Effect of surface treatment on drag coefficient of free-falling solid sphere in water

*M Sofwan Mohamad¹,², C M Mackenzie Dover¹ and K Sefiane¹

¹Institute for Multiscale Thermofluids, School of Engineering, University of Edinburgh, Faraday Building, King’s Buildings, Edinburgh United Kingdom. EH9 3DW
²School of Mechatronic Engineering, Universiti Malaysia Perlis (UniMAP), Kampus Pauh Putra, 02600 Arau, Perlis Malaysia.

*corresponding author: Muhammad.Mohamad@ed.ac.uk

Abstract. The study aims to examine the influence of different surface treatments on the drag coefficient of free-falling spheres in water. The spheres used in the experiment are classified into four categories and labelled as: ref – no surface treatment, FDTS – coated with hydrophobic perfluorodecyltrichlorosilane (FDTS) coating, E8 – 8 minutes etched in ferric chloride (FeCl₃) and E32 – 32 minutes etched in FeCl₃. No significant difference is observed in drag coefficient of the etched spheres compare with the reference sphere. However, the FDTS sphere’s drag coefficient was increased by 13%.

1. Introduction
There has been recent, significant progress in the design as well as fabrication of surface treatments that can potentially reduce skin friction drag [1], [2]. For example, the modification of surface chemistry by the addition of a hydrophobic coating. By definition, a hydrophobic surface is low-energy and characterized by a water contact angle (WCA) higher than 90° [3]. A surface can be easily coated with a hydrophobic material such as perfluorodecyltrichlorosilane (FDTS) to reduce the substrate’s energy in order to engineer a water-repellent interface [4], [5]. Surface topography (and roughness) can also have a significant effect on the hydrophobicity of the surface [6]. Moreover, a superhydrophobic surface (WCA higher than 150°) can be achieved by combining these two modifications (surface chemistry and surface roughness) appropriately [7]. Furthermore, the ability of a hydrophobic surface to sustain an air layer on the surface when immersed in water has attracted substantial research interest because it can promote a slip boundary condition at the interface which can lead to drag reduction [8]–[11]. These could have benefit to various applications such as enhanced liquid mobility at interfaces presented by ships [12], submarines [13] and piping systems [14].

The focus of the present study is to use free-falling spheres to investigate the effect of several surface treatment techniques on the motility through a fluidic environment. This is achieved by measurement of the velocity of the falling sphere in water. The measured velocity is then used to calculate the drag coefficient of the sphere.
2. Methodology

An experimental setup was designed to capture the behaviour of a free-falling sphere in water (Figure 1). The setup comprises a 1000 mm high square cross section, straight-walled column with inner side width of 70.45 mm made of clear Perspex. These dimensions were selected such that a falling sphere with a diameter of less than 7 mm could reach terminal velocity with negligible wall effects and end effects [15], [16]. The motion of the falling sphere was recorded by a high speed camera which was mounted on vertical and horizontal sliders to give the camera 2 degrees of freedom. A custom made high power LED light was used to illuminate the test section. An electromagnetic release mechanism was integrated with the top lid. The mechanism was designed such that the sphere’s motion is induced by the effect of gravity only, at the centre of the column with zero initial velocity directly above the water’s surface. The bottom part of the column was attached to a retrieval mechanism which allowed the sphere to be removed from the column easily. The temperature of the water was controlled by an electric heater and a proportional-integral-derivative (PID) controller connected to two thermocouple probes. However, all experiments were conducted at room temperature for the present paper. The spheres used in the experiments are commercially available stainless steel spheres with diameters of 7 mm. The density of these spheres is 7750 kg/m$^3$. The captured video was processed using an in-house ImageJ macro to obtain the relative position and velocity of the sphere.

The experimental samples were prepared by coating the sphere with hydrophobic FDTS coating (labelled as FDTS), and roughening the sphere’s surface via an etching process. The coating was applied over the sphere by means of molecular vapour deposition (MVD). The implementation of the MVD coating technique resulted in a mono-layer coating on the surface. Thus, the molecularly thin coating (in the order of nanometers) layer has no significant effect on the diameter of the sphere and it can still be considered to be 7 mm. The etching process was done by simply immersing the spheres in FeCl$_3$ for two different interval times; 8 minutes and 32 minutes (labelled as E8 and E32, respectively).

![Figure 1. The schematic diagram of experimental set-up.](image-url)
3. Results

3.1. Velocity
The spheres described in Section 2 were tested in free-fall in water. The evolution of the velocity of the spheres are inferred from the time derivative of the falling trajectory and this is depicted in Figure 2(a). Each curve illustrates the ensemble average of the instantaneous velocity over 3 trials. Error bars are not displayed in the figure for the sake of clarity. Surprisingly, instead of the skin-friction reducing effect of hydrophobic surface, it can be seen that the FDTS sphere falls the most slowly. On the other hand, no significant difference in velocity is observed between the etched spheres and the reference sphere. The velocity of the spheres reaches a plateau value at a time of about 0.25s, indicating a steady state condition. The terminal velocity for each sphere is calculated by averaging the instantaneous velocity in the steady state region. In the case of the FDTS sphere, due to the limited experimental data points, an empirical exponential model proposed by Mordant & Pinton [17] was used to estimate its terminal velocity (dashed black line in Figure 2(a)):

\[ v(t) = v_T(1 - e^{-\tau/\tau}) \]  

where \( v_T \) (terminal velocity) and \( \tau \) (characteristic time) in the equation are independent fitting parameters. Indeed, the FDTS sphere reached steady state condition within the field-of-view of the camera. The average terminal velocity of those spheres in the case of 7 mm diameter for 3 repeated experiments are shown in Figure 2(b). The error bars in the figure represent one standard deviation of the measured mean values.

![Figure 2](image.png)

**Figure 2.** The velocity of the free-falling spheres for all different surface treatment: (a) at transient state and (b) at steady state.

3.2. Drag coefficient
Knowing the terminal velocity, the steady-state drag coefficient for a sphere can be determined by the following equation:

\[ C_D = \frac{4}{3} \left( \frac{\rho_s - \rho_f}{\rho_f v_T^2} \right) g d \]  

where \( \rho_s \) is the sphere density, \( \rho_f \) is the surrounding fluid (water) density, \( g \) is gravitational acceleration and \( v_T \) is the terminal velocity of the free-falling sphere. Setting the unmodified sphere as
the reference, the effect of the surface treatment on drag coefficient can be estimated from
\[ \Delta C_D = 1 - \left( \frac{C_D}{C_D^{ref}} \right) \] (where superscript ref is referring to unmodified sphere) and depicted in Figure 3 as a function of Reynolds number. It can be seen that the drag coefficient of the etched spheres are identical with the reference sphere with no significant differences (less than 3%). In contrast, the FDTS sphere’s drag coefficient is higher than the reference sphere by 13%.

![Figure 3](image)

Figure 3. The ratio of steady-state drag coefficient of spheres with various surface treatments to the reference sphere.

4. Conclusion

An experimental study is conducted on the effect of surface treatment on the drag coefficient of free-falling spheres in water. The surface of the spheres were modified by two methods; coating the spheres with FDTS and roughening the surface of the spheres by a wet-etching process. The drag coefficient of the etched spheres were almost identical to the unmodified spheres. Surprisingly, the drag coefficient of the FDTS sphere was 13% higher than that of the reference sphere. There are extant experimental investigations previously reported that are discordant in their conclusions about whether an increase in surface hydrophobicity reduces [18] or enhances [19] drag coefficient. Interestingly, both researches relate the reduction and enhancement to the retaining air on the surface of the sphere. In their analytical study, McHale et al. suggest that the air layer must be at an optimum thickness so that the drag reduction effect due to the slip condition outweigh the increase in buoyancy due to presence of air layer on the surface [11]. Therefore, higher-resolution images need to be captured in order to evaluate the thickness of the air layer retained on the sphere’s surface and further detailed analysis need to be done to understand the underlying physical mechanism of the drag enhancement in the present investigation.

Acknowledgement

The author acknowledge the financial support from Kementerian Pendidikan Malaysia and Universiti Malaysia Perlis for the sponsorship which enable me to pursue this study. MEMStar Ltd. is gratefully acknowledged for the coating. The author would like to thank Mr. Alan Ross at the Scottish Microelectronics Centre (SMC) for the help with sample preparation.

References

[1] Luo Y, Wang J, Sun G, Li X and Liu Y 2016 Experimental investigations on manufacturing different-shaped bio-inspired drag-reducing morphologies and hydrodynamic testing Exp. Tech. 40 (3) 1129–1136.

[2] Abdulbari H A, Mahammed H D and Hassan Z B Y 2015 Bio-Inspired Passive Drag Reduction Techniques: A Review ChemBioEng Rev. 3 185–203.
[3] Law K Y 2014 Definitions for hydrophilicity, hydrophobicity, and superhydrophobicity: Getting the basics right J. Phys. Chem. Lett. 5 (4) 686–688.

[4] Kobrin B et al. 2006 An improved chemical resistance and mechanical durability of hydrophobic FDTS coatings J. Phys. Conf. Ser. 34 (1) 454–457.

[5] Gnanappa A K et al. 2008 Effect of annealing on improved hydrophobicity of vapor phase deposited self-assembled monolayers J. Phys. Chem. C 112 (38) 14934–14942.

[6] Öner D and McCarthy T J 2000 Ultrahydrophobic surfaces. Effects of topography length scales on wettability Langmuir 16 (20) 7777–7782.

[7] Barati Darband G, Aliofkhazraei M, Khorsand S, Sokhanvar S and Kaboli A 2018 Science and engineering of superhydrophobic surfaces: review of corrosion resistance, chemical and mechanical stability Arab. J. Chem.

[8] Ou J, Perot B and Rothstein J P 2004 Laminar drag reduction in microchannels using ultrahydrophobic surfaces Phys. Fluids 16 (12) 4635–4643.

[9] Rothstein J P 2010 Slip on Superhydrophobic surfaces Annu. Rev. Fluid Mech. 42 (1) 89–109.

[10] Panchanathan D, Rajappan A, Varanasi K K and McKinley G H 2018 Plastron regeneration on submerged superhydrophobic surfaces using in situ gas generation by chemical reaction ACS Appl. Mater. Interfaces 10 (39) 33684–33692.

[11] McHale G, Flynn M R and Newton M I 2011 Plastron induced drag reduction and increased slip on a superhydrophobic sphere Soft Matter 7 (21) 10100–10107.

[12] Dong H, Cheng M, Zhang Y, Wei H and Shi F 2013 Extraordinary drag-reducing effect of a superhydrophobic coating on a macroscopic model ship at high speed J. Mater. Chem. A 1 (19) 5886–5891.

[13] Zhang S et al. 2015 Underwater drag-reducing effect of superhydrophobic submarine model Langmuir 31 (1) 587–593.

[14] Karami H R, Keyhani M and Mowla D 2016 Experimental analysis of drag reduction in the pipelines with response surface methodology J. Pet. Sci. Eng. 138 104–112.

[15] Uhlherr P and Chhabra R 1995 Wall effect for the fall of spheres in cylindrical tubes at high Reynolds number Can. J. Chem. 73.

[16] Brown P P and Lawler D F 2003 Sphere Drag and Settling Velocity Revisited J. Environ. Eng., 129 (3) 222–231.

[17] Mordant N and Pinton J F 2000 Velocity measurement of a settling sphere Eur. Phys. J. B 18 (2) 343–352.

[18] McHale G, Shirtcliffe N J, Evans C R and Newton M I 2009 Terminal velocity and drag reduction measurements on superhydrophobic spheres Appl. Phys. Lett. 94 (6) 1–6.

[19] Su B, Li M and Lu Q 2010 Toward understanding whether superhydrophobic surfaces can really decrease fluidic friction drag Langmuir 26 (8) 6048–6052.