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Entropic transport without external force in confined channel with oscillatory boundary

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The dynamics of point-like Brownian particles in a periodic confined channel with oscillating boundaries has been studied. Directional transport (DT) behavior, characterized by net displacement along the horizontal direction, is observed even without external force which is necessary for the conventional DT where the boundaries are static. For typical parameter values, the average velocity \( V_f \) of DT reaches a maximum with the variation of the noise intensity \( D \), being alike to the phenomenon of stochastic resonance. Interestingly, we find that \( V_f \) shows nontrivial dependences on the particle gravity \( G \) depending on the noise level. When the noise is large, \( V_f \) increases monotonically with \( G \) indicating that heavier particle moves faster, while for small noise, \( V_f \) shows a bell-shape dependence on \( G \), suggesting that a particle with an intermediate weight may move the fastest. Such results were not observed for DT in a channel with static boundaries. To understand these findings, we have adopted an effective one-dimensional coarsening description, which facilitates us to introduce an effective entropic force along the horizontal direction. The average force is apparently nonzero due to the oscillatory boundary, hence leading to the net transport, and it shows similar dependences as \( V_f \) on the noise intensity \( D \) and particle gravity \( G \). The dependences of the DT behavior on other parameters describing the oscillatory channel have also been investigated, showing that DT is more pronounced for larger oscillation amplitude and frequency, and asymmetric geometry within a channel period and phase difference between neighboring periods are both necessary for the occurrence of DT. © 2015 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4939081]

I. INTRODUCTION

Particle transport through confined geometry has gained extensive research attention in recent years due to its ubiquitous importance in many disciplinaries ranging from physicochemical to biological systems.\(^1\)–\(^5\) In such systems such as zeolites, biological cells, and porous media, entropic barrier resulted from the uneven boundaries of the confined space affects dramatically the dynamics of Brownian particles.\(^6\)–\(^34\) In Ref. 12, Reguera et al. studied particle transport in a narrow corrugated channel with an external force in horizontal direction, finding that both the particle current and effective diffusion coefficient decrease with increasing temperature, which are distinct from the case for energetic barriers. For Brownian ratchets in confined environments, it has been found that the cooperativity between inherent rectification of ratchets mechanism and entropic bias due to spatial confinement could be used to control particle transport in mesostructures.\(^10\),\(^17\),\(^20\) Particles may be trapped which resulted from the combined effects of hydrodynamic interaction and entropic barrier even under external pressure\(^21\),\(^24\),\(^28\) or via the mechanism known as entropic stochastic resonance (ESR).\(^31\) In addition, particles with different sizes may transport with obviously different velocities through confined channels periodically varying in space where the free-energy barrier is dominated by entropy, which makes it possible to separate particles with different sizes or weights by adopting entropic effects, known as “entropic splitter.”\(^18\) More recently, it was shown that one could achieve fast separation with one-hundred percent purity\(^20\) in a confined space through a proper optimization of some control parameters like the frequency of an external force, which could be extremely useful to increase the efficiency of separation for dispersed phases. Moreover, in rectifying motion of natural microswimmers and Janus particles,\(^25\),\(^27\) the effect of confined boundary could enhance ratcheting efficiency by an order of magnitude. These results clearly demonstrate that entropic effects due to uneven boundary play rather important roles for Brownian particle dynamics in confined geometries.

While most studies so far have considered static boundaries for confined geometry, time-changing boundaries\(^35\)–\(^43\) may be more realistic, particularly in biological systems, such as contraction and relaxation of cells controlled by \( \text{Ca}^{2+} \) signal transduction,\(^35\),\(^37\) microvasculature channel with elastic boundaries,\(^40\),\(^42\) and swarm of microswimmers due to cell membrane deformations.\(^36\),\(^38\),\(^39\),\(^41\) The time-changing boundaries influence obviously the dynamics of particle transport in confined space. For instance, Ledesma-Aguilar and Yeomans found that elastic tubes could enhance the mobility of microswimmers with hydrodynamic effect in narrow channels.\(^43\) At low Reynolds number, the deformation membranes might promote or hinder the swimming of

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microorganisms near it due to the change of membranes. Palmieri analyzed the influence of wall’s fluctuation on the effective diffusion coefficient $D_{\text{eff}}$ of Brownian particles in confined space, finding that $D_{\text{eff}}$ decreases with decreasing the characteristic time scale of the fluctuating walls. Ai and co-workers have studied the directional transport (DT) of Brownian particles inside periodic tubes with fluctuating or vibrating walls, paying particular attentions on how DT would depend on the temperature, driving frequency, amplitude, as well as asymmetry of the system. Very recently, we have studied the influences of time-changing boundaries on ESR, finding that oscillating boundary can lead to ESR even without an external periodic force and the ESR gets more pronounced with the increment of particle gravity. Therein, we already found that time-changing boundaries might exhibit extremely different effects from the static ones. Due to the ubiquitous importance of DT as stated above, therefore, it is rather interesting for us to study how the boundary oscillation would influence the DT behaviour of Brownian particles with gravity in confined channels because most previous studies about DT in periodic channels usually ignored the influence of gravity which has strong effects on the motion of Brownian particles in confined space, such as ESR. Thus, we mainly focus on the influence of gravity on DT with oscillatory boundary.

Motivated by this, in the present paper, we use an overdamped Langevin equation (LE) to study the dynamics of a Brownian particle in a periodic confined channel as depicted in Fig. 1. The particle is subjected to a gravity force $G$ in the vertical direction, but no force in the horizontal direction $x$. We assume that the channel boundaries are periodically oscillating with possible phase lag between neighbouring cells. We find that DT behavior can occur even without an external longitudinal force, characterized by nonzero displacement in the $x$-axis. The velocity $V_x$ of DT displays rather nontrivial dependences on the noise intensity $D$ and particle gravity $G$. First, $V_x$ changes non-monotonically with $D$ for a fixed gravity, and the maximum of $V_x$ shifts to larger value with increasing $G$. Second, $V_x$ changes non-monotonically with $G$ for small noise level, while it increases monotonically with $G$ if the noise intensity is large. We have tried to illustrate such nontrivial phenomena by applying an effective one-dimensional (1D) coarsening Fokker-Planck equation, finding that an effective entropic force is present due to the boundary oscillation. Furthermore, we have also investigated how oscillation frequency $\Omega$ influences the DT behaviour, and find that DT becomes more remarkable when $\Omega$ gets larger. The velocity of DT as functions of the oscillation amplitude, the asymmetry parameter $b$ (see Fig. 1), and the phase lag $\Delta\phi$ between adjacent channel cells have also been investigated.

II. MODEL

We consider a Brownian particle moving in a two-dimensional (2D) confined channel, which is periodic in space along the $x$-direction with period $L$, as depicted in Fig. 1. The overdamped motion of the particle is described through

$$\gamma \frac{d\vec{r}}{dt} = -G\vec{e}_y + \sqrt{2\gamma k_B T} \xi(t).$$  (1)

Herein, $\vec{r} = (x,y)$ is position vector of the particle, $\vec{e}_y$ is the unit vector along the transversal direction, $G$ is a constant denoting the gravitational force, $\gamma$ denotes the frictional coefficient, and $k_B$ and $T$ are the Boltzmann constant and temperature of the system, respectively. $\xi(t)$ is Gaussian white noise with zero mean and unit variance $\langle \xi(t)\xi(t') \rangle = \delta_{ij}\delta(t-t')$ for $i,j = x,y$.

In contrast to most previous studies, here we consider that the channel boundary in the $y$-direction changes periodically by time. For the 2D structure depicted in Fig. 1, the upper wall in the range $0 \leq \overline{x} \leq L$ is defined by

$$w_u(\overline{x},t) = \begin{cases} 
 a_1(t)(\overline{x})^2 + \frac{d}{2}, & 0 < \overline{x} \leq \frac{b}{2} \\
 -a_1(t)(\overline{x} - b)^2 + c(t), & \frac{b}{2} < \overline{x} \leq b \\
 -a_2(t)(\overline{x} - b)^2 + c(t), & b < \overline{x} \leq \frac{L+b}{2} \\
 a_2(t)(\overline{x} - L)^2 + \frac{d}{2}, & \frac{L+b}{2} < \overline{x} < L 
\end{cases}$$  (2)

where $\overline{x} = x \mod L$ is the modulo function (to create a periodic structure), $d$ is the width of the bottleneck, and $b$ indicates the location of the point of maximum width. The lower boundary is given by $w_l(x,t) = -w_u(x,t)$. Note that there are many possible choices of the wall function, for instance, it can be connected by two straight lines as being used in Ref. 18. The wall we used here is constructed by four connected quadratic functions, just to make sure it is smooth everywhere which should be more consistent with channels in real systems. The continuity condition at $\overline{x} = b/2$ and $\overline{x} = (L+b)/2$ leads to $a_1(t) = 2c(t) - 2d/b^2$ and $a_2(t) = 2c(t) - 2d/(L-b)^2$. Therefore, time dependence of the channel boundary can be realized through modulation of $c(t)$, which equals to half of the maximum width of the channel located at $\overline{x} = b$.

In this model, we assume that $c(t)$ is periodically changed as follows:

$$c(t) = c_0 + c_1 \sin(\Omega t + \phi),$$  (3)

with frequency $\Omega$ and phase $\phi$. In Fig. 1, two channel cells along the $x$-direction are shown. Generally, organisms are full of incompressible fluid different periodic units shrink, and enlarge alternately. Thus, it is reasonable to assume a phase

![Fig. 1. Schematic illustration of the two-dimensional channel confining the motion of Brownian particles. The channel is periodic in the $x$-direction and two adjacent cells are depicted. The maximum width of the channel changes periodically with frequency $\Omega$ and phase $\phi$. The solid line shows snapshot of the channel at a certain time and the dashed line gives the static channel with $c_1 = 0$. The phase shift between the two cells is $\Delta\phi = \pi$.](image-url)
shift \( \Delta \phi = |\phi_l - \phi_r| = \pi \) between the two adjacent channel cells, where \( \phi_l \) and \( \phi_r \) are the phases of left and right cell in Fig. 1, such that the total volume may not change much and it can approximately reproduce the real transport channel. This will be a fixed setting in the present work if not otherwise stated. Fig. 1 shows a typical snapshot of two adjacent cells, one is shrunken and the other one is enlarged compared to the static channel given by dashed lines. We also note the phase shift \( \Delta \phi \) between adjacent segments may be chosen other values, and it will be shown that the transport behavior is actually dependent on this value.

To proceed further, we use the dimensionless description of the dynamics, by scaling length by \( L_R = \frac{L}{2} \) and time by \( \tau = \gamma L_R^2/k_BT_R \), respectively, where \( T_R \) is some reference temperature. Accordingly, the force \( G \) is scaled by \( k_BT_R/L_R \) and temperature is scaled by \( T_R \), and the boundary functions are also rescaled in time and length. The Langevin equation is then written in a form involving the dimensionless variables \( \tilde{r} = r/L_R, \tilde{t} = t/L_R \), \( \tilde{G} = G/(k_BT_R) \), etc. After removing the tilde symbols, the dimensionless LE reads

\[
d\tilde{r}/dt = -\tilde{G} \tilde{e}_y + \sqrt{2D} \tilde{e}_x(t),
\]

where \( D = T/T_R \) represents a reduced temperature characteristic of the strength of thermal noise. We use Euler method to simulate the LE with a time step \( \Delta t = 10^{-4} \), and reflecting boundary conditions have been employed to handle the interactions between particles and the wall. For the dimensionless parameters, we set \( L = 2, b = 0.2, d = 0.1, D = 0.1, c_0 = 0.45, c_1 = 0.36 \), and \( \Omega = 0.04 \) if not otherwise stated.

### III. RESULTS AND DISCUSSIONS

#### A. Directional transport

Fig. 2(a) shows typical time series of \( x(t) \) for fixed phase difference \( \Delta \phi = \pi \), gravity \( G = 5 \) and \( D = 0.05 \), \( D = 0.1 \), \( D = 0.15 \), respectively. Clearly, DT is observed even without external force in the horizontal direction, which was necessary for DT in channels with static boundary. For the boundary with shape shown in Fig. 1, \( x(t) \) which represent position of particle decreases with time indicating that the particle moves to the left. This is quite different from the study of “entropic splitter”\(^{18,30} \) where the particles move to the right as a consequence of the periodic external force in the same geometry. Note here DT is caused by the oscillatory motion of the boundaries, which seems to generate a net force to the left direction.

For the data shown in Fig. 2(a), transport displacement increases with noise intensity \( D \) from 0.05 to 0.15. Thus, we would like to study the relation between time-averaging velocity \( V_i \) of DT and noise intensity \( D \), where \( V_i \) is defined in the caption of Fig. 2. In Fig. 2(b), \( V_i \) is drawn as a function of the noise intensity \( D \), where a non-monotonic behavior is observed. This behavior is similar to the ESR behavior, where an optimal level of noise is most favorable for the coherent motion of Brownian particles in a dumbbell-shape confined geometry, with external force in the horizontal direction\(^{30} \) or under oscillatory boundary.\(^{48} \) Moreover, the plot in Fig. 2(b) also shows nontrivial dependence of \( V_i \) on the gravity \( G \). For small noise level, say \( D = 0.15 \), the speed decreases in the order \( V_{i,G=5} > V_{i,G=10} > V_{i,G=15} \) while the order is reversed for a certain large \( D \), e.g., \( D = 0.5 \). This picture is more clearly demonstrated in Fig. 2(c), where \( V_i \) as functions of \( G \) for several values of \( D \) are presented. It is interesting that \( V_i \) may also show non-monotonic dependence on \( G \), given that the noise intensity \( D \) is not too large. Such a non-monotonic variation indicates that particles with an optimal gravity move the fastest under an oscillatory boundary. More information is shown in Fig. 2(d), where the contour plot of \( V_i \) in the \( D-G \) plane is shown. The red area indicates the location of the maximum \( V_i \), which moves to larger noise intensity \( D \) with increasing \( G \).

Although the non-monotonic dependence of \( V_i \) on the noise intensity \( D \) is not surprising due to many reports about SR-like behavior in the literatures,\(^{48,50} \) the non-monotonic dependence on \( G \) is rather nontrivial. In most of the previous studies about DT in confined channels with static boundary, they ignored the gravity of particle and only investigated the effect of longitudinal external force. In our work, however, we have considered the effect of gravity on the velocity of particle and found that a heavier particle may move much faster than a lighter one when the boundary is oscillating. In addition, as shown in Figs. 2(c) and 2(d), particles with moderate weight may move the fastest when the noise is at an appropriate level. This interesting phenomenon suggests some kind of noise-selected rectification effect. For instance, to obtain the particle with \( G = 5 \) from original mixture which contains the other particle of which gravity \( G = 10 \), we could set the noise intensity \( D = 0.1 \). Under this condition, the light particle transports about five times faster than the heavier one. If the mixture is comprised of particles \( G = 10 \) and \( G = 15 \), the noise level \( D = 0.2 \) would be a better noise level to separate them.

#### B. Effective entropic force

In a recent study,\(^{48} \) we have shown that a novel type of ESR can occur in a confined space of dumbbell-shape oscillatory boundary, even without external force in the horizontal direction which was required for conventional ESR. Therein, we have also found that the ESR strength showed a non-monotonic dependence on the particle gravity \( G \). The key observation is that oscillatory boundary results in an entropic force in the horizontal direction that is \( G \)-dependent, while for the conventional ESR or geometric SR, the longitudinal force is external and not dependent on \( G \). In the present work, the concept of entropic force was still useful for us to understand the phenomenon of DT and the non-monotonic dependence of \( V_i \) on \( D \) and \( G \). Under the same approximation as that in Refs. 7, 12, 18, 48, and 50, one can obtain an effective 1D coarsening Fokker-Planck equation governing the probability distribution function \( P(x,t) \) as follows:

\[
\frac{\partial P(x,t)}{\partial t} = \frac{\partial}{\partial x} \left( D \frac{\partial P}{\partial x} + V'(x,t) P \right),
\]
where the prime refers to derivative with respect to $x$ and

$$V(x,t) = -D \ln \left[ \frac{2D}{G} \sinh \left( \frac{Gw(x,t)}{D} \right) \right], \quad (6)$$

with $w(x,t) = w_0(x,t)$. To Eq. (5) and (6), we have adopted the approximation that the boundary changes slowly compared to the particle motion in the vertical direction and the dependence of effective diffusion coefficient on coordinate $x$ is ignored. $V(x,t)$ gives an effective potential of entropic nature, being dependent on both noise intensity $D$ and the particle gravity $G$. In addition, the time-dependent boundary $w(x,t)$ makes $V(x,t)$ to be further time-dependent, which is the main difference from the case of a static boundary, wherein $V(x,t)$ reduces to a static one $V_0(x) = -D \ln \left[ \frac{2D}{G} \sinh (Gw_0(x)/D) \right]$.

With this description, one can identify $F(x,t) = -V'(x,t)$ as a time-dependent effective force applied at the $x$-direction to the particle, which undergoes free diffusion in the absence of this force. The DT behavior must be related to the property of $F(x,t)$. For any instantaneous time $t$, the probability distribution of the particle is given by $P(x,t)$, which is the solution of the 1D Fokker-Planck equation. We may then introduce an average force at time $t$ by averaging $F(x,t)$ over the length period $(0,2L)$ as

$$\bar{F}_a(t) = \int_0^{2L} P(x,t) F(x,t) \, dx, \quad (7)$$

which may be qualitatively used to measure the net force the Brownian particle is exerted along the $x$-direction. Clearly, if the boundary is static, the stationary distribution of Eq. (5) would be given by the Boltzmann distribution $P_{BD}(x) \propto \exp \left[ -V_0(x)/D \right]$. In this case,

$$\bar{F}_a(t) = \int_0^{2L} P_{BD}(x) \left[ dV_0(x)/dx \right] \, dx \propto D \int_0^{2L} \left( \frac{d}{dx} \right) P_{BD}(x) \, dx = 0,$$

i.e., the net force would be 0 and DT of the particle cannot be observed. If the boundary changes with time, surely $P(x,t)$ should be time dependent. In the long time limit, one expects the system would reach a stationary time-dependent distribution $P_{st}(x,t)$. If the boundary changes very slow, such a stationary distribution $P_{st}(x,t)$ can be approximately the Boltzmann distribution determined by the instantaneous effective potential $V(x,t)$, i.e., $P_{st}(x,t) = P_{BD,ins}(x,t) \propto \exp \left[ -V(x,t)/D \right]$. In this case, one would also have $\bar{F}_a(t) \approx 0$ and DT cannot be observed. In Fig. 3(a), we have depicted as examples the instantaneous Boltzmann distributions $P_{BD,ins}(x,t)$ for $D = 0.1$ and $G = 5.0$ at different times $t$ and the corresponding effective forces $F(x,t)$.

In the present work, however, the boundary does not change that slowly and the stationary distributions $P_{st}(x,t)$ are apparently different from the instantaneous distribution $P_{BD,ins}(x,t)$. This is shown in Fig. 3(b), wherein $P_{BD,ins}(x,t)$ for the same moments as those in Fig. 3(a) are presented. Note that while $P_{BD,ins}(x,t)$ can be calculated from $V(x,t)$ directly, $P_{st}(x,t)$ must be obtained by simulations. As can
be seen, $P_0(x, t)$ are biased obviously to the left half period (0, L), compared to $P_{BD, in}(x, t)$. Since the average force $\overline{F}_{a}(t)$ is zero for $P_{BD, in}(x, t)$ as discussed above, this bias to left side would lead to a nonzero average force $\overline{F}_{a}(t)$ to the minus $x$-direction. This is indeed the case, as shown in Fig. 3(c), where $\overline{F}_{a}(t)$ as a function of time $t$ is depicted. We find that $\overline{F}_{a}(t)$ is always less than zero (the minus sign means that the force points to the left direction) and it also oscillates with time. Such a persistent net force would certainly lead to DT of the Brownian particle as observed in Fig. 2(a). In addition, we have also investigated how this net force depends on the noise intensity $D$ and the gravity $G$. The results are given in Fig. 3(d), where $\overline{F}_{a}(t)$ for $t = T/4$ as functions of $D$ and $G$ are presented. Clearly, $\overline{F}_{a}(t)$ shows a maximum value with the variation of $G$ for $D = 0.1$, and a maximum is also observed with the variation of $D$ for fixed $G = 5$, in accordance with the observations demonstrated in Figs. 2(b) and 2(c). The main purpose of this 1D model is to reveal the underlying physical insight of this system. Although, such an analysis process is qualitative and descriptive, we can use it to understand why oscillatory boundary leads to DT and how $V_t$ depends on $D$ and $G$, qualitatively.

### C. Other parameter dependences

According to the above discussions, the DT behavior for the particle results from the time-dependent entropic force resulting from the oscillatory boundary. The entropic force is also dependent on the noise intensity $D$ and particle gravity $G$. In particular, the non-monotonic dependence of the average velocity $V_t$ on $G$ indicates an interesting possibility of entropic splitter effect to select out particles of proper weight. All the above results are obtained for fixed oscillation frequency $\Omega$ and amplitude $c_1$, as well as the geometric asymmetry parameter $b$ and the phase lag parameter $\Delta \phi$. In this following, we will briefly discuss the roles of these parameters.

As mentioned above, the average net force $\overline{F}_{a}(t)$ will be zero if the instantaneous distribution is given by the Boltzmann distribution $P_{BD, in}(x, t)$, and the real stationary distribution $P_0(x, t)$ is much different from $P_{BD, in}(x, t)$, which is the very reason that $\overline{F}_{a}(t) \neq 0$ leading to DT. If the boundary oscillates very slowly, one would expect that this difference would be negligible and $\overline{F}_{a}(t)$ would be nearly zero. This indicates that the oscillation frequency $\Omega$ must influence the DT behavior. In Fig. 4(a), the $V_t - G$ curves for several different values of $\Omega$ are shown for $D = 0.1$. Clearly, the curves move to higher values of $V_t$ with increasing $\Omega$, indicating that a faster oscillating boundary is more favorable for DT. We also note that if the particle is heavy enough, the effect of $\Omega$ is negligible. Another control parameter is the oscillation amplitude $c_1$. The range of $c_1$ is limited by the geometry of the channel, and in the present work the largest allowed value of $c_1$ is 0.36. Intuitively, $V_t$ should increase monotonically with $c_1$. This is exactly true as shown, for example, in Fig. 4(b), where $V_t$ as a function of $c_1$ for several values of $G$ is presented for $D = 0.1$. We note that if $c_1$ is less than some threshold value, $V_t$ is negligibly small. Obviously, such a threshold value is larger for heavier particles. For instance, for $G = 10$, $V_t$ almost decreases to zero for $c_1 \leq 0.32$. In other words, DT would be absent if the oscillation amplitude of the boundary is too small. For
FIG. 4. (a) $V_t$ as a function of $G$ for several values of $\Omega$ under $D = 0.1$. (b) $c_1$ is the amplitude of oscillating boundary. $V_t$ increases rapidly when $c_1$ exceed some threshold value. (c) $b$ is the widest location of channel, and it stands for the asymmetric degree of channel. The sign of $V_t$ is decided by $b$. (d) $V_t$ as a function of $\Delta \phi$ for different gravity $G$ with $D = 0.1$. Other parameters are same as Fig. 2.

other values of noise intensity $D$, the roles of the oscillation frequency and amplitude are qualitatively the same.

Finally, we would like to investigate the role of the particular geometry as depicted in Fig. 1. In particular, the parameter $b$ gives the location of the maximum width of channel, which characterize the asymmetry of the channel. If $b = L/2$, i.e., the maximum width locate at the middle of a period, the effective potential $V(x,t)$ would be symmetric inside $(0,L)$ and no net transport can be observed. We note that such an asymmetric geometric setting is also necessary for DT in static channels but with periodic external force. In Fig. 4(c), the dependence of $V_t$ on $b$ is shown for $D = 0.1$ and different values of $G$. As expected, the absolute value of $V_t$ decreases to zero for $b = L/2 = 1.0$. Also we note that $V_t > 0$ for $b < L/2$, i.e., the particle transports to the left side, while it transports to the right side with $V_t < 0$ for $b > L/2$. Another parameter relevant with the boundary is the phase lag $\Delta \phi$. If $\Delta \phi = 0$, adjacent channel cells will both enlarge or shrink, which is not reasonable in any real system such as a biological channel where the system volume should keep nearly conserved. Thus, in the present work, we have mainly investigated the case for $\Delta \phi = \pi$, corresponding to a wave-travelling along the boundary. Surely in a modeling work, it is convenient to consider the role of $\Delta \phi$. This is demonstrated in Fig. 4(d), where one can see that $V_t$ increases monotonically with $\Delta \phi$ from 0 to $\pi$, and $V_t$ is nearly zero for $\Delta \phi = 0$. We note that the roles of $b$ and $\Delta \phi$ are not dependent on the noise intensity $D$. Therefore, asymmetric geometry of

IV. CONCLUSION

In summary, we have investigated the dynamics of Brownian particle in a confined periodic channel with oscillatory boundaries. We find that boundary oscillation may lead to directional motion of the particle even without an external force in the longitudinal direction. The average velocity of the particle $V_t$ changes non-monotonically with the noise intensity $D$, something like the well-known stochastic resonance behavior. In addition, this resonance-like behavior is strongly influenced by the particle gravity $G$: The maximum value of $V_t$ increases and the optimal value of $D$ shifts to larger values with increasing $G$. More interestingly, we find that $V_t$ increases with $G$ in high noise level, while it may also show a non-monotonical dependence on $G$ if noise intensity $D$ is small. This latter nontrivial dependence on $G$ was not reported in the literature before and suggests a possible mechanism of noise-selected transport of particles of proper weights. To further illustrate such interesting features, we have used a 1D coarsening description of the kinetics to introduce an effective force of entropy nature, which can well help understand the origin of the directional motion and the non-monotonic dependence of $V_t$ on $D$ and $G$. We have also investigated how the channel shape and oscillation parameters would influence the directional transport, finding that an oscillating boundary
with larger amplitude and frequency is more beneficial for the directional motion, and asymmetric geometry within a channel period and phase difference between neighboring periods are both necessary for the particle transport. We believe that the present study of particle transport in oscillating boundaries will be useful for many practical systems whose boundaries play a constructive role. Moreover, the work may shed new light on the understanding of substance delivery as well as its optimization in confined geometry, and provide novel methods for the artificial separation of particles, which may be of great significance particularly in real biological systems.

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