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Soft Matter

ARTICLE

Drag crisis moderation by thin air layers sustained on superhydrophobic spheres falling in water

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We investigate the effect of thin air layers naturally sustained on superhydrophobic surfaces on the terminal velocity and drag force of metallic spheres free falling in water. The surface of 20 mm to 60 mm steel or tungsten-carbide spheres is rendered superhydrophobic by a simple coating process that uses commercially available hydrophobic agent. By comparing the free fall of unmodified spheres and superhydrophobic spheres in a 2.5 meters tall water tank, it is demonstrated that even a very thin air layer ($\sim 1 - 2 \mu\text{m}$) that covers the freshly dipped superhydrophobic sphere, can reduce the drag force on the spheres by up to 80 %, at Reynolds numbers 10^5 to 3×10^5 , owing to an early drag crisis transition. This study complements prior investigations on the drag reduction efficiency of model gas layers sustained on heated metal spheres falling in liquid by the Leidenfrost effect. The drag reduction effects are expected to have significant implication for the development of sustainable air-layer-based energy saving technologies.

1 Introduction

Reducing friction and drag on a solid body in contact with liquid, by the introduction of a lubricating gas layer on the solid surface, is a topic of intense research interest that has been fuelled by the drive for sustainable, energy saving technologies. Various methods to induce the gas layer on the solid surface include bubbles or gas injection near the surface,¹ cavity encapsulation,² and the use of a superhydrophobic surface that can naturally sustain a thin air layer, often referred as a plastron.³⁻⁶ The physical background of the gas layer drag reduction is in the exchange of the no-slip, or stick boundary condition at the solid-liquid interface with a partial slip boundary condition at the gas-liquid interface.⁷⁻¹⁰ This directly affects the fluid flow around the solid body and the related hydrodynamic drag.

Recently the use of the Leidenfrost effect¹¹⁻¹³ to sustain a continuous vapor layer on solid surfaces heated to a temperature that exceeds the boiling point of the surrounding

liquid, has proven to be an efficient method to study the effect of gas layer on the drag of solid objects.¹⁴⁻¹⁷ Initial experiments were conducted by measuring the terminal velocity of heated metallic spheres falling in a perfluorocarbon liquid (FC-72 mainly comprised of perfluorohexane) that has a low vaporisation heat capacity.¹⁴ Vapor layer on heated spheres were found to reduce the drag by as much as 85 % by provoking an early drag crisis transition. The drag crisis is a phenomenon in which the drag on bluff bodies moving in fluid suddenly drops for speeds above a threshold velocity due to the transition to turbulent regime in the viscous boundary layer. For a smooth solid sphere the drag crisis transition is observed at Reynold number, $Re \sim 3 \times 10^5$, when the drag coefficient of the sphere, C_D sharply drops from about 0.5 to 0.1-0.2.¹⁸⁻²¹ Here the Reynold number, $Re = 2\rho RU/\mu$ and the drag coefficient, $C_D = 2F_D/(\pi R^2 \rho U^2)$, where F_D is the drag force on the sphere, ρ the fluid density, R the sphere radius and μ the dynamic viscosity of the fluid. The Leidenfrost vapor layer effects on the drag of spheres, were later replicated for water medium.¹⁵ However because of the higher vaporisation heat capacity of water it was possible to sustain a stable vapor layer only when the water was heated to temperatures above 85 °C. Most recently, using a range of perfluorocarbon liquids of higher viscosity it was demonstrated that the Leidenfrost vapor layers drag reduction can extend the drag crisis range to much lower Reynolds numbers.¹⁶

The use of Leidenfrost vapor layers is a very effective approach to study the drag reduction by gas layers, but has limited practical applicability due to the high energy cost of heating the surfaces. For practical applications a more attractive option is the use of structured superhydrophobic

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Electronic Supplementary Information (ESI) available: A pdf file containing Fig. S1–S3: Fig. S1: photograph of the water tank; Fig. S2: velocity vs. time data for unmodified and superhydrophobic steel spheres of sphere size: (a) 20 mm, (b) 25 mm, (c) 40 mm, (d) 45 mm and (e) 60 mm; Fig. S3: velocity vs. time data for unmodified and superhydrophobic tungsten carbide spheres of spheres sizes: (a) 20 mm, (b) 25 mm, (c) 30 mm, (d) 35 mm, (e) 40 mm, (f) 45 mm and (g) 50 mm. Video 1: parallel fall of 45 mm tungsten carbide spheres with superhydrophobic (left) or hydrophilic (right) surface. Video 2: parallel fall of 50 mm steel spheres with superhydrophobic (left) and hydrophilic (right) surface. The videos are shot at the lower part of the 2.5 meter water tank. The frame rate used was 1000 fps and the video playback speed was 30 fps. See DOI: 10.1039/x0xx00000x

surfaces that can naturally sustain a thin air layer under water, e. g. a plastron. Previously McHale et al.³ has investigated the drag reduction effect of such air layers, on the free fall of acrylic spheres with various superhydrophobic surface coatings, for the Reynolds number range of $Re = 10^4 - 3 \times 10^4$. A 5 to 15 % drag reduction was found but only for thicker plastron layers (50 to 250 μm) produces on spheres coated with coarse grains of hydrophobic sands.

In the present work we investigate the effect of a relevantly thin air layer ($\sim 1 - 2 \mu\text{m}$) that is easy to produce using commercially available superhydrophobic coatings. The range of sphere Reynold numbers investigated here, $Re = 3 \times 10^4 - 3 \times 10^5$, is closer to the drag crisis transition where the drag on the sphere is expected to be most sensitive to the surface mobility condition.

2 Experimental

In our experiments we use high-speed video imaging to monitor the fall of unmodified hydrophilic or superhydrophobic metal sphere in a 2.5 meter tall water tank (ESI Fig. S1). By processing the video recording we estimate the drag reduction effect of the thin air layer plastron sustained on the surface of the superhydrophobic spheres.

2.1 Spheres modification and plastron characterisation

The metal spheres were polished steel sphere ($\rho_s = 7.8 \text{ g/cm}^3$) sphere sizes, $2R = 20$ to 60 mm, or polished tungsten carbide ($\rho_s = 14.8 \text{ g/cm}^3$) sphere sizes, $2R = 20$ to 50 mm. After washing with ethanol and water the unmodified spheres surface was hydrophilic with a water contact angle $< 30^\circ$.

The surfaces of the metal spheres were made superhydrophobic by the application of a commercial glass coating: Glaco Mirror Coat Zero (Soft 99 Ltd., Japan) to which we will refer below as Glaco. The Glaco is an alcohol based dispersion of silica nanoparticles ($\sim 40 \text{ nm}$) coated with a silane hydrophobic agent. Details on the sphere coating process and surfaces characterisation can be found in our prior work.¹² In brief, the spheres are washed with the Glaco and dried at a temperature of about 160°C to help consolidate the coating. The coating process is repeated 2 to 4 times, resulting in excellent water repellency of the spheres surface with water droplet contact angle of more than 160° .

Fig. 1a is a picture of a superhydrophobic steel sphere shortly after immersion in water. The silver mirror shine appearance of the sphere is due to reflection from the thin air layer sustained on the superhydrophobic sphere surface. As shown in Fig. 2b taken about four hours after the sphere was immersed in the water the air layer dissolution with time results in the loss of the shiny appearance. All superhydrophobic sphere experiments were conducted with sphere freshly immersed in water.

Figure 2. (a) Photograph of a 50 mm superhydrophobic steel sphere shortly after the sphere is immersed in water. The silver shine appearance of the sphere is a signature of the thin air layer sustained on the superhydrophobic surface. (b) The same sphere after four hours in still water. The loss of the shiny appearance is due to the plastron gradual dissolution in water.

Fig. 2a shows topographic image of the Glaco coating following four deposition cycles taken using an atomic force microscopy (AFM, Asylum Research MFP-3D). The typical valley to peak distances is less than one micron and we can assume that the effective thickness of the air plastron on our surfaces is of the same range of $\sim 1 \mu\text{m}$. As shown in prior studies^{3,22} the characteristic roughness of the surface is a good upper limit estimate for the effective thickness of the plastron layer.

The thickness of the plastron was further evaluated by AFM force measurements performed over a flat superhydrophobic surface sample immersed in water. The cantilever used in the measurements (MikroMasch, CSC36/Cr-Au) has a nominal spring constant of 2 N/m and a gold coated tip of about $15 \mu\text{m}$ of height. Fig. 2b shows a typical force vs. piezo displacement curve, depicting the interaction of the cantilever tip with the substrate during the AFM force measurement approach (red line) and retraction (blue line) cycle. The scan starts with the tip placed several microns above the plastron meniscus (branch A in Fig. 2b). The moment the tip contacts the air-water meniscus (B), the strong capillary force pulls the tip and it jump-in in hard-wall contact with the surface (C). In the begging of the retraction the tip is kept in hard-wall contact with the substrate (D) by the capillary adhesive force until it snaps back (E) from the surface. The plastron thickness, δ_p is estimated as the distance between the tip jump-in position and the neutral force hard-wall contact position (dashed line double arrow on Fig. 2b).

Figure 3. (a) An AFM 3D image of the Glaco coated surface topology taken over $60 \times 60 \mu\text{m}$ area. In this case four cycles of Glaco coating were repeated. (b) AFM force curve vs piezo displacement, ΔX taken above the plastron covered substrate. The force curve branches correspond to: (A to C) piezo extension during which the tip approaches the surface (red line): (A) free cantilever approaching the surface; (B) cantilever jump-in toward the surface upon the tip contact with the plastron; (C) cantilever in hard-wall contact with the surface; (D to F) piezo retraction pulling the tip away from the surface (blue line): (D) cantilever tip in hard-wall contact with the substrate; (E) the cantilever detaches from the surface plastron; (F) free cantilever moving away from the surface. The plastron layer thickness, δ is estimated as the distance between the jump-in position and the zero force hard-wall contact position. Notice that parts of the force curve are out of the force detection range of -3 mN to $+3 \text{ mN}$.

In the example given in Fig. 2b, $\delta_p \sim 1 \mu\text{m}$. Placing the tip over different sample locations we measured the plastron thicknesses in the range of $0.3 \mu\text{m}$ to $2.0 \mu\text{m}$. In all our cases the plastron layer thickness is therefore around one micron. This is far thinner than the plastron layer thickness needed to trigger the drag reduction effects in the work of McHale et al.³ (50 to $250 \mu\text{m}$) or by using Leidenfrost vapor layers^{14–16} (50 to $150 \mu\text{m}$).

2.2 Sphere free fall in water experiments

The water tank in which the sphere free fall experiments were conducted was custom manufactured by ChangTong Science and Technology (TianJin) Co. LTD, China. A photograph of the tank is given in ESI Fig. S1. The tank is 2.5 m tall and has a cross-section of $40 \times 40 \text{ cm}$. The two side walls of the tank are glaze-fortified glass windows giving the possibility to monitor the entire fall of the sphere in the tank. All experiments were conducted in water at room temperature of about 21°C .

The spheres were carefully dipped in the water and release from just below the water surface. The sphere fall in the tank was recorded using a high-speed video camera (Photron-Fastcam SA-5) with a typical filming rate of 1000 fps . The sphere trajectory coordinates vs. time and the corresponding instantaneous velocity were determined by image processing the videos with the camera software (Photron FASTCAM Viewer, PFV Ver.3670).

Each experiment for given sphere and surface modification was repeated at least three different runs, with typical data spread reflected by the error bars in Fig. 4.

2.3 Determination of the drag coefficient

The motion of a sphere during the free fall in a still Newtonian fluid is described by the classical Basset-Boussinesq-Oseen (BBO) equation, which for the high velocity range considered here, can be written in the form:^{23–25}

$$m_s \frac{dU}{dt} = (m_s - m)g - \frac{C_D}{2} \rho \left(\frac{\pi D^2}{4} \right) - k m_s \frac{dU}{dt} - \frac{3}{2} D^2 \sqrt{\pi \rho \mu} \int_0^t \frac{dU}{\sqrt{t-\tau}} d\tau \quad (1)$$

where g is the acceleration due to gravity, m_s is the sphere mass, m the mass of the displaced fluid, k is the added mass coefficient (for a sphere $k \approx 0.5$). The left-hand side of the equation is the sphere inertia force. The right-hand side first, second, third and fourth terms are respectively the submerged weight, drag, added mass and Basset history force.

If the drag coefficient dependence on the velocity is known, for the entire range of the sphere fall, the BBO equation can be solve numerically to predict the sphere velocity evolution with time.²³ Conversely, if the velocity dependence on time is known, the BBO equation can be used to estimate the instantaneous drag of the sphere falling with acceleration. For the higher velocity range considered in our experiments the Basset history force has been shown to be insignificant (less than 1%) and can be omitted.²³ In such cases from eqn 1, the drag coefficient can be approximated as:

$$C_D = \frac{4D}{3\rho U^2} ((\rho_s - \rho)g - (\rho_s + 0.5\rho) \frac{dU}{dt}) \quad (2)$$

For a sphere falling at terminal velocity U_T , this equation converges to the expression for steady free fall velocity:

$$C_D = \frac{4D}{3\rho U_T^2}(\rho_s - \rho)g \quad (3)$$

that can be derived from the balance between buoyancy, gravity and drag forces.

For all of the spheres studied the experimental velocity vs. time dependence can be fitted well by the exponential form:

$$U = U_T(1 - e^{-t/\tau}) \quad (4)$$

This exponential form has been used before to predict the terminal velocity of sphere for the case where, the sphere is still accelerating at the bottom of the tank and has not reached the terminal velocity, U_T .¹⁹ However, here we limit the use of eqn 4 only as a smoothing function for the experimentally observed U vs. t dependencies, during the sphere fall in the 2.5 meter tank (Fig. 3 and SPI Figs. S2 and S3). Respectively, all the drag coefficients data points presented in Fig. 4 where calculated using eqn 2 by taking the values of $U = U_{\text{Max}}$ measured close to the bottom of the 2.5 tank and the corresponding dU_{Max}/dt values evaluated from the experimental U vs. t dependence.

Results and Discussions

Examples for the progression of the sphere velocity with time, during the spheres fall in the 2.5 m water tank, are shown in Fig. 3. Fig. 3a compares the fall velocity of 30 mm unmodified hydrophilic steel sphere (no gas layer) with 30 mm superhydrophobic steel sphere (plastron) and Fig. 3b shows the same comparison for the case of 50 mm steel spheres. Unmodified and superhydrophobic sphere velocity vs. time data for the entire range of the spheres size used in our study are given in the SPI Fig. S2 for the 20 mm to 60 mm steel spheres and SPI Fig. S3 for the 20 mm to 50 mm tungsten carbide spheres.

As demonstrated in the typical example in Fig. 3a for the smaller size spheres (20 mm to 40 mm steel; 20 mm to 30 mm tungsten carbide) we measured almost identical velocities for the unmodified and superhydrophobic spheres. However, for the larger spheres (45 mm to 60 mm steel; 35 mm to 50 mm tungsten carbide) the plastron-covered superhydrophobic spheres fall significantly faster when approaching the bottom of the tank as can be seen in SPI Video 1 for 40 mm tungsten carbide sphere and SPI Video 2 for 50 mm steel spheres. In the Fig. 3b example for the case of 50 mm steel sphere, the velocity of the superhydrophobic sphere close to the bottom of the tank is more than 50% higher than the velocity of the unmodified sphere.

Fig. 3. Progression of the sphere velocity with time during the free fall in the 2.5 meter water tank for: (a) 30 mm superhydrophobic (red squares) or hydrophilic (blue circles) steel sphere and (b) 50 mm superhydrophobic or hydrophilic surface steel sphere. The solid line for each data set is a formal fit with the exponential form given by eqn 4. All sphere sizes velocity vs. time data are given in SPI Fig. S2 for the steel spheres (20 mm to 60 mm) and in SPI Fig. S3 for the tungsten carbide spheres (20 mm to 50 mm). See also SPI Video 1 for the 45 mm tungsten carbide spheres and SPI Video 2 for the 50 mm steel spheres.

In control runs the large superhydrophobic spheres were plasma treated to eliminate the hydrophobic coating and the related plastron from the sphere surface. The fall velocity of the spheres in this case was identical with the fall velocity of the unmodified hydrophilic sphere, confirming that the observed drag reduction effects are due to the thin air layer on the spheres surface and not to its roughness.

Fig. 4 presents the results of our experiments in terms of the drag coefficient, C_D vs Reynolds number, dependences for the unmodified (no gas layer) and superhydrophobic surface (plastron) spheres. Each data point is calculated from the experimentally measured sphere velocity and acceleration close to the bottom of the 2.5 m tank using eqn. 2 for the drag coefficient.

Figure 4. Dependence of the drag coefficient on the Reynolds number for steel and tungsten carbide spheres falling in water. Open blue triangles are for hydrophilic steel spheres (20, 25, 30, 40, 45, 50 and 60 mm). Open blue squares for hydrophilic tungsten carbide spheres (20, 25, 30, 35, 40, 45 and 50 mm). Solid red triangles and solid red squares are for the respective superhydrophobic steel and tungsten carbide spheres freshly immersed in water and covered by a plastron. Both sets of results are calculated using eqn 2 with the sphere velocity and acceleration taken at the end of the 2.5 m water tank fall. Literature values for smooth solid steel spheres falling in an "infinite" tank measured by White²⁰ are shown as crosses.

The data in Fig. 4 show an early drag crises transition for the plastron covered superhydrophobic spheres, starting from $Re \approx 1.2 \times 10^5$, which is significantly lower than the transition for the case of smooth hydrophilic spheres, occurring at $Re \approx 2.5 \times 10^5$. Data for both steel and tungsten carbide spheres seems to fall on the same master curve with drag reduction reaching about 80 % for the largest spheres (50 – 60 mm steel, 40 - 50 mm tungsten carbide). This range of drag reduction is similar to the one achieved by traditional methods to promote early drag crises as surface roughening,^{19,26} polymer addition^{19,20,23} or mass transfer.²¹

Earlier experiments with spheres covered with Leidenfrost vapor layer falling in heated 95 °C water, have demonstrated an early drag crisis transition at Reynolds numbers as low as $Re \sim 2 \times 10^4$ and a similar range was observed for Leidenfrost spheres falling in the perfluorocarbon liquids, FC-72 or PP1 for which viscosity is close to that of water.¹⁴⁻¹⁶ The extended Re range of drag reduction for Leidenfrost spheres in comparison to the superhydrophobic spheres studied here is expected because of the substantial difference in the thickness of the gas layers: ~ 50 - $100 \mu\text{m}$ for the Leidenfrost vapor layer¹⁴⁻¹⁶ vs. $\sim 1 \mu\text{m}$ for the present air layer sustained on the superhydrophobic surface. Furthermore, the Leidenfrost gas layer fully separates the liquid from the sphere surface, whether the air plastron is pinned to the asperities of the superhydrophobic surface texture.

The drag on bluff bodies (sphere) moving in liquid is composed of two major components: one is the pressure-induced form or wake drag and the other is the viscous or skin friction drag. The plastron on superhydrophobic surfaces can affect both of these components. However, the drag on the sphere for the pre-drag crises Reynolds numbers range investigated here ($Re \sim 3 \times 10^4$ -

3×10^5) is dominated by the pressure drag component, with the friction drag component accounting for less than 5% of the total drag on the sphere.^{18,27} Respectively the large drag reduction observed in our experiments is mostly due to the plastron effect on the form drag. The characteristic signature for the drag crisis transition is the move of the separation point of the sphere wake from the equator of the sphere toward the rear, thereby reducing the pressure drag. On smooth solid spheres this delayed separation is triggered by turbulent transition in the viscous boundary layer. Although the same shifting of separation point to the sphere rear, is observed in the case of Leidenfrost vapor layers,^{14,16} the underlying physical mechanism is quite different and relates to the effect of the slip boundary condition on the flow patterns around the sphere.

It is important to stress that although the effect of a thin air layer, naturally sustained on superhydrophobic surfaces, on the drag of bluff bodies moving in liquids has been often anticipated the actual extend of the effect for the high Reynolds number range approaching the drag crisis transition has not been demonstrated or quantified so far. Numerical simulations modelling the result of the Leidenfrost vapor layer experiments has shown that a Navier slip length model can be successfully used to relate the gas layer drag reduction to an effective slip length.^{16,27} The simulations predict that the drag reduction effect is a very sensitive function of the Reynolds number and the scaled slip length, which in turn depends on the gas layer thickness and vapor to liquid viscosity ratio. The present data provide further opportunities to develop and test such models by covering a range of much thinner gas layer thicknesses that have not been studied before, and which are relevant for a wide range of practical applications.

Finally we notice that the drag reduction capability of the plastron depends on the time the surface has been immersed in water. Drag reduction experiments here were conducted with spheres freshly immersed in water. At the same time the air plastron was observed to gradually dissolve in a few hours span (Fig. 1b), which can result in the loss of the drag reduction capacity. The development of novel superhydrophobic surfaces with extended plastron resistivity and plastron recovery strategies is an area of intense current research efforts.²⁸⁻³⁴ We believe that the present experimental methodology can be used to validate the sustainability of the drag reduction effect on these novel surfaces.

Conclusions

We investigated the effect of thin air layers naturally sustained on textured superhydrophobic surfaces by measuring the fall velocity and drag on metallic spheres with hydrophilic and superhydrophobic surface free falling in water. Using a large, 2.5 meter high water tank enables us to conduct experiment over a range of Reynolds numbers approaching the drag crisis transition where the drag on the sphere is most sensitive to the surface conditions. It was found that the drag on the bigger superhydrophobic spheres was dramatically reduced by up to 50 - 80 % by triggering an early drag crisis at $Re \sim 1.2 \times 10^5$, which is substantially lower than the corresponding drag crisis occurring for smooth solid spheres. The experiments demonstrate that even a very thin air layer (~ 1 - $2 \mu\text{m}$) can significantly affect the flow patterns around bluff bodies at the

drag crisis transition range. These results complement early results obtained using thicker dynamic Leidenfrost vapor layers and could have important implication in the development of gas-layer-lubrication based drag reduction strategies.

Conflict of interest

The authors declare no conflict of interest.

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Drag crisis moderation by thin air layers sustained on superhydrophobic spheres falling in water

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Table of content entry:

A thin air layer sustained on the surface of superhydrophobic spheres can reduce drag by up to 80%.