DRAG OF LAMINAR FLOW OVER TRAPPED BUBBLES

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Summary A superhydrophobic surface is modelled by bubbles trapped on a wall. Direct numerical simulations using a two-phase level-set code are performed for laminar Couette flow over the bubbles. The investigation considers both the influence of the bubble geometry, as well as the influence of physical parameters such as the contrast in dynamic viscosity of the two fluids and the Reynolds number, and focuses on the resulting change in drag. The Reynolds number dependence of the change in drag reveals that the change in drag increases with increasing Reynolds number, i.e. drag increasing bubble configurations show a further drag increase with increasing Reynolds number whereas drag reducing configurations show a lower drag reduction with increasing Reynolds number. Therefore models based on the Stokes flow assumptions are likely to overpredict a possible drag reduction by superhydrophobic surfaces for macroscopic applications, even if the deformability of the air-water interface is taken into account.

INTRODUCTION

Superhydrophobic surfaces combine a structuring on microscopic scales with a hydrophobic surface chemistry. They are valued for their self-cleaning properties and their potential to reduce friction drag. Although the self-cleaning properties of superhydrophobic surfaces have successfully been extended to macroscopic scales e.g. in the form of self-cleaning paints and surface coatings, the drag reducing properties of superhydrophobic surfaces observed in micro-channels are difficult to reproduce for macroscopic devices. This is partly caused by manufacturing constraints and the expense of creating a microstructured surface over a large area, but may also be influenced by the considerably higher Reynolds numbers typically encountered in macroscopic flows compared to microfluidic applications.

When a superhydrophobic surface is immersed in water an air-layer or air bubbles can be maintained on the surface[3]. Due to a lower shear stress at an air-water interface compared to a solid-water interface superhydrophobic surfaces can influence the friction drag on a wall. Most mathematical models for the effective slip length of a superhydrophobic surface, as well as numerical simulations resolving the air-water interface, operate under the Stokes flow assumption, i.e. in the highly viscous regime. This is suitable for typical microfluidics applications. However, for macroscopic flows over a superhydrophobic surfaces significant Reynolds numbers are attained, and non-linear effects need to be taken into account. Furthermore the influence of other physical parameters such as the contrast in viscosity and density between the two fluids, which are of importance for a fundamental physical understanding of the problem, has received little attention. These questions are investigated in this paper.

FLOW CONFIGURATION AND NUMERICAL METHOD

A superhydrophobic surface is modelled by gas bubbles trapped on a wall (see figure 1). The gas and the surrounding fluid are immiscible, with a finite surface tension force at the interface between the two fluids. The test configuration is a laminar Couette flow where the upper (bubble free) wall moves at a constant speed U_0. The initial geometric shape of the bubble is varied by changing the initial contact angle α and the extension of the bubble into the flow h. A further geometric parameter is the percentage of the lower wall covered by bubbles. Similar configurations have previously been studied for flow over droplets (see e.g. [6] and references therein). There the focus was on the stability of the droplet rather than the change in drag, and density and viscosity contrasts close to unity were employed.

For the direct numerical simulations presented in this paper a two-phase level-set code is employed. The sub-cell fix of *Russo & Smereka* [4] combined with an explicit mass fix is used to prevent long-term mass losses. The contact line of the bubble is kept fixed (i.e. pinned to a non-resolved local singularity of the underlying solid boundary) using a contact line treatment combining the approaches of *Sussman & Uto* [7] and *Spelt* [5]. All simulations presented in this paper are for the two-dimensional case.

RESULTS

Simulations have been performed investigating the geometric parameters introduced above; all parameters stated refer to the initial bubble shape which is of a circular cap form. In addition, the viscosity and density contrasts between the two fluids and the Reynolds and Capillary numbers have been varied. The change in drag compared to the one-fluid reference case is computed from the mean shear rate on the upper wall.

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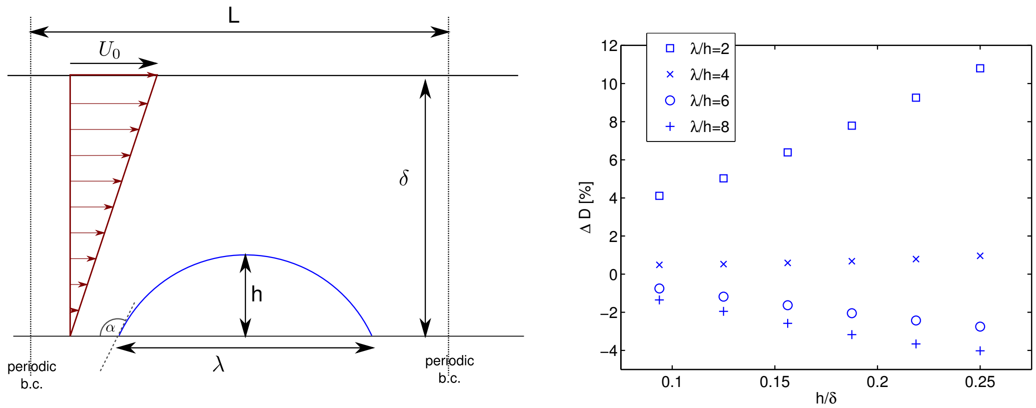

Figure 1. Left: Illustration of the flow configuration. The bubble has initially a circular cap shape and is deformed as the flow develops. Right: Influence of initial contact angle and extension of bubble into the flow onto change in drag.

Geometric parameters

With increasing protrusion angle $\beta = 180° - \alpha$ the change in drag increases. As expected [1], low protrusion angles give a drag reduction, whereas high protrusion angles lead to a drag increase. A denser bubble spacing, i.e. increasing λ/L, leads to an intensification of these trends, as does an increasing extension of the bubble into the flow h/δ. Note that for a simple Couette flow blockage effects are of little importance, unlike for pressure-driven channel flow.

Viscosity and density contrasts

The contrast of the dynamic viscosity between the two fluids is found to have the strongest effect on the change in drag. For contrast in dynamic viscosity close to unity the drag is increased for all initial bubble shapes studied here. When the dynamic viscosity is lowered inside the bubble, the drag decreases, and bubbles with low protrusion angles become drag-reducing. The density contrast shows no influence on the change in drag within the numerical accuracy, as the effects of gravity are neglected.

Reynolds number dependence

With increasing Reynolds number the change in drag increases. Bubble configurations which show a drag reduction become less drag-reducing, whereas the drag increase rises for drag-increasing bubbles. This can mainly be attributed to a higher deformation of the bubbles with increasing Reynolds numbers. The effect is stronger for bubbles with a lower initial curvature, as the stabilising effects of the surface tension force are weaker. A similar observation was made in molecular dynamics simulations by *Hyväluoma et al.* [2] who observed a decreasing drag reduction with increasing shear rate.

CONCLUSIONS AND OUTLOOK

Laminar Couette flow over a trapped gas bubble has been used as a model to study the flow over a superhydrophobic surface. The influence of both the geometric shape of the bubble as well as the viscosity and density contrasts on the drag has been investigated. The observed increase of the drag with increasing Reynolds number shows that the Stokes flow solution overpredicts a possible drag reduction. This effect is measurable even for moderate Reynolds numbers. The study is currently being extended to Poiseuille flow and to three-dimensional cases. In the future it is planned to resolve the underlying structuring of the superhydrophobic surface.

References

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