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Interfacial slip on rough, patterned and soft surfaces: A review of experiments and simulations

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ABSTRACT

Advancements in the fabrication of microfluidic and nanofluidic devices and the study of liquids in confined geometries rely on understanding the boundary conditions for the flow of liquids at solid surfaces. Over the past ten years, a large number of research groups have turned to investigating flow boundary conditions, and the occurrence of interfacial slip has become increasingly well-accepted and understood. While the dependence of slip on surface wettability is fairly well understood, the effect of other surface modifications that affect surface roughness, structure and compliance, on interfacial slip is still under intense investigation. In this paper we review investigations published in the past ten years on boundary conditions for flow on complex surfaces, by which we mean rough and structured surfaces, surfaces decorated with chemical patterns, grafted with polymer layers, with adsorbed nanobubbles, and superhydrophobic surfaces. The review is divided in two interconnected parts, the first dedicated to physical experiments and the second to computational experiments on interfacial slip of simple (Newtonian) liquids on these complex surfaces. Our work is intended as an entry-level review for researchers moving into the field of interfacial slip, and as an indication of outstanding problems that need to be addressed for the field to reach full maturity.

Contents

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1. Introduction

Reducing energy dissipation and loss, and fabricating devices that are more efficient at no added cost are challenges that arise in every aspect of technology. These requirements are even more crucial in confined systems, [1] such as micro- and nano-fluidic devices, confined biological systems, porous materials, and thin lubricating films, where the hydrodynamic drag is very high and risks reducing the flow of liquids to zero. In these systems, being able to control the boundary conditions has a major role in driving and controlling the liquid. Understanding the boundary conditions for flow of liquids at solid substrates is also of great importance in fluid dynamics, as it underpins the fundamental understanding of flow of liquids at interfaces [2].

For the past two centuries one of the key concepts in fluid dynamics has been the no-slip boundary condition, i.e. the assumption that the liquid adjacent to a solid surface moves with the same velocity as the surface (Fig. 1(a)). The no-slip boundary condition was believed to be universal for simple Newtonian liquids because it was supported by macroscopic experiments over two centuries [2–4]. Up until fifteen years ago, there were only a few situations where interfacial slip was widely accepted, such as the flow of non-Newtonian complex fluids (e.g. polymer melts, polymer dispersions, micellar solutions), in liquid spreading and corner flows, and flow at gas/solid interfaces [3].

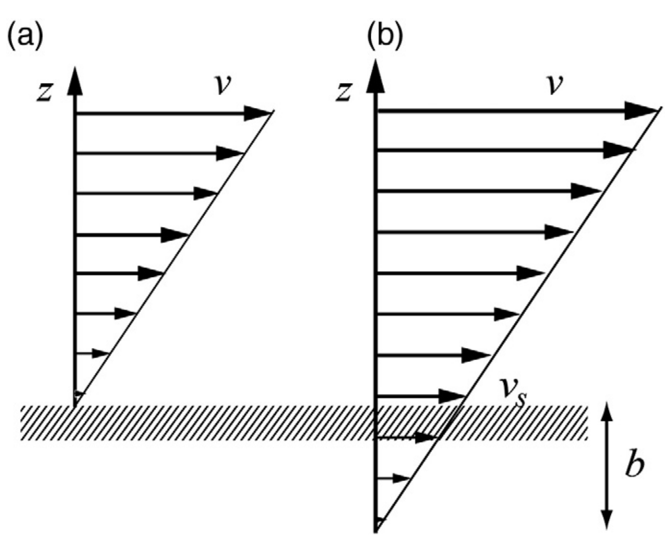

Fig. 1. Schematic illustration of (a) the no-slip boundary condition, and (b) the partial slip boundary condition and the slip length *b*. (a) The velocity of the liquid *v* far from the solid surface decreases along the direction perpendicular to the wall *z* until it reaches zero at the stationary surface itself. (b) The velocity of the liquid decreases gradually towards the solid surface, but it is still finite v_s at the surface.

Around the year 2000, a few experimental papers received great attention for using high-resolution techniques to prove anew the occurrence of interfacial slip in simple (Newtonian) liquids [5–7]. Thirteen years later, these observations are still controversial, but much more widely accepted. The occurrence of interfacial slip leads to a decrease in the hydrodynamic drag force acting to reduce the relative motion of a solid in a liquid, and has therefore potential implications in all systems with high surface area/volume ratio, where the relative proportion of liquid molecules that are in proximity with the solid is large. Determining the boundary condition for liquid flow over a surface requires very sensitive and accurate techniques, which have been available only in recent times, as the magnitude of any existing slip is generally expected to be small. Most measurements of slip on smooth surface have reported values of slip length in the range of a few tens of nm (see Section 2.1 for a definition of slip length).

There are however important scenarios where the slip of liquids may become evident also on a larger, macroscopic scale. Experiments on liquid flow over highly solvophobic surfaces with complex surface structure, such as superhydrophobic coatings, have found significant drag reduction on a macroscopic scale, which can be explained in terms of slip of liquids on air pockets or gas layers trapped on features of the surface [8,9]. These experiments establish the importance of understanding boundary conditions for flow over real-world rough surfaces.

Theoretical and experimental studies on interfacial slip over the past decade have mainly focused on smooth surfaces, and aimed to establish the relationship between the surface wetting properties and the occurrence of slip. It is now commonly accepted that, on smooth surfaces, a higher magnitude of slip is obtained on non-wetting systems, [1,3] and that slip is low or negligible on highly wettable surfaces.

Smooth surfaces (atomically smooth) are very rare in the physical world, with mica being a notable exception. Most real surfaces employed in experiments (such as solid substrates, colloid probes, channel walls and rotating disks) have a finite roughness, and surface roughness on either the micro- or nano-scale is likely to affect the interfacial flow of a liquid over a surface. Several studies have focused on the combined effect of surface wettability and surface roughness on interfacial slip. The published findings are not completely in agreement with each other, as there are many parameters that can contribute to making surface roughness act as a slip enhancer or inhibitor. Therefore at this stage no single and all-inclusive conclusion has been drawn regarding the boundary condition on rough or structured surfaces, despite numerous valid investigations.

Our aim here is to review experimental and computational studies published since the year 2000, investigating interfacial slip on *complex surfaces*, including rough and structured surfaces, surfaces decorated with chemical patterns, superhydrophobic surfaces, and soft surfaces, i.e. grafted with polymer layers and with adsorbed nanobubbles. The need for a review on interfacial slip is strongly felt, especially in the

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