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Superhydrophobic Surfaces For Friction Reduction Applications

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Abstract

The wetting behavior of solid surfaces in the presence of a liquid medium is an important aspect in transport phenomena, especially for microfluidics applications. Inspired by the unique water-repellent properties of the lotus leaf, superhydrophobic surfaces can be employed by applying a hydrophobic coating on a rough or textured surface. Maintaining a dewetted (Cassie state) condition as illustrated in Figure 1, the wetting of the groove is averted, leaving air pockets filling up the gap beneath the liquid interface. In between these small-sized structures, an approximately shear-free liquid-gas interface can be supported which allows liquid to slip over it. This could potentially lead to a reduction in viscous skin friction drag experience by the liquid flow.

The present work investigates the role of suspended liquid-gas interfaces for applications involving the reduction in flow resistance using the COMSOL multiphysics software. A pressure-driven viscous flow of a liquid through microtubes containing superhydrophobic surfaces patterned with alternating micro-grooves and ribs has been considered. Employing a 3D simulation, a fully-developed laminar flow with a uniform bulk velocity has been simulated. Neglecting the fluid dynamics of the gas within the grooves, only the liquid flow has been simulated. Along the inner wall of the tube, the superhydrophobic features are modeled using an alternating no-slip and shear-free boundary conditions to represent the ribs and liquid-gas interfaces, respectively. As illustrated in Figure 2, 8 groove-rib periodic units have been patterned along the circumferential direction.

As the liquid experiences no-slip at the solid surface and perfect wall slip occurs along the liquid-gas interface, a surface-averaged slip length has been computed to represent a macroscopic (effective) slip. The validity of the numerically calculated effective slip length at different values of shear-free fraction has been evaluated by comparing against the analytical solution of Philip (1972). As can be observed in Figure 3(a), the results yielded by both analytical and numerical methods are in good agreement. An increase in the value of the shear-free fraction (relative wall surface area occupied by the grooves) gives rise to a corresponding increase in the normalized effective slip length. A finite positive effective slip length is also equivalent to a decreasing friction factor-Reynolds number product, and thus a reduction in flow resistance through the tube, as illustrated in Figure 3(b).

Apart from the longitudinally-oriented groove-rib arrangement, applications involving the reduction in flow resistance can also be investigated for the flow through a tube patterned with other surface

topologies, such as transverse grooves (see Figure 4). By employing such surfaces, the presence of liquid slip and the concomitant decrease in the flow resistance are demonstrated, thereby suggesting that these surfaces may offer a great potential for overcoming the excessive pumping power requirements in microfluidics applications. As these surfaces can be easily engineered with different length scales of micro/nano-structures, the ability to reduce flow friction can be optimized. By manipulating the superhydrophobicity of such surfaces, the fluid flow in the micro-devices could be potentially enhanced for many applications, including lab-on-a-chip technology, drug delivery, thermal management, etc.

Reference

Philip JR (1972) Flows satisfying mixed no-slip and no-shear conditions. Journal of Applied Mathematics and Physics (ZAMP) 23 (3):353-372

Figures used in the abstract

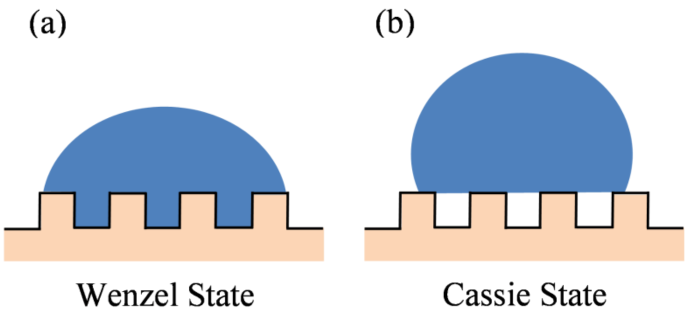

Figure 1: Wetting behavior on a microtextured surface for: a Wenzel state (hydrophilic); b Cassie state (hydrophobic)

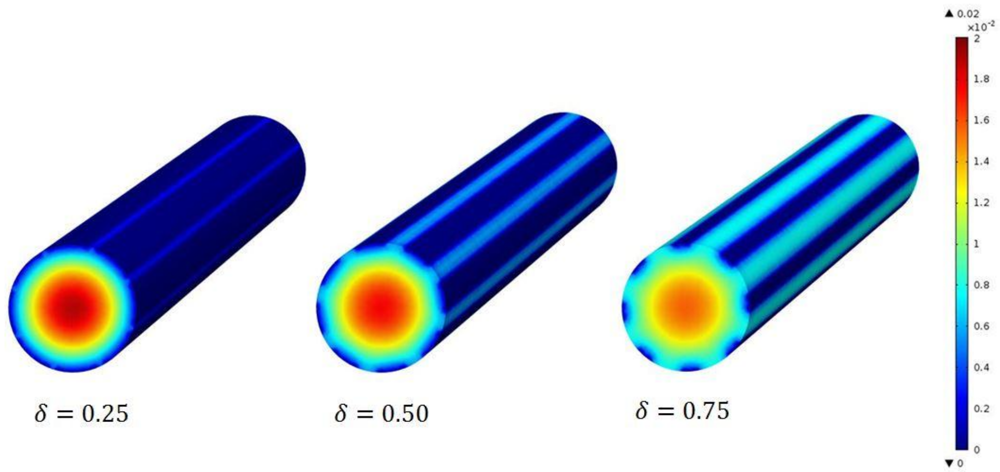

Figure 2: Streamwise velocity field for flow in a tube with different values of shear-free fraction

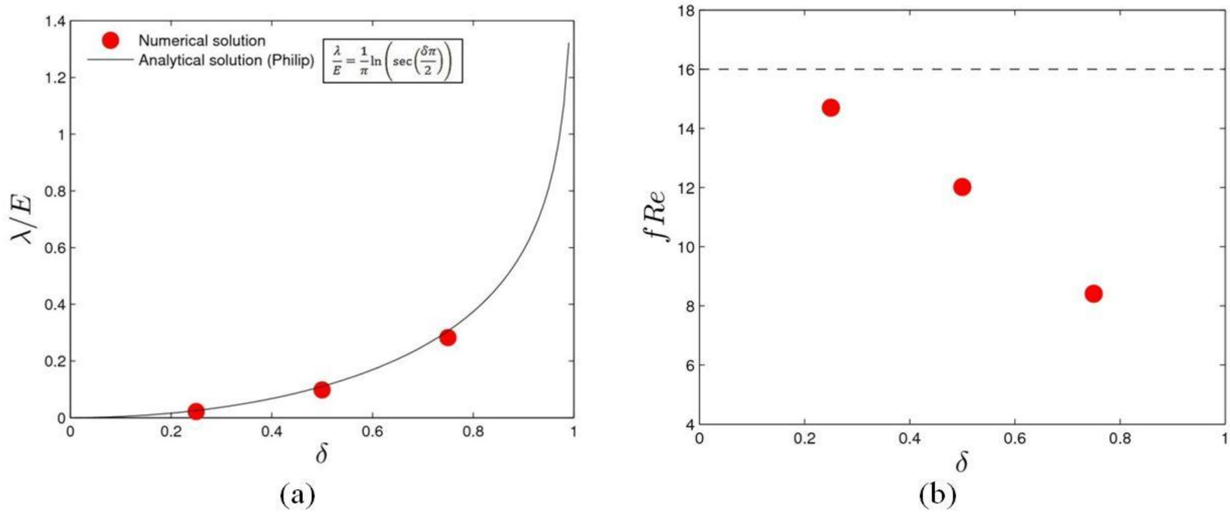

Figure 3: Numerical predictions for: a normalized effective slip length; b Fanning friction factor-Reynolds number product

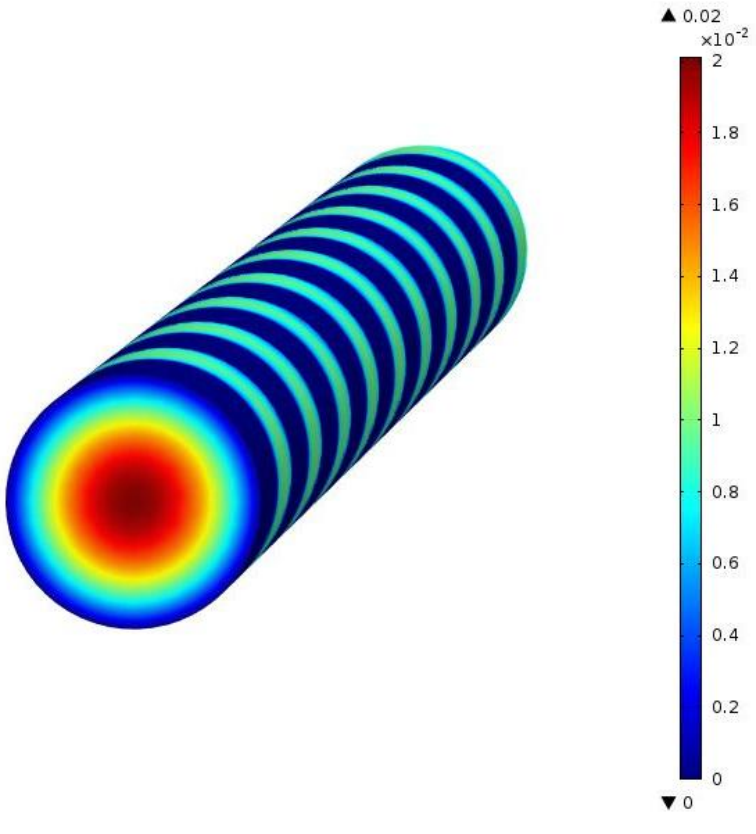

Figure 4: Streamwise velocity field for flow in a tube patterned with transverse grooves