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Liquid–Infused Surfaces with Trapped Air (LISTA) for Drag Force Reduction

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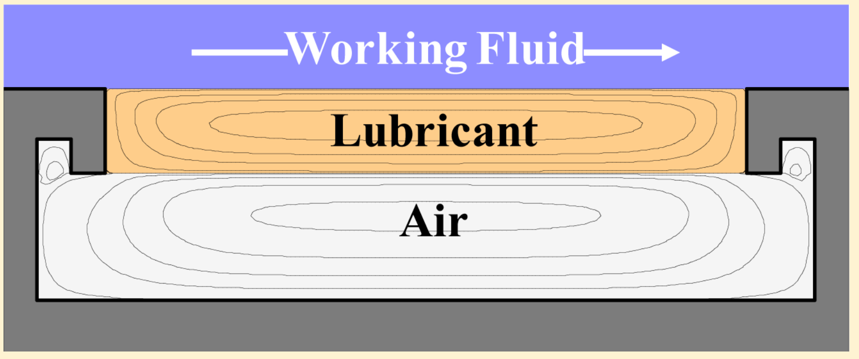

ABSTRACT: Superhydrophobic (SHP) surfaces are known for their drag-reducing attributes thanks to their ability to trap air in their surface pores and thereby reduce the contact between water and the frictional solid area. SHP surfaces are prone to failure under elevated pressures or because of air-layer dissolution into the surrounding water. Slippery liquid-infused porous surfaces (SLIPS) or liquid-infused surfaces (LIS) in which the trapped air is replaced with a lubricant have been proposed in the literature as a way of eliminating the air dissolution problem as well as improving the surface stability under pressure. While an LIS surface has been shown to reduce drag for flow of water–glycerol mixture (ref 18), no significant drag reduction has yet been reported for the flow of water (a lower viscosity fluid) over LIS. In this concern, we have designed a new surface in which a layer of air is trapped underneath the infused lubricant to reduce the frictional forces preventing the LIS to provide drag reduction for water or any fluid with a viscosity less than that of the lubricant. Drag reduction performance of such surfaces, referred to here as liquid-infused surfaces with trapped air (LISTA), is predicted by solving the biharmonic equation for the water–oil–air three-phase system in transverse grooves with enhanced meniscus stability thanks to double-reentry designs. For the arbitrary dimensions considered in our proof-of-concept study, LISTA designs showed 20–37% advantage over their LIS counterparts.

1. INTRODUCTION

A surface promoting an apparent water contact angle of 150° or higher is often referred to as a superhydrophobic (SHP) surface.[1] This is in part thanks to the peculiar ability of such a surface to trap air in its surface pores. SHP surfaces can potentially be used for drag reduction and/or self-cleaning applications among many others.[2−5] The SHP surfaces designed for underwater drag reduction applications are often affected adversely by the water hydrostatic pressure or the time in service.[6−13] Excessive hydrostatic pressures can imbalance the mechanical forces acting on the air–water interface (AWI) that forms over a SHP surface. In addition, the dissolution of the trapped air into the surrounding water can lead to the collapse of an AWI over time.[11−17] In this concern, investigators in ref 18 used a lubricant to impregnate the pores of their drag-reducing surface and thereby they extended the surface lifespan almost indefinitely. Such surfaces have been referred to as slippery liquid-infused porous surfaces (SLIPS) or lubricant-infused surfaces (LIS) and were first used in applications such as antifouling and anticoagulation.[19−22] Despite the success of LIS surfaces in providing slippery contacts with viscous fluids like crude oil, such surfaces are not likely to show a measurable drag reduction when the working fluid is a low-viscosity fluid like water.[18] LIS may also suffer from additional problems such as lubricant drainage due to shear or gravitational forces as examined in the recent LIS literature.[23−26] In the current paper, we present a new design for LIS in which an air layer is placed underneath the infused lubricant to improve the drag-reduction benefits of the surface when used with low-viscosity fluids like water. The air layer is expected to reduce the frictional forces acting against the formation of a vortical flow in the lubricant layer, and therefore allow the surface to provide a slip velocity at the lubricant–water (working fluid) interface (LWI). Inspired by a recent study reported in ref 27, a double-reentry geometry is considered in our design to enhance the mechanical stability of the lubricant layer (Figure 1) (see also ref 28). For the sake of brevity, a lubricant-infused surface with trapped air is referred

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