Abstract

Active Brownian particles (ABPs) confined in structured environments exhibit transport phenomena that have no passive analogue, arising from the interplay of self-propulsion, confinement geometry, external driving, and background flows. Understanding how these factors control transport is essential for designing microfluidic systems that manipulate active matter. This thesis investigates how obstacle softness, external bias, inertia, and channel asymmetry govern the diffusive and directed motion of ABPs in microstructured environments.

We first examine ABP transport in flat channels containing randomly distributed soft obstacles forming a quenched disordered environment and show that obstacle softness acts as a key control parameter governing the transport regimes. Soft obstacles allow nearly free diffusion, whereas increasing softness leads to repeated scattering, intermittent trapping, and eventual suppression of long-time transport. Extending this framework to undulating channels with entropic barriers and external bias reveals a rich set of transport regimes: the nonlinear mobility becomes non-monotonic, while the effective diffusion exhibits a bell-shaped dependence on the bias and transitions between normal, superdiffusive, subdiffusive, and trapped states depending on obstacle softness and external bias strength.

We then study inertial ABPs in a microchannel subject to Poiseuille flow and uncover a robust upstream drift in the overdamped limit that reverses as particle inertia increases. Both the average velocity and effective diffusion exhibit pronounced maxima at an optimal mass, revealing a tunable separation window. Finally, we demonstrate rectification and mass-based sorting of interacting ABPs in asymmetric channels driven by an oscillatory force. While non-interacting particles exhibit a single optimal mass for transport, interactions produce a bimodal response that enhances rectification for both light and moderate-mass particles. Empirical scaling relations link the optimal masses to the driving amplitude and frequency, propulsion speed, and interaction strength. Together, these results establish obstacle softness, external bias, flow, inertia, and geometric asymmetry as independent control parameters for programming active transport in confinement.

Keywords: active Brownian particles; entropic effects; obstacle softness; mechanical heterogeneity; rectification; mass-based separation; asymmetric channels.