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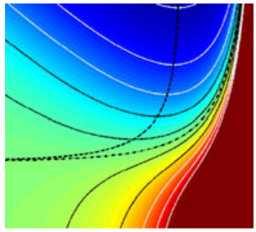
Slippery interfaces for drag reduction



Peichun Amy Tsai†

Soft Matter, Fluidics, and Interfaces Group, University of Twente, 7500 AE Enschede, The Netherlands

Inspired by natural interfaces with surprising transport properties, innovative modifications of surfaces have been engineered to reduce drag. The common theme across these new developments is the presence of lubricant patches or layers that decrease the direct contact of viscous liquid with non-slippery solid walls. For laminar flow, the traditional assumption regarding the lubricant layer is a constant shear rate or a steady pressure gradient, implying a net flow rate of the lubricant film. By challenging this assumption, Busse *et al.* (*J. Fluid Mech.*, vol. 727, 2013, pp. 488–508) rigorously found that the hydrodynamic slip is reduced by the presence of a reversal of lubricant flow close to the wall. The analytical results for velocity field and change in drag provide insight into the optimal design of slippery surfaces with lubricant layers for drag reduction.

Key words: drag reduction, microfluidics, multiphase flow

1. Introduction

In nature, a variety of creatures ingeniously modify surfaces for their own benefit in order to eat, clean, climb, swim or leap. In the fluid mechanical world, a significant advantage of surface modification is drag reduction. Hydrodynamic drag reduction has been an essential aspect of energy saving since the 1910s, remaining extremely challenging in practice. In turbulent flows, external substances such as surfactants, polymers and bubbles are often added to decrease hydrodynamic friction. On the other hand, laminar flows pose a significant challenge for drag reduction, particularly in micrometre-sized pipes constrained by non-slip solid walls. Thus, the laminar flow regime can present a bottleneck for reducing drag. Over the past decade, surface modifications using hydrophobic micro- (and nano-) textures have been successfully employed for reducing hydrodynamic friction in both laminar and turbulent regimes (Rothstein 2010).

Such interfacial modifications are inspired by the naturally self-cleaning ability of lotus leaves. This new type of engineering surface possesses hydrophobic and rough micro-cavities whereby lubricant air pockets are trapped. These so-called

† Email address for correspondence: p.a.tsai@utwente.nl

superhydrophobic surfaces are beaded with small and static water droplets with a large contact angle (≈150°). In a dynamical situation, water droplets easily roll off and clean the surfaces, with a small contact angle hysteresis (Quéré 2008). In a flowing condition, viscous liquid adjacent to the partially slippery surfaces, due to the entrapped air of a low liquid viscosity, lessens the hydrodynamic dissipation.

The paper by Busse *et al.* (2013) provides rigorous analytical solutions of flow velocity, drag reduction, and apparent slip length for laminar flow over idealized superhydrophobic surfaces. The authors systematically consider several realistic flow configurations of the entrapped air layer. Remarkably, the detailed assumptions about the mass flow of the lubricant layer, previously overlooked by most studies, significantly change the drag. Their analytical solutions provide insight into optimal design of the lubricant layer forming slippery surfaces for practical applications of drag reduction, such as underwater vehicles, co-flow pipes, and microfluidic channels.

2. Overview

With the advent of microfluidics, the study of laminar flows with heterogeneous boundary conditions has recently attracted great attention (Lauga & Stone 2003), particularly on applications of superhydrophobicity (Bocquet & Lauga 2011).

The ultra-hydrophobic surfaces energetically promote trapping of air or vapour on their rough features, thereby locally providing shear-free (gas–liquid) boundary conditions under flows. Consequently, the overall boundary condition is heterogeneous, composed of no-slip and shear-free interfaces due to the liquid–solid and gas–liquid contacts, respectively. The general theoretical approach consists of a steady laminar flow, either under a constant Couette shear or pressure gradient, with alternating no-slip and shear-free boundary conditions. At the liquid–gas interfaces the velocities and shear stresses of these two contacting liquids are continuous. In general, additional assumptions regarding the lubricant (air) layer should be specified. As shown by Busse *et al.* (2013), these assumptions turn out to be crucial. As considered in the paper, we will generalize the discussion below using a lubricant fluid layer, which can be liquid or gas.

The conventional theoretical view is that the basic flow of the lubricant layer (G) behaves the same as the main flow (L), either under a constant shear rate or a steady average streamwise pressure gradient (Vinogradova 1999). This assumption implies a constant mass flow rate of the lubricant layer ($\dot{m}_G > 0$), which requires a constant supply of lubricant in practice. The slip length is a key measurement, based on the local shear stress at the interface or global drag reduction, quantifying the slippage. The effects of shear-free fraction, flow rate, and the flow direction with respect to the orientation of the shear-free segments have been investigated theoretically, numerically and experimentally (see the references in Busse *et al.* 2013). The slip length was found to increase with the shear-free fraction for longitudinally and transversely oriented liquid–air segments. However, very recently, the profound influence of the (liquid–gas) interface geometry on slippage has been discovered (Sbragaglia & Prosperetti 2007; Davis & Lauga 2009; Hyväluoma, Kunert & Harting 2011; Karatay *et al.* 2013). Despite the shear-free conditions, which locally reduce hydrodynamic dissipation, the liquid–gas interfaces can act as obstacles for the main streamwise flow when they largely protrude towards the main flow (Steinberger *et al.* 2007; Davis & Lauga 2009). Consequently, a critical protrusion angle exists, marking the transition from a slippery to a frictional surface.

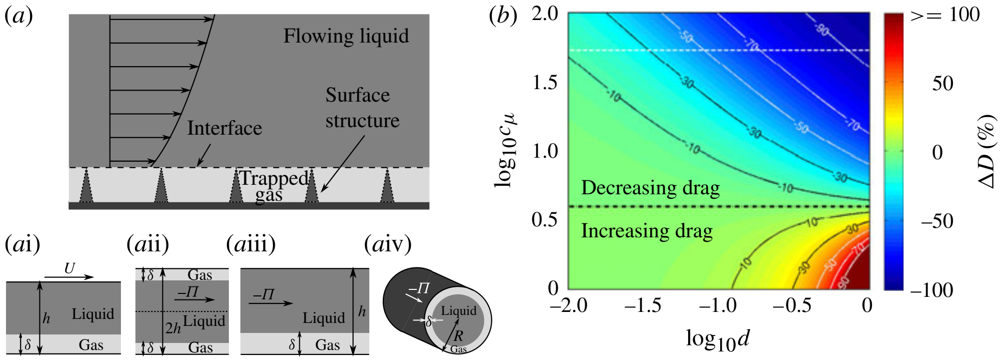


FIGURE 1. (a) Schematics of laminar flow over an idealized superhydrophobic surface, with four flow configurations considered: (ai) Couette flow; ($a$ii) symmetric pressure-driven channel flow; ($a$iii) one-sided pressure-driven channel flow; and ($a$iv) pipe flow. (b) Change in drag, ΔD, as a function of viscosity ratio (c_μ) and lubricant thickness (d), for a laminar Couette flow configuration (ai) with no net mass flow in the lubricant layer (from Busse *et al.* 2013).

Beyond the conventional view, the highlighted paper addresses the influence of a lubricating layer (G) on slippage in a steady laminar flow (L), applicable to a more general class of problems (see figure 1a). The alternative assumption is a zero mass flow rate ($\dot{m}_G = 0$) of the lubricant layer, of thickness of d. This assumption is more appropriate for superhydrophobic surfaces, where in general no external gas is injected into the main stream in experiments. The condition of $\dot{m}_G = 0$ will introduce a reverse flow within the lubricant layer, in the vicinity of the wall.

By comparison, if a constant shear rate is assumed in steady Couette flows with $\dot{m}_G > 0$, a viscosity contrast $c_\mu = \mu_L/\mu_G > 1$ is sufficient to decrease the shear rate in the main flow for drag reduction. Whereas for $\dot{m}_G = 0$, due to the counter-current in G, the shear rate of the main liquid is reduced only when $c_\mu > 4$. The reverse flow in G was found to span $2/3$ of the area of the lubricant layer. This change in flow velocity for $\dot{m}_G = 0$ contributes to the change in drag ΔD, based on the comparison between the shear rate at the upper wall (with vanishing G) with a lubricant layer and that without it. Remarkably, the $\dot{m}_G = 0$ case gives rise to smaller drag reduction compared to the assumption of a net mass flow of G. In other words, the conventional assumption ($\dot{m}_G > 0$) used in previous theoretical studies would over-predict the drag reduction for realistic superhydrophobic surfaces without air injection. Quantitatively, in the limit of thin lubricant layers and high viscosity contrasts, the drag reduction for $\dot{m}_G = 0$ was found to be $1/4$ of that under the conventional (net-flow) assumption $\dot{m}_G > 0$. Shown in figure 1(b) are the analytical solutions of drag reduction with varying viscosity contrast c_μ and lubricant thickness, d, assuming $\dot{m}_G = 0$.

In steady laminar pressure-driven flows, qualitatively similar results are obtained: under the assumption of $\dot{m}_G = 0$, a reverse lubricant flow is also present. In the pressure-driven channel and pipe flows, the lubricant layer G has two counteracting effects on drag reduction. One beneficial effect is to provide a slippery boundary condition with its low dynamic viscosity μ_G, whereas the counter influence is the blockage effect by reducing the cross-section of the main channel. Consequently, an optimal thickness of the lubricant layer depending on the viscous contrast can be anticipated. Promisingly, for the common choice of the lubricant layer of air, i.e. $c_\mu = 50$, relatively thin gas layers with a thickness of about a few per cent of the total channel height would be needed for achieving a drag reduction of ≈50–80 %.

3. Future

A variety of applications of tailoring slippery surfaces for drag reduction can benefit considerably from the rigorous results by Busse *et al.* (2013). In addition to the superhydrophobic substrates discussed, superoelophobic, ominiphobic, heated Leidenfrost and slippery-liquid-infused surfaces will be amenable to the analytical calculations.

Using the realistic assumption of the trapped lubricant layer having zero net mass flow, the highlighted paper presents the upper limits of apparent slip length and drag reduction for idealized superhydrophobic surfaces. At present, the superhydrophobic surfaces considered in the paper have no effects of roughness but merely provide a lubricant gas layer. Beyond rigid and regular hydrophobic microstructures, the theoretical framework may be extended for more complex substrates, for example, of roughness of multi-length scales or fractal topography. In addition, the current work can be extended to estimate the slip lengths produced by bubble-covered surfaces. Some hydrophobic surfaces are spontaneously covered with nano-bubbles, which might result in slip with widespread gas pancakes (Seddon & Lohse 2011).

Slippery surfaces are of great interest, not only for enhancing hydrodynamic transport but for other types of amplification, such as transport of heat and ions. However, at present only hydrodynamic aspects have been explored considerably. In the near future, optimizing the surface designs and modifications for realistic slippery surfaces using theories, simulations and experiments will continue to have an important impact on drag reduction and processes for amplifying transport.

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