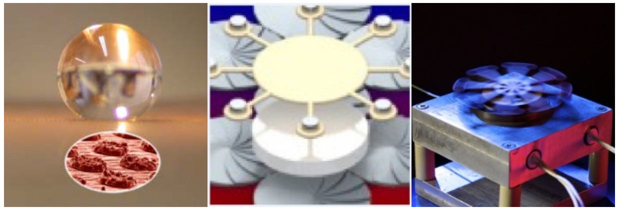
Wetting/Superhydrophobic Surfaces, Evaporation and Leidenfrost Effect

EPSRC Thermoelectric Network UK Event: National Physical Laboratories, Teddington, UK
Acknowledgement: Organisers (Alex Cuenat and Professor Robert Freer)

Professor Glen McHale

Smart Materials & Surfaces Lab, University of Northumbria, Newcastle, UK
Public Understanding http//:www.naturesraincoats.com/

20th April 2016



Overview

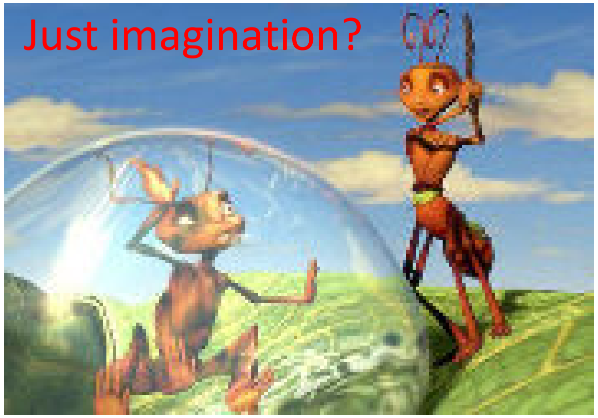
1. Wetting and Superhydrophobicity
2. Plastrons and Drag Reduction
3. Liquid Infused Surfaces (LIS), Evaporation and Pinning
4. A Leidenfrost (Heat) Engine

Wetting and Superhydrophobicity

(with Dr. Michael I. Newton and Dr. Neil J. Shirtcliffe at Nottingham Trent University)

Amplifying Surface Chemistry

Just imagination?

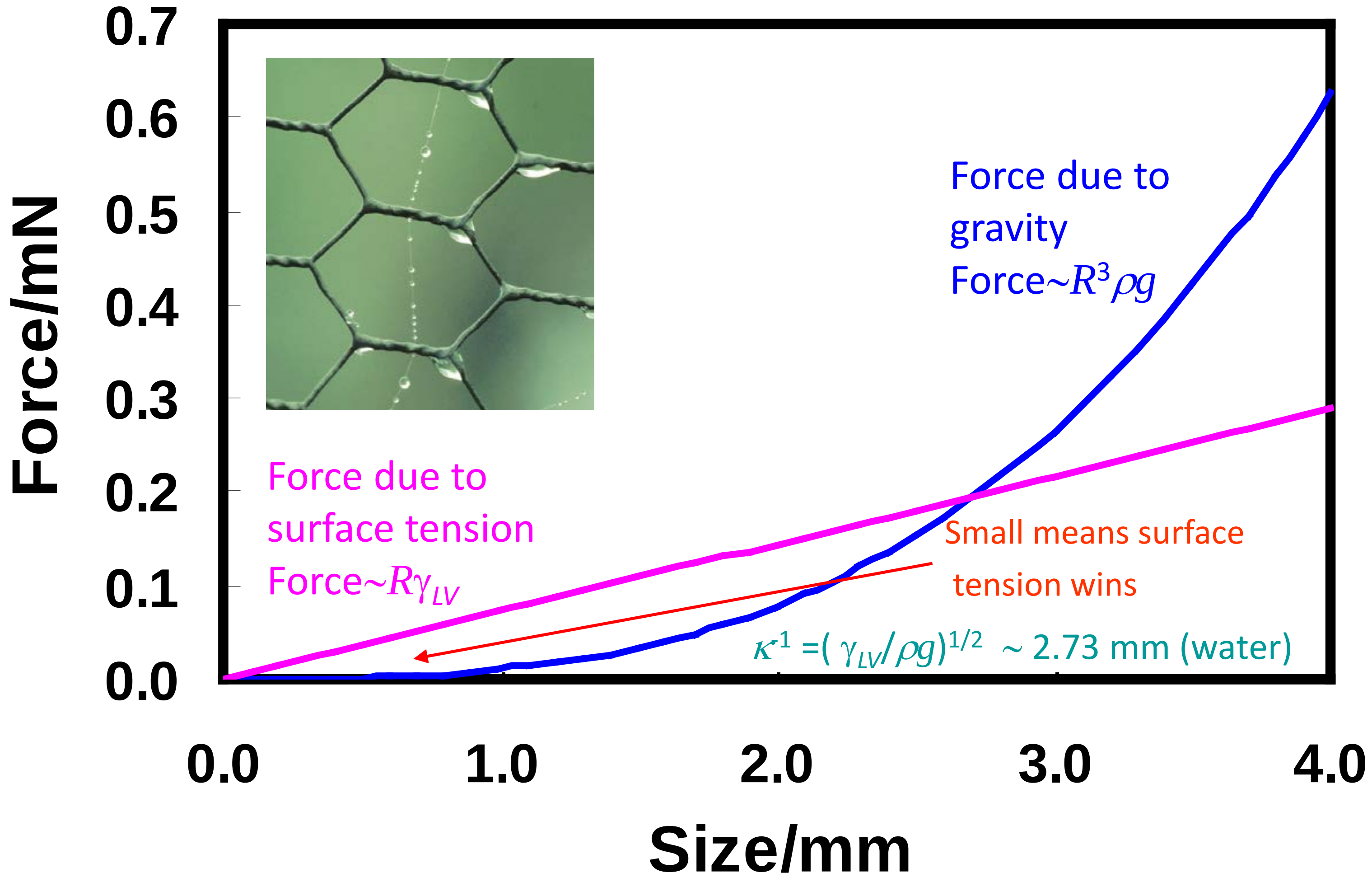


Courtesy: BigWave Productions

The Movie – Antz (1998)

Copyright: DreamWorks Animation (1996)

Surface Tension and Size



Force due to gravity

Force~$R^3\rho g$

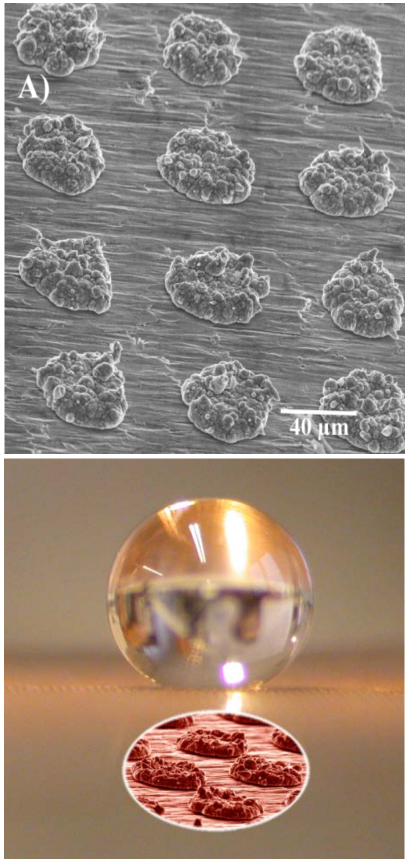
Force due to surface tension

Force~$R\gamma_{LV}$

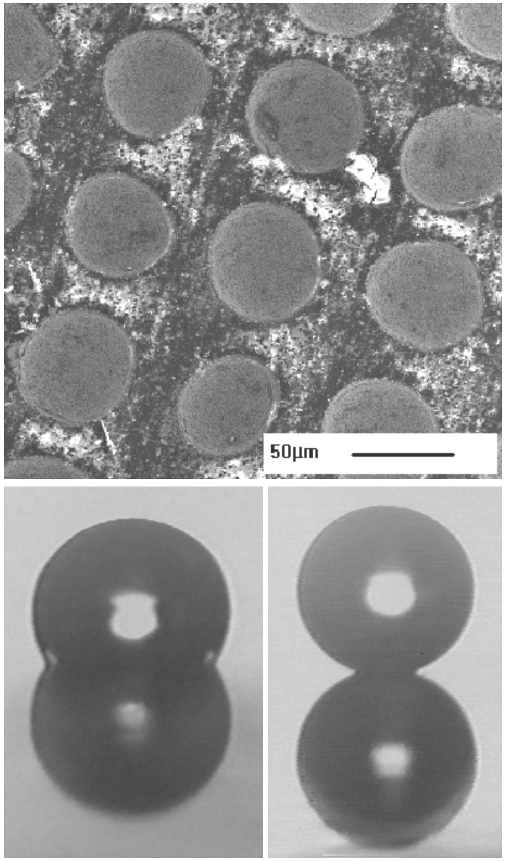
Small means surface tension wins

$\kappa^{-1} = (\gamma_{LV}/\rho g)^{1/2}$ ~ 2.73 mm (water)

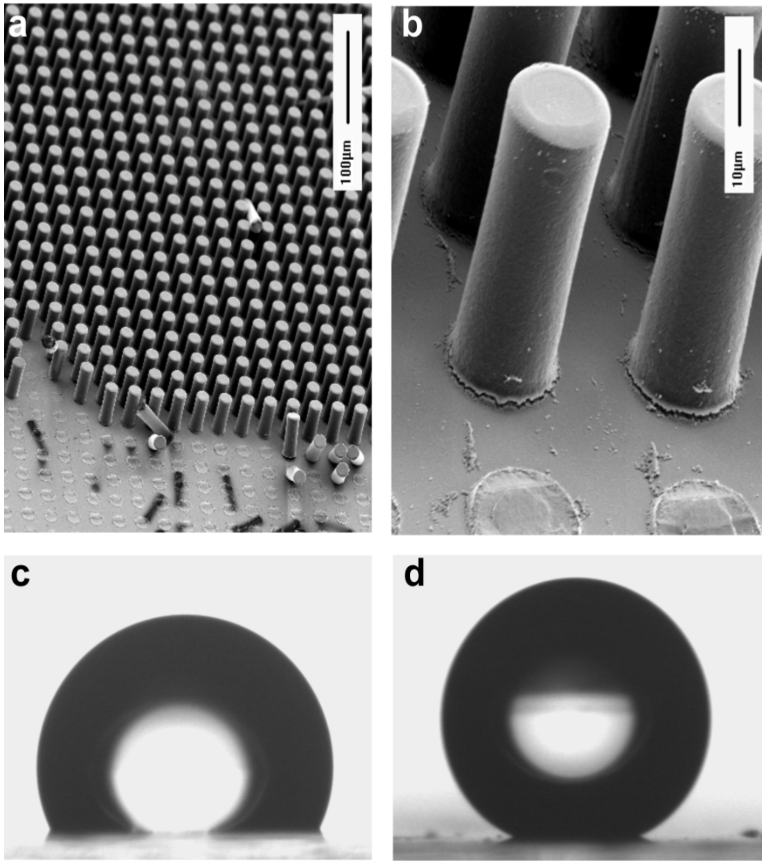
Superhydrophobic Surfaces



Depositing metal
“Choc-chip cookies”



Etching metal
“Lunar landscapes”

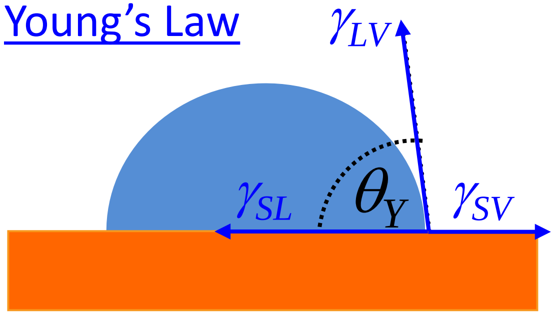


Polymer microposts
“Beds of nails”

Shirtcliffe, et al., Adv. Mater. (2004) 16 1929, Langmuir (2005) 21 937; McHale, et al. PRL (2004) 93. 036102.

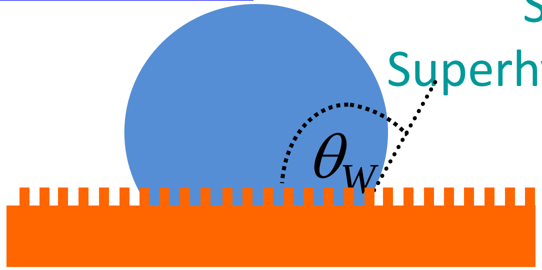
Super- and Perfect Hydrophobicity

Young's Law



Surface Chemistry θ_Y

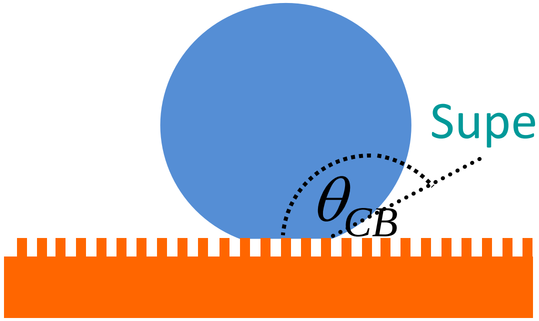
Wenzel State



Sticky Superhydrophobic

Roughness $r(x)$ and Surface Chemistry θ_Y

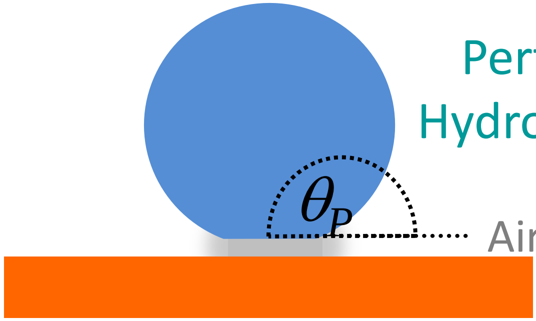
Cassie-Baxter State



Slippy Superhydrophobic

Topography *via* solid surface area fraction $f_s(x)$

Perfect Water-Repellent State

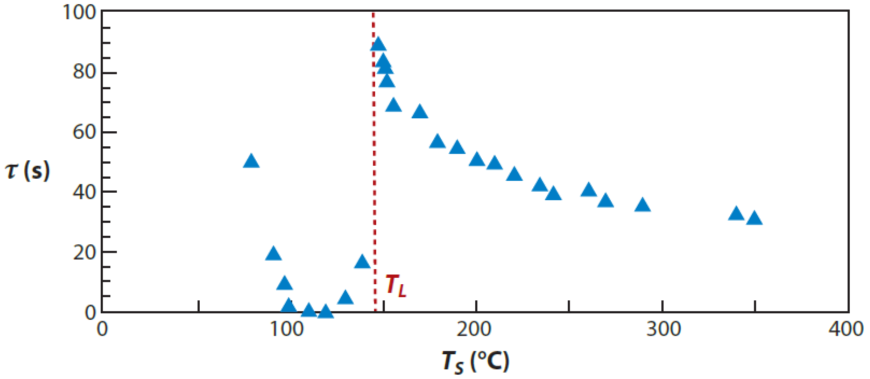


Perfectly Hydrophobic

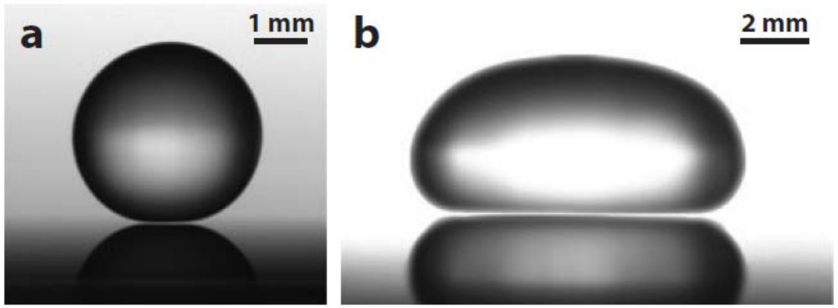
Air Supported, $f_s(x)=0$

Cassie & Baxter, Trans. Faraday Soc.(1944) 40 546. Wenzel, Ind. Eng. Chem. 28 (1936) 28 988, J. Phys. Coll. Chem. (1949) 53 1466.

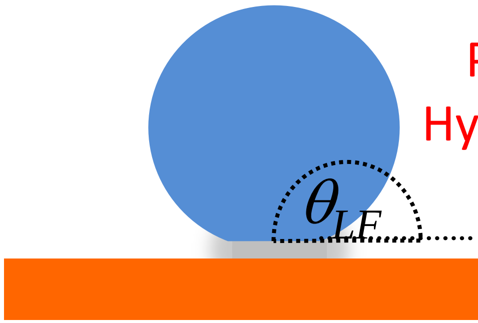
The Leidenfrost Effect



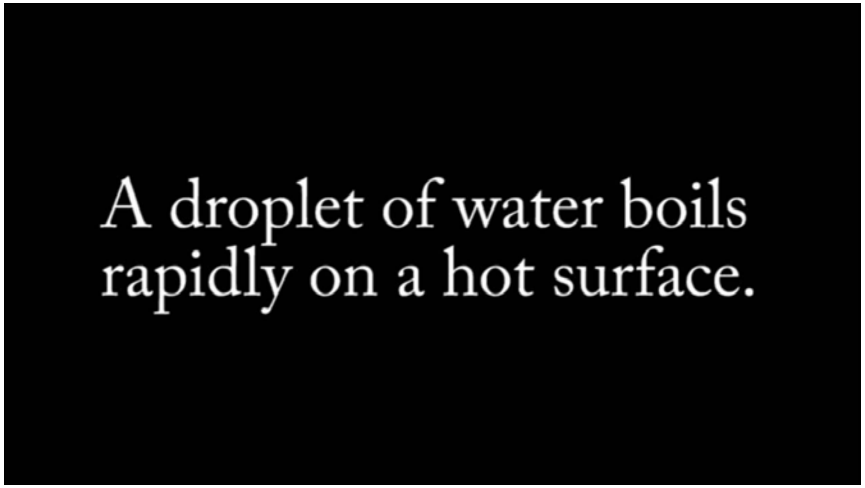
Lifetime of a droplet on a polished metal plate



Droplets on a hot metal plate (300 °C) (Quéré, 2013)



Perfectly Hydrophobic



A droplet of water boils rapidly on a hot surface.

Supported by vapour and flattened by gravity

Quéré, Annu. Rev. Fluid. Mech. (2013) 45 197.

Phase Change & Thermal Issues?

1. Deposition as a liquid droplet is not the same as growth by condensation
2. Texture shape can be far more complex including re-entrant curvature
3. Texture can be multiscale with nanostructures/particles on microstructures
4. Growth of droplets on adjacent surface protrusions can lead to droplets "pinging off" when merging – relevant to heat exchangers
5. Reduced effective droplet solid-liquid contact area/footprint A_{SL} – relevant to heat transfer and anti-icing
6. Texture material, shape and air-surface fraction – relevant to heat transfer
7. Droplets may evaporate in different modes (constant A_{SL} versus constant θ)
8. Perfect rebound or impaling for impacting droplets – relevant to anti-icing
9. Switching surface chemistry leads to hemi-wicking – relevant to heat pipes
10. Properties can be patterned – relevant to fog collection and directed flow

Plastrons and Drag Reduction

Plastrons and Drag Reduction

(with Dr. Michael I. Newton at Nottingham Trent University,
Dr. Morris R. Flynn at University of Alberta
and Professor Neil D. Sandham at Southampton University)

Drop Tank Experiments

Superhydrophobic Sphere in Water with a Plastron

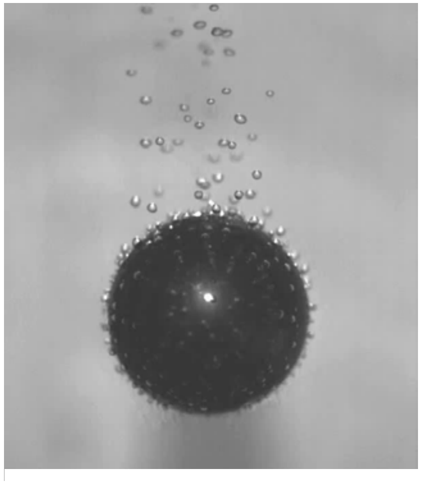
Solid sphere

Plastron bearing sphere

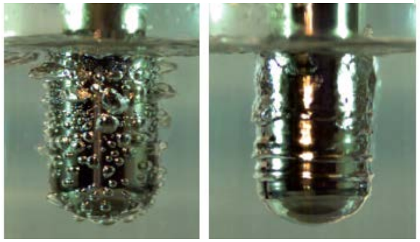
Same sphere

Sphere in FC-72 with Leidenfrost Effect

Vakarelski, I. et al. PRL. (2011) 106 214501.



Heat Transfer in Water

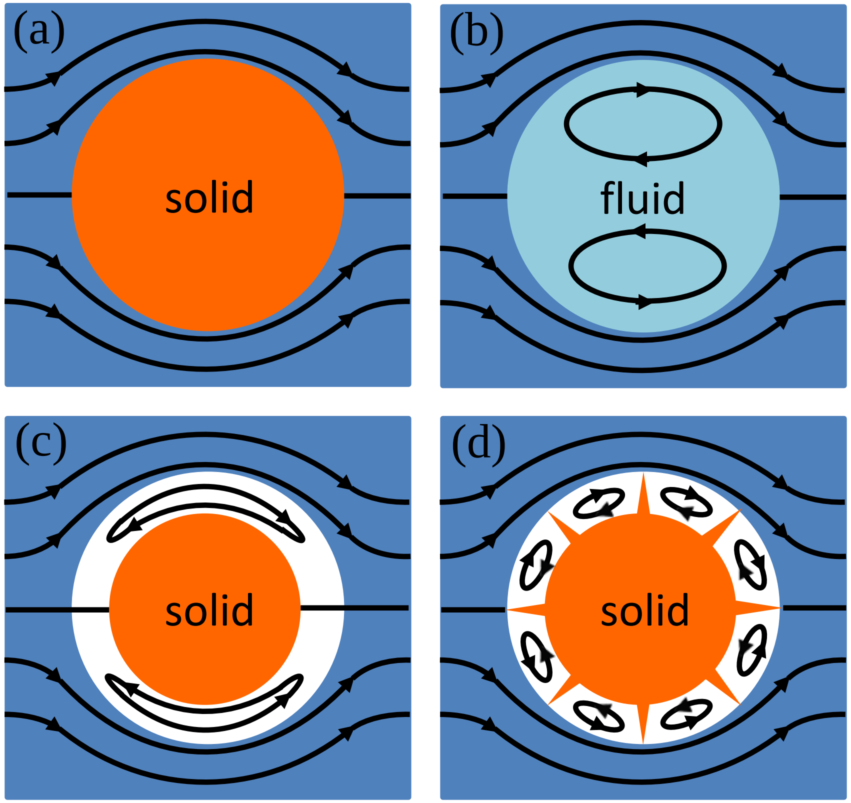


Hydrophobic: nucleate-boiling at T_s=106 °C
S/H Surface: Leidenfrost regime, T_s=210 °C

McHale, G. et al., Appl. Phys. Lett.(2009) 94 064104. Vakarelski ,I. et al., Phys. Rev. Lett.(2011) 106 214501; Nature (2012) 489 274-277.

Plastron Drag Reduction Model

Stokes Law and Bubbles



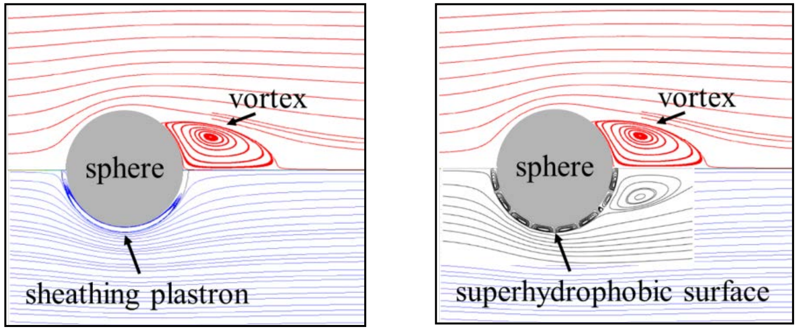
Hadamard-Rybczynski is 25% less than Stokes drag

Perfectly Hydrophobic Surfaces Modelling

Fundamental boundary condition is not "no-slip", but is continuity of shear stress – Creeping flow is:

$$\xi_{SH} = \frac{F_d^{SH}}{-6\pi\eta_l b U_\infty} = \frac{2}{3\varepsilon}\left[\frac{1+3\eta_{gl}F(\varepsilon)}{1+2\eta_{gl}F(\varepsilon)}\right]$$

ξ_{SH} = Drag of sphere with plastron/drag of sphere
η_{gl} = ratio of dynamic viscosities
$\varepsilon = b/a$ = *solid radius/(sphere+air-layer radius)*



At higher Re separation points and vortices change

McHale, et al, Soft Matter (2010) 6 714; (2011) 7 10100. Gruncell, et al. Phys. Fluids. (2013) 25 043601. Busse, et al. J. Fluid Mech. (2013) 727 488 (Also see: A.P. Tsai, 736).

Phase Change & Measurement?

1. What is the mechanism by which superhydrophobic surface texture lowers the Leidenfrost transition temperature and stabilizes the vapor layer at temperatures above the boiling point?
2. How can plastrons or vapor layers be observed and properties measured?
3. In drag measurements (external and internal flow) how can flow profiles in both the sheathing vapor layer and bulk liquid be measured?
4. To what extent does the recirculation that occurs in a sheathing vapor layer alter heat transfer from the object to the fluid in which it is immersed?
5. Can low energy cost generation of Leidenfrost effect be achieved and how do we measure it? *(The answer in a paper we are submitting is “yes”)*

LIS, Evaporation and Pinning

Liquid Infused Surfaces (LIS), Evaporation and Pinning

(with Dr. Gary G. Wells, Dr. B Xu and Mr. James Guan
at Northumbria University,
Professor David Wood at Durham University
and Professor James Martin and Dr. Simon Stuart-Cole at Reece Innovation)

REECE INNOVATION

northumbria UNIVERSITY NEWCASTLE

Lotus Leaf versus Pitcher Plant

Acknowledgement: STOLotusan
(http://www.sto.com/)

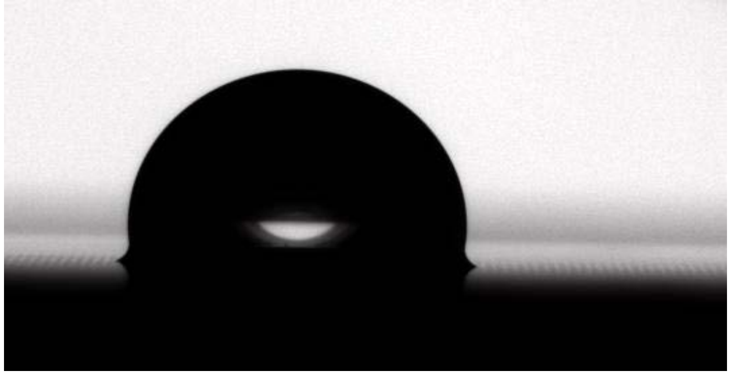
Acknowledgement: Aizenberg Group
(http://aizenberglab.seas.harvard.edu/)

1. Both biological approaches use topography/surface texture to make surfaces slippery
2. Both use surfaces having low contact angle hysteresis
3. Lotus leaf has high static contact angles (superhydrophobic)
4. Pitcher plant has low contact angle hysteresis, but can have high static contact angle (SLIPS/LIS)

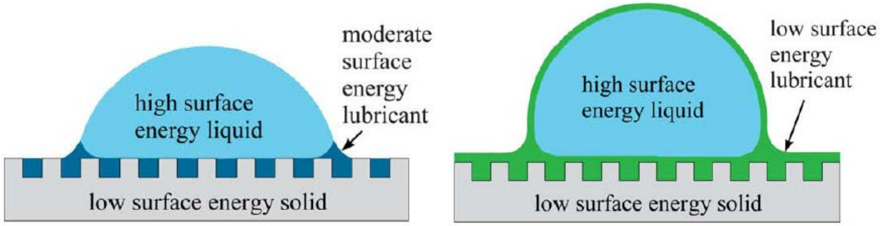
Barthlott, W., & Neinhuis, C., Planta (1997) 202 1. Wong, T. -S., et al., Nature (2011) 477 1232.

Liquid Infused Surfaces (LIS)

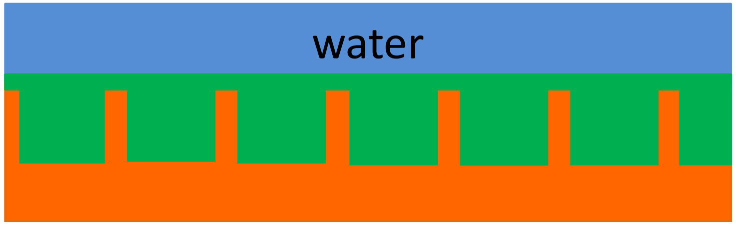
Slippery Liquid Infused Porous Surfaces (SLIPS): Wong, T.-S. *et al. Nature* **477**, 443–447 (2011)



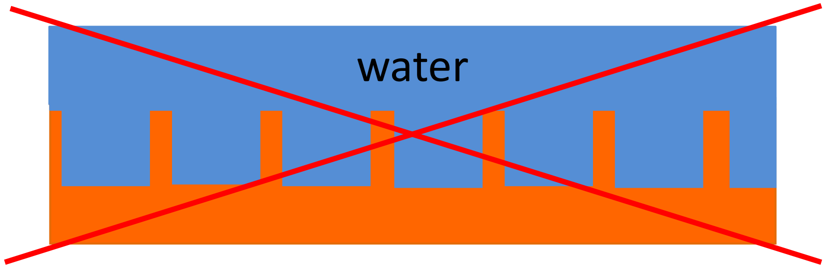
Water droplet sliding at a tilt angle of 0.8°.



Smith, J. D. *et al. Soft Matter* **9,** 1772–1780 (2013).



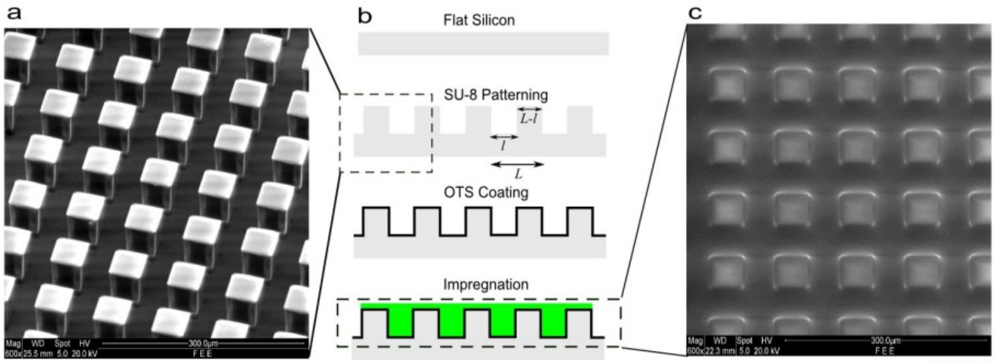
Wenzel induced complete wetting by lubricant including tops of pillars

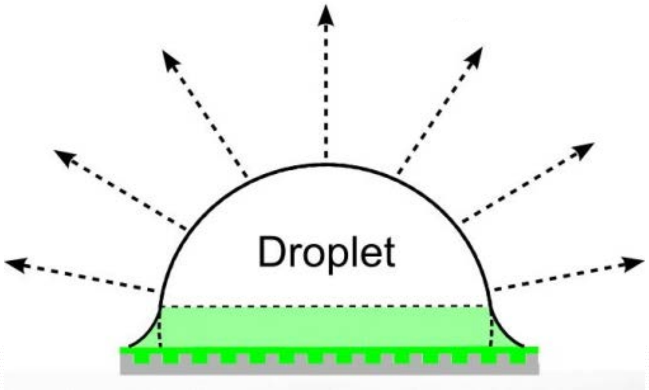


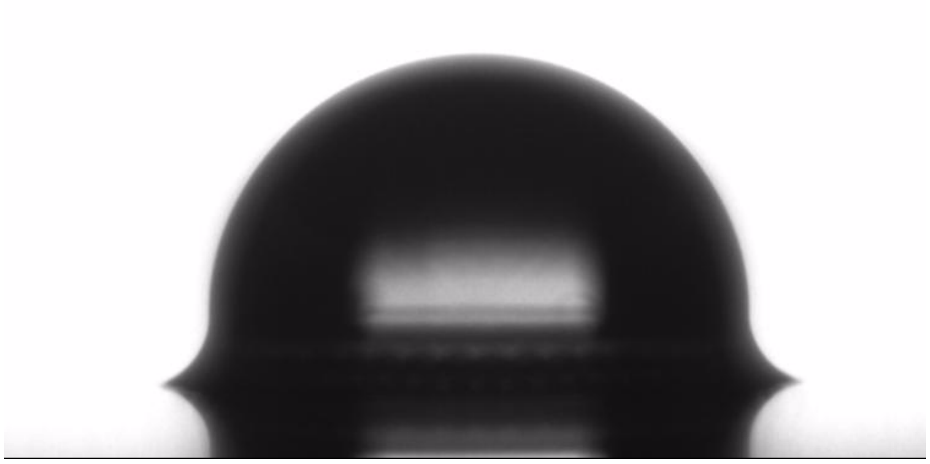
Displacement of the lubricant

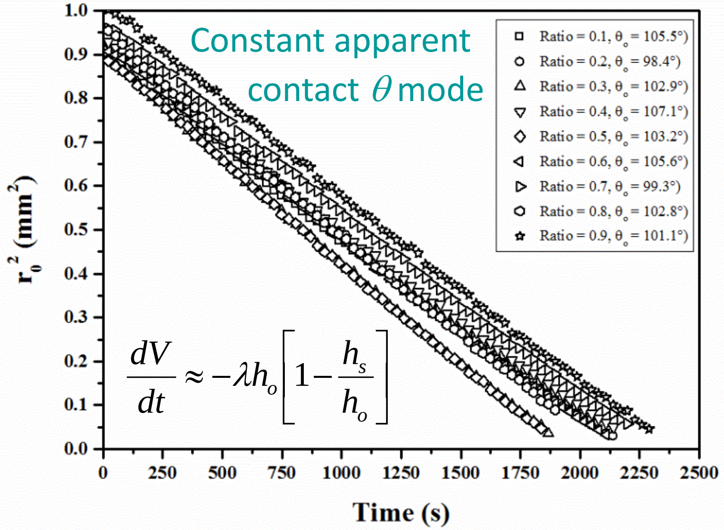
Wong, T.-S.. et al., Nature (2011) 477 443. Smith, J.D., et al. Soft Matter (2013) 9 1772.

Evaporation from LIS Surfaces









Constant apparent contact θ mode

$$\frac{dV}{dt} \approx -\lambda h_o\left[1-\frac{h_s}{h_o}\right]$$

Wetting ridge $\Rightarrow$ wetting skirt on A_{LV}

Gives estimates of diffusion coefficients

Wells, G.G. et al, Langmuir (2015) on-line 20/10/2015.

Reflections on Opportunities?

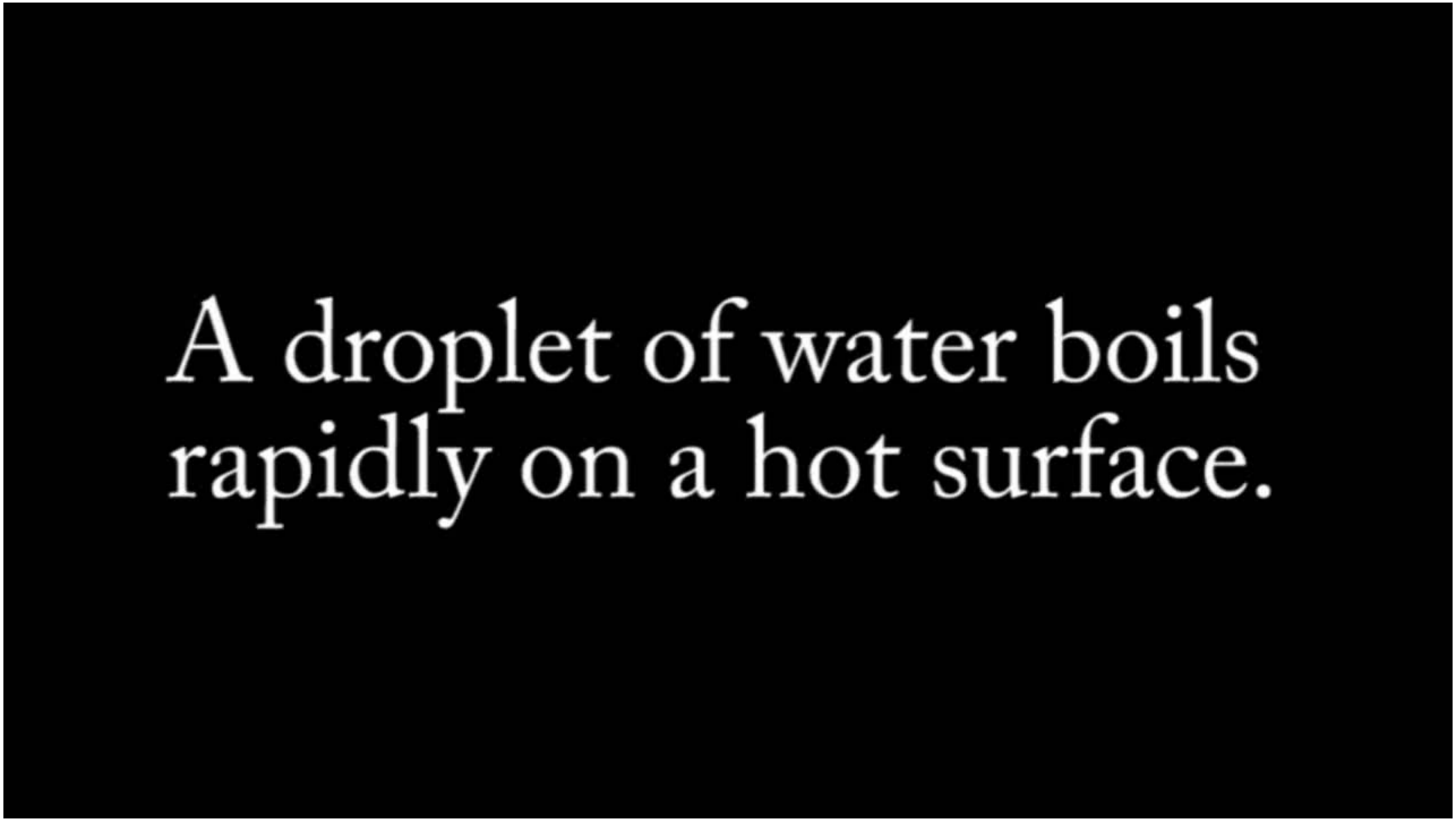
1. Surfaces achieve liquid shedding without need for droplets to ball up – relevant to heat transfer
2. Previous questions about potential of superhydrophobic surfaces for anti-icing, condensation, drag reduction all apply to SLIPS/LIS surfaces
3. How do we measure thermal properties of SLIPS/LIS surfaces?
4. Lubricating infusing liquid properties still to be optimised – How do we determine best properties/liquids? Tunable properties of, e.g., ionic liquids
5. How do we characterize lifetime of immiscible liquids locked into surfaces?
6. Removal of contact line pinning for liquids is analogue of zero static friction for solids – relevant to stiction and tribology *(a paper has been submitted)*

A Leidenfrost (Heat) Engine

A Leidenfrost (Heat) Engine

(with Dr. Gary G. Wells and Dr. Rodrgio Ledesma-Aguilar at Northumbria University
and Professor Khellil Sefiane, Edinburgh University)

The Leidenfrost Engine Concept

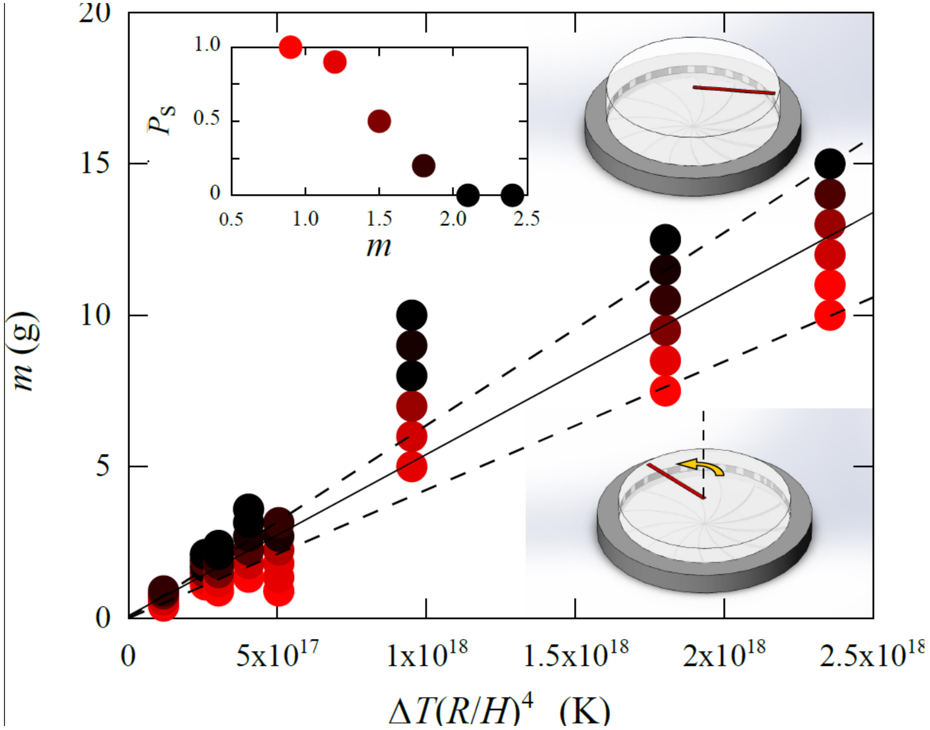


A droplet of water boils rapidly on a hot surface.

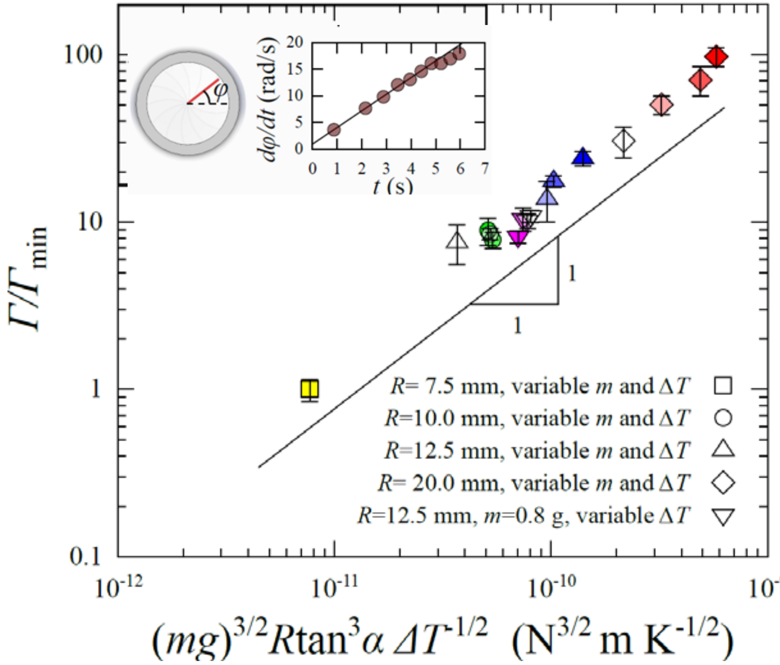
Wells, et al. Nature Commun. (2015) 6 6390.

Spin Initiation and Torque

1. Experiments with changes in (ΔT, R, H) to work out probability of dry ice disk spinning (R=7.5-20 mm, T_h=300-500 C, H=165-229 μm)
2. ca. 60 experiments per mass to determine probability P_S with m_c defined by P_S=0.5

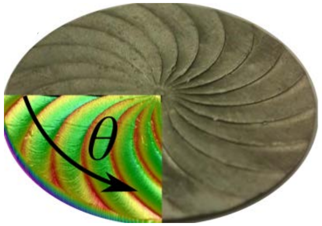


1. Measured angular velocity of dry ice disks ⇒ angular accel'n and hence torque (Γ=Iα) (α=2.25-4.15°, m=0.19-5.13 g)
2. Minimum torque Γ_{min}=0.0109 μN m.

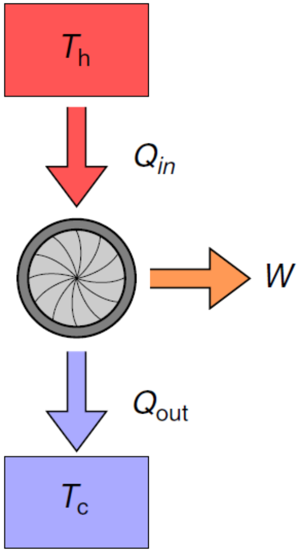


Sublimation Heat Engine Concept

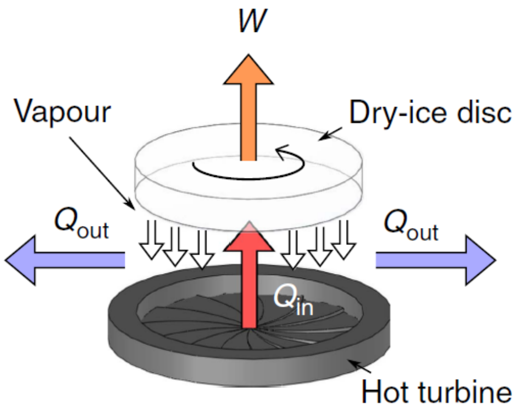
Turbine-like Surface



Heat Engine Principle



Realization



Sublimation Thermal Cycle

1. Sublimation (solid-vapor) equivalent to the Rankine cycle used in steam powered engines
2. The working substance is a solid (e.g. CO_2 but could be other ices such as H_2O or CH_4)
3. Harvest thermal energy Q_{in} via difference in temperature between reservoirs at T_h and T_c
4. Released vapor is rectified to produce mechanical work, W
5. Cooling releases Q_{out} to surroundings
6. Maximum theoretical efficiency limited by Carnot engine efficiency $\varepsilon=1\text{-}T_c/T_h\approx1\text{-}T_c/T_{ave}\approx0.67$

Wells, et al. Nature Commun. (2015) 6 6390.

Reflections on Opportunities

1. Self-levitation is energetically expensive (on Earth) – relevant to use of bearings
2. Continuous and batch operation should both be possible
3. Energy harvesting in extreme environments and/or microsystems might be possible
4. Space and planetary environments have dry ices and temperature extremes
5. Materials and/or coatings need to be found to reduce the Leidenfrost transition temperature
6. Thermal imaging of surfaces will be needed
7. Accurate models and measurements of heat flux and flow are not available

A grant application has been submitted to develop ideas further

Summary

- ❑ Interplay of surface texture and surface chemistry is rich in effects
  - ⇒ super water repellence and hemi-wicking
- ❑ Vapour layers reduce drag:
  - ⇒ plastrons and Leidenfrost effect gas/vapor layers lubricate flow
- ❑ Liquid Infused Surfaces (LIS) create slippery surfaces:
  - ⇒ first observations of completetly mobile contact line mode of evaporation
- ❑ Leidenfrost effect can generate rotational motion of droplets, ices and plates:
  - ⇒ first example of a sublimation heat engine
- ❑ Much of the above work presents opportunities and challenges for:
  - ⇒ thermal/heat transfer effects
  - ⇒ accurate measurements
  - ⇒ new types of experiments

Acknowledgements

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  - NPL, Professor Robert Freer and colleagues in the EPSRC Thermoelectric Network UK
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  - Northumbria University: Dr. Rodrigo Ledesma-Aguilar, Dr. Gary Wells, Dr. Ben Xu, Dr. Zuzana Brancova, Dr. Nic Geraldi, Mr James Guan
  - Nottingham Trent Univ: Dr. Michael I. Newton, Prof. Carl V. Brown, Dr. Neil J. Shirtcliffe
    Dr. Joe Brennan, Dr. David Fairhurst, Dr. Fouzia Ouali, Prof. Carole Perry, Dr. Simon Stanley, Dr. Christophe Trabi, Dr. Sanaa Aqil, Dr. Steve Elliott, Dr. Carl Evans, Dr. Shaun Atherton, Dr. Yong Zhang
  - University of Alberta: Dr. Morris R. Flynn
  - Durham University: Prof. David Wood, Dr. Linzi Dodd
  - University of Edinburgh: Prof. Khellil Sefiane
  - Southampton University: Prof. Neil Sandham, Dr. Brian Gruncell, Dr. Angela Busse (now at Glasgow)
  - Reece Innovation: Prof. James Martin, Dr. Simone Stuart-Cole
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  - Mr Ian Campbell, Dr. Martyn Prince
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Questions?

Group website and reprints: http://www.naturesraincoats.com/

Academic Staff

Professor Glen McHale (Theory/Experiment)

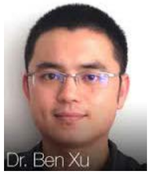
- Superhydrophobic/hydrophilic surfaces, dynamic wetting
- Drag reduction (experiment and theory), Leidenfrost effect
- Electrowetting and dielectrowetting

Dr. Gary Wells (Experiment/Instrumentation)

- Liquid optics (diffraction gratings, lenses), liquid crystals
- Self-organising polymers, dielectric elastomers, Leidenfrost effect

Dr. Ben Xu (Experiment/Materials)

- Lithography, 3D printing, micro-PIV
- Elastomers, creasing and micromechanics



Dr. Rodrigo Ledesma-Aguilar (Theory/Modelling)

- Lattice Boltzmann methods, dynamic wetting, elastocapillarity
- Low Re number flow, microswimmers, Leidenfrost effect

Dr. Richard Fu and Dr. Yifan Li (Experiment/Microsystems)

- Microsystems and microfluidics
- Surface acoustic waves (SAWS), sensors, electrowetting