NOTTINGHAM TRENT UNIVERSITY

Immersed Superhydrophobic Surfaces: Anti-Fouling and Drag Reduction Surfaces

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Overview

1. Functional Superhydrophobic Surfaces

- Underwater/Plastron respiration
- Superhydrophobic sol-gel mimic

2. Anti-fouling Microfluidic Channels

- Protein adsorption and flow enhanced detachment

3. Flow Enhancement in Macroscopic Pipes

- Four tube comparison of surface finish effects
- Flow enhancement visualization experiment

4. Drag Reduction for Settling Spheres

- Terminal velocity experiment
- Plastron drag reduction

Functional Surfaces

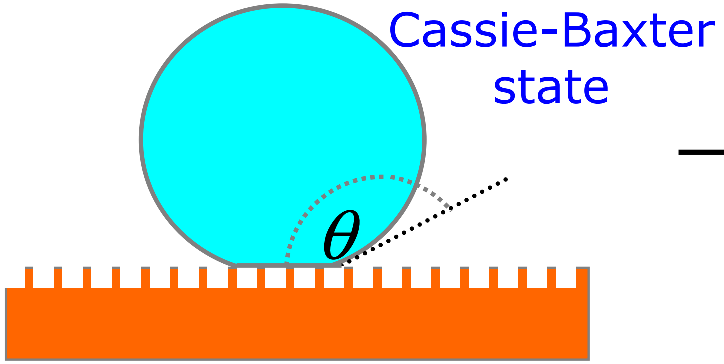
Underwater and plastron respiration

Superhydrophobicity and Plastrons

Immersed Superhydrophobic Surfaces

Provided design of features correct, penetration of water can be resisted

A silvery sheen can be seen when immersed – due to surface retained layer of air.



Plastron Respiration

Insect physiologists have studied immersed S/H surfaces since 1940's

Silvery sheen from air layer indicates an air-water interface, e.g diving spider - acts as a gas exchange membrane to extract oxygen from water and remove carbon dioxide from insect

Microcosmos © Allied Films Ltd (1996)

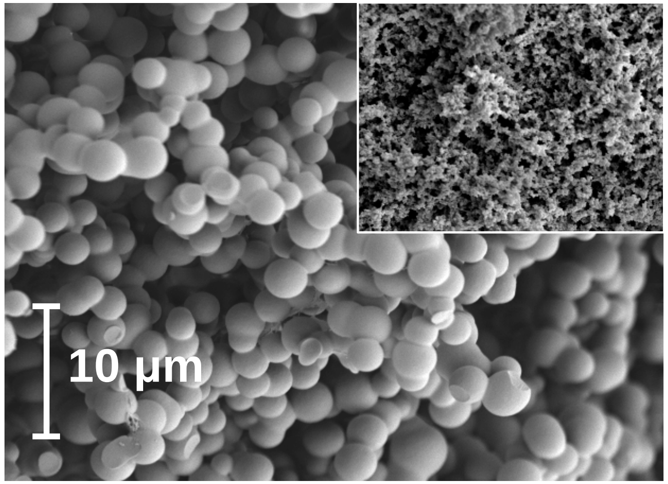
References

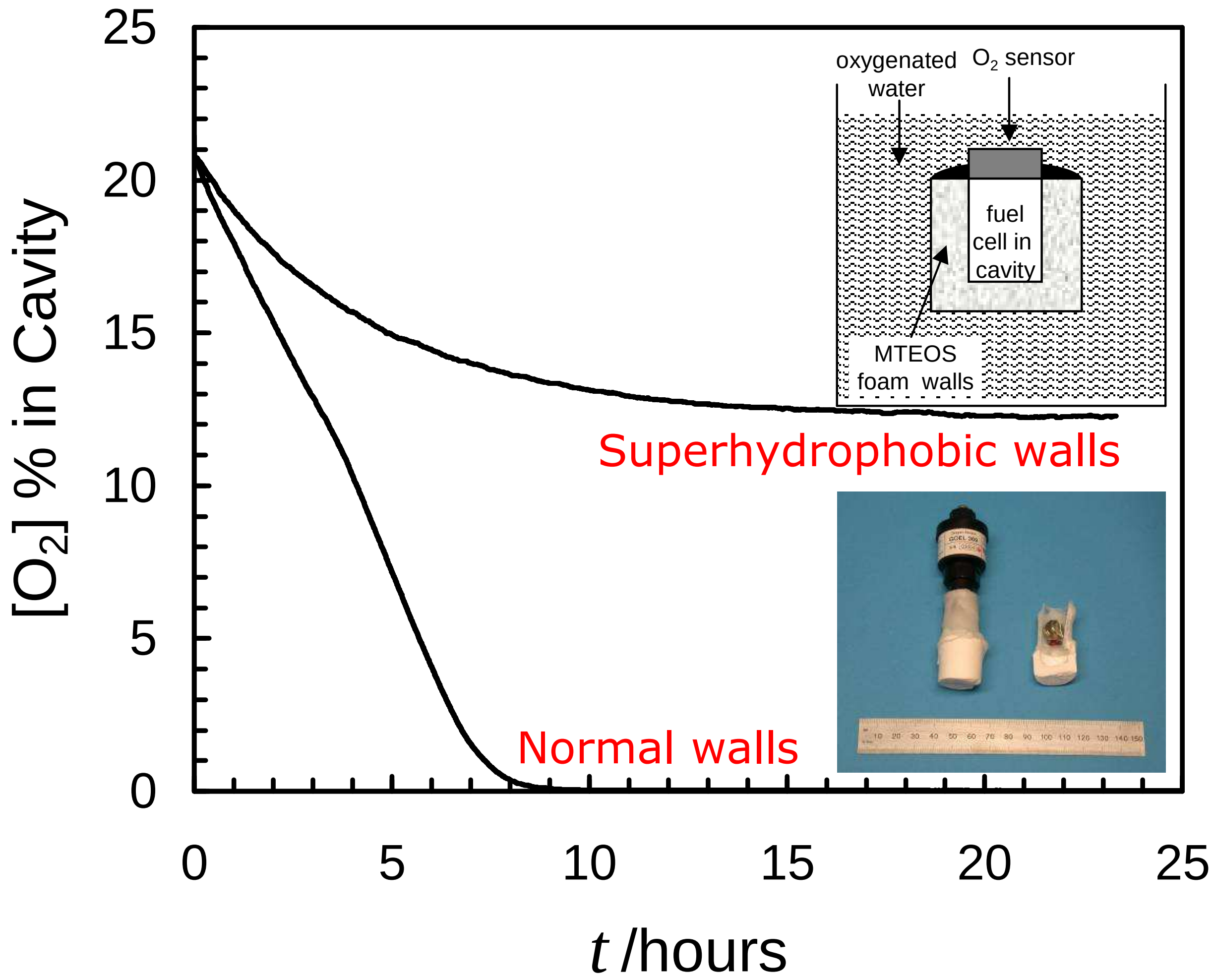
McHale, G., *et al*., Appl. Phys. Lett. 89 (2006) art. 104106.
Thorpe, W. H.; Crisp, D. J., J. Exp. Biol. 24 (1947) 227.

Plastron Biomimic

Intrinsically superhydrophobic MTEOS organo-silica sol-gel foam surfaces

Structure controllable from nano- to macro-porous





References: Shirtcliffe *et al.*, Langmuir 19 (2003) 5626-5631; Shirtcliffe, N.J.; McHale, G., *et al.*, Appl. Phys. Lett. 89 (2006) art. 104106.

Anti-fouling Surfaces

Protein Adsorption and Flow Enhanced Detachment

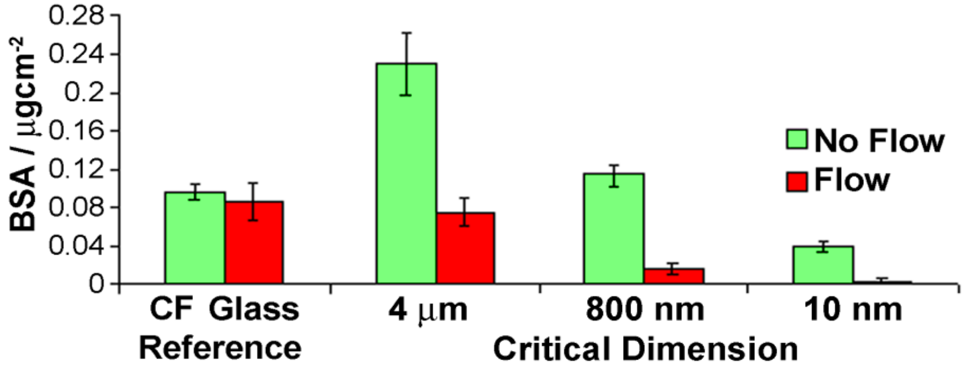
Biofouling and Superhydrophobic Channels

Superhydrophobic Surfaces Used

1. Glass slides
2. Sputter coated 200 nm Cu on 5 nm Ti on slides
3. Large grained (4 μm particles, 20 μm pores) superhydrophobic sol-gel on slides
4. Small grained (800 nm particles, 4 μm pores) superhydrophobic sol-gel on slides
5. CuO nanoneedles (10 nm) on Cu sheet

Proteins on Superhydrophobic Surfaces

1. Substrates incubated in BSA protein (15 nm in size) in phosphate buffer
2. Flow cell 1500μm x 650μm x 65mm using buffer solution
3. Fluorimetric assay to quantify protein removal



Fluorinated nanoscale superhydrophobic surfaces showed almost complete removal of protein under shear flow

Reference Koc, Y.; de Mello, A.J., McHale, G.; Newton, M.I.; Roach, P.; Shirtcliffe, N.J. Lab on a Chip 81 (2008) 582-586.

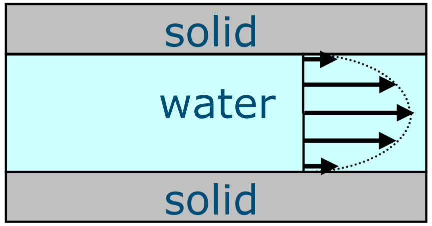
Flow Enhancing Surfaces

Superhydrophobic Tubes

Flow in Pipes with Superhydrophobic Walls

Concept

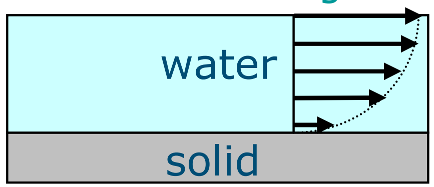
Closed-channel



Two walls cause
frictional drag

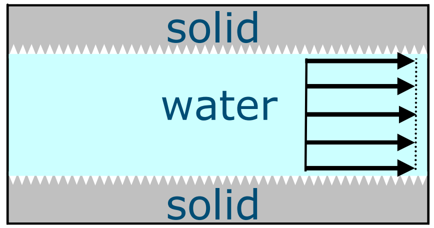
Open-channel

Low frictional drag to air



High frictional drag to solid

Super-channel



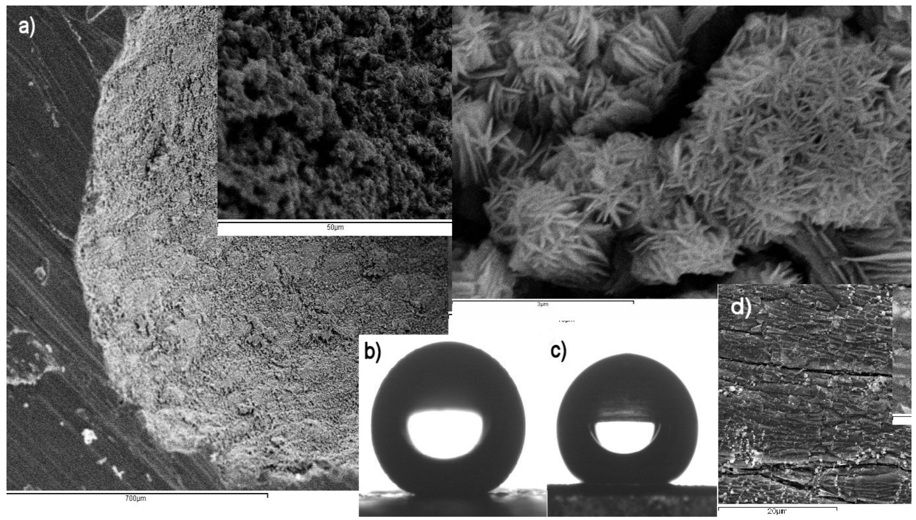
Walls appear as
cushions of air

Experiment

Forced flow through small-bore Cu tubes

Electron microscope images of hydrophobic nano-ribbon (1μm x 100nm x 6nm) decorated internal copper surfaces of tubes (0.876 mm radii).

Side-profile optical images of droplets of b) water, and c) glycerol on surface shown in a) the original surface is shown in d)

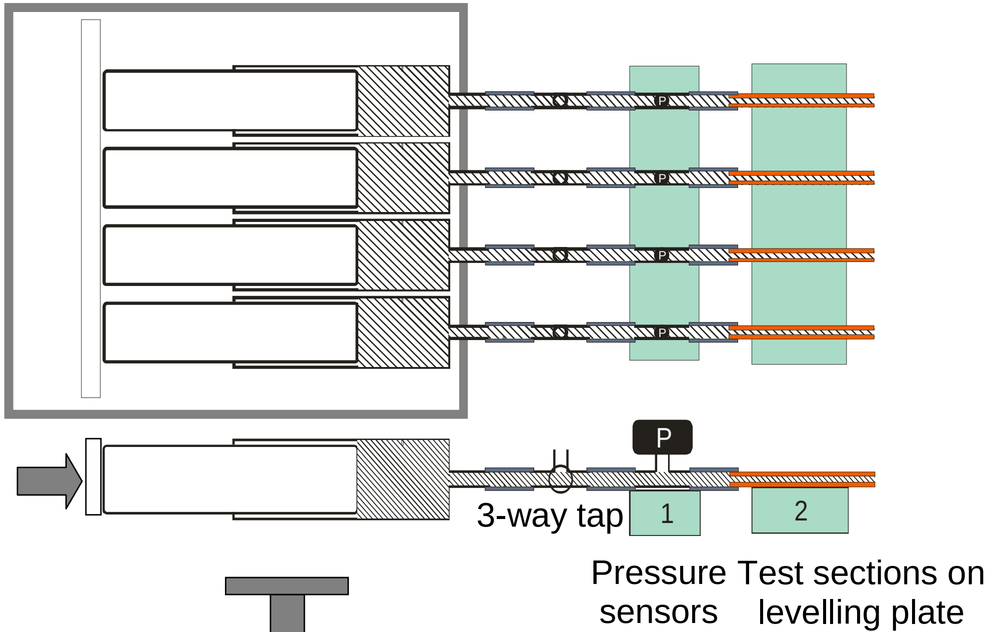


Reference Shirtcliffe, N.J.; McHale, G.; Newton, M.I.; Zhang, Y. ACS Appl. Maters. Interf. 1 (2009) 1316-1323.

Flow in Pipes with Superhydrophobic Walls

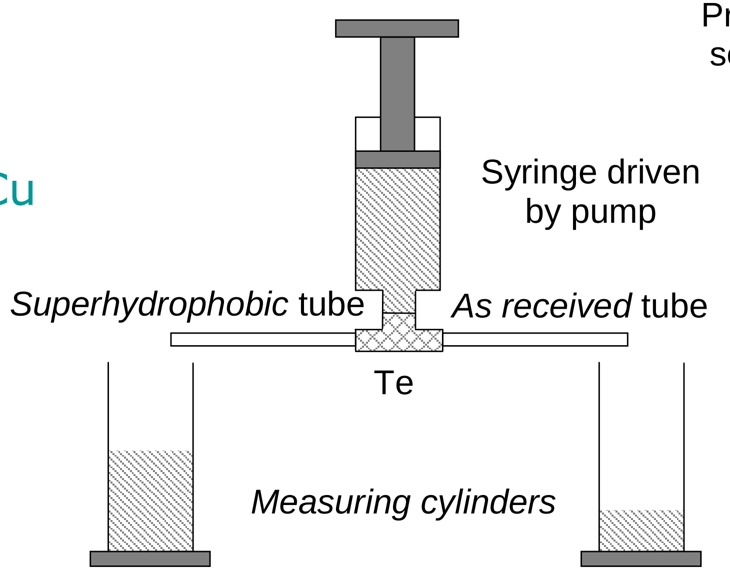
Quantitative Experiment

1. 4 parallel tubes with 4 surface finishes
2. Cu, hydrophobic Cu, nanoribbon Cu and hydrophobic nanoribbon Cu
3. Syringe pump to force flow in all 4
4. Measure pressure drop across each



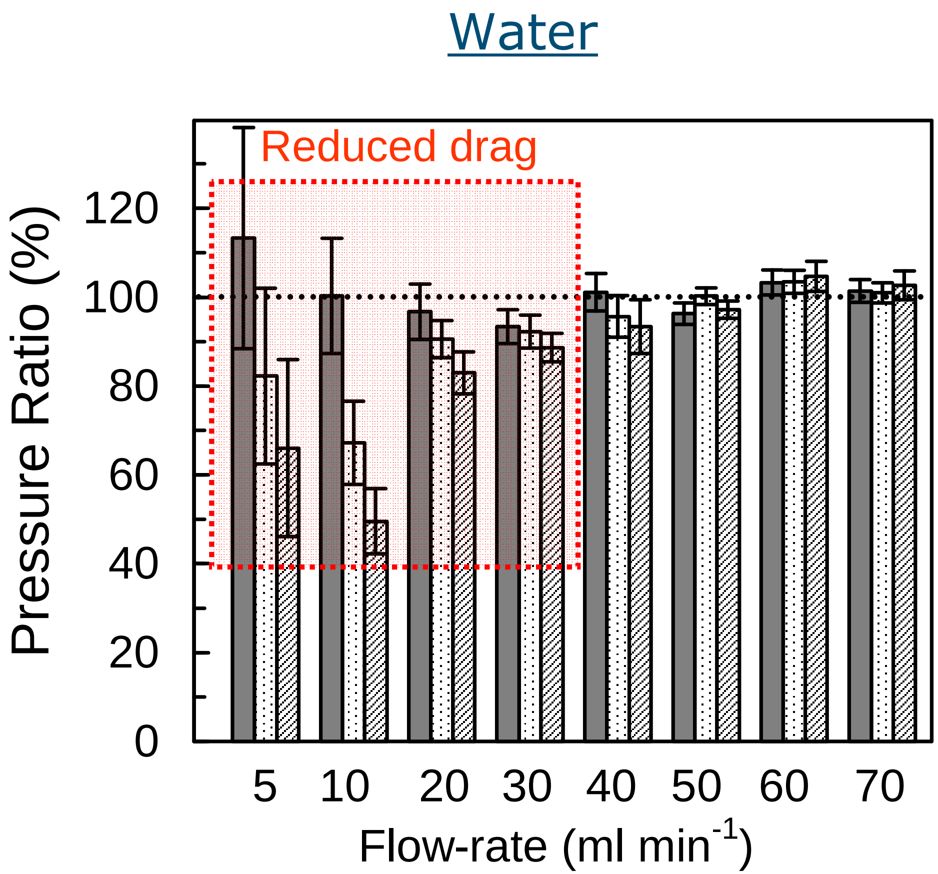
Visualization Experiment

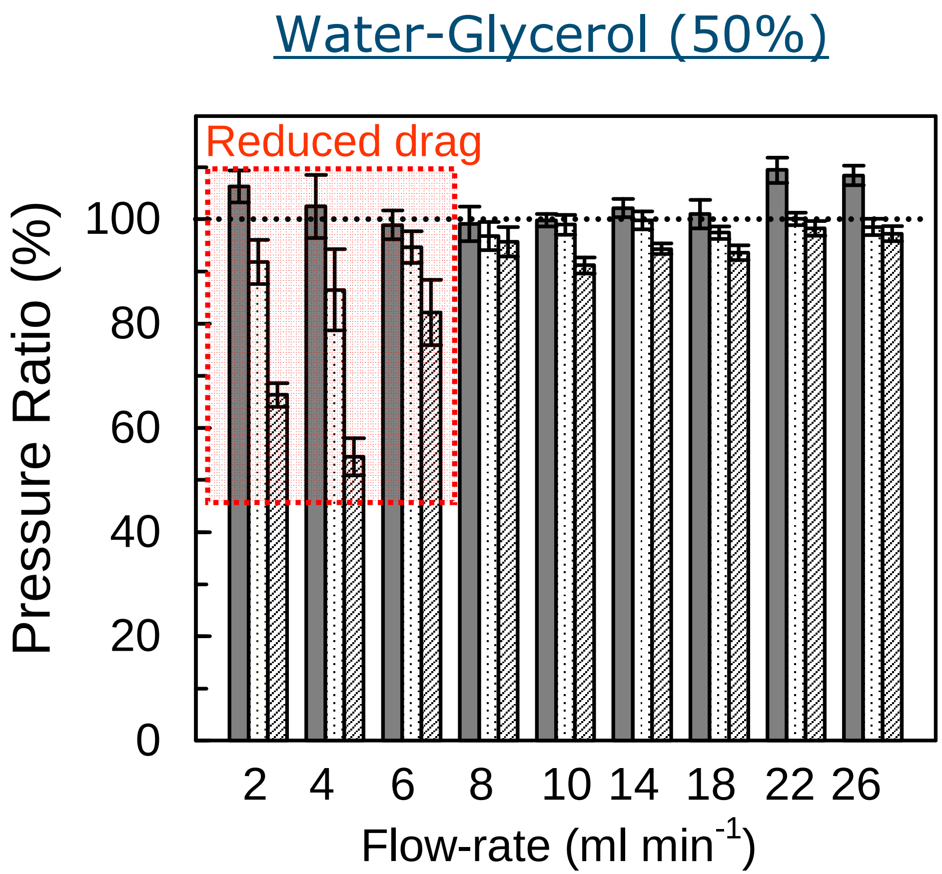
1. 2 tubes in T-arrangement
2. Cu and hydrophobic nanoribbon Cu
3. Syringe pump to force flow
4. Outlet volumes collected



Reference Shirtcliffe, N.J.; McHale, G.; Newton, M.I.; Zhang, Y. ACS Appl. Maters. Interf. 1 (2009) 1316-1323.

Quantitative Results



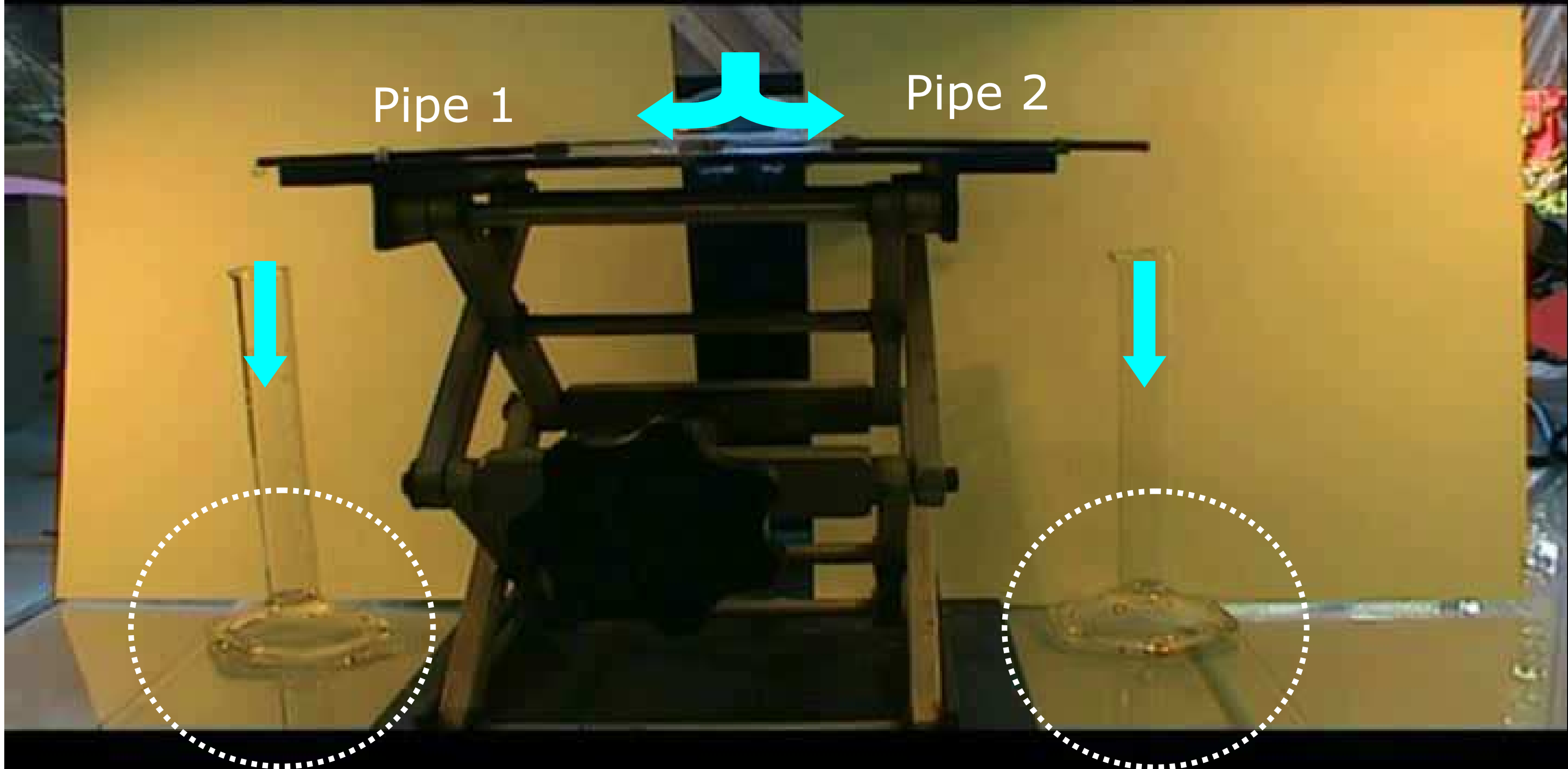


Copper tubes with superhydrophobic inner surfaces show significantly increased flow-rates

Reference Shirtcliffe, N.J.; McHale, G.; Newton, M.I.; Zhang, Y. ACS Appl. Maters. Interf. 1 (2009) 1316-1323.

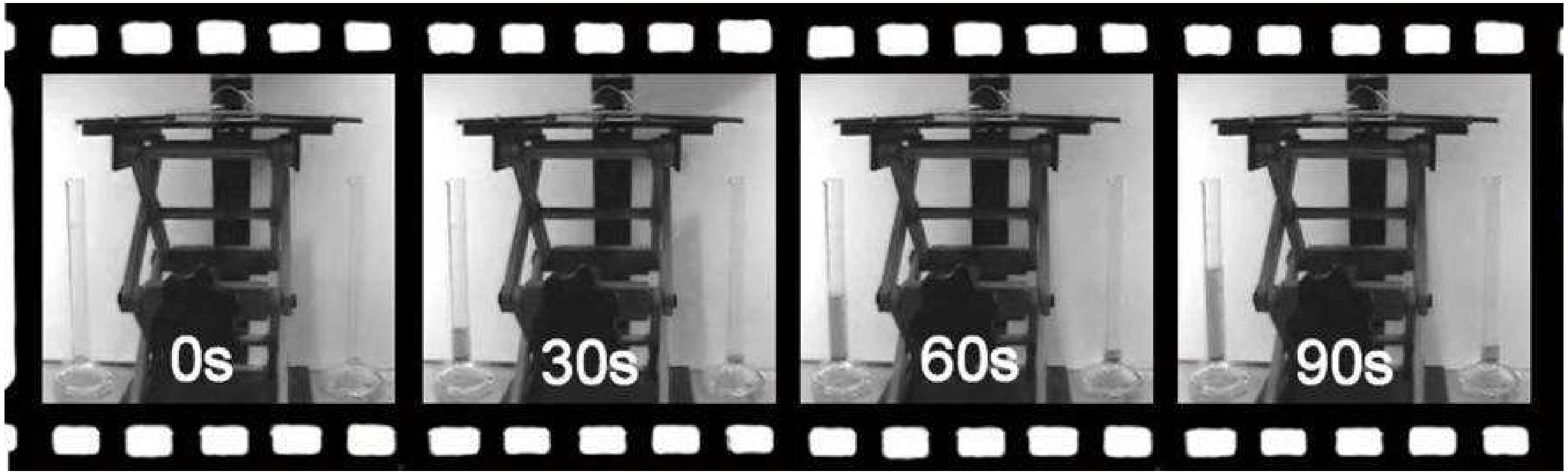
Visualization Results – Set-up and Video

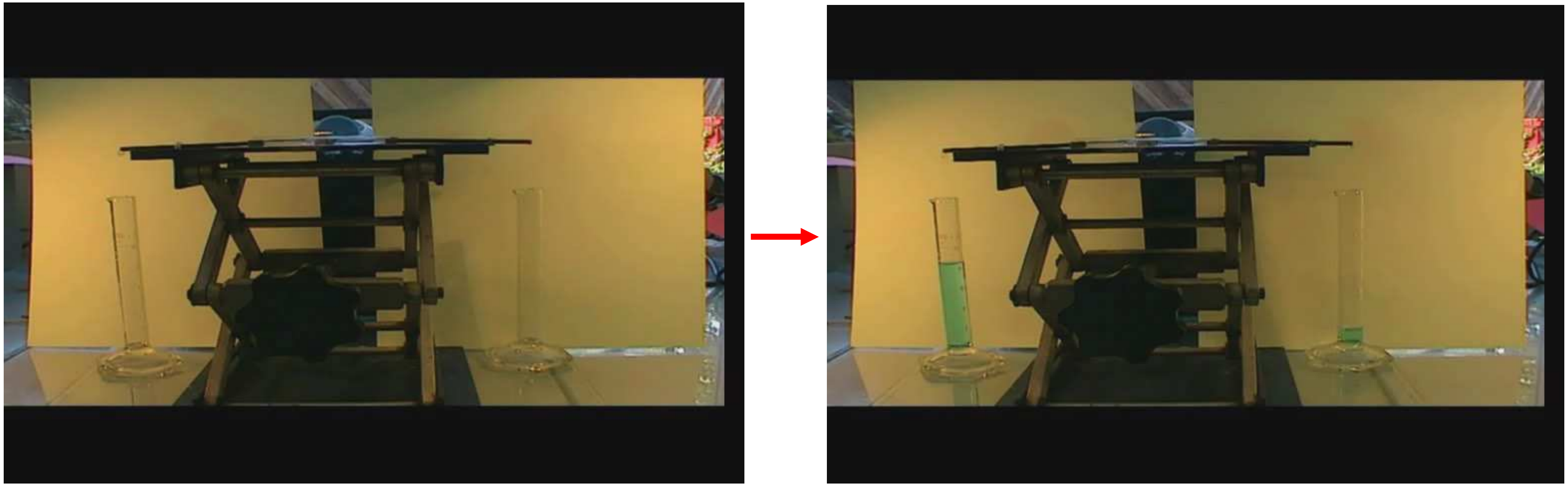
Two horizontal pipes –inside walls of one are coated with superhydrophobic nano-ribbons



Reference Shirtcliffe, N.J.; McHale, G.; Newton, M.I.; Zhang, Y. ACS Appl. Maters. Interf. 1 (2009) 1316-1323.

Visualization Results – Extracted Frames





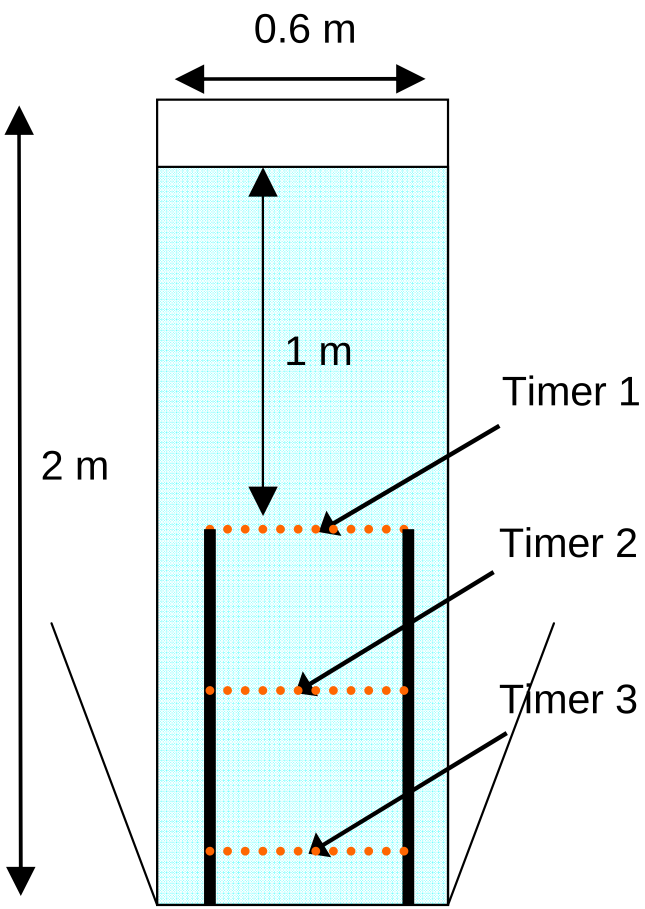
Reference Shirtcliffe, N.J.; McHale, G.; Newton, M.I.; Zhang, Y. ACS Appl. Maters. Interf. 1 (2009) 1316-1323.

Drag Reduction

Terminal velocities of settling spheres

Terminal Velocity

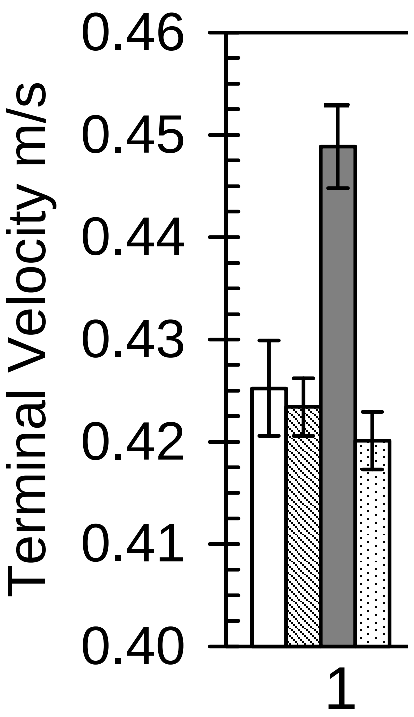
In the presence of a fluid, a falling object eventually reaches a terminal velocity. Textbooks tell us that in water the terminal velocity does not depend on the surface chemistry …. But is that true?



 Reference McHale, G. *et al.*, Appl. Phys. Lett. 94 (2009) art. 064104.

Terminal Velocity Results

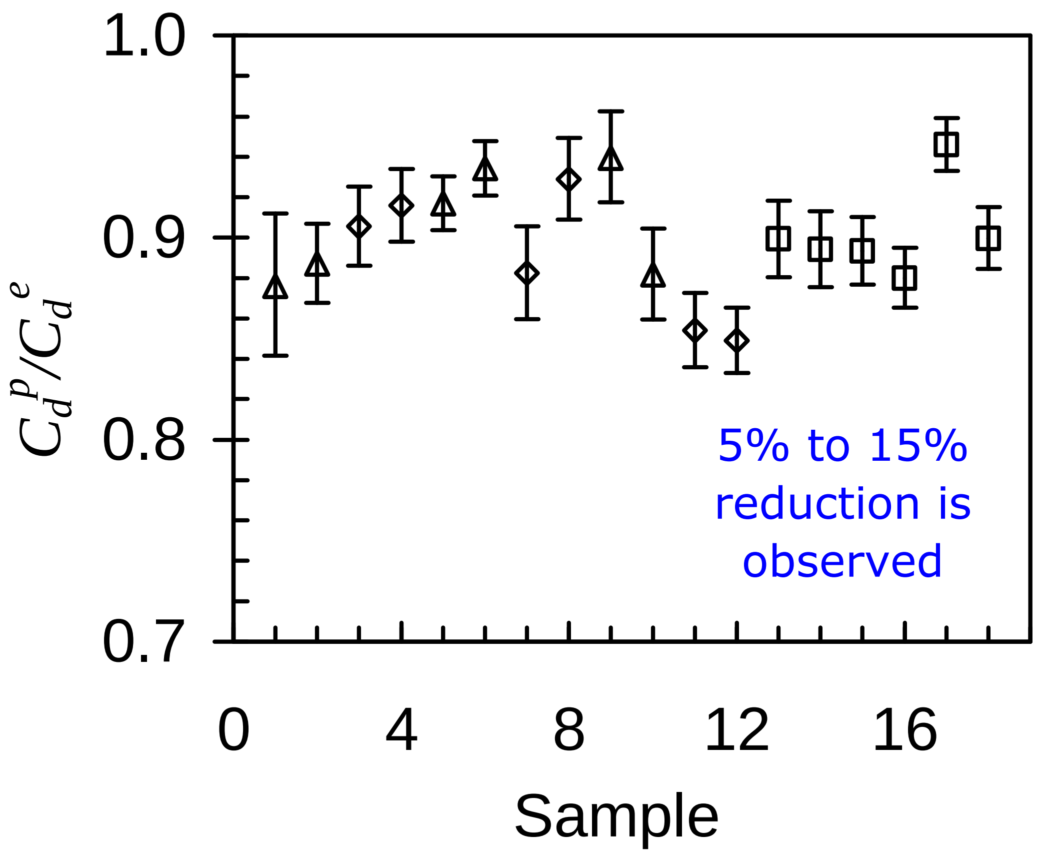
Results for 1-inch Diameter Sphere



Sequence of Four Bars

1. Blank surface
2. Sieved sand surface
3. (Super) Hydrophobic sand
4. Hydrophobic sand with ethanol pre-treatment to prevent plastron

Reduction in Drag Coefficient



Superhydrophobicity alone is not enough. Also need a plastron to persist to achieve drag reduction

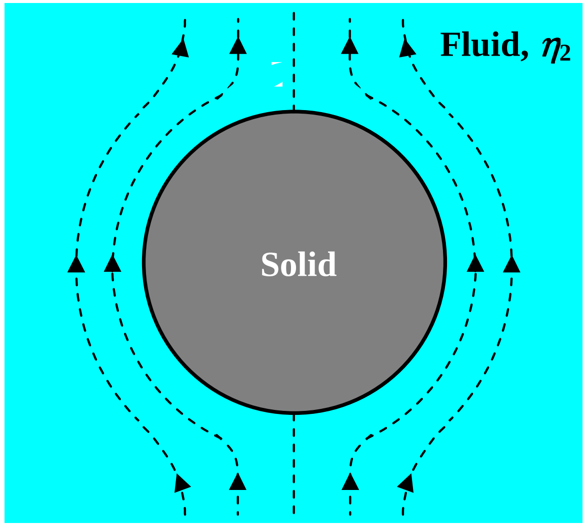
 Reference McHale, G. *et al*., Appl. Phys. Lett. 94 (2009) art. 064104.

Drag Reduction – Boundary Conditions

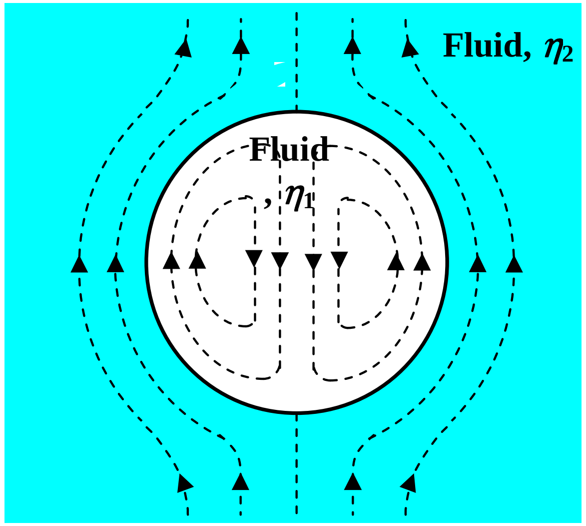
Fundamental boundary condition is not "no-slip", but is continuity of shear stress

Well-known drag reduction effects for gas bubbles with non-rigid interfaces in water

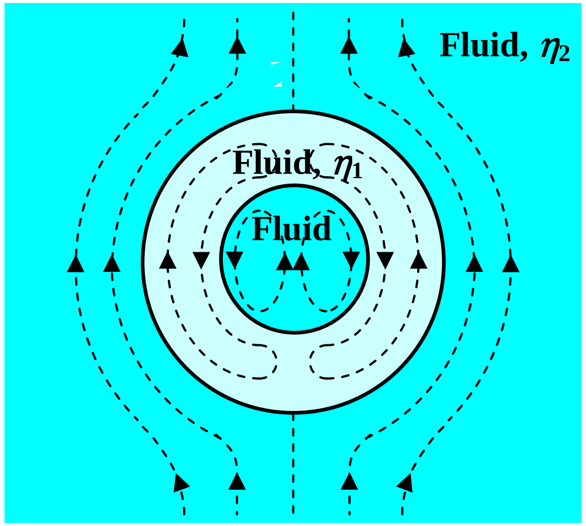
Stokes Drag (Low Re)



Hadamard-Rybczynski



Encapsulated Droplet

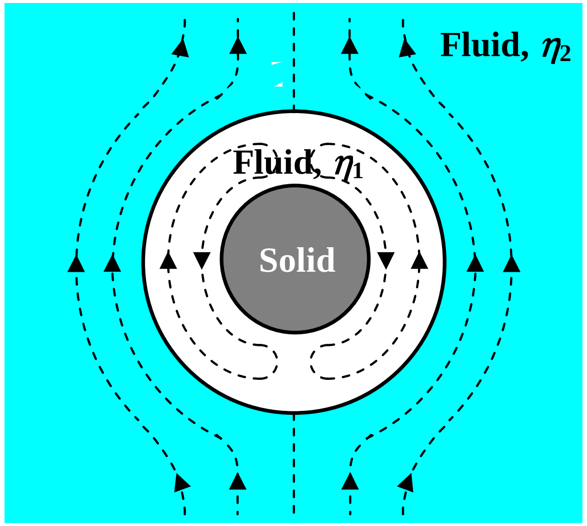


Hadamard-Rybczynski drag is 25% less than Stokes drag

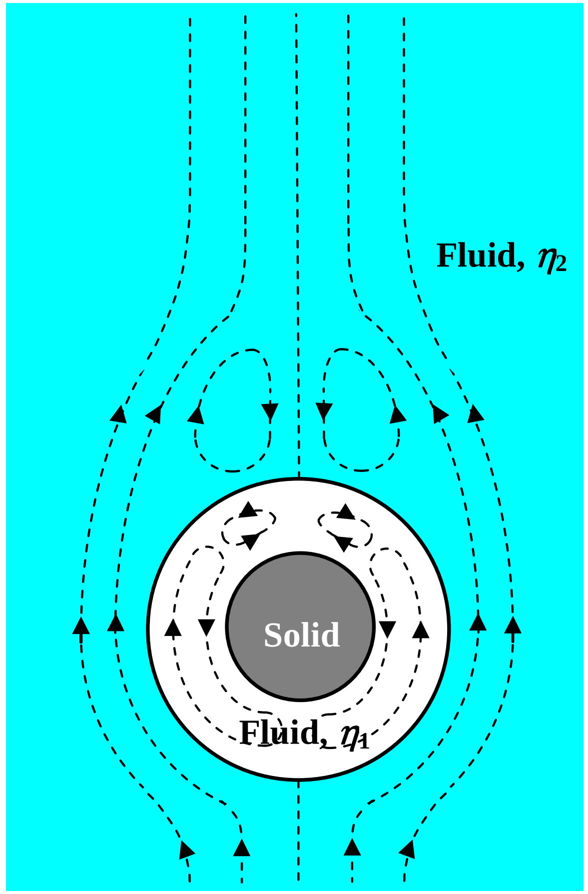
 Reference McHale, G. *et al*., Appl. Phys. Lett. 94 (2009) art. 064104.

Low and Intermediate *Re* numbers?

At low *Re*, a plastron/air layer may cause a Hadamard-Rybzcynski effect and reduce drag



At intermediate *Re*, an air layer is likely to alter flow patterns and modify wake separation – possibly reducing drag



A persistent plastron/air layer is needed to achieve drag reduction

 Reference McHale, G. *et al.*, Appl. Phys. Lett. 94 (2009) art. 064104.

Conclusions

1. Immersed Superhydrophobic Surfaces can be Functional
   - Oxygen can be extracted from water
   - Underwater/plastron respiration is possible
2. Biofouling can be Reduced
   - Protein adsorption can be reduced
   - Flow induced detachment can be enhanced
3. Flow through Macroscopic Tubes can be Enhanced
   - Visible enhancement is possible
4. Drag can be Reduced
   - Plastron like boundary layers of air can lubricate flow and reduce drag

The End

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