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# Scalable superhydrophobic coating with controllable wettability and investigations of its drag reduction

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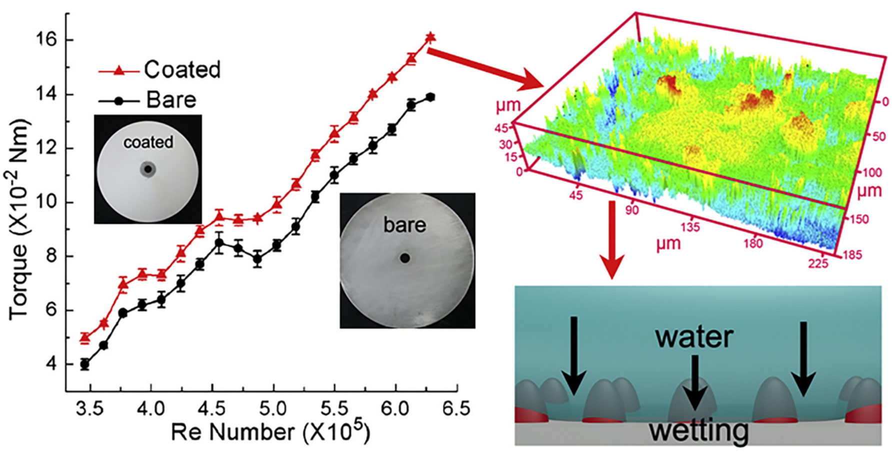
## GRAPHICAL ABSTRACT




## ARTICLE INFO

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## ABSTRACT

Superhydrophobic surface (SHS) has always been considered to be favorable for reducing drag force due to the air layer in surface asperities, however, debates over whether such surface could reduce the drag force still remains. In this study, steel surface was sprayed with suspension that contained PMMA and hydrophobic nanoscale silica, and the obtained surface showed variable contact angle from 94° to 159°, sliding angle from 90° to 2°, suggesting the controllable wettability; besides, the facile preparation process showed promising prospect to be scaled up. We studied the drag-reducing property of treated steel *via* sailing test and rotary disc test, results showed that SHS could efficiently reduce the drag force under low fluidic condition; surprisingly, for the intense turbulent flow, the SHS exhibited a drag-increasing effect, indicating that such surface only functions under mild flow condition.

## 1. Introduction

Inspired by Lotus leaves, superhydrophobic surface(s) (SHS) have attracted tremendous scientific interests due to its extremely low water affinity, which could be applied in anti-icing [1–3], metal protection [4,5], medical science [6,7], water/oil separation [8,9], and directional

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fluid transport [10,11], *etc*. In recent years, methods such as chemical etching [12,13], sol-gel [14,15], depositions [16,17], nanomaterial-polymer [18], laser treatment [19,20], *etc*, have been developed to prepared SHS. It is commonly accepted that the appropriated design of surface structures could dramatically increase the surface hydrophobicity [21–23]. Though the fabrication procedures are variable, they mainly abide by following two principles: the micro-nano hierarchical structures and low surface free energy components. The main concerns of SHS are the weak surface structures and poor scalability of fabrication process. Researchers have found that the combination of nanomaterials and polymer could effectively improve the mechanical stability [24,25], as the polymer could act as the adhesive between the weak nanostructures and could effectively improve the stability. In our previous research, we obtained super robust SHS by incorporating nanoscale silica and ultra-high molecular weight polyethylene (UHMWPE). Y. Shen et al. studied the bouncing behaviors on SHS, the water-repellency has been greatly improved with special design of surface structures [26–28]. P. Wang *et al.* prepared super-robust SHS by incorporating PS/silica or graphene and polymers [29,30], they also prepared pump-free oil droplet transfer system by combining microfiber array and superoleophobic mesh [31].On the other hand, the scalability of SHS is of vital importance for practical use, for the routine methods (*e.g.* CVD, sputtering, soft lithography, and spin coating *etc.*), the size/shape of the SHS is usually restrained by limitations of fabricating apparatus; compared with which, the spraying method is facile, economic, and could meet the requirements of various shapes/sizes.

SHS have been widely discussed in the field of drag reduction [32–36]. Taking advantage of the low water affinity, large amount of air pockets on the surface roughness would form an air layer, which could greatly reduce the friction between substrate and water, thus reducing the drag force. Srinivasan et al. prepared a sprayable SHS, demonstrating an effective drag reduction property in turbulent *Taylor-Couette* flows [34]. Wei et al. treated the SHS on model of submarine, and sailing tests showed that a drag-reducing rate of 49.1% was yielded and the sailing velocity were successfully improved [37]. Hu et al. prepared alternative superhydrophobic/hydrophilic strips to form an “air ring” under water, and resultant surface showed drag reduction up to 77.2% [38]. However, on the other hand, some researchers argued that the SHS are not always favorable to the drag reduction [39]. Thus, whether the SHS could reduce the drag under water still remains to be revealed.

In this paper, we prepared SHS *via* spraying a suspension that contained PMMA and hydrophobic nanoscale silica onto 1045 steel substrate. The fabrication process could be easily scaled up, showing prospective industrial application. We studied the drag reduction of prepared SHS: 1) sailing tests - the surface was treated on model of vessels, and monitored the velocity under different power supplies; 2) rotary disc test - a self-made system was developed to study the drag reduction under intense turbulent flow. The results indicated that the SHS showed superior drag-reducing effect when placed under relatively mild fluidic water; quite contrary, SHS exhibited a “drag-increasing effect” when exposed in intense flow, indicating that SHS is not always favorable to the drag reduction.

## 2. Experimental section

### 2.1. Materials

Tetraethylorthosilicate (TEOS) and ammonia hydroxide (25%) ($NH_4OH$) were obtained from Sinopharm Chemical Reagent Co., Ltd, China. 1*H*,1*H*,2*H*,2*H*-perfluoroalkyltriethoxysilane (97%) (FAS-17) was purchased from Sigma-Aldrich. All other reagents were obtained from Aladdin Co., Ltd, China and used as received. 1045 Steel disk (diameter: 20 cm) and steel model vessels (1045 steel) were supplied by local stores.

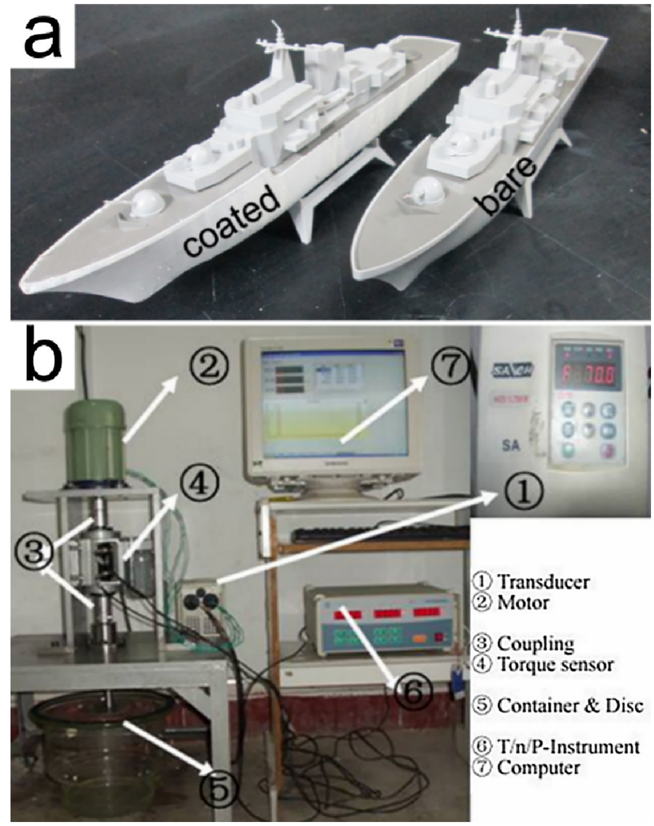


**Fig. 1. Testing systems.** (a) Sailing experiments of vessels. The surface was treated on the model of naval vessel with different power supplies. (b) Self-made rotary disc apparatus.

### 2.2. Pretreatment of steel surface

Steel specimens were grounded with waterproof abrasive paper sheets up to no. 1800 and then polished with diamond paste. The polished surfaces were rinsed with ethanol and ultrasonically degreased in ethanol for 10 min to remove the surface contamination and dust.

### 2.3. Preparation of silica nanoparticles (SNs)

The nanoscale silica were mainly prepared according to our previous method [40]. First, 2.5 mL of ammonium hydroxide (25%) was added to 50 mL of ethanol and stirred at 55 °C for 40 min. Then, 2 mL of tetraethylorthosilicate (TEOS) was added dropwise and stirred for 1 h, and the solution was dried at 40 °C to obtain the nanoparticles. Finally, the nanoparticles were soaked into 2.5 wt.% 1*H*,1*H*,2*H*,2*H*-perfluorodecyltriethoxysilane ($C_{10}F_{17}H_4Si(OCH_2-CH_3)_3$, FAS-17) in hexane and ultrasonically treated at 40 °C for 2 h, then the silica were rinsed with hexane and dried.

### 2.4. Preparation of superhydrophobic surface

Poly (methyl methacrylate) acrylic (PMMA) powder, nanoscale silica, and tetrahydrofuran (THF, solvent) were mixed at mass ratios of 1: X: 100, and stirred at 30 °C for 1 h to dissolve the polymer. Then the solution was sprayed on substrate *via* a spray gun (jet nozzle diameter = 0.6 mm) with pressure of 350 kPa from a distance of 25 cm, the obtained surface was desiccated at 50 °C for 20 min to remove the residual solvent. The values of X were 0, 1, 3, 5, and 7, the corresponding surfaces were denoted as P0, P1, P2, P3 and P4, respectively.