hydrodynamic interactions of two particles as a function of their interspaning. Magnetic interactions are strong but short-range. Hydrodynamic interactions are not so strong but are long range, which dominate already a couple of particle radii away.

**Figure 4:** a) Calculated velocity profiles of two particles (thin lines), showing that the fluid velocity decrease is inversely proportional to the distance (s) from the particle. The resulting axis velocity profile (bold line) is obtained by superposition of the two velocity curves, which demonstrates an even increase of both particle velocities: a constant spacing over time. (b) Hydrodynamic interactions of three particles give a higher velocity enhancement for the center particle by contributions of bother neighbors. (c) The difference in velocities leads to formation of a twin that increases velocity with respect to the left particle and travels away.

### 3. PARTICLE MANIPULATION SYSTEMS

To investigate the particle and chain dynamics induced by external magnetic fields, two experimental setups were fabricated (figure 5 and 6). For particle translation and rotation, a first magnetic setup has been designed with four miniaturized solenoids to generate a wide variety of magnetic field shapes. A second magnetic setup has been designed that is able to create an isodynamic force field to separately study the magnetic and hydrodynamic particle interactions.

The quadrupole solenoid setup (figure 5, left) has a cylindrical fluid volume placed in the center with a diameter of 1 mm and a depth of 200 µm, because future miniaturized biosensor applications will generally consume sub-microliter volumes. The particles are observed with an optical microscope that is able to resolve particles with a diameter down to 300 nm. The working distance of the microscope limits the outer diameter of the solenoids. Soft iron cores are inserted in the solenoids and are coupled with a surrounding yoke to minimize air gaps and to increase the field intensity in the fluid volume. To suppress the influence of flaring field lines, the inner diameter of the solenoids is larger than the fluid volume diameter. The four
solenoids with an inner diameter of 1 mm, an outer diameter of 2.5 mm, a length of 5 mm and 294 windings were constructed using a Ø 100 µm bonding wire. The cores and surrounding yoke are machined out of soft-iron to minimize remanent magnetic fields. A casing to assemble all components in the exact position is machined out of aluminium with a very low magnetic permeability to minimize the influence on the magnetic fields. The disposable fluid containers are fabricated out of molded polydimethylsiloxane (PDMS). BSA (Bovine Serum Albumin) is applied on all walls of the fluid container to increase the hydrophilicity of the PDMS surface (originally highly hydrophobic). To close the containers, glass cover sheets are used that were sawed into the same lateral dimensions. Numerical simulations were carried out in Comsol Multiphysics in order to investigate a variety of magnetic fields induced by the electromagnets. Many complex field variations have been found, which demonstrate the high performance and flexibility of the magnetic particle manipulator. By applying a maximum current of 130 mA on every solenoid in clockwise direction, the setup is able to generate field intensities of 48.5 mT with magnetic driving forces in the order of 1 T²/m, as shown in figure 5 on the right.

Figure 5: The design of the quadrupole magnetic particle manipulator contains a sub-microliter fluid volume that is surrounded by four miniaturized solenoids (left), capable to create a large variety of magnetic field shapes (right). Maximum field intensities of 48.5 mT are generated with a maximum of 1 T²/m as the driving force.

The second magnetic isodynamic setup consists of a simple plastic holder, a polycarbonate fluidic chip and a magnetic system with a simple solenoid and two soft-iron yokes for particle actuation, as shown in figure 6, left. In a polycarbonate fluidic chip, a square micro channel (1 – 5 mm in length and 10 – 250 µm in width/depth) was created by excimer laser ablation. The channel in- and outlet are coupled by two large backflow channels (total cross-section 2 mm²) to minimize external pressures. A glass slide was used to close the complete channel circuit. To study both interactions individually, the magnetic field has been shaped in a way to have the least correlation with the hydrodynamic part of interactions: Because the magnetic field lines are oriented perpendicular to the micro channel, particles are magnetized perpendicular to its direction of motion, inducing a repelling magnetic interaction force between each other. With use of the equi-potential theory [10], an isodynamic force field (where \( \nabla B^2 \) is constant) is calculated over the poles line of symmetry that is aligned with the micro channel axis using the following constraint:

\[
B_x \frac{\partial B_y}{\partial y} = \text{const.} \tag{13}
\]

Because of the small height of the poles, end effects have been corrected with a numerical optimization step using Comsol Multiphysics. The cross-sectional area of the yokes has been maximized where possible to maintain a high flux and minimize the risk of saturation in the yokes. The final shape is illustrated in figure 6, which achieves about 0.22 T²/m with only 50 mT as maximum field using a current of 1 A through the solenoid. With this setting, an isodynamic field of about 5 mm long can be achieved within 10% accuracy.

The magnetic setups are placed under a microscope (Olympus, objective M=65, NA=0.70, WD=1.30 mm) equipped with a digital camera (Olympus, resolution 1600 by 1200 pixels, frame rate 50 fps), connected to a DVD recorder. This way, the motion of micron sized particles can be tracked, or tenfold larger magnetic particles can be used in the same system to study the fluid flow by micron sized fluid tracers (micro PIV). A four-channel home-built current source is used to power the solenoid(s). With use of a D/A converter, the current source is controlled with scripts that are written in Matlab. A height gauge is mounted just below the microscope base-plate to control the position of the view plane in the fluid volume.
Figure 6: The design of the isodynamic force field setup with pole tips that create a perpendicular field with respect to the travel direction of the particles in the micro channel. A large solenoid is used to generate the magnetic field inside the yokes. The final shape achieves about $0.22 \text{T m}^{-2}$ with only 50mT as maximum field using a current of 1A through the solenoid. With this setting, an isodynamic field of about 5 mm long can be achieved within 10 % accuracy.

4. EXPERIMENTS

The first two experiments described below were carried out in unbounded fluid volumes to to verify the travel velocities of single particles and chains as expected by equation (5) and (9), using a magnetic field prediction from the simulations. By applying the current of 75 mA through the left solenoid of the quadrupole setup, single particles and chains are attracted towards the solenoid. Particles with a diameter of 1 $\mu$m were used: their magnetic saturation occurs at much higher field intensities than reached in these experiments and therefore the magnetic susceptibility ($\chi_{b,\text{eff}} = 1.52$) [4] can be assumed to be constant (figure 1). The stock solution of particles was diluted with deionized water into two different concentrations. A low concentration of 200 $\mu$g/ml ($\approx 2 \cdot 10^8$ particles/ml) minimizes chain formation, suitable to study the travel of single particles. A higher concentration of 500 $\mu$g/ml ($\approx 5 \cdot 10^8$ particles/ml) forces the particles to aggregate in chains under the application of a magnetic field, which is used in the study on chains. By adding the inorganic salt sodium-polytungstate (SPT), the particle solution was tuned to have a matching density as the particles itself ($\rho = 1.8 \text{ g/cm}^3$). This avoids out-of-plane traveling of the particles, to enable a complete particle tracking in the whole imaging plane of the microscope. SPT does not affect the neutral properties of the fluid, but increases the viscosity $\eta$ to a value of 0.021 kg/m$^3$, lowering the expected experimental velocities (already taken into account in the simulations). The path of every single particle or chain was tracked from a recorded movie, using home developed processing software that is written in Matlab (figure 7, left). Every movie frame is averaged with the 25 surrounding frames to suppress background noise and subsequently all intensity peaks in the frame are identified. Neighboring intensity peaks are joined to one area and divided by the actual area of a single particle, giving the number of particles in the chain or identifying a single particle. The particle or chain position is determined with sub-pixel resolution by an estimation of the center of mass. To exclude chains that do not move in an axial direction, the relative alignment with the direction of movement is determined, which was not allowed to exceed a difference of 5 degrees. The obtained tracks are visualized in the movie as trajectory lines.

For each single particle position located with the movie processing software, the actual velocity is calculated. We have plotted the experimental velocities as function of the calculated values of $\nabla B^2$ (figure 7, right). The measured velocities are on average noticeable lower than predicted by equation (5), quantified by an average relative error (RE) of 0.33. Furthermore, the measurements show a large spread that is expressed as a coefficient of variation (CV) of 0.22. This RE and CV can be caused by uncertainties in the following parameters (in brackets the function in equation (5) is given): the radius and hydrodynamics particle including shape and surface roughness (by $r_b^3$), the viscosity of the surrounding fluid (by $1/\eta_f$), the magnetic susceptibility of the particles (by $\chi_{b,\text{eff}}$), the magnetic field characteristics (by $\nabla B^2$), and (computational) errors in the velocity measurement itself (by $v_b$). Light scattering experiments show a small distribution in particle diameter. The viscosity of the surrounding fluid has been measured, where temperature influences of the solenoid and illumination have been taken into account. The magnetic field simulations have been verified with a magnetic field mapping calibration as a function of position. The average magnetic susceptibility per particle has been estimated by a VSM measurement in a concentrated volume of magnetic
particles. Magnetic interactions between particles in the suspension may occur during this measurement. The obtained value may therefore not reflect the single particle magnetic susceptibility. The measurement also conceals a variation that could exist because of a possible but unknown variation in the iron oxide content. Considering the many potential sources of deviation, the single particle experiments were in good agreement with the established equations of motion.

Figure 7: The measured (left) velocities of single particles show a large variation, which could be explained by particle-to-particle variations due to the average magnetic susceptibility (right). The experimental data (dotted curves) is on average lower than the velocity predicted with equation (5) (solid line), caused by possible (static) uncertainties in the bulk properties of the particles.

For particle chains, equation 2, 5, 7, and 9 shows that chains will align with the field lines, and will move in the direction of $\vec{\nabla}B^2$. For all obtained chain trajectory lines, the resulting velocities as a function of $\vec{\nabla}B^2$ are calculated (figure 8, left). The shape of these curves is comparable with the curve of the single particle experiments (roughly linear). Quantitatively, we observe for the velocity of each chain length an enhancement factor normalized to the velocity of a single particle: $VEF = \frac{v_c}{v_b}$. This velocity enhancement factor depends in a logarithmic way only on the number of particles in the chain ($n$), as shown in figure 8 (right) and is approximated by:

$$VEF = 1 + 0.77 \cdot \ln(n)$$

The obtained function is in agreement with the velocity enhancement factor we found in equation (10). Using $\alpha_{mag} = 1.2$, we find a corresponding fit with $C_1 \approx 9$ and $C_2 \approx 0.56$. A comparison with values for an ordinary cylinder dragged in an axial direction through the fluid ($C_1 = 4$ and $C_2 = -0.72$) indicates that the hydrodynamic drag force of a chain of particles is evidently higher. The undefined surface roughness and the undulating shape of the chain of particles is most likely the main reason for the higher hydrodynamic drag force.
The third experiment was carried out to investigate the interplay of particles by magnetic and hydrodynamic interactions, using the isodynamic force setup. Under the action of the applied magnetic field ($\nabla B^2 \approx 0.2 \text{T}^2/m$, individual particle force $20 \text{ fN}$), $20 \mu m$ particles with $\chi_{\text{b,eff}} = 0.06$ travel through the fluid in the microchannel. The presence of the channel walls induces a hydrodynamic focusing on the particles that leads to a particle lineup along the channel axis with an initially arbitrary interspacing. However the particles are influenced by the channel walls, we noticed a repetitive self organization for the lined up particles. As explained in the 1-D model, the two particles in front of the moving row reduce their interspacing, form a twin and travel away with an increased velocity along the channel axis, as shown in figure 9a. The new heading particles of the row follow successively the same re-organization processes, through which the row shortens until a full stable poly twin system is formed, however where the twinned micro particles do not completely touch. This experiment has been repeated, where the isodynamic force field is generated by gravity in stead of magnetics. We observed fully developed twins with particles in complete contact as shown in figure 9b. The gravitation driven particles are not subjected to (short range) repelling forces, in contrast with the micro particles driven by magnetics (by the applied magnetic field perpendicular to the motion direction). This proves that the successive twinning effect is induced by hydrodynamic interactions only [6]. The (attracting) hydrodynamic interactions and (repelling) magnetic forces appear to equilibrate at an interspacing of about a particle diameter. The self assembly of particles to a spread configuration in for instance micro channels gives the advantage of a high pump efficiency of fluids by an enhanced drag, together with a reduction of required pressure needed to obtain sufficient fluid flow [6].

Figure 9: (a) Traveling superparamagnetic particles focuses on the axis of a microchannel by hydrodynamic wall interactions. A twin is formed at the front of the row and travels away, but keeps a small intraspacing ($s$) caused by repelling magnetic forces. (b) Gravity driven experiment, where only hydrodynamic particle interactions occur that allow twins to fully come in contact as particles 4 and 5 show. Particles 2 and 3 are still at the onset of twinning.

5. CONCLUSIONS AND OUTLOOK

We performed studies on the dynamics of single magnetic particles and chains of particles inside unbounded and confined sub-microliter volumes. Using a quadrupole solenoid setup, experiments on single particles showed large velocity variations, most probably by particle-to-particle variations and an error in the average susceptibility of individual particles. Equations for the influence of chain formation on the magnetization and the hydrodynamic drag force have been established and compared to experimental data. We observe a logarithmic dependence of velocity on the chain length. For a given magnetic field, the velocity of chains is proportional to the velocity of single particles with an enhancement factor that depends on the number of particles in the chain and the hydrodynamic properties of the chain. Using the isodynamic setup, we observed a hydrodynamic particle interaction effect that leads to successive formation of stable particle twins (in case of at least three particles) in low Reynolds number regimes. The observed self
organization can be explained by a superposition of particle velocity contributions that vary as a function of interspacing. The long range hydrodynamic- and short range magnetic interactions between particles and (within) twins can be controlled to tune the interspacing between particles and twins.

Our experiments show that magnetic and hydrodynamic interactions in combination with chain formation can in principle be used for accelerated transport in fluids. We envisage that the controlled rapid manipulation of particles and chains can be beneficial for bio-assays, for example when target molecules are to be bound to magnetic particles or when enhanced mixing or transport is required. The interplay of magnetic and hydrodynamic interactions shows possibilities for using particles as fluid drivers in micro systems. Next steps will involve the study of particle and chain manipulation in dynamic fields, for example to generate a rotational field. Off axis particle configurations in channels will be studied on the application of fluid drivers in high-surface-area microfluidic systems to enhance local convection streams near the walls.

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