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Maintenance of air layer and drag reduction on superhydrophobic surface

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ABSTRACT

Hydrophobic surface for drag reduction on marine vehicles and structures has been proposed for many years. However, the drag reduction effect has been found to be unstable under high flow speed/pressure conditions because of the destruction of air-water interface. In this paper, an air layer was maintained experimentally by continuous air injection on hydrophobic surfaces. Good hydrophobicity was found to benefit the spread of air bubbles and the formation of a wide and flat air layer on solid surfaces. Based on this recognition, a method combining air injection and surface hydrophobicity adjustment was proposed to maintain the air layer. Through flow field analyses, it has been found that the roughness of irregular micro-structures on superhydrophobic surfaces became dominant and the frictional drag was increased in the Wenzel state. However through air injection, the Cassie state was able to be recovered and the slip could also be re-formed at the solid surface. Because of the slip effect, vortices and shears in the turbulent boundary layer were restrained, and a drag reduction up to 20% was obtained in the study. This method was promising to maintain a robust air-water interface on superhydrophobic surfaces and sustain the drag reduction effect in engineering applications.

1. Introduction

Inspired by the hydrophobic phenomenon in nature, many researchers have concentrated on its utilization on the drag reduction of marine vehicles and structures (Bechert et al., 2000; Feng et al., 2002; Song et al., 2014). Hydrophobic materials can be sprayed on solid surfaces. Hydrophobicity can also be adjusted by controlling the microstructures and surface energy of the solid surface. These properties make hydrophobic surfaces applicable in real situations. By using this technique, the frictional drag on marine vehicles can be greatly reduced, thus increasing vehicles' speed and decreasing the energy consumption. The states of water on hydrophobic surfaces can always be classified into two categories: Wenzel state and Cassie state (Fig. 1) (Rothstein, 2010). In the Wenzel state, water enters into the spaces between micro-structures, while in the Cassie state, water is sustained over the space and air-water interfaces are formed. Many investigations have demonstrated the drag reduction effect of hydrophobic surfaces, both numerically (Martell et al., 2009; Min and Kim, 2004) and experimentally (Ou and Rothstein, 2005; Tretheway and Meinhart, 2002), due to the slippage at the air-water interface (Ou and Rothstein, 2005; Park et al., 2013; Samaha et al., 2011; Truesdell et al., 2006). Ou and Rothstein (2005) conducted direct velocity measurements using μ–PIV in a superhydrophobic microchannel and found there existed slippage at the air-water interface, which was considered as the primary mechanism for the drag reduction.

Regardless of the inspiring results, the drag reduction on hydrophobic surfaces was also found to be unstable in recent years. Using an annulus model, Song et al. (2013) found the drag on hydrophobic surfaces increased in high Reynolds number flows, which was unlike those under small Reynolds numbers. Aljallis et al. (2013) also found the drag was increased in fully developed turbulence because the air layer was depleted by highly shearing flows. The results showed that drag reduction did not solely depend on surface hydrophobicity, the morphology and stability of the air-water interface also played important roles. Samaha et al. (2012a), (2012b) investigated the time-dependent hydrophobicity of a submerged coating and found that the longevity of hydrophobicity deteriorated with increasing flow rate and pressure, which appeared to enhance the dissolution of the air into water and leaded to a loss of the drag reduction.

Some researchers have started investigating the behaviors of the air layer and their effects on the drag reduction. Kwon et al. (2014) examined flows in a microchannel with convex air bubble array sitting on the wall. Momentum flux was found to increase around bubbles. Jagdish et al. (2014) adopted the air lubrication technique on hydro-

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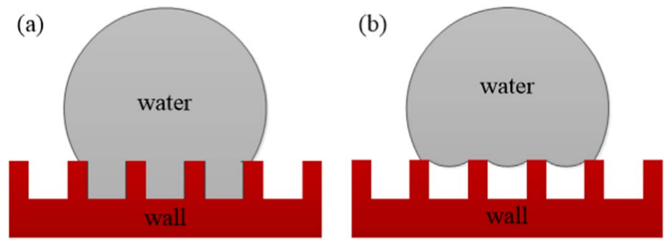

Fig. 1. Two wetting states of water on hydrophobic surfaces: (a) wenzel state; (b) cassie state. (Rothstein, 2010).

phobic surfaces and found an air layer can be entrained around the plate. Wang et al. (2014) designed transverse grates to sustain air pockets on hydrophobic surfaces, and a drag reduction of 13% lasting 1 h was achieved. However, characteristics of the air layer on hydrophobic surfaces are still not fully discovered, and exploring a method to maintain the air layer thus reduce the frictional drag is imperative.

In light of the importance of the air pocket entrapped in the hydrophobic surface, the longevity of hydrophobicity has become a hot spot recently. By fabricating microscale trenches in hydrophobic materials, Xu et al. (2014) realized infinite lifetime of superhydrophobic state (> 50 days). Environmental fluctuations, e.g. temperature, atmospheric pressure, flow conditions, water salinity, etc. were main factors influencing the hydrophobic state, and they cannot be completely eliminated, but can be minimized in reality. Some formulations have been proposed to predict the longevity of hydrophobic surfaces (Hemeda and Tafreshi, 2014; Xue et al., 2015). By designing the surface structures satisfying certain geometrical criterions or adopting gas-generation methods, the goal of sustaining long-term hydrophobicity has been achieved on a certain level (Hemeda et al., 2014; Lee and Kim, 2011; Lv et al., 2015). For practical application, the expenses on the surface fabrication should be considered and random structures are always preferred. Besides, real conditions are more complex than laboratories and active control methods to resist different disturbances can be a better choice if possible, such as mass injection techniques.

Drag reduction using the air injection and bubble mattress has been proposed for many years. Dershin et al. (1967) injected nitrogen on a porous flat plate. Skin friction was found to decrease with the improvement of the blowing ratio. Karatay et al. (2013) produced microbubbles at the boundary of the superhydrophobic microchannel using microfluidic devices. Slip length was found to decease with the increase of the bubble protrusion angles. Liu et al. (2004) investigated the skin friction reduction using micro-blowing method. The skin friction coefficient was found to decrease with the increase of the blowing ratio. When the blowing ratio was kept constant, the skin friction decreased more significantly at higher Reynolds numbers.

In this paper, a method combining the air injection and hydrophobicity adjustment was proposed to maintain the air layer on solid surfaces underwater. By testing the state of the air layer and instantaneous flow field on hydrophobic surfaces, the morphology of the air layer, flow field, slip effect and drag reduction were investigated. The prospect of this method was finally discussed for real applications.

2. Experimental details

2.1. Experimental setup

Our experiments in this study were carried out in a closed circuit water tunnel as schematically shown in Fig. 2. To maintain a uniform flow distribution, three honeycomb-like rectifiers were placed in the water tank and one in the stabilization section. Preliminary measurements showed that the flow velocity can be adjusted in the range of 0–1.21 m/s. Velocity deviation and turbulence intensity in the experimental section are lower than 2.5% and 2.0%, respectively.

The schematic diagram of experimental setups is depicted in Fig. 2(b). The internal size of the experimental section is $0.1m \times 0.1m \times 0.5m$. This section is made of polymethyl methacrylate (PMMA) to obtain good illuminations for PIV measurements. Test plates were fixed on the bottom of the experimental section. The head region of the plate was attached with a 100 grit sandpaper to induce the turbulent boundary layer. The head of test plates was sharpened to guarantee a well-developed boundary layer flow. The back region is the test plate, which is replaceable and coated with different hydrophobic materials.

Flow field was measured using a PIV system (see Fig. 2(b)). A continuous 532 nm laser generator was used to lighten the flow field. A high speed camera (MotionXtra NX-4) was used to capture the flow field with the frame rate 1000 fps. The air injection method is also shown in Fig. 2(b). A small hole with diameter D=0.6 mm was drilled at the front end of the target plate. The hole was connected to an injection pump (WZ-50C6, Smiths Medical Instrument Ltd, China), to supply air to hydrophobic surfaces. The volume rate of the injected air can be adjusted accurately using the injection pump.

2.2. Surface fabrication methods

Two kinds of hydrophobic surfaces were applied during the experiments. One is a Lab-Made Hydrophobic (LMH) coating, with the intrinsic contact angle (CA) 134.5°, advancing CA 140°, receding CA 120° and surface roughness (Ra) 2.63 ± 0.37 μm. The CAs are measured at an ambient temperature of 20 ℃ using the contact angle meter (DSA-100, Kruss Company, Ltd, Germany). The roughness is measured using the surface roughness tester (TR101, Beijing TIME High Technology Ltd, China). Another surface is a commercial superhydrophobic coating “Ultra-Ever Dry” (UED) (UltraTech International, Inc, US), with the intrinsic CA 165.8°, advancing CA 167°, receding CA 165° and surface roughness 3.04 ± 0.41 μm. The LMH coating was made of acrylic solvent with additive polytetrafluoroethylene (PTFE), and carbon tubes were added to increase the surface roughness (Hu et al., 2015). Hydrophobicity of the coating could be adjusted by controlling the amount of PTFE and carbon tubes. Both surfaces are with random micro-structures, which are easy to fabricate practically. The Scanning Electron Microscope (SEM) images are shown in Fig. 3. On the LMH surface, structures and aggregations of carbon tubes can be clearly observed. A polished hydrophilic smooth aluminum plate, with the intrinsic CA 42.3°, advancing CA 70°, receding CA 35° and surface roughness 0.28 ± 0.01 μm , was also tested for comparison.

2.3. Boundary layer tests

Traditionally, the turbulent boundary layer can be divided into two regions: the inner region close to the wall which is the emphasis of this study, and the outer flow region further away from the wall, which extends to the edge of the shear layer (Monty, 2005). The inner region can be further divided into three layers: viscous sublayer, buffer layer and logarithmic layer (Monty et al., 2009). Prandtl's law of the wall $u^+ = f(y^+)$ denotes that the dimensionless velocity profile of the inner flow reduces to a universal curve. The scaled velocity u^+ and scaled distance y^+ are described as:

$$u^+ = u/U_\tau \tag{1}$$

$$y^+ = yU_\tau/\nu \tag{2}$$

where ν represents the kinematic viscosity and U_τ is the friction velocity. Experiments have confirmed this behavior and many researchers have proposed curve-fits to the data (Reichardt, 1951; Spalding, 1961). Reichardt (1951) gives one formula to describe the complete inner flow velocity profile:

$$u^+ = \frac{1}{\kappa}\ln(1+\kappa y^+) + \left(A - \frac{\ln(\kappa)}{\kappa}\right)\left(1 - e^{-\frac{y^+}{11}} - \frac{y^+}{11}e^{-0.33y^+}\right) \tag{3}$$