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DYNAMIC RESPONSE OF GAS-LIQUID INTERFACES IN SUPERHYDROPHOBIC SURFACES

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INTRODUCTION

Superhydrophobic surfaces have received a great deal of attention recently as a means for turbulent drag reduction for naval applications. Superhydrophobicity enables textured surfaces immersed in water to entrap pockets (or bubbles) of air. When the groove size is small enough, the bubbles can lodge within the texture grooves, and the overlying water flow is mostly in contact with the entrapped air, instead of with the solid surface. This air layer can act as a lubricant for the outer flow, which can then effectively slip over the wall, experiencing reduced friction compared to conventional, smooth surfaces [7].

In spite of all the recent research, the interaction of these surfaces with the flow is not yet fully understood. Most experimental measurements reported have been conducted at texture sizes of order $L^+ \approx 0.5$–5, where the + superscript denotes scaling with the kinematic viscosity ν and the friction velocity u_τ. Although no clear reason is given, it is likely that for larger textures the stability of the bubbles is lost, and with it the drag-reducing effect. In contrast, numerical simulations have often been conducted at $L^+ \approx 100$–200, in a compromise between computational cost and physical fidelity, but it is not clear if some of the dynamics that are dominant in this range of L^+ are also important at the smaller sizes of real applications. Even more, it is questionable whether the air bubbles would even remain attached to the surface at such large L^+, were their stability not forcefully imposed by assuming that the gas-liquid interfaces maintain a perfectly flat, rigid shape, as is often done. The reduction predicted in numerical studies always increases with L^+, in agreement with theoretical predictions [6, 3, 12], even if the behaviour deviates from theory for large textures. In real flows, however, the superhydrophobic effect would be completely lost for sufficiently large grooves, once the bubbles become unstable and the surface is fully wetted [1]. Some work has begun to appear on possible degrading effects, which would eventually lead to the depletion of the gas pockets, but the mechanisms that cause the degradation remain largely unknown. [5] and [11] study the effect of bubble shape when the interface is not perfectly flat, while [2] analyses how the performance degrades as the texture crests begin to protrude out of the air layer. [1] considers in turn the effect of shear on bubble depletion. Our group has previously studied the effect of fluctuating pressure on the gas-liquid interfaces as L^+ increases [8].

Here we present the work conducted during the past Summer Program at the Center for Turbulence Research in Stanford, where we have studied the effect of gas-liquid interfacial deformation in fully turbulent simulations [4]. Once the interfaces are allowed to deform through a finite surface tension, spanwise-coherent, upstream-travelling waves can develop, increasing the pressure fluctuations that the interfaces experience. The results suggest that the waves are not directly connected to the overlying turbulence or the lengthscale of the roughness protrusions, but to the capillary waves that develop from the normal modes of oscillation of the interface as a membrane.

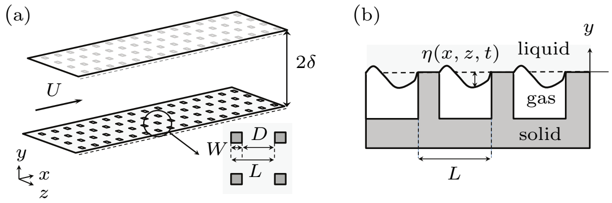

Figure 1: (a) Schematic representation of a channel with superhydrophobic-surface boundary conditions on both walls, formed by an array of squared-section solid posts, and the free-slip gas interfaces interspersed between them. W is the post width, D the distance between posts, and $L = W + D$ the total size of the pattern. (b) Sketch illustrating the deformation of the gas-liquid interface, η.

DIRECT SIMULATIONS WITH NON-RIGID INTERFACES

We conduct direct simulations of the turbulent, liquid flow, imposing modelled boundary conditions to represent the presence of the protruding roughness elements and of the gas pockets interspersed between them. No-slip is imposed at the solid-liquid interfaces, and free shear at the gas-liquid ones. All the boundaries are impermeable, but, while the solid-liquid ones are considered to be rigid, the gas-liquid ones deform in response to the local instantaneous pressure jump across, $p_{gas} - p_{liquid}$, following a Young-Laplace equation,

$$\nabla^2 \eta = \frac{p_{liquid} - p_{gas}}{\sigma}, \tag{1}$$

where σ is the surface tension and η the interface height measured from the plane that contains the no-slip, flat top of the posts, as sketched in Figure 1. We neglect the dynamics of the gas within the pockets, and therefore assume that p_{gas} is uniform and that the mass of gas is globally preserved.

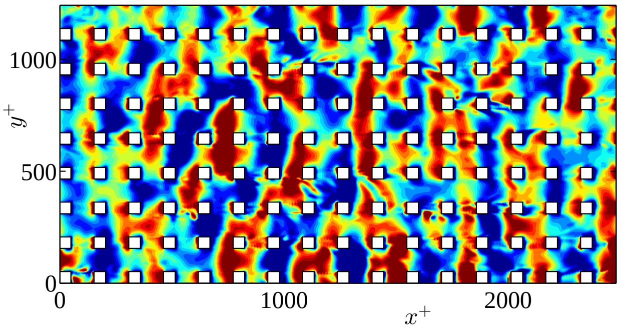

Figure 2: Instantaneous pressure fluctuations p^+ at $y^+ = 0$, for case L155.

The problem is then governed by a series of dimensionless parameters. Beyond the standard friction Reynolds number $\mathrm{Re}_\tau = u_\tau \delta/\nu$, another important Reynolds number is the size of the texture in viscous units $L^+ = u_\tau L/\nu$, which measures how much the flow deviates from a canonical, smooth-wall flow. Typical experimental values are $L^+ \approx$2–4, but, because of computational realizability, we have run our simulations at $L^+ \approx$ 75–150. These values produce unrealistically large slip velocities and drag reductions, but they are comparable to the state-of-the-art simulations with patterned textured surfaces. The last key dimensionless number is a Weber number, which measures the relative importance of the surface tension, $\mathrm{We}_L = \rho u_\tau^2 L/\sigma$. Another option would be to define $\mathrm{We}^+ = \rho u_\tau \nu/\sigma$, but this would be less relevant for realistic-size textures, as it is adequate to measure the effect on η of the turbulent pressure fluctuations, of size $\sim 100\nu/u_\tau$. Since we are interested in reproducing the deformability of the interfaces for empirically realizable values L^+, we select the value of σ so that We_L matches that of smaller textures, typically $\mathrm{We}_L \sim 10^{-3}$. The motion of the interface is introduced in the simulations through a linearised model, which assumes that η is small. Eq. (1) connects the overlying pressure with η, which is in turn connected to the wall-normal velocity through its material derivative, $v_{y=0} = \partial_t \eta + u\partial_x \eta + w\partial_z \eta$. The coupling between pressure, interface location, and velocity is resolved explicitly.

RESULTS

We have conducted a set of simulations systematically varying Re_τ, L^+ and We_L. The results show little dependence with Re_τ, as expected, since the superhydrophobic surfaces perturb only the near-wall region of the flow. The appearance of upstream-travelling, spanwise-coherent structures is clear only for large texture spacings, $L^+ \approx 155$, as shown in Figure 2. For $L^+ \approx 78$, their coherence is apparently lost. Even if there are still structures travelling in the upstream direction, their presence is obscured by the superimposed turbulent fluctuations. A more quantitative representation of these waves can be obtained through the space-time correlation of the pressure signal. In these correlations, not shown, the coherence of the waves is clear both in space and time. Two distinct motions appear at the interface, the conventional advection of near-wall turbulence and the coherent upstream-traveling waves. For simulations at $L^+ \approx 155$, the streamwise wavelength is $\lambda_x^+ \approx 320$, and the phase velocity is $U_c^+ \approx -35$. The wavelength and velocity of the waves change for the two cases at smaller L^+. A first rough analysis suggests that U_c^+ is essentially inversely proportional to We_L. The scaling of the streamwise wavelength λ_x^+ is somewhat less clear, but the results suggest that λ_x^+ depends only weakly on L^+, and that instead $\mathrm{We}_\lambda = \rho u_\tau^2 \lambda_x/\sigma$ remains essentially constant across different simulations. Defining $\sigma^+ = \sigma/\rho\nu u_\tau$, the wavelength for all simulations roughly follows $\lambda_x^+ \approx 5 \times 10^{-3}\,\sigma^+$.

The above results suggests that, even if the upstream-travelling waves are triggered and modulated by the presence of the posts, their scaling is essentially independent of the lengthscale of the post layout. This would be consistent with the characterization of the waves as essentially capillary, similar to conventional capillary waves over smooth, unobstructed gas-liquid interfaces [9, 10]. To corroborate this hypothesis, we have developed a quasi-analytical model based on a linearised potential flow over the deformable interfaces. The model, which will be presented at the meeting, reproduces the spanwise-coherent, upstream-travelling waves observed in the simulations.

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