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Experimental investigation of viscous drag reduction of superhydrophobic nano-coating in laminar and turbulent flows

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ABSTRACT

In this research, effects of superhydrophobic nano-coating on frictional drag force have been investigated. The result of this study could be considered to be used as a method in applications concerned with fuel consumption reduction, less CO_2 emission and environmental problems as well as speed increase; while, its significance can also be of great use in marine applications. A rotating disc apparatus was used as the experimental set-up to compare the frictional drag force on an aluminum disc with TiO_2 superhydrophobic nano-coating and a smooth coatless aluminum disc. The superhydrophobic nano-coating was prepared using sol–gel method and was shown to be able to produce a contact angle of about 160°. Experiments were performed in the Reynolds numbers, ranging from 10^5 to 2×10^6. Results indicated the drag reduction values of up to 30% and 15% in laminar and turbulent flows, respectively.

1. Introduction

High fuel and energy consumption and CO_2 emission are major concerns in automotive, aerospace and ship transportation industries [1]. In this regard, developing new methods to decrease the amount of energy consumption has always been of a great interest. One of the effective approaches in this field is drag reduction. Since, at the present, major part of drag force is attributed to the frictional drag in most applications such as ships, marine vehicles, airplanes, pumps, turbines and pipe lines, great attention has been drawn to decreasing the frictional drag force. Moreover, drag reduction could result in increase of range and speed of vehicles [1].

Numerous active and passive methods have been utilized so far, with the purpose of drag reduction, namely, micro bubbles [2], riblets [3], compliant walls [4], suction or blowing [5] and using long chain polymers [6].

Owing to the extensive developments of nanotechnology in recent years, much attention has been paid to utilizing this technology in the field of drag reduction. Especially, with the development of superhydrophobic surfaces, which show novel characteristics such as self-cleaning [7], anti-icing [8–10], anti-fouling [11–14] and drag reduction [15], a great deal of research have been performed on these surfaces. In this regard, works of Balasubramanian et al. [15,16] are worth citing. By mimicking lotus leaf structure, they have developed a hydrophobic surface coating and experimentally investigated its effect on drag reduction in flow over a flat plate, flow inside a pipe and flow over an elliptic model. They have measured velocity by means of PIV and reported that velocity is not zero at the vicinity of the plate's coated surface; therefore, there is a slip velocity condition rather than a no-slip condition on the superhydrophobic surface. This slip velocity causes the drag reduction. Henoch et al. [17], using silicon wafers, have developed two hydrophobic nano-coatings, namely nanobrick and nanograss, and investigated the effects of these coatings on flow over a flat plate. A 50 percent drag reduction in laminar flow was reported in this work. Rothstein et al. [18,19] studied flow over hydrophobic silicon surfaces used in microchannels. In these studies a 50 percent pressure drop reduction was achieved in particular cases. Choi et al. [20] also focus on slip length in hydrophobic microchannels. They have used a high precision flow rate measurement system to measure the water flow rate in both hydrophobic and hydrophilic silicon wafer microchannels with 1 and 2 μm depth and found out that in hydrophobic surfaces, slip length and shear rate are proportional. A slip length of 30 nm on hydrophobic microchannel was reported in this study for shear rate of $10^5\ s^{-1}$. Cui et al. [21] utilized two phase Lattice-Boltzmann method to numerically investigate the effect of hydrophobic wall in flow inside a channel. They related the pressure drop reduction to the contact angle and claim that surface roughness could magnify the drag reduction effect of superhydrophobic surfaces. In addition to all the literature

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mentioned above, the works of Ünal et al. [22], You and Moin [23], Min and Kim [24], Huang et al. [25], El-Genk and Yang [26] and Srinivasan et al. [27] on the related area are worth citing.

In the present research, a rotating disc apparatus has been utilized to investigate the influence of TiO_2-based superhydrophobic surface coated on 7075 aluminum disc, on frictional drag reduction. The coating was prepared by a sol–gel method and its effect on drag force in both laminar and turbulent flow has been investigated. High value of drag reductions in both laminar and turbulent flow were achieved using the coating method proposed in this work.

2. Experimental

The experimental procedure of this work is divided into two sections. First section dealing with the preparation of the coated sample with superhydrophobic surface with micro/nano scale asperities; and, second section involved with the explanation of experimental set-up used for conducting drag reduction tests. At what follows, the two experimental procedure sections have been discussed in detail.

2.1. Model preparation

It is well established that hierarchical surfaces with micro-nanoscale structures could result in combined Wenzel/Cassie-Baxter state, which could trap air pockets in the surface asperities, consequently, producing high superhydrophobic and drag reduction characteristics [28,29]. In this work, as well, a micro-nano-size structure was produced by sol–gel coating of the 7075 aluminum sample using TiO_2 nano particles. The 7075 aluminum alloy was selected due to its high applicability in industry [30].

Two disc shape samples of 220 mm diameter and 20 mm thickness were machined in the first place. The first sample was polished and was used as reference sample. The other one sandblasted using 0.2 μm SiC particles for 30 s, so that micron-size asperities were formed on the sample surface. The samples are shown in Fig. 1. Surface roughness of both reference and sandblasted samples was measured using R_a and R_z measurement techniques. The reported measured values were determined on three different regions of each sample and are the average of at least five measurements each. The coating process performed on the sandblasted sample according to the following steps:

(1) The sol solution was prepared by mixing pure ethanol, titanium Butoxide, deionized water and Diethanolamine with $Ti(OC_4H_9)_4$:EtOH:H_2O:$NH(C_2H_4OH)_2$ = 14:112:2:3 ratio, in order to produce the sol solution, sufficient titanium Butoxide was gradually added to the ethanol, while, the mixture was stirred for 1 h at room temperature and with high stirring speed of 2400 rpm. Afterwards, the deionized water and the Diethanolamine, were added to the mixture and the solution was stirred for an additional hour in order for the solution to become homogenous.
(2) When the sol mixture turns to a pale bright yellow color, the solution was aged for 24 h at room temperature.
(3) Sandblasted sample was immersed in a solution containing acetone and deionized water for 1 h. It was then dried at room temperature for another hour.
(4) The produced sol was diluted by isopropanol with an isopropanol to gel ratio of 9:1 and was sprayed on the sample's surface. The spraying process was repeated for three times to make sure that the desired coating thickness has been achieved.
(5) In next step, to assure the stability of the coating, coated sample was remained in the room temperature for 24 h.

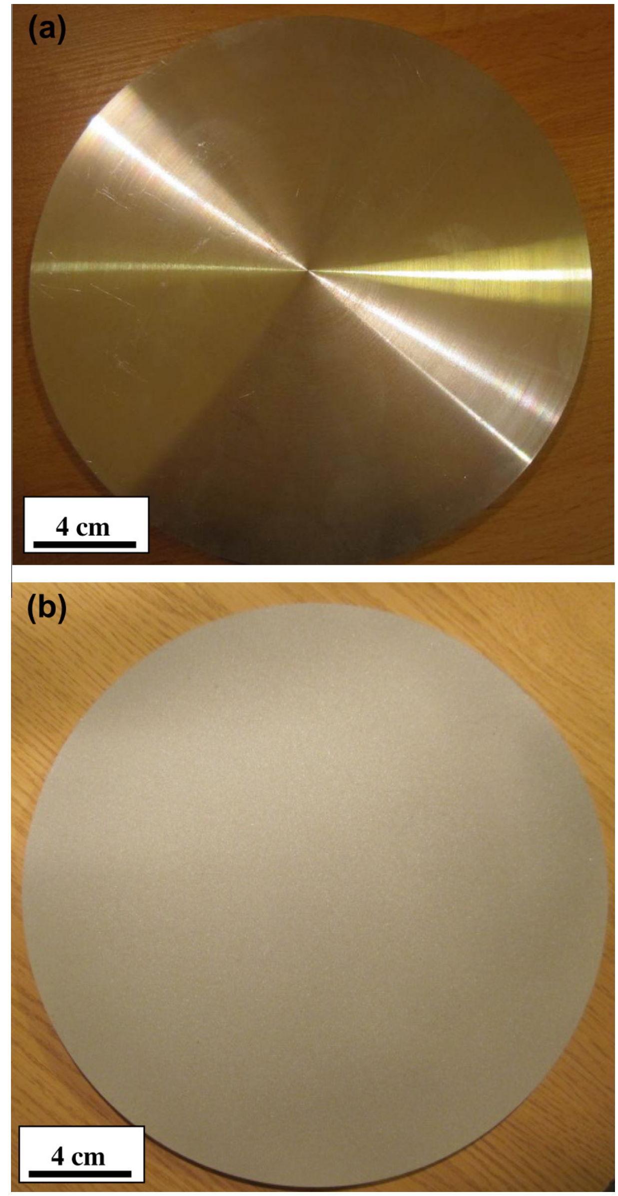

Fig. 1. (a) Reference and (b) sandblasted discs, used in this work.

Note that morphology of the coating in this work was studied by Scanning Electron Microscope (SEM). A more detailed sol preparation method used in this work can be found in Ref. [31].

2.2. Experimental set-up

Schematic view of experimental set-up has been shown in Fig. 2. It consists of a steel frame to support the container, motor and control/measurement cabinet. The AC motor used in this apparatus was a 1.5 kW three-phase motor with maximum speed of 3000 rpm, supplied by G.E.C England. The motor is used to provide the required torque for the spinning of the disc-shape samples and was equipped with an LS600 inverter (from Japan Autonics) in order to adjust and control the spinning speed. A rotation sensor supplied by Japan Omega with the capability of measuring the spinning speed along with an ammeter and a voltmeter from the same company which have a range from 0 to 5 A and 0 to 700 V, respectively, was integrated in the set-up. The ammeter and voltmeter are capable of measuring current and voltage of any of the