Abstract

This thesis examines how microscopic particles and swimmers can be steered and optimized by tailoring their surface properties and shapes in low-Reynolds-number flows. Across four core studies, the work shows how heterogeneous slip, localized activity, and controlled deformations serve as design knobs for translation, rotation, and efficiency.

First, we analyze the hydrodynamics of a passive slip-stick sphere in an arbitrary ambient Stokes flow, with its surface divided into regions of different slip lengths. Using the double-curl method, we derive Faxén-type analytic expressions for drag and torque in both cap/strip and general patch configurations. In Poiseuille flow, we show how polar and azimuthal patch widths, together with the slip–length ratio, determine the sphere's translation and rotation. We identify optimal polar angles that maximize swimming velocity and critical patch configurations that reproduce the behavior of a uniformly rough sphere, and we highlight near-field streamline distortions induced by non-axisymmetric patches. These results extend classic slip–stick theory and provide design rules for Janus-type carriers in targeted transport.

Next, the thesis turns to active, chiral microswimmers with heterogeneous surfaces. We study the hydrodynamics of a spherical swimmer whose activity is confined to a surface patch on an otherwise hydrophobic slip surface. For both symmetric and arbitrary patches, we obtain analytic formulas for the swimming velocity, rotation, and the flow field. We identify patch geometries that maximize swimming speed and efficiency. A symmetric cap can already outperform a fully active swimmer, and an optimally placed arbitrary patch performs even better. Localized activity generates Stokeslet and Rotlet signatures that alter near-field flows while preserving far-field structure, with implications for synthetic active particles in drug delivery and taxis.

Extending this framework, we next investigate the hydrodynamics of a chiral swimmer whose surface activity is restricted to a symmetric patch and is hydrophobic elsewhere, compared with swimmers with different swimming strategies. Higher surface-active slip modes contribute directly to both speed and rotation, and we show that the configuration that maximizes speed does not, in general, maximize efficiency. Efficiency improves with hydrophobic slip, and pullers are typically more efficient than pushers, yielding clear targets for patch design and mode selection.

Finally, we introduce a semi-analytical framework for deformed swimmers with prescribed tangential active slip. Using an eigenfunction expansion on an enclosing domain, we map how deformation modes and active slip modes, together with swimmer type (pusher, puller, neutral), shape propulsion, reversals, and flow topology. For the third shape deformation mode, puller-type swimmers achieve their highest propulsion speeds, whereas pusher-type swimmers attain a pronounced minimum in speed with the second shape deformation.

Taken together, these studies show that surface slip heterogeneity, localized activity, hydrophobicity, and controlled shape deformations can be used as complementary design knobs to tailor the motion, rotation, and efficiency of passive and active microscale particles, providing a rational basis for future microrobot and carrier design.

Keywords: Nanoparticle, Solid-fluid interfaces, Hydrophobic effect, Patchy sphere, Low Reynolds number swimmers, Dry active matter, Patchy chiral swimmer, Eigenfunction expansion, Least square approximation, Nearly spherical swimmer.