Complete Electrolytic Plastron Recovery in a Low Drag Superhydrophobic Surface

*Ben P. Lloyd\*†, Philip N. Bartlett‡, Robert J. K. Wood†*

†National Centre for Advanced Tribology at Southampton (nCATS), University of Southampton, SO17 1BJ, UK

‡Chemistry, University of Southampton, SO17 1BJ, UK

# Abstract

We present a superhydrophobic surface capable of recovering the lubricious gas layer known as the ‘plastron’ from a fully wetted state underwater. It is shown that full plastron recovery is possible without a second layer of structural hierarchy which is prone to irreversible wetting transitions. This allows us to use a cheap, fast and potentially scalable method to fabricate the surface from silicone and carbon black in a moulding process. We demonstrate plastron recovery from the fully wetted state and immediate plastron recovery after pressure induced wetting transitions. The wetting state can be measured remotely and quickly by measuring the capacitance. The slip length is measured as ~135 µm, agreeing well with the theory given the geometry of the surface. The ability of the surface to conform to small radii of curvature and withstand damage from loading is also demonstrated. The work presented here could allow superhydrophobic surfaces to reduce drag on ships and in pipes where the plastron would otherwise rapidly dissolve.

# Keywords

Superhydrophobic, low drag, dewetting, plastron recovery.

# Introduction

As a large ship passes through the water up to 70% of the fuel is burned to overcome skin friction drag acting on the hull(1) and in hydroelectric facilities skin frictional drag can cause energy losses of up to 20%.(2) Superhydrophobic surfaces can significantly reduce skin friction drag in laminar(3) and turbulent flows.(4) When submerged in water a lubricious gas layer is trapped on the surface by hydrophobic surface features, which leads to effective slip of water over the surface.(5) Superhydrophobic surfaces may be able to minimise these losses in real-world scenarios,(6) however before this technology could be adopted there are several problems which must be solved.

A significant obstacle for prolonged drag reduction using superhydrophobic surfaces is the inherent fragility of the gas layer trapped between the liquid and the solid also known as a ‘plastron’. It can be lost through excessive pressure difference between itself and the water which leads to an initial compression(7) and subsequent dissolution.(8) Once lost the plastron is hard to recover as generally the wetted state is thermodynamically more favourable.

A convenient measure of resistance to wetting is the critical depth, . This is the depth at which water pressure overcomes capillary pressure and dissolution of the plastron starts to occur. To make a superhydrophobic surface more resistant to wetting the geometry should be altered to reduce the pitch, , (the centre to centre spacing between channel walls) and reduce the gas fraction, , (the fraction of the surface occupied by the plastron averaged over a large area of the surface) as shown in equation 1.(9)

|  |  |  |
| --- | --- | --- |
|  |  | **Equation (1)** |

Where is side wall contact angle, is the surface tension, is the liquid density and is acceleration due to gravity. Equation 1 is valid for the normal case where dissolved gases in the water are in equilibrium with the atmosphere. Figure 1 a)i) shows a superhydrophobic surface made of parallel channels and ii) identifies the defining parameters.

However this surface with small pitch and gas fraction which has good wetting resistance would be very poor at generating slip, the streamwise movement of the water at the liquid/gas interface. A large slip length, , is achieved with large pitch and large gas fraction as shown in equation 2.(10)

|  |  |  |
| --- | --- | --- |
|  |  | **Equation (2)** |

This dichotomy is shown graphically in figure 1, where isopleths of slip length and critical depth are plotted as a function of gas fraction and pitch for a surface consisting of parallel channels, which has been shown to be an effective superhydrophobic surface geometry for drag reduction.

Although there is a benefit in choosing large gas fraction and small pitch to maximise both properties, even in this ideal case critical depth and slip length still oppose one another. There is no point on this gas fraction/pitch landscape where we can achieve a desirable outcome of both large slip length and large critical depth, it will always be a compromise.





**Figure 1 a)i) Schematic of a surface consisting of parallel channels a)ii) Schematic of one channel with key parameters identified. b) Graph showing dependence of critical depth and slip length on the gas fraction and pitch of a superhydrophobic surface consisting of parallel channels. It is not possible to have both large critical depth and slip length. Isopleths of critical depth are calculated using equation 1 assuming a side wall contact angle of () of 110o and plotted in red. Isopleths of slip length are calculated using equation 2 and plotted in blue.**

Whilst passive methods such a sidewall texturing, where nano-sized structures are added to the sides of micro-sized structures, have shown that plastron loss from dissolution and pressure can be delayed (which acts to move the isopleths of critical depth upwards and rightwards in figure 1 by increasing in equation 1) ultimately plastron loss cannot be avoided.(11) Passive dewetting of conical pores is possible at ambient pressures. However this behaviour requires very small pores and thus would not generate a large slip length.(12)

If we accept there is no escaping the dichotomy presented in figure 1 a solution could be to employ a system where the plastron is actively maintained. If one had the ability to replenish the plastron the surface could be designed to prioritise large slip length over wetting resistance and accept that whilst the plastron is easily lost it could also be recovered on demand. Methods to generate a new plastron when submerged under water include chemical decomposition of hydrogen peroxide,(13) thermally induced supersaturation of gases in surrounding water,(14) thermal vapourisation,(15) pumping of pressurised air(16) and electrolysis(17-18). Very recently, the electrolysis has been shown to be powered by the corrosion of magnesium avoiding the use of an external power supply, however with the downside of having finite use due to consumption of magnesium.(19)

To this end, Lee and Kim used electrolytic gas evolution as an effective means of plastron replenishment.(17) To achieve successful plastron recovery they identified that the capillary pressures acting on the evolved gas must be lower for lateral spreading along the channels than vertical growth out of them. If this condition was not met the newly generated gas was lost as bubbles exiting the top of the surface. A caveat to their surface design was that a nano-sized superhydrophobic base must be used between the micro-sized superhydrophobic structures and that the plastron of this nano-sized superhydrophobic base must stay intact for full plastron to be recovered, figure 2. This meant that the plastron could not be recovered when the surface was fully wetted. If for some reason this became wetted *eg.* from a prolonged period without active gas generation, large pressures generated by waves or water with low dissolved gas concentration, then the surface would not be able to recover, thus irreversibly losing its low drag properties.



**Figure 2 Successful and unsuccessful plastron recovery in a channel with superhydrophobic base viewed looking through the side of a channel. When the base becomes fully wetted the plastron cannot be recovered. a)i) shows the native gas film present in the channel ii) the channel is wetted however the plastron of the nanostructured base remains intact. iii) gas is generated and as the forces opposing lateral growth are less than forces opposing vertical growth, the plastron fills the channel. In b)ii) the nanostructured base is wetted. iii) when gas is generated the forces opposing lateral growth are greater than forces opposing vertical growth so the plastron is lost as bubbles from the top of the channel.**

Another more practical problem for large scale drag reduction is how one might make a surface which can be produced in large areas at reasonable cost so that it could coat something as large as a ship. To give an appreciation of the areas required a Maersk triple E has a wetted area of 27,500 m2.(20) Most low drag superhydrophobic surfaces have been made using cleanroom techniques on the order of centimetres squared which could not be scaled to produce large areas at low cost. Furthermore these surfaces are often made of silicon which would not conform to the hull and surfaces features could be easily damaged.

In this paper we demonstrate that the need for a nanostructured base as used by Lee and Kim(17) can be avoided in some situations. This has the significant benefit that the plastron can be recovered by electrolysis even when the surface has been fully wetted and therefore ensure that drag reduction will not be compromised, which has not previously been demonstrated. Further to this the fact that we do not need to use a nanostructured base means the fabrication of our surface is easy, economic and fast to make. We also demonstrate: immediate recovery when the plastron is partially removed by an impinging water jet, fast and accurate sensing of the wetting state by measuring surface capacitance, measurement of the slip length and the surface’s mechanical flexibility and damage resistance to loading.

# Results and Discussion

## Plastron Recovery without a Superhydrophobic Base

To successfully recover the plastron the capillary pressure must be lower for lateral spreading than vertical spreading, otherwise the newly generated gas will be lost as bubbles. This criterion can be expressed in terms of the minimum channel height to pitch ratio which would lead to the desired capillary pressures, shown in equation 3.(17) In the work of Lee and Kim h/pmin was only considered as a function of gas fraction.

|  |  |  |
| --- | --- | --- |
|  |  | **Equation (3)** |

Here, in figure 3 we show equation 3, the minimum height/pitch ratio as a function of the base contact angle for typical values of ϕg = 0.9 and θs = 110o. This clearly shows that horizontal spreading is very much possible without the need for a superhydrophobic base and is possible even using a hydrophilic base and reasonable h/p aspect ratios.



**Figure 3 Regimes of successful and unsuccessful plastron recovery shown as the minimum channel height to pitch ratio as a function of base contact angle. Plotted using equation 3 for a sidewall contact angle of 110o. Plastron recovery should be possible even with a hydrophilic base at reasonable channel height to pitch ratios.**

## Fabrication of Surface

Removing the requirement for a superhydrophobic base allows us to use a moulding process to generate the surface, shown schematically in figure 4a). An acrylic (lucite) mould is used where channels have been machined using a CNC router. Poly(dimethylsiloxane) (PDMS) is used to fill the channels in the mould by pulling the uncured liquid PDMS over the mould using a rubber ‘squigie’, these regions become the walls of the channels. After curing the mould is lightly polished with water and a fine polishing cloth to clean away any excess PDMS remaining on the top of the mould. A layer of conductive PDMS is applied over the top of the PDMS filled channels and a wire is embedded; this is the base of the surface. After curing the surface is de-moulded and the exposed areas of the conductive silicone are covered by PDMS to be electrically insulative. Figure 4 b) shows a 3d microscope image of the resulting surface.



**Figure 4 a) Fabrication of the surface using a moulding process. i) A mould is created ii) liquid PDMS fills the channels in the mould and is left to cure iii) excess PDMS is cleaned from the top of the mould iv) PDMS and carbon black mixture with embedded wire covers the top of the mould and left to cure v) the surface is de-moulded. b) Optical height image of the surface. c) Contact angle measurements of water drops on the surface. i) Measuring the contact angle perpendicular to the channel gives a contact angle of 162o ii) parallel to the channels gives a contact angle of 130o.**

Poly(dimethylsiloxane) (Sylgard 184 from Dow) is used for the side wall for its high contact angle (110o), and electrically insulative properties. For the base we used a poly(dimethylsiloxane) and carbon black composite (Vulcan xc-72 R 20% by weight in Sylgard 184) which had a reasonable receding contact angle of 65o and good electronic conductivity. We used a wall thickness of 200 µm at a pitch of 600 µm with a height of 850 µm. This gives a gas fraction of 0.66. From equation 3 the h/pmin is 0.92, the h/p of our surface was 1.42, capable of recovery if the expanding plastron was pinned to a maximum of 55 degrees. Using equation 1 the critical depth is 12.5 mm. Using equation 2 the slip length is 134 µm.

Interestingly we see that the contact angle on this surface is heavily dependent on the orientation to the channels, figure 4 c). We observe a contact angle of 162o when measuring perpendicular to the channels and 130o when measuring in the parallel direction, a similar phenomenon to the crystal face dependant spreading in earlier work. (21)

Our fabrication method overcomes two key challenges when making such a surface. Firstly there is good selectivity over where the two components are located, it is important that no insulative PDMS covers the conductive PDMS. During fabrication, when filling the channels in the mould a very thin layer of insulative PDMS also covers the top of the mould. This was easily sheared off with light polishing without removing the PDMS in the channels ensuring that the conductive PDMS was fully exposed on the base. Secondly there is excellent adhesion between the walls and the base – this was hard to achieve due to the necessarily low surface energy of the wall material, however this was not a problem when using a silicone for both wall and base. Furthermore, silicones are already established as a ‘foul release’ type anti fouling coatings on ships, *eg.* Hempel Silic One, and therefore represent a reasonable material; choice for this application.

By basing the fabrication on a moulding process the time consuming process of micro structuring the surface is only required once. Replicas of the mould are fast to produce and do not lead to degradation of the mould. Several samples were made using the method described here all of which behaved similarly, one of these samples was characterised in depth to assess full plastron recovery, immediate partial plastron recovery and sensing of the wetting state.

## Full Plastron Recovery

The dewetting performance of the surface was investigated by submerging in 10 mm of 0.06M NaCl solution and displacing the plastron. A potential difference of -10 V vs Pt wire was applied to the surface to run the electrolysis reaction and platinum gauze was used at the counter electrode. The process was filmed from above using a camera mounted to a macroscope.

Figure 5 shows the current transient as the plastron is recovered with images of the process shown below. A video of this process is available in the supplementary information S1. We see that initially as the potential is applied and electrolysis begins, many small bubbles are generated on the conductive PDMS. As they grow they start to coalesce into larger bubbles through an Oswald ripening type process until only two gas domains occupy each channel with a small area of base exposed between them. Due to reduced base area and blocking by the adjacent bubbles the gas evolution slows down throughout the process with coalescence of the last two bubbles in each channel taking the longest to occur. When the channel is filled with gas the base is fully blocked from the solution preventing the further passage of current. The average and standard deviation of time to dewet is 42 ± 11 s, average charge required is 367 ± 56 mC cm-2 and average energy 3.67 ± 0.56 j cm-2, based on three full plastron recoveries. Further example full dewetting data is available in the supporting information, figures S1 and S2.



**Figure 5 Full plastron recovery from a fully wetted state. The graph shows the current transient when a potential of -10 V is applied to the surface. Images below the graph show the growth and coalescence of bubbles to recover the plastron. As the circuit is closed small bubbles are formed which coalesce into larger bubbles until the plastron is recovered with blocks the conductive base and prevents further gas evolution.**

## Immediate Partial Plastron Recovery

The ability to restore a partially compromised plastron immediately after a pressure induced wetting transition was also investigated. Figure 6 shows the current transient and images of the process, a video is available in the supplementary information. Initially the plastron is intact, the potential of the surface is held at -10 V but no current is drawn as the plastron blocks the conductive base. At 2 s the plastron is partially removed exposing the conductive base and immediately generating gas by electrolysis for 11 s before the plastron is fully recovered, returning the current to zero. Further example immediate partial plastron recovery is available in the supporting information, figure S3.

****

**Figure 6 Immediate recovery when the plastron is displaced by a water jet and the surface held at a potential of -10 V. The graph shows the current transient and images shows the process below. Initial no current passes but when the plastron is partial removed the current increases, generating more gas which recovers the plastron.**

## Sensing of wetting state

To demonstrate remote measurement of the wetted state capacitance measurements were used in a similar manner to our previous work.(18) This method could be useful to quickly asses the integrity of the plastron without the need for a direct visual observation. To show the relationship between capacitance and wetted area the surface was wetted in a stepwise fashion, removing small amounts of plastron over several steps and measuring the capacitance and the wetted area at the base of the channels from the macroscope image. Figure 7 shows strong linear relationship between the two, where the gradient gives a capacitance density of 0.88 µF cm-2. The proportional scaling allows fast and accurate analysis of the wetting state without the need for direct visual access.



**Figure 7 Sensing of the wetting state using capacitance measurement. By displacing the plastron in a stepwise manner we observe a proportional relationship between wetted area and capacitance.**

## Slip Length Measurement

The slip length of water over the surface was measured with a rheometry system using a 6 cm diameter cone, based on the method shown by Choi and Kim by converting the torque measurement to a slip length.(22) A sample was fabricated with the same channel geometry as before (*p* = 600 µm, *ϕ* = 0.66) but in a concentric arrangement so that the channels were always arranged parallel to the flow. Support structures joining adjacent channels were introduced to channels longer than 13.4 mm to improve wall stability.

The slip length of water over a flat surface and over our superhydrophobic surface is shown against shear rate in figure 8a) and a 3d confocal microscope image is shown for the sample used for the measurements in 8b). The measured slip length shows some change with shear rate as also seen by Choi and Kim(22) and is ~ 135 µm which shows good agreement with equation 2. We see that the flat steel surface measured as a control holds the no-slip condition as expected. There was no difference in slip length between the ‘native’ plastron and recovered plastron. This slip length is large enough to reduce drag in macro sized laminar flows with boundary layers of the order of millimetres. We would also expect a significant reduction to drag in turbulent flows, which also scales with pitch and gas fraction.(4)



**Figure 8 Measurement of slip length over the surface. a) A good agreement between the experimental data, measured using a rheometry system and theory, using equation 2. Our surface produces a slip length of ~135 µm compared to a flat surface which holds the no-slip condition as expected. b) a height image of the test sample used for slip measurements, 6 cm in diameter with concentric channels.**

## Flexibility and Damage Resistance

Due to the silicone based construction the surface can deform elastically without damage and return to its initial shape. Figure 9 shows a submersed sample bent to a radium of curvature of ~ 1 cm. This property would allow the surface to conform to a wide range of shapes *eg.* the hull of a boat or a pipe without modification to the manufacture process. To simulate a collision with another body we used an indentation test loading a 6 mm diameter steel sphere on the surface. We found the loads of up to 50 N (load rate of 50 N s-1) could be withstood without damage or effect to the dewetting performance.



**Figure 9 Demonstration of the flexibility of the surface. The photo shows a sample bent to a radii of curvature of ~1 cm.**

# Discussion and Conclusion

This work has showed that it is possible to recover the plastron from a truly fully wetted state and without the need for a superhydrophobic base, which has not previously been demonstrated. This means that there is no possibility of failed plastron recovery as in the case where a nanostructured superhydrophobic base is used.

Our surface has a significant slip length of 135 µm, large enough to reduce drag in laminar flows around macro-sized objects. We would also expect a large reduction to drag in turbulent flows.

We have also demonstrated other important engineering aspects to this surface. The wetting state of the surface can be quickly measured through analysis of the capacitance. Remote sensing of the plastron integrity would no doubt be important in real world scenarios. We have also shown good damage resistance thanks to the silicone construction deforming elastically under load. This is an important consideration as minor collisions with debris in the ocean is a frequent occurrence. Hypothetically, the surface could be powered by the cathodic protection systems already present in ships and pipes which are used to prevent corrosion by holding the structures at cathodic potentials.

Further improvements to decrease the resistance of the base material could reduce the energy required to run such a system. The general approach presented in this work could be a viable route to bring sustained underwater drag reduction to ships and pipes.

# Experimental Methods

## Fabrication of Surface

The mould was manufactured by routing channels into lucite acrylic using a 200 µm diameter cutter.

A platinum curing silicone compound, Sylgard 184 by Dow was used for the channel walls, in a 10:1 base:curing compound mix ratio. The Sylgard 184 was mixed by hand for 2 minutes then degassed under vacuum to remove any bubbles. The mixture was applied to the mould using a flexible silicone spatula and spread to fully fill the channels and remove any excess from the top of the mould, so that the silicone in the channels was flush with the top of the mould. The mould was placed in an oven at 80 oC for 4 hours to fully cure the silicone. After letting the mould to cool to room temperature, a lint-free polishing cloth was used to remove any small amount of silicone on the top of the mould between the channels filled with cured silicone.

The base comprised of the same Sylgard 184 in 10:1 mix ratio which was mixed by hand for 10 minutes with 20 % by weight Vulcan XC 72R by Cabot Corp, a high electronic conductivity carbon black powder, until a homogenous mixture was obtained. The mixture was degassed under vacuum to remove any bubbles then applied to the mould using a silicon spatula to coat the silicone filled channels fully at a thickness of around 2 mm. The plastic insulation from a stranded metal wire was stripped from the last 1 cm of the wire and the strands spread apart. The stripped end of the wire was placed on the uncured silicone and carbon black mixture and further 2 mm of the mixture was added to fully encase the end of the wire. Samples were cured at a temperature of 80 oC for 4 hours. After letting cool to room temperature the sample was demoulded. To insulate the back and sides of the sample Sylgard 184 in 10:1 mix ratio was carefully spread over these areas in a thin film, which was cured at a temperature of 80 oC for 4 hours after which the sample was ready to use.

Contact angle measurements were made using a Krüss DSA100 contact angle apparatus.

## Dewetting and Capacitance Experiments

An Autolab PGSTAT302N with FRA32M module was used for all dewetting and capacitance measurements. The potential was measured against a platinum wire as a quasi-reference electrode. A large area platinum gauze electrode was used for the counter electrode. For capacitance measurements electrochemical impedance spectroscopy was used by scanning ten frequencies between 1000 and 10000 Hz with potential modulation of ±5 mV about a potential of -0.4 V vs Pt wire reference. A Randle’s circuit was fitted to the data from which the capacitance was obtained.

## Rheometry

The rheometer used was an AR2000 by TA Instruments. Before the measurements were taken a full calibration was undertaken and confirmed with testing of a reference oil. The same precautions were taken to reduce the errors discussed as in Choi and Kim(23). A cone of 6 cm diameter, 2o cone angle and 53 µm truncation was used. The temperature controlled plate was held at 20 oC.

# Supporting Information

Video showing full dewetting and immediate partial plastron recovery, graph showing repeat data for full plastron recoveries, graph showing multiple partial plastron recoveries.

# Author Information

## Corresponding Author

Ben P. Lloyd - National Centre for Advanced Tribology at Southampton (nCATS), University of Southampton, SO17 1BJ, UK. Email: benlloyd424@gmail.com

## Notes

The authors declare no competing financial interest.

# Acknowledgements

We gratefully acknowledge Dr. Maria Salta and Dr. Marta Roldo of University of Portsmouth for allowing us to access their rheometry system.

This work was funded by EPSRC ‘Green Tribology’ (EP/J001023/1)

# Data Statement

All data supporting this study are openly available from the University of Southampton repository at https://doi.org/10.5258/SOTON/xxxxx

# References

1. Fukuda, K.; Tokunaga, J.; Nobunaga, T.; Nakatani, T.; Iwasaki, T.; Kunitake, Y., Frictional drag reduction with air lubricant over a super-water-repellent surface. *J. Mar. Sci. Technol.* **2000,** *5* (3), 123-130.

2. Nogueira, H. I.; Pfister, M.; Schleiss, A. J., Approaches to Reduce Friction Losses in Headrace Waterways of Hydropower Plants. *J. Hydraul. Eng.* **2016,** *142* (5), 02516001-1 - 02516001-9.

3. Ou, J.; Perot, B.; Rothstein, J. P., Laminar drag reduction in microchannels using ultrahydrophobic surfaces. *Phys. Fluids* **2004,** *16* (12), 4635-4643.

4. Daniello, R. J.; Waterhouse, N. E.; Rothstein, J. P., Drag reduction in turbulent flows over superhydrophobic surfaces. *Phys. Fluids* **2009,** *21* (8), 085103-1 - 085103-9.

5. Rothstein, J. P., Slip on superhydrophobic surfaces. *Annu. Rev. Fluid Mech.* **2010,** *42*, 89-109.

6. Xu, M.; Grabowski, A.; Yu, N.; Kerezyte, G.; Lee, J.-W.; Pfeifer, B. R., Superhydrophobic drag reduction for turbulent flows in open water. *Phys. Rev. Appl.* **2020,** *13* (3), 034056-1 - 034056-10.

7. Vüllers, F.; Peppou-Chapman, S.; Kavalenka, M. N.; Hölscher, H.; Neto, C., Effect of repeated immersions and contamination on plastron stability in superhydrophobic surfaces. *Phys. Fluids* **2019,** *31* (1), 012102-1 - 012102-10.

8. Poetes, R.; Holtzmann, K.; Franze, K.; Steiner, U., Metastable underwater superhydrophobicity. *Phys. Rev. Lett.* **2010,** *105* (16), 166104-1 - 166104-4.

9. Xu, M.; Sun, G.; Kim, C.-J., Infinite Lifetime of Underwater Superhydrophobic States. *Phys. Rev. Lett.* **2014,** *113* (13), 136103-1 - 136103-5.

10. Lauga, E.; Stone, H. A., Effective slip in pressure-driven Stokes flow. *J. Fluid Mech.* **2003,** *489* (8), 55-77.

11. Lee, C.; Kim, C.-J. C., Maximizing the giant liquid slip on superhydrophobic microstructures by nanostructuring their sidewalls. *Langmuir* **2009,** *25* (21), 12812-12818.

12. Jones, P. R.; Kirn, A. T.; Ma, Y. D.; Rich, D. T.; Patankar, N. A., The thermodynamics of restoring underwater superhydrophobicity. *Langmuir* **2017,** *33* (11), 2911-2919.

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

14. Simovich, T.; Rosenhahn, A.; Lamb, R. N., Thermoregeneration of Plastrons on Superhydrophobic Coatings for Sustained Antifouling Properties. *Adv. Eng. Mater.* **2020,** *22* (3), 1900806.

15. Saranadhi, D.; Chen, D.; Kleingartner, J. A.; Srinivasan, S.; Cohen, R. E.; McKinley, G. H., Sustained drag reduction in a turbulent flow using a low-temperature Leidenfrost surface. *Sci. Adv.* **2016,** *2* (10), e1600686.

16. Li, Z.; Marlena, J.; Pranantyo, D.; Nguyen, B. L.; Yap, C. H., A porous superhydrophobic surface with active air plastron control for drag reduction and fluid impalement resistance. *J. Mater. Chem. A* **2019,** *7* (27), 16387-16396.

17. Lee, C.; Kim, C.-J., Underwater restoration and retention of gases on superhydrophobic surfaces for drag reduction. *Phys. Rev. Lett.* **2011,** *106* (1), 014502-1 - 014502-4.

18. Lloyd, B. P.; Bartlett, P. N.; Wood, R. J., Active Gas Replenishment and Sensing of the Wetting State in a Submerged Superhydrophobic Surface. *Soft Matter* **2017,** (13), 1413-1419

19. Xu, M.; Liu, C. T.; Kim, C.-J. C., Self-powered plastron preservation and one-step molding of semi-active superhydrophobic surfaces. *Langmuir* **2020,** *36* (28), 8193–8198.

20. Heimann, M., Personal Communication ed.; Maersk Line Newbuilding: 2017

21. Lloyd, B. P.; Bartlett, P. N.; Wood, R. J., Wetting of surfaces made of hydrophobic cavities. *Langmuir* **2015,** *31* (34), 9325-9330.

22. Choi, C.-H.; Kim, C.-J., Large slip of aqueous liquid flow over a nanoengineered superhydrophobic surface. *Phys. Rev. Lett.* **2006,** *96* (6), 066001-1 - 066001-4.

23. Choi, C.-H.; Kim, C.-J., Choi and Kim reply. *Phys. Rev. Lett.* **2006,** *97* (10), 109602.

# For Table of Contents Only

