



# Investigation on superhydrophilic surface with porous structure: Drag reduction or drag increasing



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## ABSTRACT

In this paper, different apertures of superhydrophilic porous TiO<sub>2</sub> films are fabricated by sol-gel method with PEG2000 additive. The drag reduction effect of the films is investigated through experiment of falling-ball method and FEM simulation. The larger PEG2000 content, the bigger size and the more regular and homogeneous of the pores. The joint action of anatase crystal, hydroxyl groups and water molecules adsorbed on the surface and porous structure causes the superhydrophilicity. The resistance test shows that when the addition amount of PEG2000 changes from 0.25 g to 2 g, the drag reduction efficiency increases from −17.9% to 8.6% and −16.8% to 9.4% with 12 mm and 25 mm diameter balls. The drag reduction mechanism can be obtained from Finite Element Method simulation. The result shows that vortexes are formed in the pore which can reduce the frictional drag by lowering the velocity gradient and giving a frictional driving force. Meanwhile, an “extra press drag” is formed between the front and back wall. If the degree of friction drag reduction is greater than the degree of press drag increase, the film will show the effect of drag reduction overall.

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## 1. Introduction

The performance of on-water/under-water vehicles marks a country's comprehensive marine power, especially the route speed and energy consumption rate, which mainly depend on the efficiency of the engine and the water resistance. According to statistics, the international shipping energy consumption rose crazily from 64.5 million MT in 1950 to 280 in 2001 [1], and more than half of the energy was consumed in overcoming the surface drag. The same issue also exists in pipeline transportation, a large part of the fluid conveying power provided by the pump is consumed to overcome the pipe wall resistance [2]. So, it is highly economic valuable to reduce drag. The drag during the voyage includes three parts [3]: wave drag, pressure drag and frictional drag. The wave drag is decided by the strength of wave. The pressure drag is related to the shape of the vehicles. The frictional drag strongly depends on the flow state near the wall of the vehicles. Generally, the wave drag is uncontrollable. For a particular shaped vehicle, the pressure drag is also a fixed value. The sum of these two factors accounts for about 20% of the whole drag [4]. Therefore, the frictional drag is the core factor which is caused by the viscous force between the vehicle surface and water. Fortunately, the frictional drag can be controlled by surface design [5].

Recently, Special wettable surface has aroused wide attention because of its important applications in many fields [6–9]. As the name suggests, the special wettable surface is defined as a surface which has a special wettability like superhydrophobicity, superhydrophilicity, superoleophobicity and superoleophilicity. Recently, superhydrophobic [10–14] and superhydrophilic [15–17] surfaces are widely studied in drag reduction.

The superhydrophobic surface is defined as a surface with a high static water-contact angle (CA, >150°) and a low sliding angle (SA, <10°). Its most important characteristic is that air would be trapped in the surface texture. This phenomenon can significantly reduce the real contact area between vehicle surface and water. If the vehicle surface is smooth, the value of frictional drag can be formulated as followings.

$$R_f = \int_S \tau dS \quad (1)$$

$$\tau = \mu \left. \frac{\partial v}{\partial y} \right|_{y=0} \quad (2)$$

where  $R_f$  is the frictional drag,  $\tau$  is the frictional shear stress,  $S$  is the real contact area between the vehicle and water,  $v$  is the vehicle's speed,  $\mu$  is the water viscosity,  $y$  is the vertical distance to the vehicle surface in the boundary layer [18]. According to Eq. (1), decreasing  $S$  can effectively reduce the frictional drag. However, the drag reduction effect of superhydrophobic surface is still controversial. E Aljallis et al. tested

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the drag reduction effect on flat aluminum plates at low Reynolds number conditions [19]. The superhydrophobic surfaces showed significant drag reduction effect, even up to 30%. But the surface drag increased obviously in the fully developed turbulent flow regime. This is because the surface changed from de-wetting (Cassie) state to the wetted (Wenzel) state due to the depletion of air bubble. However, the problem that how to keep bubbles stable in high pressure and high speed conditions has never been solved [20].

On the contrary, superhydrophilic surface refers to a surface that liquid can completely diffuse on it and the CA is equal to or close to 0°. Compared with superhydrophobic surface, the research on superhydrophilic surface is relatively few in the field of drag reduction, because classically, hydrophilic surface has larger damping compared with hydrophobic surface. But Huang et al. have drawn the conclusion that the relationship between surface wettability and surface damping is not a one-to-one correspondence [21]. This conclusion proposed the drag reduction possibility of superhydrophilic surface. More importantly, there are lots of real examples of superhydrophilic surfaces with drag reduction property in nature, like shark, dolphin and fish. The surface of these marine lives is hydrophilic with regular groove structure. Inspired by the marine organisms, scientists have done some related work about the drag reduction of superhydrophilic surface.

At present, the researches are mainly focused on the superhydrophilic polymer coatings. T.H. Shepherd et al. described a hydrophilic drag-reduction coating using water insoluble polymer [22]. The water-water interface could stabilize the laminar flow on the boundary layer through reducing the turbulence. Other hydrophilic coatings using different polymers are also applied [23–25]. On this basis, additives can be added into pipe flow with flexible polymers to enhance the drag reduction effect. Adam Steele et al. used dispersing carbon nanotube (CNT) additives to increase the turbulent drag reducing capabilities of polyethylene oxide (PEO). CNTs can interact with polymers to form structure that increasing the chain length while maintaining some flexibility [26]. However, whether superhydrophilic materials with microstructure on the surface have drag reduction effect is still controversial now and also there are few relevant research reports. The research on textured superhydrophilic/hydrophilic surface is quite important in the field of drag reduction, hydrophilic polymer coating will be subject to many factors, like the stability of the polymer, the adhesion of the coating and whether the material is environmentally friendly [27]. While, if we build micromorphology on the surface rather than using water insoluble polymers, the morphology is steady, durable and does no harm to the environment as well. Therefore, the material is suitable for long time use.

In this work, we investigated the flow field and drag reduction effect of superhydrophilic porous TiO<sub>2</sub> film via simulation and drag test experiments. The film was prepared by sol-gel and dip-coating method with different aperture of micro pores on the surface. The relationship between drag reduction rate and the pore morphology was studied. Contrary to superhydrophobic material, the pores are filled with water instead of air, and the formation of micro vortex in the pore is the key to the drag reduction effect according to simulation result. This preparation method can provide a new kind of thinking for practical application due to the merit of easy process, large area and low cost.

## 2. Experimental section

### 2.1. Preparation of superhydrophilic surfaces

All chemicals used in this work were purchased from Sinopharm Chemical Reagent Co., Ltd. (Beijing, China) and Aladdin Industrial Corporation (Shanghai, China). All of the water used is deionized water which is homemade in our laboratory.

Glass slides with dimensions of 75 \* 25 \* 1 mm<sup>3</sup> were used as substrate. Before dip-coating, the glass slides were cleaned in newly configured Piranha Solution (mixture of 3:1 (v/v) concentrated sulfuric acid and 30% hydrogen peroxide) for 10 min, then ultrasonically cleaned in

ethanol for about 20 min, rinsed with large quantity of deionized water several times, and finally dried in air.

According to the previous studies [28], the preparation of the sol for coating was as follows [14]: tetrabutyl titanate (17.02 ml) and diethanolamine (4.8 ml) were dissolved in ethanol (67.28 ml). After stirring magnetically for 30 min, water (0.9 ml) and ethanol (9 ml) were mixed together and added into the solution, then various amounts of PEG (polyethylene glycol, HO(CH<sub>2</sub>CH<sub>2</sub>O)<sub>n</sub>H) were added into the solution which served as the final sol for coating. The average molecular weight of the PEG is 2000. After stirring magnetically for 2 h, the sol which became transparent and pale yellow was preserved in dark for 24 h, for the purpose of standing and ageing.

The TiO<sub>2</sub> film was prepared by dip-coating method [29]: The withdrawal speed was 40 mm min<sup>-1</sup>, the soaking time was 1 min. After coating, the gel film was dried in vacuum drying box at 80 °C for 5 min, and then repeated coating. Finally the samples were heat treated in a Muffle furnace. The temperature was elevated to 500 °C with a heating rate of 5 °C min<sup>-1</sup>, and kept constant at 500 °C for 1 h. The thickness of the film was controlled by the repeating coating time.

### 2.2. Characterization

The two dimensional and three dimensional surface morphologies were observed by a high resolution scan electron microscopy (HR-SEM, FEI Quanta 250 FEG, U.S.) operated at an acceleration voltage of 20.0 kV and an atomic force microscope (AFM, Dimension3100V, U.S.). The CAs were measured with a contact angle measurement (OCA20, Dataphysics, Germany) in ambient atmosphere at room temperature. All the CAs reported here are the averages of five measuring points with 3 μl pure water droplets. The surface energy was calculated with a surface tension meter (DCAT 21) by measuring the CA of water and n-Hexadecane. The X-ray diffraction patterns were collected using an X-ray diffractometer with Cu Kα radiation (Bruker AXS D8 Advance). The chemical components were analyzed via X-ray photoelectron spectroscopy (SHIMADZU AXIS UTLTRADLD) with Al Kα radiation source. The thickness of the film was gauged by a Profile Meter (Alpha-Step IQ, U.S.). The flow state and stress situation was simulated by a Finite Element Analysis Method using ANSYS FLUENT software.

We used gravitational method and particle image velocimetry to measure the frictional drag with a high speed camera (FastcamMini UX100, Photron Inc.), the schematic diagram of the device and four typical stills obtained from the movie are shown in Scheme 1. Here, we used steel balls made of plain carbon steel instead of glass slides to do the test in order to ensure the validity of the experiment. Two kinds of balls were used with diameter of 12 mm and 25 mm respectively and the whole coating procedure was similar.

The whole test process was as follows: shooting and recording the falling process of the ball from point A to point B, and calculating the average velocity and average acceleration of the ball within the distance of x so as to calculate the drag resistance, the frame rate of the high speed camera used in this experiment is 2000 fps.

## 3. Results and discussion

TiO<sub>2</sub> is a very famous material and widely used as inorganic functional material and photocatalytic material because of the excellent optical and photocatalytic properties as well as chemical stability [30–33]. TiO<sub>2</sub> with porous structure can be prepared by various ways, like sol-gel method [34], plasma electrolytic oxidation [35], hydrolysis method [36] and precipitation method [37]. In this work, we investigate the drag reduction effect of superhydrophilic porous TiO<sub>2</sub> film in flow field. Fig. 1 shows the SEM images of the as-prepared surfaces of TiO<sub>2</sub> films. In Fig. 1a, the surface of TiO<sub>2</sub> film prepared by the precursor solution without PEG2000 is smooth and compact. Micro structure begins to appear with the gradual addition of PEG2000. There are enormous numbers of regular micro pores on the coating surface, the size and the number of the pores are

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