Smart Liquid Manipulation on Structured Surfaces

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Introduction

Directional liquid manipulation is crucial for applications in energy harvesting, microfluidics, and biomedicine. Bioinspired heterogeneous structured surfaces, which exploit unbalanced interfacial forces, offer a promising approach to guide energy-free liquid manipulation. In this study, we explore directional liquid manipulation on curvature-ratchet surfaces (Fig. 1). Variations in the liquid-solid interfacial relationship (e.g., altering the liquid, where c is the water content in the water-ethanol mixture) and modifications to surface structural features (e.g., changing the tilt angle β of curvature-ratchets) can influence liquid behaviors. However, a unified understanding of these phenomena is lacking, impeding the establishment of general surface design guidelines.

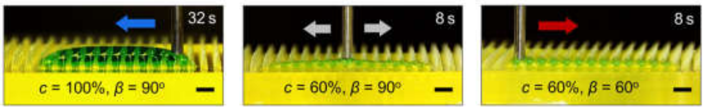

Fig. 1. Directional/bidirectional liquid transport on structured surfaces (scale bars: 1 mm).

Objectives

In this work, we have two primary objectives:

- To investigate the underlying interfacial liquid dynamics of directional liquid manipulation on structured surfaces
- To establish a general understanding of tunable liquid behavior under varying solid-liquid interfacial energy conditions

Methodology

We define key structural parameters of the curvature-ratchet model: the bottom semicircle radius (R), the body length (L), and the tilt angle (β). The arrayed curvature-ratchets are the main surface design and are characterized using SEM (Fig. 2).

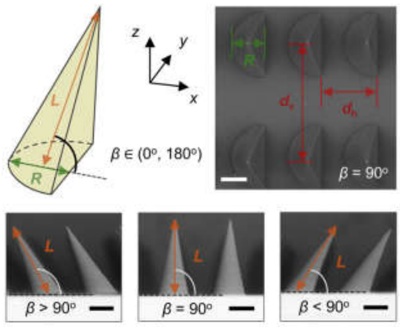

Fig. 2. Basic model and SEM images (scale bars: 300 µm).

Surface wettability (Fig. 3) is modified by plasma hydrophilic treatment and superhydrophobic nanoparticle coatings. The surface tension of the experimental liquids (water-ethanol mixture) is adjusted by varying the mass fraction c of water.

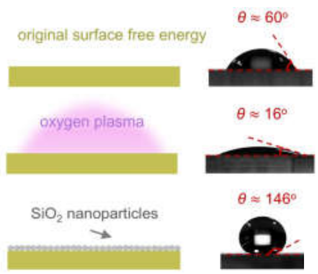

Fig. 3. Illustration of surfaces with different wettability.

Research accomplishments

We show how curvature and tilt features lead to asymmetric interfacial Laplace pressure, which allows directional liquid manipulation (Fig. 4). In addition, we evaluate the mechanism involved in multimodal liquid manipulation through the coupling of dual structural features.

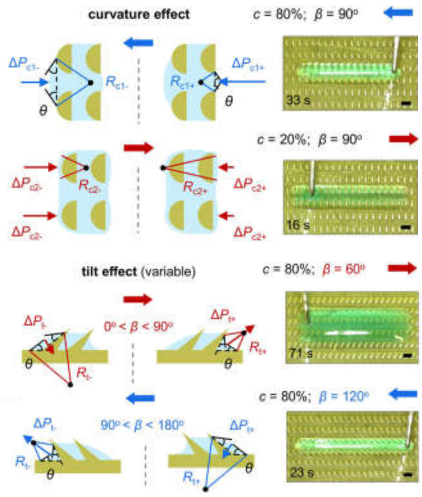

Fig. 4. Selective directional liquid manipulation on heterogeneous surfaces (scale bars: 1 mm).

We introduce a new dimensionless number ζ to describe the liquid-solid interfacial energy relationship, defined as the ratio of surface free energy (γ_S) to liquid surface tension (γ_L), i.e., $\zeta = \gamma_S/\gamma_L$. It delineates three liquid control regimes (Fig. 5): excessive ($\zeta \gg 1$), balanced ($\zeta \sim 1$), and insufficient ($\zeta \ll 1$). We reveal the balanced regime enables diverse liquid manipulation patterns. Based on this, we propose a liquid-based information encryption technique, where only the correct ζ can render the digits 0-9 on surfaces (Fig. 6).

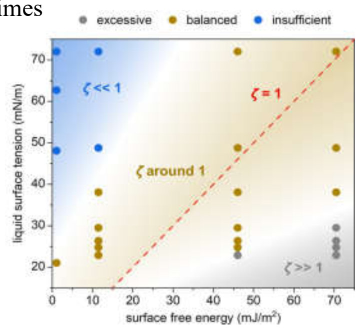

Fig. 5. Three liquid control regimes.

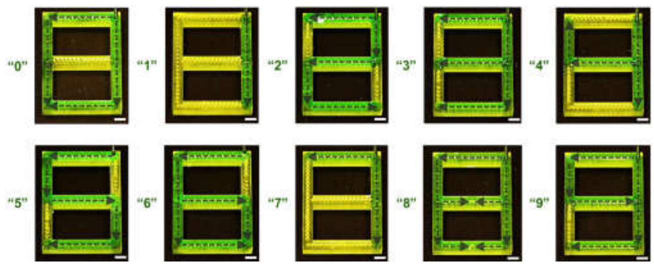

Fig. 6. Liquid-based information encryption technique (scale bars: 2 mm).

Conclusions

We illustrate that the effective integration of ζ with surface designs is crucial for smart directional liquid manipulation. These findings are particularly relevant for microscale liquid management technologies and their diverse applications.

Reference:

[1] J. Miao, **A. C. H. Tsang***. ***ACS Nano***, 2025, 19, 5829-5838.

[2] J. Miao, J. Li, **A. C. H. Tsang***. ***Nano Letters***, 2025, in press.

[3] J. Miao, **A. C. H. Tsang***. ***Advanced Science***, 2024, 11, 2405641.