TURBULENT FLOW OVER SUPERHYDROPHOBIC SURFACES - ROUGHNESS VERSUS SLIP

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Abstract Superhydrophobic surfaces have the potential to reduce drag both in the laminar and turbulent regimes. However, the slip at the air-water interface can be adversely affected by the roughness of the structure of the surface which is needed to support the air layer. The conflicting effects of roughness and slip are investigated by direct numerical simulations of turbulent channel flow over patterned slip - no-slip surfaces. It is found that even a relatively small exposed roughness height can counteract the drag reducing effects of the slip at an air-water interface.

INTRODUCTION

Superhydrophobic surfaces combine a structuring on micro- or nano-scales with a hydrophobic surface chemistry. When submerged in water, an air layer or pockets of air can be trapped on the surface. Due to reduced shear at a water-air interface compared to a water-solid interface superhydrophobic surfaces can in principle be employed for drag reduction. The drag reducing properties of superhydrophobic surfaces have been demonstrated in small scale experiments both in laminar and turbulent cases[4]. In large scale experiments it is difficult to reproduce the drag reducing effects of superhydrophobic surfaces. Towing tank experiments at the University of Southampton have shown that a superhydrophobic surface stripped of its air layer has a higher drag than the same surface with an intact air layer. However, compared to a smooth surface a superhydrophobic surface with an intact air layer has in many cases still a higher drag [2]. A possible explanation for this behaviour is that the superhydrophobic surface is not fully covered by an air layer. Part of the structure of the surface, which is necessary for supporting the air layer, is exposed to the flow and can act as a roughness. Therefore, the drag reducing effects of the air layer are adversely affected by the roughness effects of the supporting structure. Since it is difficult to perform detailed measurements of the turbulent flow near superhydrophobic surfaces direct numerical simulations are used in this study to investigate the opposing effects of roughness and slip.

SETUP OF THE STUDY

In direct numerical simulations of turbulent flow over superhydrophobic surfaces the air-water interface is usually modelled by a slip boundary condition since the full resolution of the two-phase flow problem would be punitively expensive. *Martell et al.*[3] modelled a superhydrophobic surface by a flat surface on which a pattern of no-slip (corresponding to the top of the surface structure) and full-slip (the air-water interface) boundary conditions is applied. In this study a similar approach is taken. The main difference is that part of the surface structure can be above the level of the air-water interface giving an exposed structure height k. An example is shown in figure 1. The basic surface structure consists of uniformly spaced square posts covering $1/9$ of the surface. In between the posts a slip boundary condition is applied to simulate the effect of the air-water interface. Several degrees of slip are studied ranging from full slip over partial (Navier-) slip to no slip. In the partial slip case the slip length is set to $L^{+_0} = 10$, which is known to give a significant drag reduction for a smooth, unstructured surface[1]. A no-slip boundary condition is used on the surface of the posts in all cases. Several heights of the exposed posts are studied $k^{+_0} = 0,\ 5,\ 10,\ 15$. This type of surface can be seen as a simplified model for

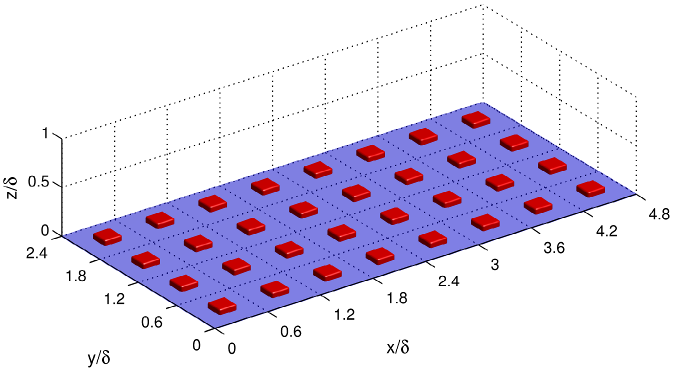

Figure 1. Example for surface structure of channel walls for posts with an exposed height of $k^{+_0} = 10$. In the blue region of the surface a slip-boundary condition is applied whereas a no-slip boundary conditions is used on the post surfaces shown in red. Only the lower half of the channel is shown.

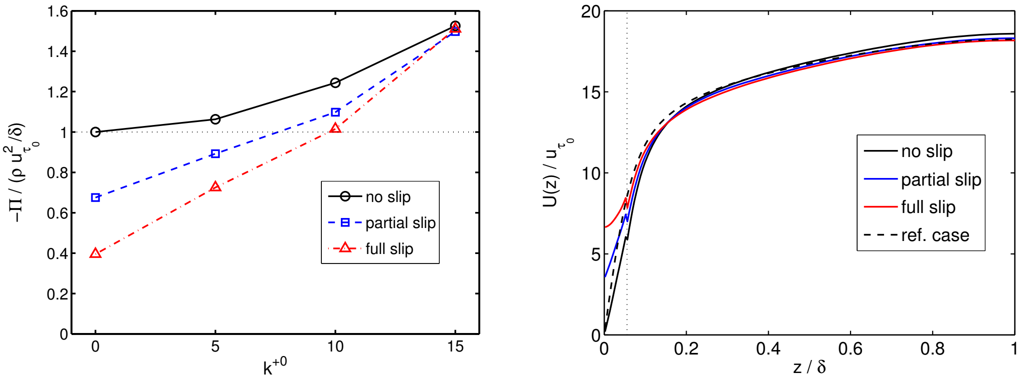

Figure 2. (a) Mean streamwise pressure gradient versus exposed roughness height for three different boundary conditions at the surface, i.e. the interface, in between the posts. (b) Mean streamwise velocity profile in the case $k^{+0} = 10$; the vertical black dotted line indicates the exposed post height.

either a superhydrophobic surface where the meniscus of the air water interface is depressed between the surface structure or as a model of an imperfect superhydrophobic surface, where part of the surface structure is exposed.

Direct numerical simulations of turbulent channel flow are performed using a standard staggered-grid second order finite difference scheme with second order Adams-Bashforth time integration. Periodic boundary conditions are used in the streamwise and spanwise directions. The patterned surface is applied to both the upper and the lower wall of the channel. The square posts are resolved using an immersed boundary method. In all cases a constant mass flow rate is maintained by varying the mean streamwise pressure gradient in time. All simulations have been run at a Reynolds number of $Re = U\delta/\nu = 2800$, where U is the mean streamwise velocity, δ the channel half height and ν the kinematic viscosity, corresponding to a Reynolds number of $Re_{\tau_0} = \delta u_{\tau_0}/\nu = 180$ in the reference case, a smooth channel with standard no-slip conditions on both walls.

RESULTS

The drag of the different surfaces can be measured by the average mean streamwise pressure gradient Π, shown in figure 2, required to maintain a constant mass flow rate. In the case of a vanishing exposed post height $-\Pi$ decreases as expected with increasing slip between the posts. If a no-slip boundary condition is imposed the surface is a regular rough surface and $-\Pi$ increases with increasing exposed post height. In the cases where a partial or full-slip boundary condition is applied at the interface a similar increase in $-\Pi$ can be observed. The increase of $-\Pi$ with k^{+0} is significantly stronger in the full-slip case compared to the partial and no-slip cases. In the full-slip case a stronger increase of the form drag of the roughness elements with increasing roughness height can be observed (not shown) which can be connected to a higher near-wall velocity of the flow (see figure 2 (b)). As can be inferred from figure 2 (a) even for a comparatively small exposed post height of $k^{+0} = 10$ the drag reducing effects of the slip surface between the posts can be cancelled by an increased drag component due to roughness effects.

OUTLOOK

An extension of this study to higher Reynolds numbers and to different surface patterns, e.g. a sparser spacing of the posts, is planned. Furthermore, standard turbulence statistics, such as the Reynolds stresses, vorticity and correlation of the velocity, will be used to assess the change of the turbulent flow in the vicinity of the surface.

References

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