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# 1 Particle Actuation by Rotating Magnetic Fields in Microchannels: 2 A Numerical Study

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## 7 Abstract

8 Magnetic particles confined in microchannels can be actuated to perform translation motion  
9 using a rotating magnetic field, but their actuation in such a situation is not yet well understood.  
10 Here, the actuation of a ferromagnetic particle confined in square microchannels is studied using  
11 immersed-boundary lattice Boltzmann simulations. In wide channels, when a sphere is away  
12 from channel corners, it experiences a modest hydrodynamic actuation force parallel to the  
13 channel walls. This force decreases as the sphere is shifted toward the bottom wall but the  
14 opposite trend is found when the channel is narrow. When the sphere is positioned midway  
15 between the top and bottom channel walls, the actuation force decreases as the channel width  
16 decreases and can reverse its direction. These phenomena are elucidated by studying the flow  
17 and pressure fields in the channel-particle system and by analyzing the viscous and pressure  
18 components of the hydrodynamic force acting on different parts of the sphere.

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# 1 Introduction

2 Manipulating microscale objects in a liquid environment is challenging. One of the reasons is  
3 that the motion of small objects is often governed by Stokes flows. A key characteristic of Stokes  
4 flows is that reciprocal movement of a "swimmer" in these flows cannot lead to a net displacement  
5 due to the time-reversibility in them, which is known as Purcell's scallop theorem.<sup>1</sup> Many tech-  
6 niques have been developed to manipulate microscopic objects in liquids, e.g., dielectrophoresis,  
7 diffusiophoresis, magnetophoresis, and so on.<sup>2,3</sup> Magnetism-based methods are popular because  
8 they are typically bio-compatible, e.g., magnetic fields can penetrate most media without adverse  
9 effects.<sup>4-6</sup> Magnetism-based particle manipulation methods can be broadly divided into two cate-  
10 gories: driving particles using a net magnetic force and driving particles using a magnetic torque.  
11 For particles with a characteristic dimension  $r$ , the net magnetophoresis force they experience often  
12 scales as  $r^3$ ,<sup>7,8</sup> and the induced translation speed scales with  $r^2$ .<sup>9</sup> Therefore, actuation based on net  
13 magnetic force typically requires very strong magnetic fields when the particle is small. Actuation  
14 based on magnetic torques, on the other hand, has more favorable scaling laws (e.g., the translation  
15 speed can scale with  $r$ )<sup>10</sup> and can provide large translation speed with weak or moderate magnetic  
16 fields. As such, torque-based magnetic actuation has attracted much attention in recent years.

17 To actuate microparticles using a magnetic torque, it is essential to break the time-reversal  
18 symmetry inherent in Stokes flow. Such a symmetry can be broken by using asymmetric geometry  
19 such as an artificial flagella or introducing a substrate.<sup>11-16</sup> Particles exhibiting magnetic torque-  
20 induced translation motion near substrates are often called surface walkers, and they are being  
21 studied intensively by many research groups.<sup>10,17-22</sup> Many interesting phenomena related to surface  
22 walkers have been discovered.<sup>5,23-29</sup> For example, when magnetic particles rotate above a solid wall,  
23 a chain of rotating particles travel faster than an individual particle rotating near the same wall;<sup>19</sup>  
24 hydrodynamic interaction between rotating particles can lead to particle clustering;<sup>30</sup> particle  
25 clustering can emerge spontaneously due to fingering instability in a swarm of particles;<sup>31,32</sup> rolling  
26 particles can exhibit flocking behavior at some frequencies of the applied magnetic field;<sup>33</sup> clusters of  
27 magnetic particles can be disassembled into shorter chains near uneven substrates using three-axis  
28 dynamic magnetic fields.<sup>20</sup>

29 Many potential applications of surface walkers require them to be actuated in confined spaces.<sup>34,35</sup>  
30 Therefore, it is worthwhile to study the dynamics of magnetic surface walkers under confined condi-  
31 tions. Research in this direction begins to receive attention only most recently, but some interesting

1 phenomena have already been reported. For instance, the reversible response of superparamagnetic  
2 particles confined in a microchannel has been analyzed. It was found that the particle assembly  
3 is reconfigurable and the shape of the particle assembly depends strongly on the channel-particle  
4 size ratio.<sup>36</sup> The rheology of a sphere particle suspension confined between two plates under an  
5 external uniform magnetic field was studied. It is discovered that the magnetic torque applied to  
6 the sphere is transmitted to the fluid via viscous force, and consequently, the induced shear stress  
7 drives a unidirectional flow of the suspension.<sup>37</sup>

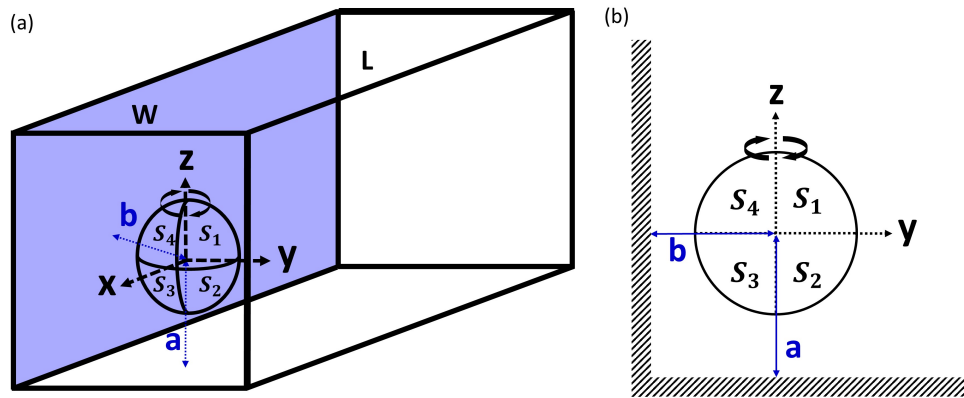
8 Understanding the actuation of magnetic surface walkers, or more generally, dynamics of mag-  
9 netic particles in fluids, using experiments alone is challenging. Computational modeling is a  
10 powerful tool to complement experimental investigations. In the literature, many different meth-  
11 ods, including Stokesian dynamics,<sup>38</sup> dissipative particle dynamics,<sup>39</sup> finite element method,<sup>40,41</sup>  
12 smoothed particle hydrodynamics,<sup>42,43</sup> and lattice Boltzmann method (LBM),<sup>44,45</sup> have been de-  
13 veloped to investigate the dynamics of magnetic particles suspended in liquids. Using LBM, we  
14 recently studied the dynamics of surface walkers confined between two infinite walls.<sup>46</sup> It was found  
15 that the degree of confinement and the nature of the confining walls (slip vs no-slip) not only affect  
16 the speed of a sphere actuated by a rotating field, but also its direction. For example, for a sphere  
17 positioned at a fixed height above a lower no-slip wall, as the no-slip upper wall is brought closer  
18 to the lower wall, the translation of the sphere first slows down, then reverses direction, and finally  
19 reaches zero when the sphere is exactly in the middle way between the two walls.

20 While existing studies provided useful insights into the effects of confinement on the actuation  
21 of magnetic surface walkers by rotating fields, the confinement considered so far is usually afforded  
22 by two parallel walls that are normal to the rotating axis of surface walkers. In practice, a surface  
23 walker may be confined in more complex environment such as inside a channel with a finite aspect  
24 ratio. Understanding the actuation of surface walkers in such environment is useful for harnessing  
25 them for applications such as drug delivery through capillaries.<sup>47</sup> However, research on this is  
26 scarce at present. In particular, how the confinement by walls normal to the sphere's axis of  
27 rotation changes the fluid flow and actuation force has not been studied and is poorly understood.  
28 In this work, we investigate the actuation of a spherical surface walker confined in a square-shaped  
29 microchannel. The flow field and actuation force acting on the sphere in the channel length direction  
30 are computed numerically by varying the position of the sphere inside the channel and the dimension  
31 of the microchannel. The variation of the net actuation force is elucidated by examining its various  
32 components and the flow fields inside the microchannel.

## 2 Models and Methods

### 2.1 Physical and mathematical models

As shown in Fig. 1, the simulation system consists of a ferromagnetic sphere and a water-filled square channel, in which the sphere is immersed. The sphere has a radius of  $r$ . The channel has a width of  $W$  and a length of  $L$ . The sphere is positioned at a distance  $a$  and  $b$  from the bottom wall and the purple-shaded side wall, respectively. The bottom channel wall is in the  $xy$ -plane and the side channel wall is in the  $xz$ -plane. Under the action of an external magnetic field  $B$ , the sphere rotates around the  $z$ -axis in the clockwise direction. If the sphere is free, it may move in all three directions, which changes its confinement by the channel walls (i.e.,  $a$  and  $b$ ) and complicates the study of how confinement affects its actuation. To circumvent this problem, as is widely practiced,<sup>48–50</sup> the sphere is allowed to rotate but its center is fixed. The rotation-induced hydrodynamic force acting on the sphere in the  $x$ -direction,  $F_x$ , is measured as the actuation force.



**Figure 1:** A three-dimensional view (a) and side view (b) of the system used to study the actuation of a magnetic sphere in a square channel. The sphere surface is divided into  $S_1$ ,  $S_2$ ,  $S_3$ , and  $S_4$ . In (b), only the channel walls closest to the sphere are shown. The origin of the coordinate system is set on the sphere's center.

Without losing generality, the sphere's radius is set to  $12\mu\text{m}$ . Its magnetic moment is  $\mathbf{m} = 1.45 \times 10^{-10} \text{A}\cdot\text{m}^2$ . A magnetic field  $\mathbf{B} = B \cos(2\pi f_B t)\mathbf{i} - B \sin(2\pi f_B t)\mathbf{j}$  is applied, where  $B$  is the strength of the magnetic field and  $f_B$  is the rotational frequency.  $B$  and  $f_B$  are set to  $3 \text{mT}$  and  $20 \text{Hz}$ , respectively. With the above parameters, the sphere rotates synchronously with the magnetic field in all of our simulations. The rotational Reynolds number  $Re_\omega = 2\pi\rho f_B r^2/\mu = 4.52 \times 10^{-3} \ll 1$ .

1 We note that the sphere also experiences forces in the  $y$ - and  $z$ -directions. These forces can  
 2 change the position of a free particle across the channel, but they are much weaker. Specifically,  
 3  $F_x \sim \pi\mu\omega r^2$ .<sup>48,50,51</sup> Forces in the  $y$ - and  $z$ -directions ( $F_y$  and  $F_z$ ), unlike  $F_x$ , originate from  
 4 inertia effects and scale as  $F_{y,z} \sim \pi\rho\omega^2 r^4$ ,<sup>46,50</sup> i.e.,  $F_{y,z}/F_x \sim Re_\omega$ . Because  $Re_\omega \ll 1$ , inertia  
 5 effects are negligible and  $F_y$  and  $F_z$  are very small. In addition, other forces (e.g., Brownian forces)  
 6 in those directions may be more important in understanding how a particle is driven away from  
 7 walls. For these reasons, we will not elaborate on  $F_y$  and  $F_z$ . Because a free particle can depart  
 8 from its initial position relative to channel walls due to non-zero  $F_{y,z}$ , we study the implications of  
 9 such departure by examining how  $F_x$  varies with  $a$  and  $b$  in Fig. 1.

10 Three series of systems are studied to probe the effects of confinement on actuation by channel  
 11 walls (see Table 1). In all systems, the sphere is positioned at a distance  $b = 1.5r$  from the purple-  
 12 shaded side wall. This distance is chosen so that particle actuation can be effectively studied using  
 13 direct numerical simulations. For surface walkers, the actuation force decreases rapidly as  $b/r$   
 14 increases. Hence, a small  $b/r$  is preferred. However, if  $b/r$  is too small, resolving the flow between  
 15 the sphere and wall necessitates an extremely fine grid and high computational cost. With  $b = 1.5r$ ,  
 16 our tests showed that a strong actuation force is generated and the force can be computed accurately  
 17 using a reasonably fine grid (see below). The channel length is selected to  $60r$  to minimize the  
 18 finite size effects.<sup>46</sup> In the first series of systems, the channel is wide ( $W = 6.5-30r$ ) and the sphere  
 19 is fixed at various distances above the bottom wall to study the actuation near walls of a wide  
 20 channel. In the second series of systems, the sphere is positioned midway between top and bottom  
 21 walls while the channel width is varied to study the actuation with symmetric top/bottom walls.  
 22 In the third series of systems, the channel is narrow ( $W = 3.5-6r$ ) and the sphere is fixed at  $1.2-3r$   
 23 above the bottom wall to study the actuation near walls of a narrow channel.

**Table 1:** A summary of the simulations performed in this study.

Series	$a$	$b$	$W$	$L$
1	$1.2r$ to $W/2$	$1.5r$	$6.5$ to $30r$	$60r$
2	$W/2$	$1.5r$	$3$ to $30r$	$60r$
3	$1.2r$ to $W/2$	$1.5r$	$3.5$ to $6r$	$60r$

24 The fluid motion is governed by the Navier-Stokes (NS) equations:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{u}) = 0 \quad (1)$$

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla[\mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] + \mathbf{F} \quad (2)$$

1 where  $\rho$  is the fluid density,  $\mathbf{u}$  is the velocity,  $p$  is the pressure,  $\mu$  is the viscosity, and  $\mathbf{F}$  is the body  
 2 force. The no-slip boundary condition is imposed on channel walls and the sphere's surface. The  
 3 periodic boundary condition is imposed in the  $x$ -direction. The sphere's rotation is governed by

$$I_p \frac{d\boldsymbol{\omega}_p}{dt} = \int_s (\mathbf{X}_s - \mathbf{X}_p) \times (\boldsymbol{\sigma} \cdot \mathbf{n}) ds + \mathbf{m} \times \mathbf{B} \quad (3)$$

4 where  $I_p$  is the sphere's moment of inertia,  $\boldsymbol{\omega}_p$  is the sphere's angular velocity,  $\boldsymbol{\sigma}$  is the fluid stress  
 5 tensor,  $\mathbf{n}$  is the unit normal vector of the sphere's surface,  $\mathbf{X}_s$  and  $\mathbf{X}_p$  denote the sphere's center  
 6 and position on the sphere's surface, respectively. Equation 3 is solved together with Eq. 1 and 2 to  
 7 compute a sphere's rotation. For the rotating magnetic field considered in this work, our simulation  
 8 shows that the sphere rotates synchronously with the applied magnetic field.

## 9 2.2 Numerical methods and code validation

10 The mathematical models described in the previous section are solved by combining the LBM  
 11 and the immersed boundary method (IBM).<sup>52,53</sup> These methods and their implementation have  
 12 been described in details in our recent publication.<sup>46</sup> Here we highlight the salient features of these  
 13 methods and present key implementation details.

14 The NS equations are solved using LBM. In LBM, evolution equations of the density distri-  
 15 bution function, which can recover to the NS equations via the Chapman–Enskog expansion, are  
 16 solved on a Eulerian lattice to obtain the fluid's density and velocity fields. The basic operations in  
 17 LBM are the collision step and the streaming step. In the collision step, the distribution function  
 18 components on each lattice is computed. In the streaming step, the post-collision distributed func-  
 19 tions are spread to neighbor lattices by following designated microscopic velocity vectors. Because  
 20 collision and streaming are local operations, LBM is highly efficient and easily parallelized.

21 The interactions between fluids and the solid sphere are handled using a fixed-grid method  
 22 IBM.<sup>53</sup> Briefly, each solid boundary is represented using a set of Lagrangian forcing points and  
 23 the flow field is solved on the Eulerian lattice, which covers both inside and outside of the solid  
 24 boundary. The velocity of Lagrangian points on the solid boundary is interpolated from adjacent  
 25 Eulerian lattice points through a discrete delta function. Meanwhile, the force density evaluated  
 26 on Lagrangian points is spread to nearby Eulerian lattice points through the same discrete delta

1 function. These treatments enforce the no-slip condition on the solid boundary and allow the effects  
 2 of solid boundary on fluid flow to be modeled.

3 When implementing LBM, we adopt the three-dimensional 19-velocity (D3Q19) multi-relation-  
 4 time scheme to solve the evolution equations<sup>54–56</sup>

$$g_\alpha(\mathbf{x} + \mathbf{e}_\alpha \delta t, t + \delta t) - g_\alpha(\mathbf{x}, t) = -(\mathbf{M}^{-1} \mathbf{A} \mathbf{M})_{\alpha\beta} [g_\beta - g_\beta^{eq}] + \delta t F_\alpha, \alpha = 0 \cdots 18 \quad (4)$$

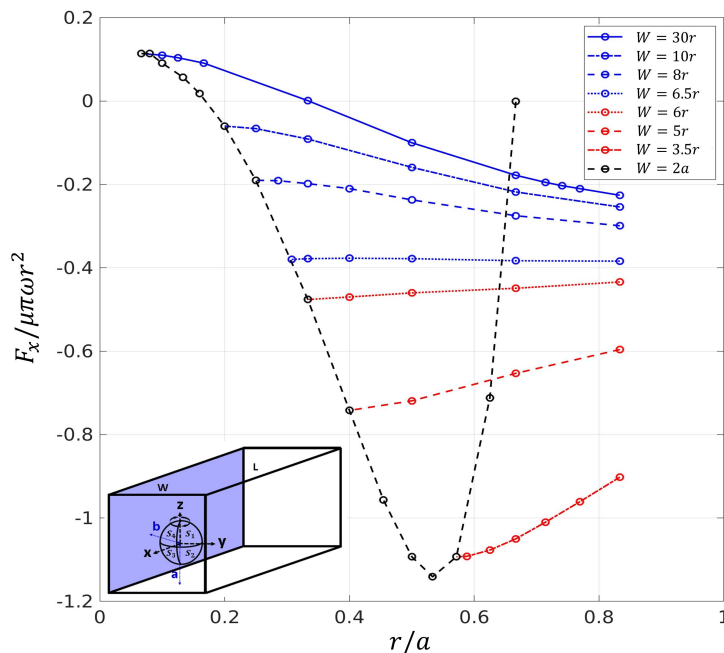
5 where  $g$  is the density distribution function,  $\mathbf{e}_\alpha$  is the discrete velocity along the  $\alpha$  direction, and  $\mathbf{A}$   
 6 is the collision matrix. The free relaxation parameter related to the kinematic viscosity is set to 1.25  
 7 while others are set to 1. The hydrodynamic force acting on fluids due to fluid-sphere interactions is  
 8 treated using the techniques developed by Guo et al<sup>57</sup> and Kang et al.<sup>53</sup> The no-slip wall boundary  
 9 condition is enforced using the halfway bounce-back scheme.<sup>56</sup> A uniform lattice spacing of  $r/6$  is  
 10 used to solve the Eq. 4. For the systems listed in Table 1, the total number of grid points ranges  
 11 from 160,000 to 12,000,000, and there are at least two lattice points in the gap between the sphere  
 12 and the wall (corresponding to  $a/r = 1.2$ ). Grid-dependence is tested by comparing actuation force  
 13 in representative cases with that obtained using a finer grid of  $r/10$ , with a deviation less than 2%.  
 14 When implementing IBM, the sphere's surface is discretized into 536 Lagrangian nodes according  
 15 to the method proposed by Feng et al,<sup>52</sup> leading to the spacing between neighbor Lagrangian nodes  
 16 approximately equal to that between the Eulerian lattices.<sup>52,56</sup> The range of kernel function (Dirac  
 17 delta distribution) to deal with the fluid-solid interaction function is twice the lattice spacing.

18 A code implementing the above methods has been developed and validated extensively for  
 19 actuation of spherical surface walkers.<sup>46</sup> First, the rotation of a magnetic sphere driven by a rotating  
 20 field in a unbounded fluid was simulated. The evolution of the sphere's rotation speed as a function  
 21 of the field frequency, including the transition from the synchronous regime to the asynchronous  
 22 regime, was accurately captured. Next, the hydrodynamic forces experienced by a sphere enclosed  
 23 between two no-slip walls separated by  $30r$  were studied systematically. When the domain size  
 24 reaches  $60r$  in the longitude direction and  $30r$  in the transverse direction, the computed drag  
 25 acting on a sphere translating near the lower wall agrees well with the analytical prediction for  
 26 spheres moving parallel to a semi-infinite wall.<sup>48</sup> The hydrodynamic forces acting on a center-fixed  
 27 sphere rotating at a height of  $1.5r$  above the lower wall computed by the code converges within  
 28  $\sim 5\%$  of the analytical predictions by Goldman and colleagues.<sup>48,50</sup>



### 3 Results and Discussion

Here we study the hydrodynamic actuation force experienced by a magnetic sphere inside a square channel under the actuation of a rotating magnetic field. As mentioned in Section 2.1, we let the sphere rotate around the  $z$ -axis in the clockwise direction but fix its center. We measure the hydrodynamic force on the sphere in the  $x$ -direction. Figure 2 summarizes the actuation force  $F_x$ , for the various  $a$  and  $W$  listed in Table 1. We observe that, in a very wide channel (e.g.,  $W = 30r$ ), when the sphere is away from the corner (e.g.,  $a = 15r$ ),  $F_x$  is positive as shown in prior works,<sup>46,50</sup> but becomes negative as the sphere is shifted toward the bottom wall (i.e., as  $r/a$  increases). In addition, as a sphere is shifted toward the bottom wall,  $F_x$  decreases if the channel is wide but increases when the channel is narrow ( $W < \sim 6r$ ). These phenomena are examined in details in Sections 3.1 and 3.3, respectively. When the sphere is positioned midway between the top and bottom channel walls,  $F_x$  decreases as the channel width decreases and becomes strongly negative when the sphere becomes highly confined by the channel, and sharply recovers to zero when the symmetry is reached at  $W = 3r$  and  $a = 1.5r$ . This series of study is discussed in Section 3.2.

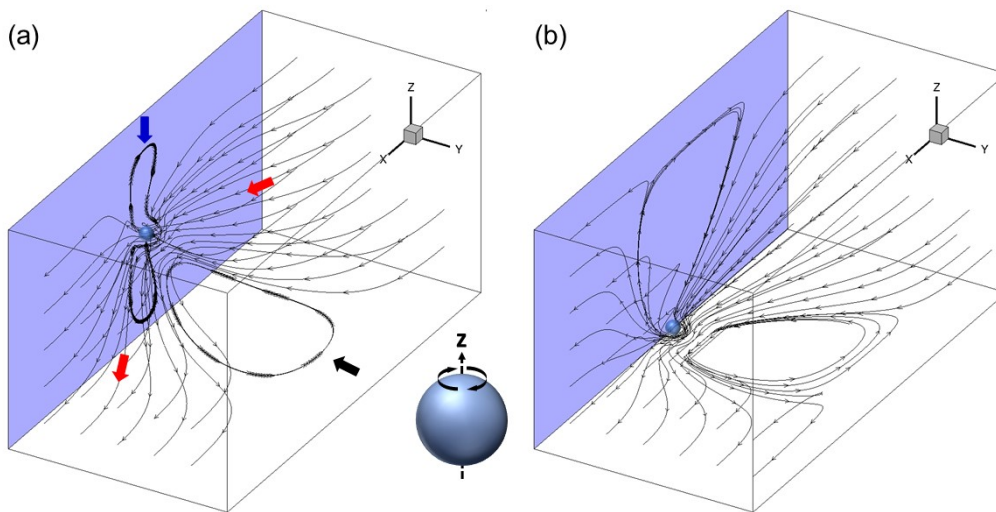


**Figure 2:** The evolution of the  $x$ -direction hydrodynamic actuation force on a rotating sphere as a function of channel width  $W$  and the sphere's distance from the bottom channel wall  $a$ . The blue, red, and black lines correspond to the Series 1, 3, and 2 simulations in Table 1.

### 1 3.1 Sphere actuation near walls of a wide channel

2 For the system shown in Fig. 1, the situation with  $W \gg r$  and  $a \gg r$  (i.e., when a sphere is  
 3 positioned close to a semi-infinite vertical wall), has been studied in the literature.<sup>10,46</sup> Here, we  
 4 set the sphere at a distance  $b = 1.5r$  from the purple-shaded vertical wall and position the bottom  
 5 wall at a distance  $a$  beneath the sphere. To understand how the sphere's actuation is affected by  
 6 the corner formed by the bottom and side walls of a wide channel, we focus our discussion on a  
 7 representative set of simulations where  $W$  is set to  $30r$  and  $a$  is varied from  $15r$  to  $1.2r$ .

8 We first examine the flow and pressure fields in two sample cases with  $r/a = 1/15$  and  $1/1.5$ .  
 9 Figure 3 show sample streamlines in the channel. At  $r/a = 1/15$ , when there is little confinement by  
 10 the bottom wall, the rotating sphere induces a global flow in the channel in the positive  $x$ -direction  
 11 (see Fig. 3a). Fluids are drawn toward the vertical wall on one side of the sphere and ejected  
 12 away from the wall on the other side of the sphere (marked by red arrows). This global flow is  
 13 accompanied by two recirculations, one primarily in the horizontal plane (marked by a black arrow)  
 14 and one primarily in the vertical plane (marked by a blue arrow). Because the global flow is in the  
 15 positive  $x$ -direction, hereafter, upstream of the sphere refers to the space in which  $x < 0$  while  
 16 downstream refers to the space in which  $x > 0$ .



**Figure 3:** Sample streamlines in two channel-particle systems with  $r/a = 1/15$  (a) and  $r/a = 1/1.5$  (b).  $W = 30r$  and  $b/r = 1.5$  in both systems.

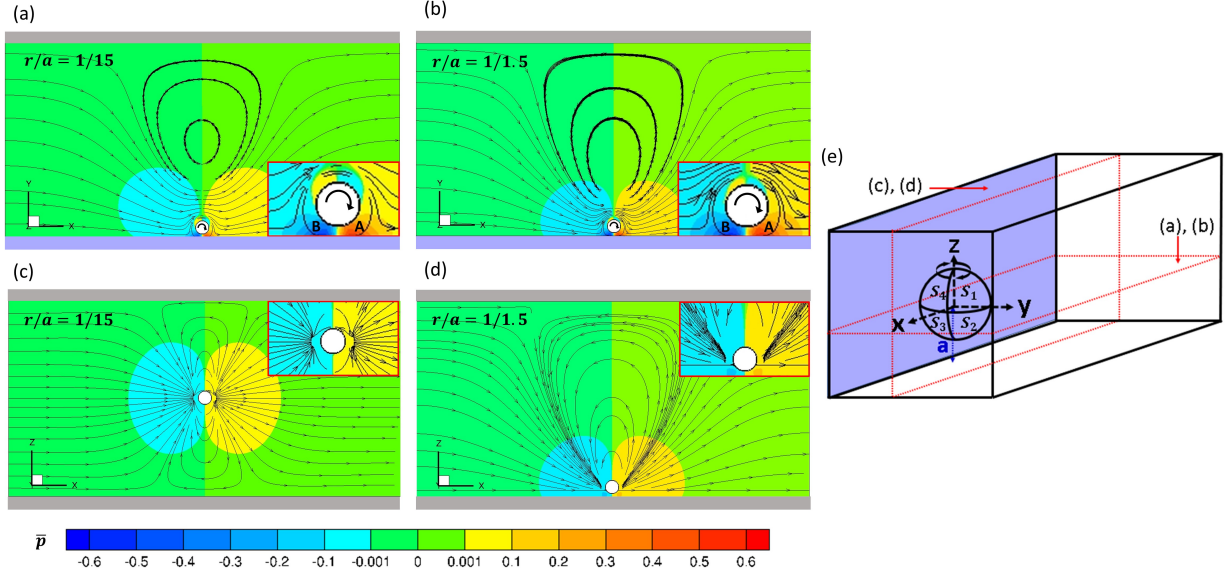
17 At  $r/a = 1/1.5$ , when there is significant confinement by the bottom wall, Fig. 3b shows that  
 18 the basic features of the flow field remain similar, e.g., a global flow in the positive  $x$ -direction  
 19 and recirculations still exist. Nevertheless, the additional confinement by the bottom wall leads

1 to important differences from those shown in Fig. 3a. First, the bending of streamlines toward  
 2 and away from the vertical wall becomes somewhat stronger. Practically, because there are often  
 3 many particles in a channel, this effect makes it easier to entrain other particles toward a rotating  
 4 particle located near a channel corner (note that the trajectory of entrained particles may differ  
 5 from the streamlines showed here if the particle density in the channel is not low). This can be  
 6 useful because the motion of an entrained, passive particle (e.g., a biological cell), once close enough  
 7 to the rotating particle, can be controlled indirectly by manipulating the rotating sphere (e.g., push  
 8 and pull of cells by a magnetic particle rotating near a semi-infinite wall have been demonstrated  
 9 in recent experiments).<sup>17</sup> Second, in the horizontal plane, the recirculation zone moves closer to  
 10 the sphere, which tends to increase the velocity gradient near the sphere's surface that faces away  
 11 from the vertical wall. As we shall see later, this contributes to the reversal of the hydrodynamic  
 12 actuation force on the sphere as  $r/a$  increases from 1/15 to 1/1.5.

13 Figure 4 shows the pressure field in the horizontal ( $z = 0$ ) and vertical ( $y = 0$ ) planes passing  
 14 through the sphere's center for  $r/a = 1/15$  and 1/1.5. As shown in Fig. 4a, at  $r/a = 1/15$ ,  
 15 where the confinement by the bottom wall is negligible, the confinement of a rotating sphere by  
 16 the vertical wall induces a heterogeneous pressure field in the channel. Specifically, the rotating  
 17 sphere draws fluids on one of its sides toward the wall to rise the pressure there (region A in Fig.  
 18 4a's inset) but reduces the pressure on its other side (region B in Fig. 4a's inset). This, along with  
 19 the recirculation of fluids near the sphere, cause the fluid pressure to rise on one side of the sphere  
 20 and to decrease on the other side. Examination of the pressure fields in the  $z = 0$  and  $y = 0$  planes  
 21 (see Fig. 4a and 4c) reveals that the recirculation-induced pressure heterogeneity exists in a region  
 22 up to many  $r$  from the sphere, which is consistent with the global flow shown in Fig. 3a. On the  
 23 sphere's surface facing the vertical wall ( $S_3$  and  $S_4$ ), this kind of pressure heterogeneity creates a  
 24 net force pushing the sphere in the negative  $x$ -direction.<sup>46,50</sup>

25 The global flow generated by the rotating sphere and its interactions with the *center-fixed*  
 26 sphere, however, create a opposite pressure force on the sphere. Specifically, the pressure on the  
 27 sphere's upstream surfaces is enhanced by the global flow, while the opposite occurs on the sphere's  
 28 downstream surfaces. As shown in the inset of Fig. 4a, on the sphere's surface facing the vertical  
 29 wall, this pressure imbalance by the global flow is weaker compared to the recirculation-induced  
 30 pressure imbalance; however, on the sphere's surface facing away from the vertical wall, this pressure  
 31 imbalance dominates and creates a net pressure force in the positive  $x$ -direction.

32 When the rotating sphere is positioned close to the bottom wall with  $r/a = 1/1.5$ , Fig. 4b

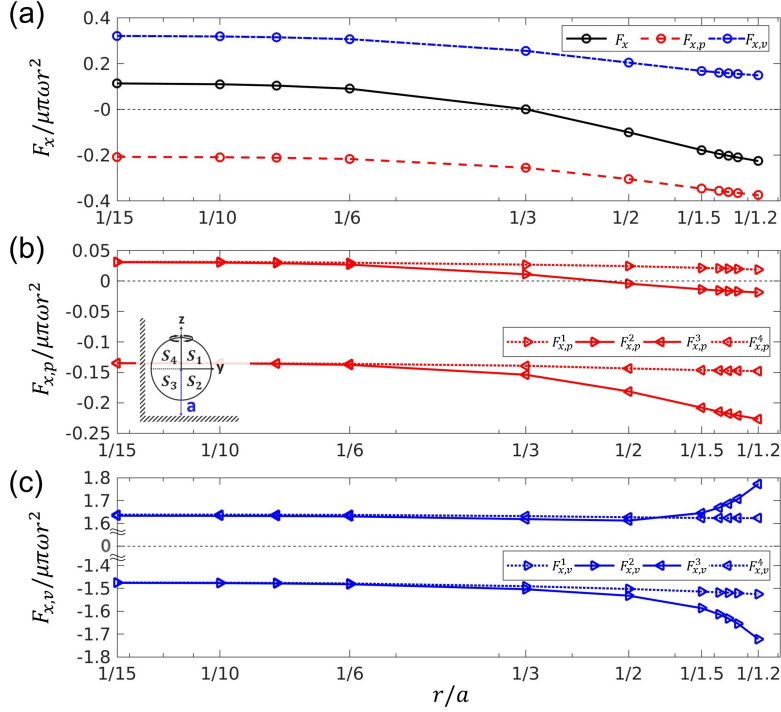


**Figure 4:** Pressure field and streamlines in channel-particle systems with different  $r/a$  but same  $b/r = 1.5$ . (a, b): flow in the  $z = 0$  plane. (c, d): flow in the  $y = 0$  plane.  $\bar{p} = (p - p_{ref})/\mu\omega$ .

1 and 4d show that the pressure field in the system is qualitatively similar to that at  $r/a = 1/15$ .  
 2 However, because of the stronger confinement by the horizontal wall, the pressure heterogeneity  
 3 due to recirculation flow is enhanced and thus the pressure imbalance on the sphere's surface facing  
 4 the vertical wall is enhanced (see Fig. 4b's inset). Meanwhile, the global flow around the sphere  
 5 is weakened and thus the pressure imbalance on sphere's surface due to the interactions between  
 6 the global flow and the center-fixed sphere is weakened. As a result, although this kind of pressure  
 7 imbalance remains important on the sphere's surface facing away from the vertical wall, the region  
 8 of surface where it dominates over the recirculation-induced pressure imbalance becomes smaller  
 9 (see Fig. 4b's inset). As we shall see later, this change contributes to the reversal of hydrodynamic  
 10 force on the sphere as  $r/a$  increases from  $1/15$  to  $1/1.5$ .

11 Having studied the flow induced by a rotating sphere, we now evaluate the hydrodynamic  
 12 force experienced by the sphere. Because the sphere rotates around the  $z$ -axis, the most significant  
 13 hydrodynamic force acting on sphere is in the  $x$ -direction. Figure 5a shows the total hydrodynamic  
 14 force  $F_x$ . We observe that, as  $r/a$  increases,  $F_x$  decreases and reverses sign at  $r/a > 1/3$ . In other  
 15 words, as the confinement by the bottom wall increases, the actuation force decreases and ultimately  
 16 reverses its direction.

17 To understand the origins of the observed evolution of  $F_x$  as a function of  $r/a$ , we first compute  
 18 the components of  $F_x$  due to the pressure and viscous forces acting on the sphere's surface ( $F_{x,p}$

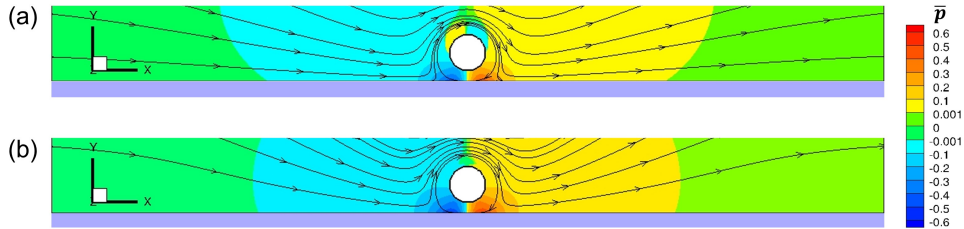


**Figure 5:** The hydrodynamic force acting on a rotating sphere positioned near walls of a channel with  $W = 30r$ . (a) The net force in the  $x$ -direction and its pressure and viscous components, (b-c) The  $x$ -direction pressure (b) and viscous (c) forces acting on surface  $S_1$  to  $S_4$  labeled in the inset of panel (b) (see Fig. 1a for a 3D view).

1 and  $F_{x,v}$ ). As shown in Fig. 5a, at  $r/a = 1/15$ , when the sphere is essentially confined only by  
 2 a semi-infinite vertical wall,  $F_{x,p}$  is negative due to the large pressure difference across the sphere  
 3 induced by the flow recirculation. As elucidated earlier,<sup>46</sup> the net viscous force on the sphere is in  
 4 the positive  $x$ -direction and stronger than the pressure force. As  $r/a$  increases, both  $F_{x,p}$  and  $F_{x,v}$   
 5 decreases. Eventually, at large enough  $r/a$  (i.e., the sphere is positioned close to the bottom wall),  
 6 pressure forces dominate the viscous forces, which differs qualitatively from the situation when the  
 7 sphere is close to a semi-infinite vertical wall and leads to the reversal of  $F_x$ . To gain insight into  
 8 the evolution of these pressure and viscous forces, we next decompose each force into that acting  
 9 on the sphere's four surfaces labeled in Fig. 1b ( $S_1, \dots, S_4$ ). Hereafter, the pressure and viscous  
 10 force on piece  $i$  of the sphere's surface are denoted as  $F_{x,p}^i$  and  $F_{x,v}^i$ , respectively.

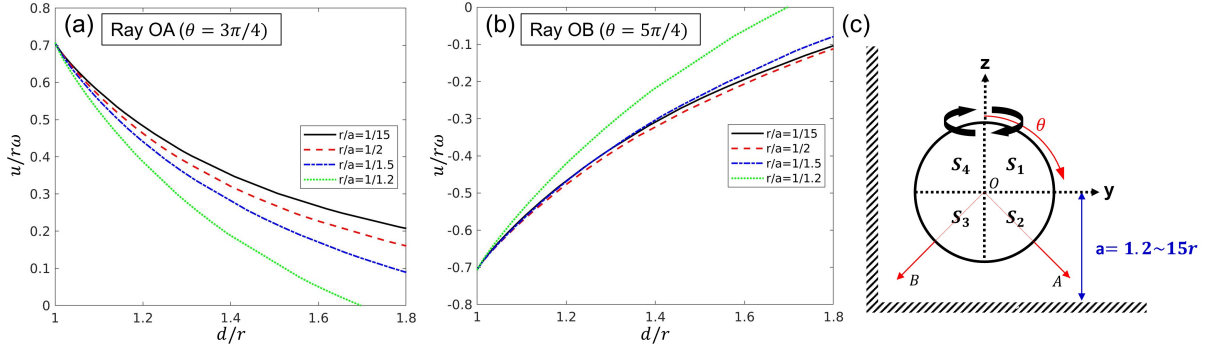
11 Figure 5b shows the variation of  $F_{x,p}^{1\cdots 4}$  as  $r/a$  increases (note that, throughout this work,  $r/b$   
 12 is fixed at 1/1.5). While each force becomes more negative with increasing  $r/a$ , the decrease of  
 13  $F_{x,p}^2$  and  $F_{x,p}^3$  are far greater than that of  $F_{x,p}^1$  and  $F_{x,p}^4$ . This is expected because the flow near

1 surfaces facing toward the bottom wall ( $S_2$  and  $S_3$ ) is affected more significantly than that near  
 2 surface facing away from the bottom wall ( $S_1$  and  $S_4$ ). The more negative  $F_{x,p}^3$  at larger  $r/a$   
 3 is caused by the enhanced pressure buildup on the downstream of the sphere and the pressure  
 4 depression on the upstream (cf. regions B and A in Fig. 4a and 4b), which is in turn caused  
 5 by the increased confinement by the bottom wall as explained above. The decrease and eventual  
 6 reversal of  $F_{x,p}^2$  as  $r/a$  increases is expected. Specifically, as the confinement by the bottom wall  
 7 increases, recirculation-induced pressure difference along the sphere in the streamwise direction  
 8 (which produces a negative pressure force) is enhanced while global flow-induced pressure difference  
 9 in the same direction (which produces a positive pressure force) is reduced as discussed above. To  
 10 see this more clearly, we study the pressure field in the  $z = -0.4r$  plane when  $r/a = 1/15$  and  
 11  $r/a = 1/1.5$ . Figure 6 shows that, as  $r/a$  increases from  $1/15$  to  $1/1.5$ , the pressure gradient along  
 12 the surface facing toward the vertical wall increases, while that along the surface facing away from  
 13 the vertical wall reverse direction, which is in line with the fact that  $F_{x,p}^3$  becomes more negative  
 14 while  $F_{x,p}^2$  changes from positive to negative.



**Figure 6:** Pressure field and streamlines in the  $z = -0.4r$  plane when  $r/a = 1/15$  (a) and  $r/a = 1/1.5$  (b).

15 Having analyzed the evolution of the pressure force  $F_{x,p}$  acting on the sphere as  $r/a$  increases,  
 16 we now analyze the evolution of the viscous force  $F_{x,v}$ . Figure 5c shows that, similar to the pressure  
 17 forces, as  $r/a$  increases, only the viscous forces on the two surfaces facing the bottom wall ( $S_2$  and  
 18  $S_3$ ) change markedly. Because the sphere rotates in the clockwise direction, the viscous shear on  
 19  $S_2$  and  $S_3$  ( $F_{x,v}^2$  and  $F_{x,v}^3$ ) are in the negative and positive  $x$ -directions, respectively. As  $r/a$   
 20 increases, the strength of  $F_{x,v}^2$  increases monotonically. This increase is caused by the enhanced  
 21 velocity gradient  $\nabla_r u_x$  ( $r$  denotes the sphere's radial direction) in region near surface  $S_2$ , which  
 22 can be inferred from Fig. 3 as discussed earlier and is a result of the reduced distance between  
 23  $S_2$  and the no-slip bottom wall. The enhanced  $\nabla_r u_x$  can also be more clearly shown in Fig. 7, in  
 24 which  $u_x$  along a ray OA passing through surface  $S_2$  is shown at different  $r/a$ .



**Figure 7:** The variation of the  $x$ -component fluid velocity along rays OA and OB when the sphere is positioned at different height above the bottom wall. Both rays originate from the sphere's center and reside in the  $x = 0$  plane. Rays OA (OB) passes through surface  $S_2$  ( $S_3$ ) and forms an angle of  $3\pi/4$  ( $5\pi/4$ ) with the positive  $z$ -axis.

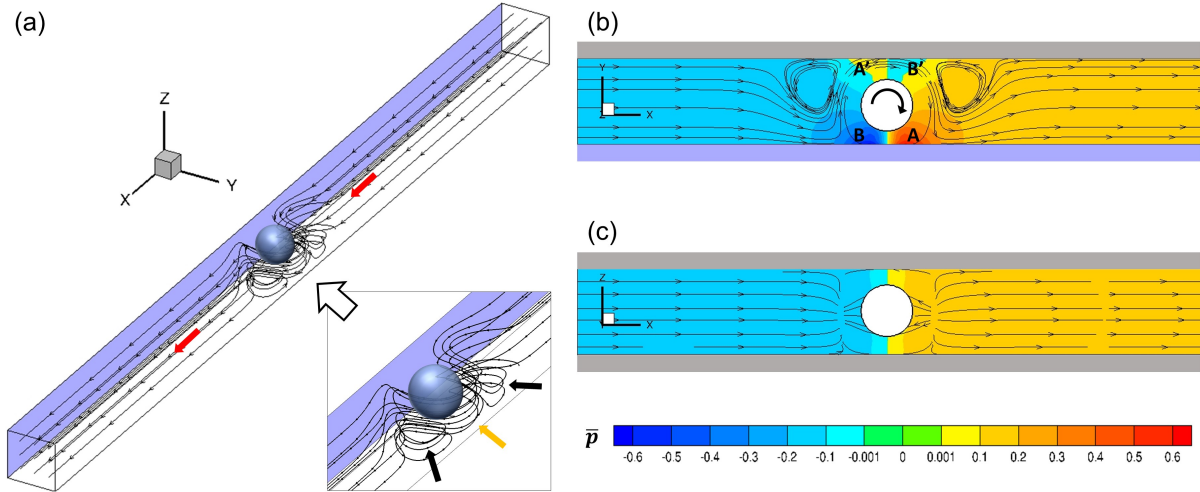
1 The variation of  $F_{x,v}^3$  with  $r/a$  however, is more complicated. As  $r/a$  increases from  $1/15$  to  
 2  $\sim 1/2$ ,  $F_{x,v}^3$  decreases slightly; as  $r/a$  increases further,  $F_{x,v}^3$  increases markedly. The initial, slight  
 3 decrease of  $F_{x,v}^3$  as the bottom wall moves toward to the sphere is mostly caused by the increase of  
 4 the induced pressure gradient in the  $x$ -direction in the region between the sphere and the vertical  
 5 wall. Specifically, although reducing the distance between the bottom wall and the sphere tends to  
 6 increase  $\nabla_r u_x$  near surface  $S_3$  just like that near surface  $S_2$ , the increased pressure gradient tends  
 7 to increase the fluid velocity in the region between surface  $S_3$  and the vertical wall, thus reducing  
 8  $\nabla_r u_x$  near surface  $S_3$ . The latter is supported by the velocity profile along ray OB passing through  
 9 surface  $S_3$  as shown in Fig. 7. As the bottom wall moves very close to the sphere (i.e.,  $r/a > \sim 1/2$ ),  
 10 the enhancement of  $\nabla_r u_x$  due to the proximity of the no-slip bottom wall to surface  $S_3$  dominates  
 11 the reduction of  $\nabla_r u_x$  due to the enhanced pressure gradient, and  $F_{x,v}^3$  increases markedly.

12 Overall, as  $r/a$  increases, the increase of the positive  $F_{x,v}^3$  is weaker compared to the increase of  
 13 the negative  $F_{x,v}^2$ , leading to a decrease of  $F_{x,v}$ . The weakening of the positive  $F_{x,v}$  and strengthening  
 14 of the negative  $F_{x,p}$  with the increase of  $r/a$  eventually allows the pressure force to dominate the  
 15 viscous force and makes the overall actuation force negative as shown in Fig. 5.

### 16 3.2 Sphere actuation in channels with symmetric top and bottom walls

17 We now fix the sphere at a distance  $a = W/2$  from the bottom wall and vary  $W$  from  $30r$  to  
 18  $3r$  to study the effects of confinement by four walls on the actuation of the sphere (see Series 2 in  
 19 Table 1 for details). In all studies,  $b$  is fixed at  $1.5r$ . The channel has a square cross-section, and

- 1 the system geometry is symmetric in the  $z$ -direction. As in Section 3.1, we compute the flow in  
 2 the system and measure the hydrodynamic force on the sphere in the  $x$ -direction.



**Figure 8:** Flow in a channel-particle system with  $a = W/2$ ,  $b = 1.5r$ , and  $W = 3.5r$ . (a) Sample streamlines. The sphere rotates around the  $z$ -axis in the clockwise direction. (b-c) Pressure field and streamlines in the  $z = 0$  plane (b) and  $y = 0$  plane (c) passing through the sphere's center (c).  $\bar{p} = (p - p_{ref})/\mu\omega$ .

3 We first study the flow field in a representative system where  $a = W/2$  and  $W = 3.5r$ . Figure  
 4 8a shows the streamlines near the sphere. Similar to the situation shown in Fig. 3, a global flow in  
 5 the  $x$ -direction is induced (marked by red arrows). However, because of the proximity of the two  
 6 vertical walls, the fluids drawn from the sphere's one side are ejected onto the wall on the sphere's  
 7 other side. The recirculation of fluids around the sphere's surface (marked by an orange arrow)  
 8 induces two predominately horizontal recirculation bubbles near the vertical wall that is further  
 9 away from the sphere (marked by two black arrows).

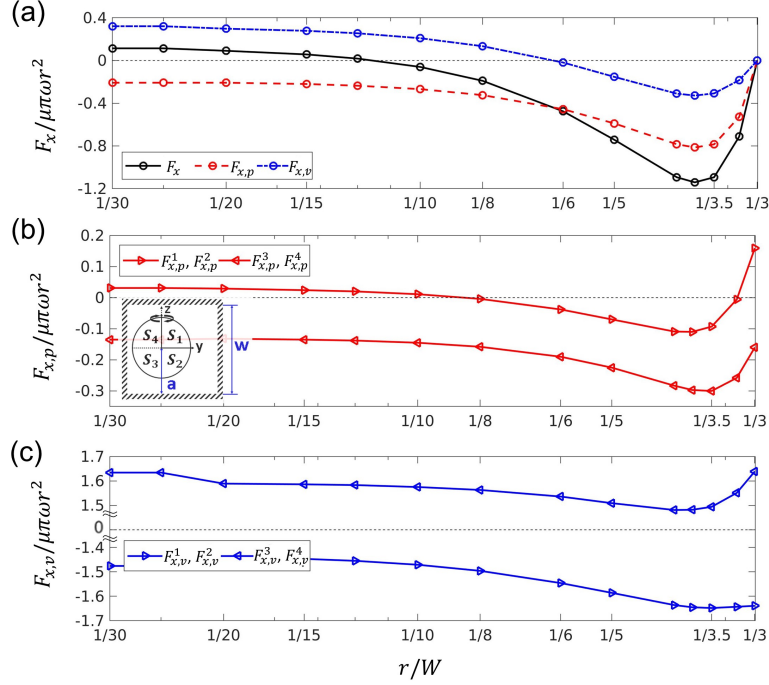
10 Figure 8b and 8c show the pressure field in the horizontal ( $z = 0$ ) and vertical ( $y = 0$ ) planes  
 11 passing through the sphere's center. Because of the small  $W$ , both vertical walls affect the fluid  
 12 flow. Such a flow rises the pressure in region A and lowers it in region B near the vertical wall that  
 13 is closer to the sphere. At the same time, the flow rises the pressure in region A' and lowers it in  
 14 region B' near the other vertical wall that is slightly further away from the sphere. Overall, the  
 15 pressure imbalance between regions A and B is higher than that between regions A' and B'. Such  
 16 kind of pressure imbalance occurs very close to the vertical walls – as shown in Fig. 8c, it is hardly



1 noticeable in the  $y = 0$  plane (i.e.,  $1.75r$  from the vertical walls). In addition to the above highly  
 2 localized pressure heterogeneity, a pressure difference accompanying the global flow shown in Fig.  
 3 8 is developed along the channel: the pressure upstream of the sphere is lower and the pressure  
 4 downstream of the sphere is higher. As discussed in Section 3.1, this pressure distribution creates  
 5 a net force pushing the sphere in negative  $x$ -direction.

6 Figure 9a shows the variation of the hydrodynamic force acting on the sphere in the  $x$ -direction  
 7 ( $F_x$ ) as a function of  $r/W$ . As  $r/W$  increases,  $F_x$  decreases slightly, becomes negative at  $r/W =$   
 8  $1/3.75$ , then increases sharply and eventually reaches zero at  $r/W = 1/3$ .  $F_x = 0$  at  $r/W = 1/3$  is  
 9 expected, because at this ratio, all four channel walls are distributed symmetrically with respect to  
 10 the sphere. To understand the variation of  $F_x$ , we again decompose  $F_x$  into a pressure component  
 11  $F_{x,p}$  and a viscous component  $F_{x,v}$ . Figure 9a shows that the variations of  $F_{x,p}$  and  $F_{x,v}$  with  $r/W$   
 12 are both similar to that of  $F_x$ , thus indicating that the changes of these forces contribute similarly  
 13 to that of  $F_x$ . To understand these forces, we next decompose each pressure/viscous force into  
 14 that acting on the sphere's four surfaces delineated in Fig. 1b and analyze these forces (note that,  
 15 because the top and bottom walls are symmetric with respect to the sphere, the force acting on  
 16  $S_1(S_3)$  is the same as that acting on  $S_2(S_4)$ ). Figure 9b shows the variation of  $F_{x,p}^{1\cdots 4}$  as a function  
 17 of  $r/W$ . As  $r/W$  increases from  $1/30$  to  $1/10$ ,  $F_{x,p}^1$  to  $F_{x,p}^4$  all decreases slightly; as  $r/W$  increases  
 18 further, all four components decrease significantly; at  $r/W > \sim 1/3.5$ , all four components increase  
 19 sharply as  $r/W$  increases.

20 The change of  $F_{x,p}$  shown in Fig. 9a is a result of the modified pressure imbalance on the  
 21 sphere's four surfaces as  $r/W$  increases. When  $r/W$  increases, the three non-shaded walls in Fig.  
 22 1a all move closer to the sphere. For  $r/W < \sim 1/3.5$ , such an enhanced confinement has a similar  
 23 effect on  $F_{x,p}^i (i = 1 \cdots 4)$  with the enhanced confinement of a sphere by the bottom wall (see Section  
 24 3.1 and Fig. 5b). Specifically, an increase of the confinement of the sphere by these walls enhances  
 25 the recirculation-induced pressure imbalance near the sphere's surface facing the shaded vertical  
 26 wall, which makes the negative  $F_{x,p}^{3,4}$  more negative (see Fig. 9b), reduces  $F_{x,p}^{1,2}$  and eventually  
 27 makes it negative. Because the confinement by three walls is stronger than by one bottom wall of  
 28 a channel corner, the variation of  $F_{x,p}^i$  is stronger in the present case. For example,  $F_{x,p}^2$  becomes  
 29 negative at  $r/a \sim 1/2.5$  in Fig. 5b while  $F_{x,p}^2$  becomes negative at  $r/W \sim 1/9$  (i.e.,  $r/a \sim 1/4.5$ )  
 30 in Fig. 9b. As  $r/W$  increases to  $\sim 1/3.5$ , the non-shaded vertical wall in Fig. 1a approaches the  
 31 sphere to a distance comparable to that of the purple-shaded vertical wall. Therefore, the pressure  
 32 imbalance across the space between by the sphere and the non-shaded vertical wall (cf. pressure



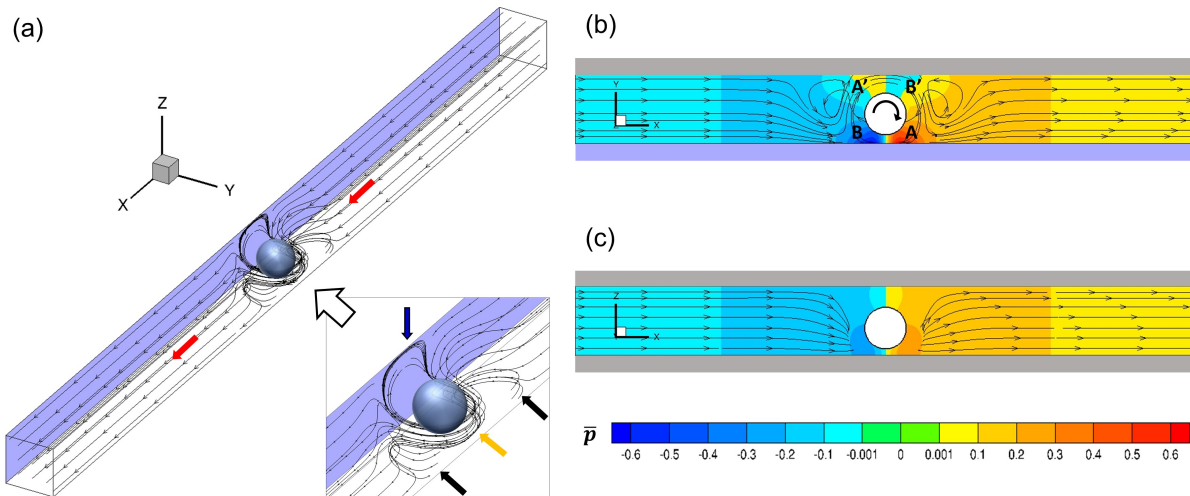
**Figure 9:** The hydrodynamic forces acting on a rotating sphere in square channels with different  $W$  ( $a = W/2$  and  $b = 1.5r$ ). (a) The net force in the  $x$ -direction and its pressure and viscous components, (b-c) The  $x$ -direction pressure (b) and viscous (c) forces acting on surface  $S_1$  to  $S_4$  labeled in the inset of panel (b) (see Fig. 1a for a 3D view).

1 imbalance between regions A' and B' in Fig. 8b) becomes more positive. Further increasing  $r/W$   
 2 enhances this pressure imbalance and eventually makes  $F_{x,p}^{1,2}$  positive as shown in Fig. 9b.

3 Figure 9c shows the variation of  $F_{x,v}^{1\cdots 4}$  as a function of  $r/W$ . As  $r/W$  increases from  $1/30$  to  
 4  $1/3$ ,  $F_{x,v}^{3,4}$  decreases first and then increases sharply as  $r/W$  grows larger than  $1/3.5$ . Meanwhile,  
 5  $F_{x,v}^{1,2}$  generally becomes more negative as  $r/W$  increases but increases minutely at  $r/W > \sim 1/3.5$ .  
 6 These trends are similar to those shown in Fig. 5c. As in Section 3.1, they can be attributed  
 7 to the evolution of the velocity gradient near the sphere with the confinement by channel walls,  
 8 which depends on the sphere's proximity to the no-slip walls and is also regulated by the pressure  
 9 gradient along the gaps between the sphere and its adjacent walls. At  $r/W = 1/3$ , when the two  
 10 vertical walls are distributed symmetrically with respect to the sphere,  $F_{x,v}^{1,2}$  and  $F_{x,v}^{3,4}$  become equal  
 11 as expected.

### 1 3.3 Sphere actuation near walls of a narrow channel

2 In the previous section, we studied the actuation of a sphere in narrow channels by keeping  
 3 the distance of the sphere to the top and bottom channel walls the same (i.e.,  $a = W/2$ ). Here, we  
 4 relax this symmetric restriction by varying  $a$  and  $W$  independently (see Series 3 in Table 1). As  
 5 before,  $b$  is fixed at  $1.5r$  and the sphere rotates around the  $x$ -axis in the clockwise direction.

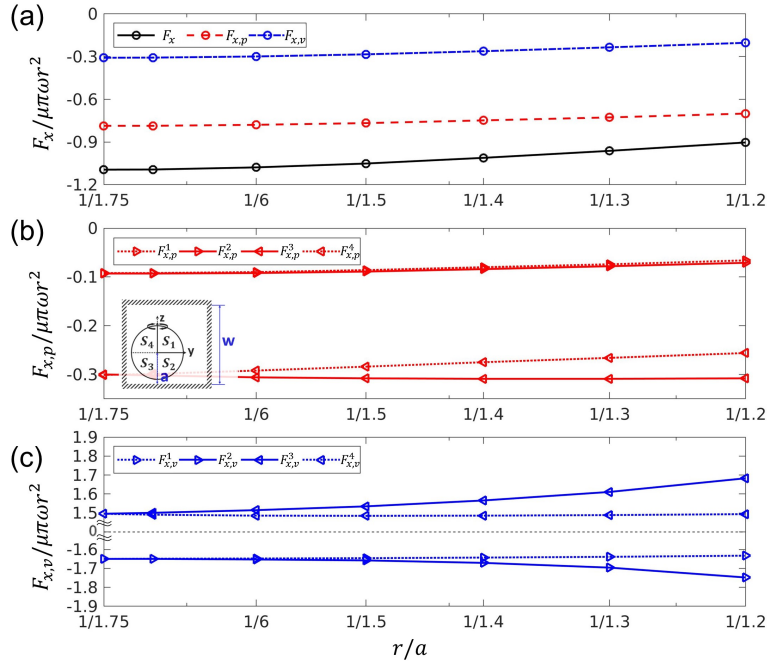


**Figure 10:** Flow in a channel-particle system with  $a = 1.2r$ ,  $b = 1.5r$ , and  $W = 3.5r$ . (a) Sample 3D streamlines. The sphere rotates around the  $z$ -axis in the clockwise direction. (b-c) Pressure field and streamlines in the  $z = 0$  plane (b) and  $y = 0$  plane (c) passing through the sphere's center.  $\bar{p} = (p - p_{ref})/\mu\omega$ .

6 We first investigate the flow field in a representative case with  $a = 1.2r$  and  $W = 3.5r$ . Figure  
 7 10a shows sample streamlines near the sphere. Like the flow field of Series 2 shown in Fig. 8, a  
 8 global flow is induced in the  $x$ -direction (marked by red arrows), the fluids drawn from the sphere's  
 9 one side are ejected onto the wall on the sphere's other side, and the recirculation of fluids around  
 10 the sphere's surface (marked by an orange arrow) induces two horizontal recirculation bubbles  
 11 (marked by two black arrows). However, unlike that shown in Fig. 8a, because the sphere is closer  
 12 to the bottom wall than the top wall, a vertical recirculation (marked by a blue arrow) is created.  
 13 Further, a recirculation around the sphere's surface (marked by an orange arrow) is formed near  
 14 the bottom wall. Because of this recirculation, compared to those shown in 8c, the streamlines near  
 15 the top wall are shifted toward the bottom wall as they approach the sphere (see Fig. 10c).

16 Figure 10b and 10c show the pressure field in the horizontal ( $z = 0$ ) and vertical ( $y = 0$ )

1 planes passing through the sphere's center. The pressure field is similar to that in Series 2 with the  
 2 same  $W$  (see Fig. 8b and c) in that two kinds of pressure heterogeneities exist. First, a pressure  
 3 imbalance arises due to the interactions between the recirculating fluids around the sphere and the  
 4 vertical walls. This pressure imbalance is localized near the vertical walls (e.g., in regions marked  
 5 by A, B, A', and B' in Fig. 10b) and is hardly noticeable at a distance  $\sim r$  away from the vertical  
 6 walls. Second, as shown in Fig. 10c, a pressure difference caused by the global flow is created  
 7 along the channel so that the pressure upstream of the sphere is lower while the opposite occurs  
 8 in downstream. As mentioned earlier, this pressure distribution generates a net force pushing the  
 9 sphere in the negative  $x$ -direction.



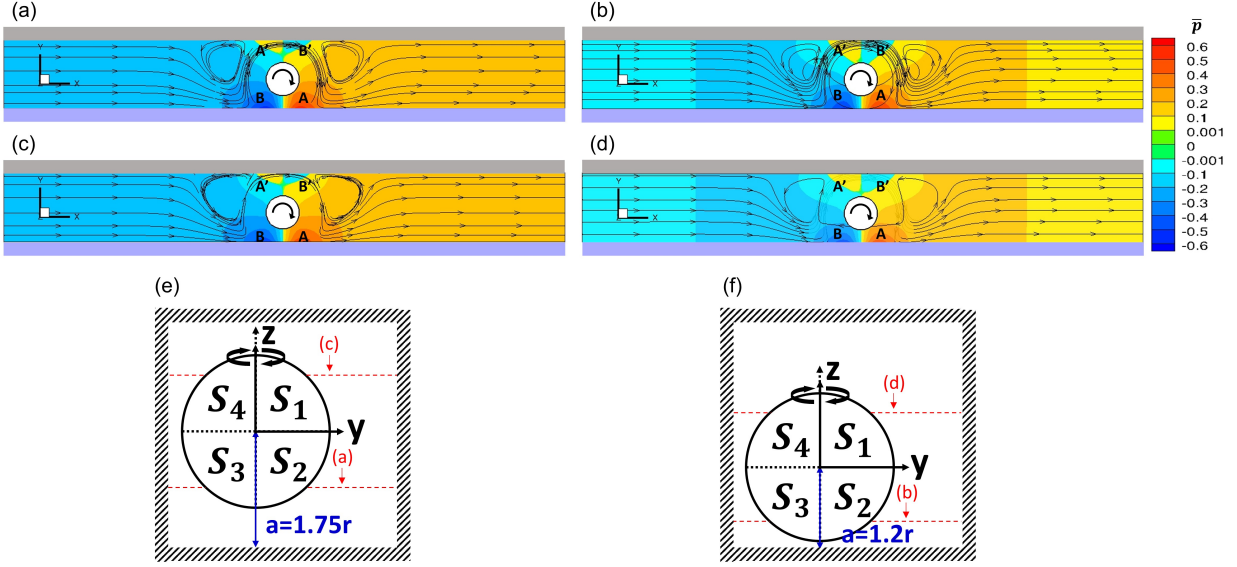
**Figure 11:** The hydrodynamic forces acting on a rotating sphere in square channels with different  $r/a$  ( $W = 3.5r$  and  $b = 1.5r$ ). (a) The net force in the  $x$ -direction and its pressure and viscous components, (b-c) The  $x$ -direction pressure (b) and viscous (c) forces acting on surface  $S_1$  to  $S_4$  labeled in the inset of panel (b) (see Fig. 1a for a 3D view).

10 Figure 11a shows the evolution of the hydrodynamic force and its components due to pressure  
 11 and viscous forces as a function of  $r/a$  when  $W$  is fixed at  $3.5r$ . As  $r/a$  increases from 1/1.75 to  
 12 1/1.2,  $F_x$ ,  $F_{x,p}$ , and  $F_{x,v}$  all increase. The trend of these forces is opposite to that in the Series 1  
 13 study (where  $W = 30r$ ) but is similar to that shown in the Series 2 study over the same range of

1  $r/a$  (i.e., in the range of  $1/3.5 < r/W < 1/2.4$  in Series 2 study). These differences highlight the  
 2 importance of confinement by narrow channels on particle actuation. To understand the origins of  
 3 the observed evolution of the hydrodynamic force as a function of  $r/a$ , we again decompose each  
 4 force into that acting on the sphere's four surfaces labeled in Fig. 1b ( $S_1, \dots, S_4$ ).

5 Figure 11b shows that, as  $r/a$  increases,  $F_{x,p}^{1,2,4}$  become less negative but  $F_{x,p}^3$  changes little.  
 6 These changes originate from the different responses of pressure in different regions near the sphere  
 7 as it is shifted toward the bottom wall. As  $r/a$  increases, the sphere is confined more by the bottom  
 8 channel wall while less confined by the top channel wall. The pressure field in the gap between  
 9 the purple-shaded vertical wall and surface  $S_3$  changes little, which is supported by the comparison  
 10 of pressure fields in the  $z = -0.6r$  plane for  $r/a = 1/1.75$  and  $1/1.2$  (see Fig. 12a and b). As  
 11 such,  $F_{x,p}^3$  changes little. On the other hand, as  $r/a$  increases, the local pressure imbalance between  
 12 regions A' and B' becomes stronger (see Fig. 12a and b) and thus  $F_{x,p}^2$  becomes less negative. A  
 13 similar trend is found for the pressure imbalance along the gap between surface  $S_1$  and its adjacent  
 14 wall (see region A' and B' in Fig. 12c and d, where the pressure fields in the  $z = 0.6r$  plane are  
 15 compared). Thus  $F_{x,p}^1$  also becomes less negative as  $r/a$  increases. A comparison of the pressure  
 16 along the gap between surface  $S_4$  and the purple-shaded wall shows that, as  $r/a$  increases, the  
 17 pressure imbalance along the gap (e.g., between region A and B in Fig. 12c and d) decreases and  
 18 hence  $F_{x,p}^4$  becomes less negative.

19 Figure 11c shows the variation of  $F_{x,v}^{1\dots4}$  as  $r/a$  increases from  $1/1.75$  to  $1/1.2$ . Similar to those  
 20 shown in Section 3.1, as  $r/a$  increases,  $F_{x,v}^2$  becomes more negative and  $F_{x,v}^3$  becomes more positive.  
 21 These behaviors and their origins are similar to those discussed in Section 3.1. Specifically, because  
 22 the sphere is already very close to the no-slip bottom wall ( $r/a > 1/2$ ), shifting the sphere closer  
 23 to the no-slip bottom wall enhances the radial gradient of the  $x$ -velocity ( $\nabla_r u_x$ ) and thus the  
 24 magnitude of the viscous shear stress and  $F_{x,v}^2$  and  $F_{x,v}^3$ . On the other hand, as  $r/a$  increases,  $F_{x,v}^1$   
 25 and  $F_{x,v}^4$  show little change. This is because, for the  $r/a$  considered here,  $\nabla_r u_x$  near and on the  
 26 sphere surface is affected primarily by the no-slip non-shaded vertical wall rather than by the top  
 27 wall (note that the sphere rotates around the  $z$ -axis). Since the distance between the sphere and  
 28 the vertical wall is fixed as  $r/a$  increases,  $F_{x,v}^1$  and  $F_{x,v}^4$  show little variation.



**Figure 12:** (a-b) Pressure field and streamlines in the  $z = -0.6r$  plane when  $r/a = 1/1.75$  (a) and  $1/1.2$  (b). (c-d) Pressure field and streamlines in the  $z = 0.6r$  plane when  $r/a = 1/1.75$  (c) and  $1/1.2$  (d).  $W = 3.5r$  and  $b = 1.5r$  in all cases.  $\bar{p} = (p - p_{ref})/\mu\omega$ .

## 1 4 CONCLUSIONS

2 In summary, the actuation of magnetic spheres confined inside square channels by a rotating  
 3 magnetic field is studied using immersed-boundary lattice Boltzmann simulations. The sphere is  
 4 positioned at a fixed distance from one of the vertical channel walls and rotates around the  $z$ -axis  
 5 with a small rotational Reynolds number. The hydrodynamic actuation force acting on the sphere  
 6 in the  $x$ -direction,  $F_x$ , is computed as a function of the channel width and the sphere's distance  
 7 to the bottom channel wall.

8 Our simulations show that, in very wide channels, when a sphere is away from top and bottom  
 9 walls,  $F_x$  is positive.  $F_x$  decreases and eventually reverses its direction as the sphere is shifted toward  
 10 the channel corner. The opposite trend is discovered in channels that are sufficiently narrow. When  
 11 the sphere is positioned midway between top and bottom walls,  $F_x$  decreases to become negative  
 12 as the channel width decreases but then recovers to zero when all four channel walls are symmetric  
 13 with respect to the sphere. These different trends are traced to the modulation of the flow in  
 14 the channel, which features both recirculation near the sphere and a more global flow across the  
 15 entire channel, by the confinement of channel walls. Such modulation is more complicated than  
 16 that encountered when a rotating sphere is confined between two parallel walls.<sup>46</sup> In particular, the  
 17 pressure heterogeneity near the sphere induced by fluid recirculation and global flow is modified

1 greatly as the confinement by the four channel walls changes. The resulting pressure force can  
2 dominate the viscous force on the sphere and control the direction of  $F_x$ . The observed variations  
3 of  $F_x$  and their underlying mechanisms highlight the rich behavior of magnetic actuation inside  
4 microchannels and can be important for the application of magnetic actuation in microfluidic  
5 environment.

## 6 ACKNOWLEDGMENTS

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