Magnetic forces produced by rectangular permanent magnets in static microsystems†

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Finite element numerical simulations were carried out in 2D geometries to map the magnetic field and force distribution produced by rectangular permanent magnets as a function of their size and position with respect to a microchannel. A single magnet, two magnets placed in attraction and in repulsion have been considered. The goal of this work is to show where magnetic beads are preferentially captured in a microchannel. These simulations were qualitatively corroborated, in one geometrical case, by microscopic visualizations of magnetic bead plug formation in a capillary. The results show that the number of plugs is configuration dependent with: in attraction, one plug in the middle of the magnets; in repulsion, two plugs near the edges of the magnets; and with a single magnet, a plug close to the center of the magnet. The geometry of the magnets (h and l are the height and length of the magnets respectively) and their relative spacing s has a significant impact on the magnetic flux density. Its value inside a magnet increases with the h/l ratio. Consequently, bar magnets produce larger and more uniform values than flat magnets. The l/s ratio also influences the magnetic force value in the microchannel, both increasing concomitantly for all the configurations. In addition, a zero force zone in the middle appears in the attraction configuration as the l/s ratio increases, while with a single magnet, the number of maxima and minima goes from one to two, producing two focusing zones instead of only one.

Introduction

Magnetic beads (MBs) have received a growing interest during the last few years. They have become a powerful and widespread tool for both *in vivo* and *in vitro* applications in various fields such as chemistry, biochemistry, biology and medicine.¹ Their expansion takes advantage of a nowadays well-developed surface chemistry and a tailor-made functionalisation.² Several companies now propose ready-to-use functionalised magnetic particles with well-controlled surface chemistry providing at the same time a high specific binding capacity and low non-specific adsorption.¹ Furthermore, their success certainly remains on their easy manipulation by externally placed magnets, possible automation and miniaturization.

Microfluidics is also a growing field, meeting the needs for low sample consumption and fast analysis time. In this context, MBs can be considered as a very valuable alternative to more

conventional and complex microfabrication techniques as microstructures of high-aspect ratio can be easily fabricated *in situ*. As an example, long DNA samples were separated by microfluidic electrophoresis in self-assembling matrices of magnetic columns,^{3,4} when the fabrication of an array of pillars would require more demanding and time-consuming processes. In addition to this kind of structure-related application, MBs have also been used for many other purposes in microfluidics, such as analyte labelling for detection, sorting and separations of cells, mixing, transport of MBs using magnetic forces instead of a liquid flow and finally immunoassay.^{5–7}

In immunoassays, the sensitivity is directly linked to the specific surface area available for molecule adsorption. Despite the already large surface-to-volume ratio of open microchannels as compared to classical formats, this ratio can be significantly improved to further increase the sensitivity of the assay. An interesting way is to integrate a 3-dimensional phase. In addition to enhance the binding capacity, it reduces significantly the diffusion pathway for molecules and subsequently the analysis time. Technologies issued from the chromatographic field are generally employed. A packed bed of beads or an *in-situ* polymerized monolithic phase can be used to this extent. Although the use of packed beds can significantly enhance the binding capacity, it requires the use of frits to retain the beads and large backpressure related drawbacks and/or clogging problems are often encountered.^{6,8} The monolithic approach is more convenient regarding the fabrication process, the monoliths being polymerized directly in the microchannel, either by temperature or UV light.⁸ Moreover, the use of a monolithic column, as compared to a packed one, usually induces a lower pressure drop

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due to the presence of macropores, in addition to the mesopores. Nevertheless, the synthesis of a monolith is complex and the problem of non-specific adsorption rather difficult to deal with.⁹ As a valuable alternative, MBs can be easily trapped in a microchannel and their surface chemistry is well developed. Also, it gives the additional possibility to replace the phase in between two experiments by simply removing the magnetic field and rinsing the microchannel, minimizing the problems linked to cross-contamination. Studies relating the use of MBs as a solid phase for example aimed at protein immunocapture,^{10–13} mainly to extract a selected analyte for further analyses, at immunoassays^{14–18} or at support for on-chip enzymatic digestion,¹⁹ increasing the digestion speed as compared to a batch wise system.

As the literature often focuses mainly on the biological application itself, relatively little information on the magnetic aspects has been published. Indeed, experimental parameters as the kind of magnets, their number, their strength, their size and/or configuration are often overlooked. To the best of our knowledge, only one article considering the magnetic design parameters for permanent magnets has been so far reported.²⁰ The effect of magnet geometry is treated for cylindrical magnets and analytical expressions are presented for calculation of the magnetic flux density. The trajectories of MBs were computed by the finite element method (FEM).²¹ The motion and capture of MBs in a microfluidic channel was also theoretically treated.^{22–24} Different designs of microelectromagnets were theoretically and experimentally studied for biomolecular manipulation²⁵ or integrated to a microfluidic chip for creating arrays of MBs in a microchannel.²⁶ Permanent magnets were associated with soft magnetic elements to increase the local magnetic field gradient with the purpose of cell separation,^{27,28} and an analytical model predicting the magnetic field and force in a magnetophoretic microsystem was developed.²⁹ Finally, patterned micromagnets were fabricated to bias the moments of magnetic particles in a flowing stream.³⁰

This article, by means of numerical simulations using the finite elements method, aims to quantify the magnetic field produced by permanent magnets, in particular its spatial distribution according to the size and the configuration of the magnets. More precisely, a single magnet, two magnets placed in attraction and in repulsion have been considered respectively. Permanent magnets alone were chosen because of their simplicity of use. Indeed for a given size, they produce a higher magnetic field than electromagnets. Soft magnetic elements could be used to optimize the field, but they need to be integrated to the chip, being inaccessible to labs without clean room facilities. To make the link between the magnetic flux density and the MBs capture, the magnetic force distribution has also been simulated to determine where, in a microchannel, the beads are more likely to be attracted depending on the chosen configuration. Finally to corroborate the simulation results, the formation of MBs based plug was visualized by microscopy in the case of millimeter-sized rectangular magnets.

Theory

Magnetism

The term magnetic field is unfortunately often confused with the magnetic flux density, which can, in the presence of a permanent magnet, be written as:

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}) \quad (1)$$

with μ_0 being the permeability of free space, $\mathbf{H}$ the magnetic field, and $\mathbf{M}$ the magnetization produced by the permanent magnet.³¹

The magnetic force acting on a magnetic dipole moment $\mathbf{m}$ can be expressed as the gradient of the magnetic potential energy U .³² If we assume $\mathbf{m}$ constant, this force is simply given by:

$$\mathbf{F}_m = -\nabla(U) = \nabla(\mathbf{m} \cdot \mathbf{B}) = (\nabla \mathbf{m}) \cdot \mathbf{B} + \mathbf{m} \cdot \nabla \mathbf{B} \approx (\mathbf{m} \cdot \nabla) \mathbf{B} \quad (2)$$

In the case of superparamagnetic nanoparticles in a non-magnetic medium like pure water, the magnetic dipole moment can be written as $\mathbf{m} = V\mathbf{M} = V\chi\mathbf{H}$, with V being the volume of the superparamagnetic particle, χ its effective magnetic susceptibility (if we assume that water has a negligible susceptibility) and $\mathbf{M}$ its magnetization. As $\mathbf{H}$ and $\mathbf{B}$ differ only by the constant μ_0 , the magnetic force can finally be written as:

$$\mathbf{F}_m = \frac{V\chi}{\mu_0} (\mathbf{B} \cdot \nabla) \mathbf{B} \quad (3)$$

This equation shows that a magnetic field gradient is required to exert a translation force on a particle. In a homogeneous field, the particle would only be submitted to a torque, forcing it to align along the direction of the magnetic field.²⁴ More information about the $(\mathbf{B} \cdot \nabla) \mathbf{B}$ term is given in ESI 1.†

Numerical model and assumptions

In the case of permanent magnets and in the absence of charges in movement, the magnetic field is conservative. So a scalar magnetic potential ϕ can be introduced, such that:

$$\mathbf{H} = -\nabla\phi \quad (4)$$

In magnetostatics, the second Maxwell's equation simplifies to give $(\nabla \cdot \mathbf{B}) = 0$. Inserting Equation (1) and (4) into this equation, we obtain for the present case (assuming that all the regions have the permeability of free space):

$$\nabla \cdot (-\nabla\phi + \mathbf{M}_0) = 0 \quad (5)$$

This local form is integrated on the domain of study (ESI 2†) to be solved by the finite elements method, carried out on the numerical software Flux-Expert® (Astek Rhône-Alpes, Grenoble, France), in 2D Cartesian form. The following assumptions are made:

- magnetostatic case ($\partial\mathbf{B}/\partial t = 0$ and no external source of electric or magnetic field)
- homogeneous media (μ uniform, that is to say μ_0 everywhere)
- 2D Cartesian form (the third dimension, that is to say the depth of the magnet, being much larger than the horizontal components, is neglected)
- air box big enough for not perturbing the magnetic field distribution
- constant magnetic susceptibility of the magnetic beads and magnetic moment of the beads assumed to be unsaturated
- no flow in the microchannel (static bead solution)
- the model doesn't take into account the interactions between MBs

Numerical parameters

The magnetic field and force were calculated in a 2D geometry for a reference system depicted in Fig. 1. It is composed of a microchannel (100 μm high and 1 mm long) closed by insulating layers of PET (50 μm high and 1 mm long), surrounded by one or two permanent square micromagnets (200 μm), providing a spacing of 200 μm between the two magnets. The whole reference system is placed in an air box (whose size is determined by the parameters h_{air} and l_{air} , representing the distance between the top of the magnet and the beginning of the infinite layer, and between the end of the microchannel and the beginning of the infinite layer respectively), surrounded by an infinite air layer (100 μm thickness, represented by the area between the double lines in Fig. 1), enabling the magnetic field to rotate freely from one pole to the other. The total proportions of the system are a length of 1.8 mm for a height of 1.4 mm. The x - and y -axes pass exactly in the middle of the microchannel and of the magnets respectively, and the origin location is shown on Fig. 1.

The size of the air box, that is to say the value of h_{air} and l_{air} , is dependent on the dimensions of the magnets. It was optimized such as the error is smaller than 0.2%. The mesh size adopted for the middle of the microchannel was $\delta = 5$ microns (1/20 of channel height), for its ends $\delta = 10$ microns (1/100 of channel length) and for the edges of the magnets $\delta = 10$ microns (1/20 of magnet length). The validation of these values is presented in ESI 3.†

The numerical parameters values for the simulations are summed up below:

μ_0 (permeability of free space): 1.256×10^{-6} [H/m]

μ_r (relative permeability): 1 [–]

B_0 (imposed magnetic flux density): ± 1 [T]

χ (MBs magnetic susceptibility): 1 [–]

d (diameter of the beads): 1 [μm]

The three geometric parameters of the system, notified in Fig. 1, and their ratios are used to quantify the distribution of the magnetic field and force: the height h and the length l of the

Fig. 1 Scheme of the system composed of a microchannel (light grey) placed between two square permanent magnets (dark grey). The frame represents the infinite air box. The origin is represented by a dot (0,0). The letters h , l and s represent respectively the height of the magnets, their length and the spacing between them. h_{air} and l_{air} are parameters that define the size of the air box.

magnets, and finally their spacing s . Two different ratios are studied: h/l (magnet shape) and l/s (relative gap). The magnetic force calculation (Equation 3) and its smoothing are performed at the post processing level.

Calibration

The model was validated by comparison with the work of Bronzeau *et al.*,¹⁸ who used the FEMM 4.0 software to simulate the magnetic field produced by two NdFeB magnets (5 mm high and 2 mm long) in attraction configuration with a spacing of 0.5 mm. Good agreement with their results was shown (ESI 4†).

Experimental

Chemicals

The NdFeB permanent magnets (8 mm high, 2 mm long and thick) were from ChenYang Technologies (Finsing, Germany). Fused-silica capillaries (100/375 μm id/od) were obtained from BGB Analytik AG (Böckten, Switzerland). Protein-A coated superparamagnetic beads of uniform size (300 nm diameter) were purchased from Ademtech (France). The bead suspensions were prepared in water produced by an alpha Q Millipore System (Zug, Switzerland).

Imaging of magnetic beads

The MBs were observed with a microscope Axiovert 200 (Carl Zeiss, Gottingen, Germany) and a CCD-IRIS camera (Sony, Tokyo, Japan). The permanent magnets were stuck on a microscope slide in the three different configurations, with a spacing s of 1 mm. The external polyamide layer of the capillary was removed on a 1 cm long window, allowing the visualization of the beads in transmission. This window was placed symmetrically between the magnets. The magnetic beads were freshly diluted 10 times in water and infused in the capillary at a flow rate of 100 nL min^{-1} . The magnets were set in place before flowing the MBs through the capillary. The situation is thus not exactly the same as in the numerical simulations, where the beads are supposed to be present before the implementation of the magnetic field.

Results and discussion

Reference micromagnets

The first step of this work was to simulate three reference cases with the geometry pictured in Fig. 1. The first one places the two magnets in an attractive configuration, with both magnetizations pointing up. The second considers two magnets in a repulsive configuration, the top magnet having a negative magnetization and the other a positive one. The last case describes a single magnet only, placed on the microchannel with a negative magnetization.

As a conservative field ($\text{div} \mathbf{B} = 0$), an essential property of the magnetic flux density is the formation of complete closed loops around the magnet. The loops spatial distribution is a function of the number, position and magnetization's orientation of the magnets, as shown on the first line of Fig. 2, which represents the $\mathbf{B}$ vectors. In attraction, they go straight from one magnet towards

Fig. 2 Vector representation of the magnetic flux density $\mathbf{B}$ (top) and of the magnetic force $\mathbf{F}$ (bottom) for the 3 reference configurations. (a) + (d) attraction, (b) + (e) repulsion, (c) + (f) single magnet.

the other, forming a big loop around the magnets. This is fully true in the middle of the magnets, while near the edges the lines enlarge and finally tend to form a loop around only one magnet. Nevertheless, this configuration gives principally a y component to $\mathbf{B}$. Unlike attraction, the repulsive configuration compels the lines to turn horizontally before the horizontal symmetry axis of the microchannel, giving rise to a strong x component of $\mathbf{B}$. The single

magnet configuration is a combination of both attraction and repulsion. The lines simply form a loop around the magnet, giving rise to two significant $\mathbf{B}$ components.

The second line of Fig. 2 and Fig. 3 present respectively, in the microchannel, the magnetic force vectors and isovalues (x and y components, in the left and right columns respectively), in order to explain where the MBs are attracted. If two magnets are

Fig. 3 Isovalue representations of the two components of the magnetic force (left: F_x and right: F_y) for the three reference configurations. (a) attraction, (b) repulsion, (c) single magnet. The force is calculated for a bead diameter of $1\ \mu\text{m}$ and a susceptibility of 1.

used, Fig. 2d,e shows that the exerted forces can be directed toward the center or the edges of the configuration depending on whether attraction or repulsion is chosen, respectively. If the situation with only a single magnet is considered (Fig. 2f), the exerted forces are oriented toward it. Then taking into account the isovalue representation (Fig. 3), the relative importance of each component of the magnetic force can be precisely examined. The x component of the force induces a magnetic velocity that is superimposed on the convective flow in a dynamic case. Indeed, it will amplify or counterbalance the Stokes force due to the viscous drag exerted by the fluid on a moving bead. The three configurations present a symmetry axis (the y -axis) for the x component. In attraction, this component has a positive value on the left and a negative one on the right, concentrating the beads towards the middle of the magnet. In repulsion, there are two positive and two negative alternating forces, giving two focusing zones near the corners of the magnets. With a single magnet, the x component of the force is logically the strongest near the magnet and decreases with the distance to it. Concerning the y component, the behaviour is easier to predict: the value is simply larger near the magnets for all the configurations. Again there is a symmetry axis (the x -axis) for the attractive and repulsive configurations. In the single magnet case, the y component coupled to the decreasing x component drive the beads towards the magnet.

Paramagnetic particles form dynamic and reversible self-assembled regularly spaced column like structures when exposed to an external magnetic field. These structures align in the direction of the magnetic field. They are spaced because their poles are aligned and repel each other.³³ If we consider the reference cases shown in Fig. 2 and what would be the resulting beads accumulation zones (according to the x -axis in the middle of the magnets in attraction and near the magnets corners in repulsion), we see that the magnetic field is oriented differently. The attraction configuration induces a strong y component in the middle of the magnets, such as the beads would form vertical columns. In contrast, the repulsion arrangement produces a significant x component near the magnets corners, such as the beads would form horizontal columns. Considering the potential influence of the column orientation if a horizontal flow is present, the attractive and repulsive configurations are not equal. Vertical columns may induce more resistance to the flow, as the surface exposed to it would be increased as compared to horizontal columns.

Shape considerations

The next part of this study concerns the influence of the system parameters (h , l and s) on the magnetic flux density inside the magnets. Depending on the h/l ratio, the y component of $\mathbf{B}$ varies significantly. Fig. 4 shows this variation in the case of a single magnet, on its x symmetry axis, for ratios ranging from 0.25 to 10. In the reported cases, the magnet length is kept constant while its height is varied. At small h/l ratios (flat magnets), the value of $\mathbf{B}$ is smaller in the middle of the magnet than near the edges. When increasing the ratio (bar magnets), $\mathbf{B}$ increases, reaching a homogeneous value higher than 90% of B_0 for h/l of 10. For the bar magnet, the distance the magnetic field lines have to cover, inside and outside the magnet, is roughly the same, the length l of the magnet being very small as compared to its height h . For the flat magnet, the distance outside the magnet becomes significant

Fig. 4 Behaviour of magnetic flux density (y component) in function of h/l for a single magnet, with l constant ($l = 200 \mu\text{m}$). The values are taken along the x symmetry axis of the magnet. h/l ratios: (A) 10, (B) 5, (C) 2, (D) 1, (E) 0.5 and (F) 0.25.

because the length of the magnet is not negligible anymore as compared to its height. This effect, that reduces the local $\mathbf{B}$ value in the magnet, is particularly important for the central lines ($x = 0$) and decreases progressively when going towards the side of the magnets ($x = \pm l/2$) explaining the $\mathbf{B}$ distribution of Fig. 4. Consequently in order to obtain a high magnetic field density in a magnet, and subsequently in the microchannel, the h/l ratio needs to be high.

Fig. 5a shows, for the three considered configurations, the evolution of $\mathbf{B}$ as a function of the l/s ratio inside square magnets ($h/l = 1$). The size of the square magnets was increased keeping their spacing s constant. The plotted values represent the value of the y component of the magnetic flux density at the middle of the upper magnet's bottom boundary ($x = 0$, $y = 100 \mu\text{m}$. Other points are plotted in ESI 5†). When the ratio is low (high relative gap value), the three configurations are nearly equal. Upon increasing the ratio, the value for the single magnet configuration remains constant (simulation error excepted). If attraction or repulsion is chosen, an increase or a decrease is observed respectively. Fig. 5b and 5c present what happens to the y component of $\mathbf{B}$ along the y -axis when changing the l/s ratio in attraction and repulsion respectively. The vertical dashed lines show the magnets position against the microchannel. In attraction, it can be seen that the “ $\mathbf{B}$ well” in the microchannel disappears gently with the l/s increase. This can be explained by the fact that as l/s increases, more flux lines flow from one magnet to the other, rather than turning around only one of them. As they are relatively closer to each other, they form like a single magnet. In repulsion, the maximum value of $\mathbf{B}$ decreases with l/s because the magnetic lines are compressed in the microchannel and part of the magnetic flux density is brought back into the magnets, increasing $\mathbf{H}$ in the magnet and as a consequence decreasing the total $\mathbf{B}$.

Towards millimeter-size magnets

The results presented in Figs. 2 and 3 present micromagnets cases. In reality, it is more common to use magnets in order of the millimeter size. Fig. 6 shows how the magnetic force changes

Fig. 5 Behaviour of magnetic flux density (y component) for square magnets in function of l/s , with s constant ($s = 200 \mu\text{m}$). (a) Values taken at the middle of the upper magnet's bottom boundary ($x = 0$, $y = 100 \mu\text{m}$) for (A) attraction, (B) single magnet and (C) repulsion. (b) and (c) Magnetic flux density along the y axis in attraction and repulsion respectively for different l/s ratios: (A) 10, (B) 7.5, (C) 5, (D) 3, (E) 2, (F) 1.5, (G) 1, (H) 0.5 and (I) 0.25. The vertical dashed lines show the magnets position (microchannel between the dashed lines).

when the size of square magnets is increased, keeping their spacing constant. For each l/s ratio, the value of the force x component was plotted along the x -axis for the three configurations, with (a), (b) and (c) representing attraction, repulsion and a single magnet respectively. The curves were normalized by

dividing the x values by l . It can be seen that the maxima of the magnetic force increase with the l/s ratio. Additionally, the shape of the curves can also evolve with this ratio. This is the case for attraction where, when the ratio is 10, the middle of the magnets doesn't "work" anymore, producing a zero force zone for the

Fig. 6 Variation of the magnetic force (x component) in function of the ratio l/s for square magnets with a constant spacing ($s = 200 \mu\text{m}$). The force was calculated for a bead with following parameters: diameter $= 1 \mu\text{m}$ and $\chi = 1$. The values are taken along a horizontal path (the x axis). The vertical dashed lines show the magnets position. (a) attraction, (b) repulsion, (c) single magnet. l/s ratios: (A) 10, (B) 5, (C) 2, (D) 1 and (E) 0.5. For clarity reasons, the (B) curve for attraction was omitted (nearly superimposed to (A)).

Fig. 7 (a) Magnetic force (x component) calculated for a bead of diameter = 1 μm and $\chi = 1$. The values are taken along a horizontal path (the x axis). (A) attraction, (B) repulsion and (C) single magnet. The vertical dashed lines show the magnets position. Microscopic visualizations of the MBs plug in a capillary according to the magnets configurations. (b) attraction, (c) repulsion, (d) one magnet. $h = 8$ mm, $l = 2$ mm and $s = 1$ mm. capillary i.d. = 100 μm .

x component. As previously explained, in the middle zone all the flux lines go through both magnets and form like one unique magnet. Consequently, except near the edges, there is no variation of the magnetic flux density and no force on the x axis ($(\mathbf{B} \cdot \nabla)\mathbf{B} = 0$). In repulsion, the force also increases with the l/s ratio, but the shape is globally the same as for micromagnets, with two focusing regions delimited by the forces. The most surprising case is the single magnet one. Depending on the l/s ratio, there are either one or two maxima (and minima respectively). It can be supposed that when the ratio is sufficiently high, two plugs can be formed against the microchannel's wall, near the edges of the magnet, like in repulsion. This distinctive feature may represent an interesting study perspective. One can note that points of unstable equilibrium exist at $x = 0$ for Fig. 6a and 6b, akin to a ball balanced on the tip of a mountaintop.

To illustrate the numerical simulations, microscopic visualizations were carried out with rectangular magnets for the three configurations ($h = 8$ mm, $l = 2$ mm and $s = 1$ mm). Thus, the ratios h/l and l/s of these magnets are 4 and 2 respectively. Fig. 7a shows the value of the force x component plotted along the x -axis for the three configurations. By comparison with the reference cases, it can be seen that the number and position of possible plugs is the same, but of course the absolute value of the force x component is different. Concerning the y component, the spacing between the magnets is now 1 mm, with a capillary of

100 μm internal diameter, while before we considered a spacing of 200 μm with a microchannel of 100 μm height. The following consequence is a decrease of the y component of the force, the beads being relatively further from the magnets compared to the reference cases. This experimental case is 3D, while the numerical simulations are in 2D Cartesian form, enabling only a qualitative comparison. Fig. 7b–d shows the MBs plugs obtained in attraction, repulsion and with a single magnet. It confirms the presence of one central plug in attraction, two corner-situated plugs in repulsion and one magnet-sided plug with the single magnet. The beads have been accumulated in the presence of a flow and this one was stopped to take the pictures. So it is not a real static situation like simulated, but it presents the plugs, as they would be in an experiment.

Conclusions

Numerical simulations using the finite element method (FEM) have been carried out, in 2D Cartesian form, to study the magnetic field produced by permanent magnets, its distribution according to the size and the configuration of the magnets, that is to say in attraction, in repulsion or with a single magnet. The magnetic force distribution has also been simulated to determine where, in a microchannel, magnetic beads may be attracted in function of the magnets configuration. The simulations were qualitatively

corroborated, for millimeter-size rectangular magnets, by microscopic visualizations of MBs plugs in a capillary.

The results showed that the number of plugs is configuration dependent. In the attraction configuration, one plug is observed in the middle of the magnets. In repulsion, two plugs are formed near the corners of the magnets. With a single magnet, the plug forms against the magnet. The orientation of the beads is different in attraction and in repulsion, where vertical and horizontal columns are respectively encountered, as MBs align along the magnetic field lines.

The geometry of the magnets and their relative spacing has a significant impact on the magnetic flux density. Its value and uniformity inside a magnet increases with the h/l ratio (magnet shape). Consequently, bar magnets produce larger B than flat magnets. The magnetic flux density inside the magnets is also influenced by the relative gap of the magnets or the l/s ratio. In the attraction configuration, increasing the l/s ratio generates a favorable B coupling between the two magnets, which form like a single one, while in the repulsion configuration, this coupling is unfavorable and the B value is decreased in the magnets as compared to a single magnet.

For square magnets, the l/s ratio also influences the magnetic force value in the microchannel, both increasing concomitantly for all the configurations. In addition, a zero force zone in the middle appears in the attraction configuration as the l/s ratio increases, while with a single magnet, the number of maxima and minima goes from one to two, producing two focusing zones instead of only one.

All these simulations have been realized in a 2D static case, without flow. The microscopic visualizations confirmed the predictions of the numerical simulations, like the number of plugs, but it would be necessary to couple the magnetic force with the Stokes one to predict the exact position of the plugs, to study their formation dynamics or their stability according to the configuration.

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