

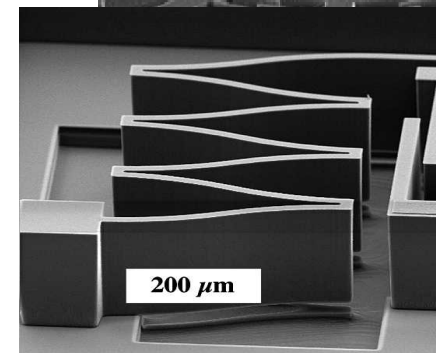
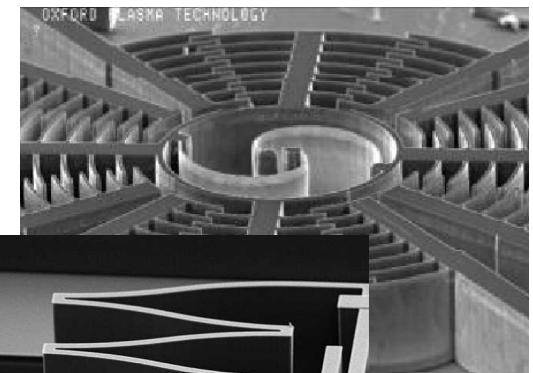
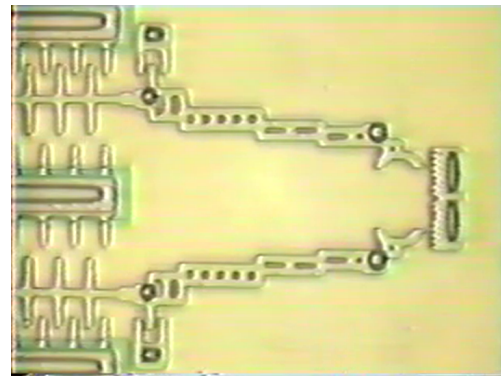
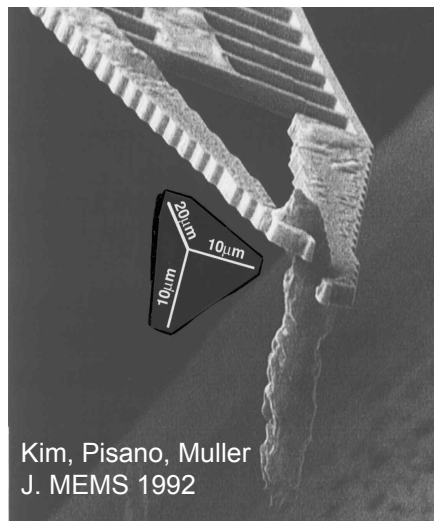
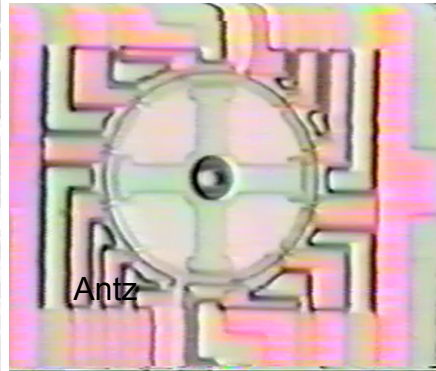
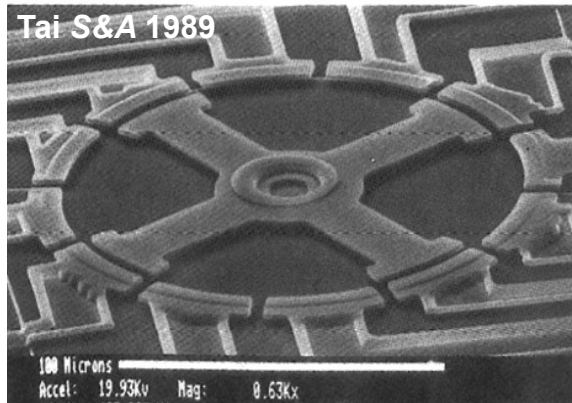
Superhydrophobic Surfaces for Reducing Frictional Drag: Dream or Reality?

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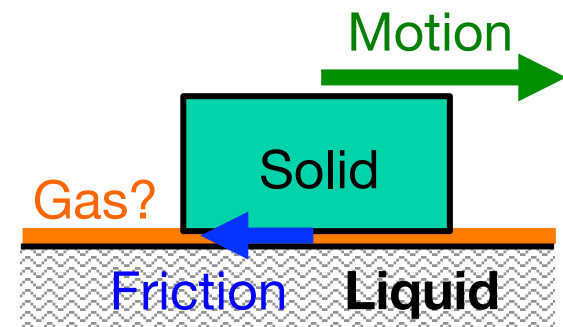
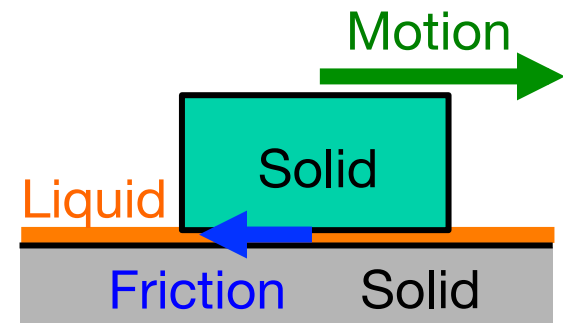
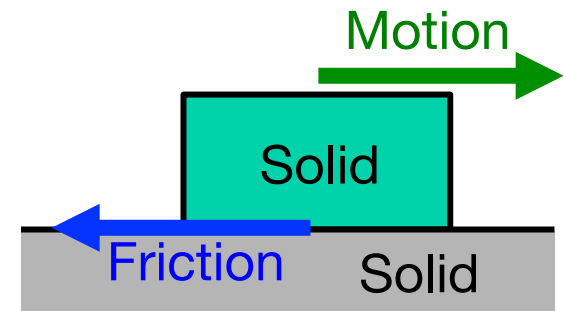
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I do micro electro mechanical system (MEMS) research



Friction between moving objects

- Friction impedes a solid object moving against another solid object. We use a liquid lubricant to reduce the friction.
- How about a solid object moving against a liquid? Can we use a gas lubricant?



Drag between solid and liquid

- A solid object moving in a liquid:
e.g., watercraft
- A liquid flowing in a solid
confinement: e.g., pipe flows
- Our interest is to reduce the drag
of traveling watercraft

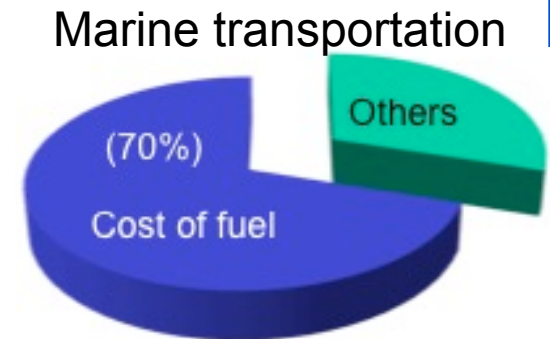
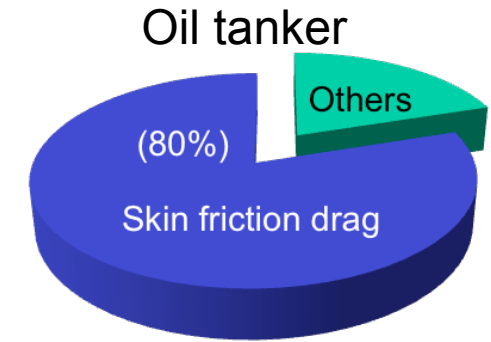


- Drag of a boat = skin friction + form drag + wave resistance
- We address the skin friction drag
How important is the skin friction drag?

Consider marine transportation

According to Guardian 2009:

- Skin friction drag is 60-70% of the total drag for a cargo ship, 80% for a tanker and 90% for underwater vehicles
- Shipping alone accounts for 8.5% of the global oil supply



Global marine fuel consumption

- 300M tons (IMO 2012)
- \$150B (e.g., \$ 500/ton)
- \$120B by skin friction drag



Consider marine transportation

- Shipping alone accounts for 3.3% of the global CO₂ emissions
- Low-grade fuel used by cargo ships contains up to 2000 times the sulfur in the fuel used for automobiles



Cancer and asthma causing pollutants ~ 50 million cars

- Huge market
- Vital to environment

Lubricate the skin friction with air

Conventional: gas injection



Ceccio, Annu. Rev. Fluid Mech. (2010)

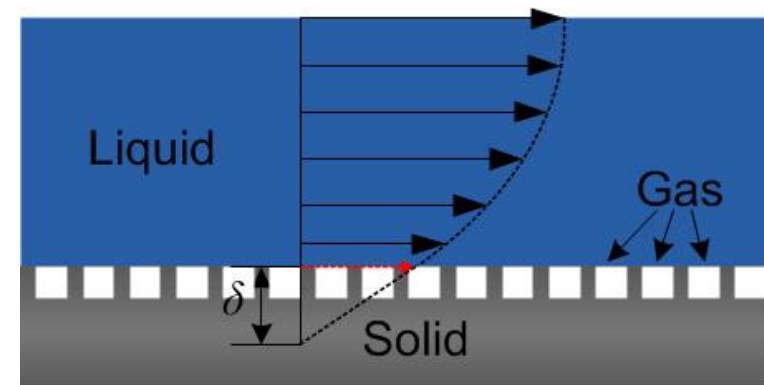


Center for Smart Control of Turbulence, Japan

Gas leaves as bubbles

- 80-90% DR w/ gas film formation
- 10-20% DR w/ micro gas bubbles
- **The issue: not energy efficient**
- Robust under dynamic conditions?
- Worth the complication?

Superhydrophobic (SHPo) surface

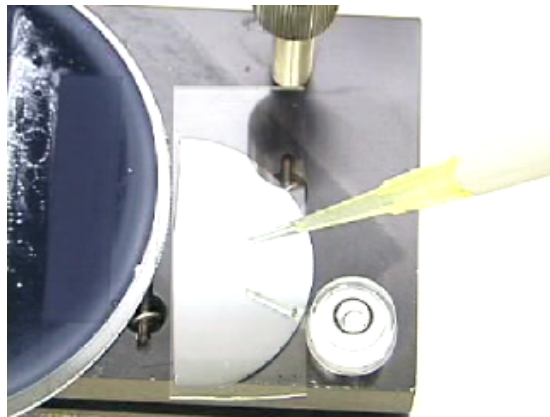


Gas is trapped on surface

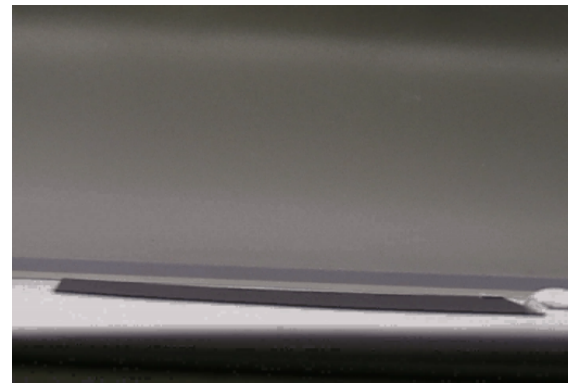
- **How much DR is obtainable?**
- **How long would the gas stay?**
- How practical and economical?

Superhydrophobic (SHPo) surfaces

- Water forms contact angle greater than 150°
- Water rolls easily on the surface



Kim, Proc. *IEEE MEMS* (2002)



Chiou, *Nat. Nanotech.*(2007)

- Widely spread misunderstanding: the air trapped on a SHPo surface makes water repelled and its droplets roll off, so the surface should also reduce drag of water flows
- Water droplets rolling on a surface in air is different from water slipping by on a submerged surface

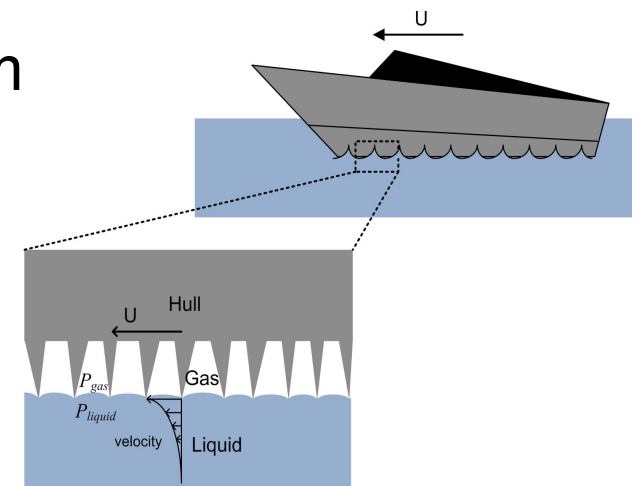
To obtain drag reduction of engineering utility

A SHPo surface should be able to reduce the frictional drag of water flows by a useful amount (e.g., $> 10\%$) even for a large flow system (e.g., boat), as far as:

(#1) the slip is large enough for the system

“and”

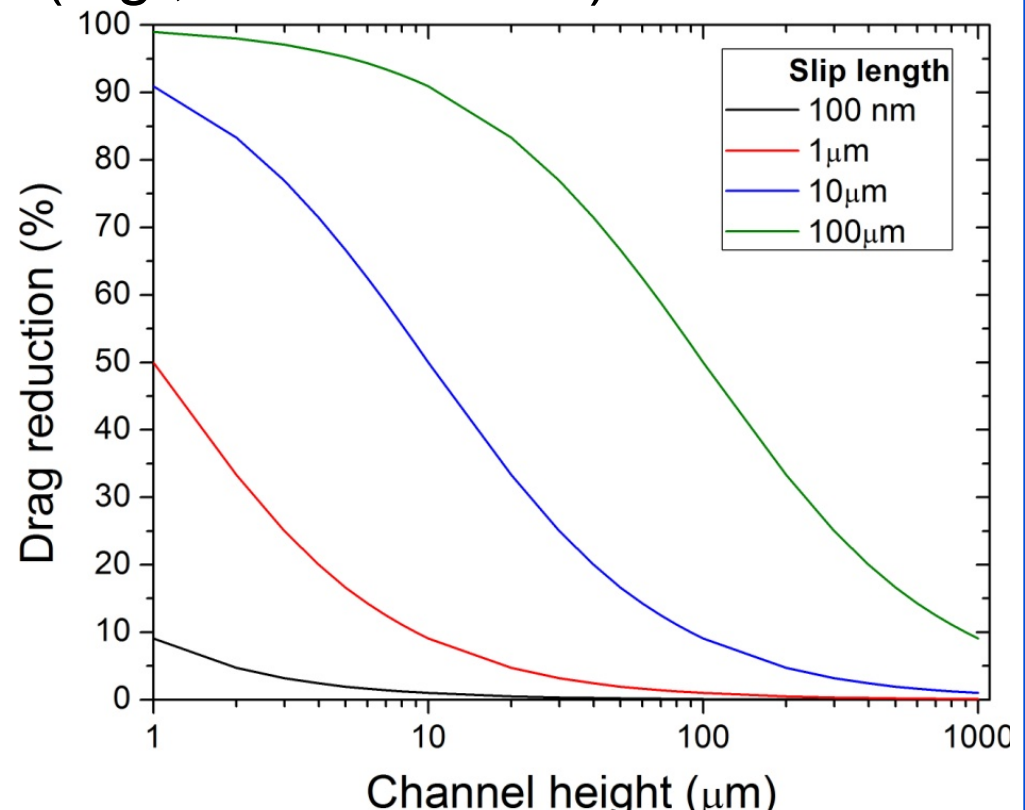
(#2) the air layer persists during service



#1. Would the given slip lead to enough drag reduction?

First, it is important to use the slip length, not the drag reduction, to describe how slippery a surface is, because:

- Drag is not only a function of the surface slip but also a function of the characteristic size of the flow.
- For a given surface, drag reduces more for flows with a smaller characteristic size (e.g., microchannel)

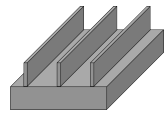


Need a slip large enough for regular (macro-scale) flows

- To use a liquid slip for a drag reduction in a regular (macroscale) flow system (e.g. boundary layer ~ 1 mm), a giant slip length ($> 100 \mu\text{m}$) is desirable
- To design a SHPo surface of such a large slip, the correlation between surface parameters and slip length should be understood first
- Early experimental studies did not provide conclusive information about the effect of surface parameters on slip length
- Let's consider laminar flows first

Theory of slip length on regular structures

Analytical solution on grates (Philip ZAMP 1972; Lauga & Stone JFM 2003)

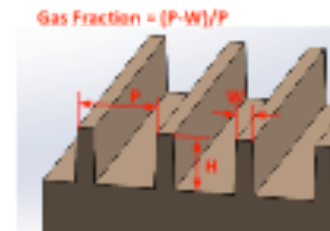


Slip length \rightarrow

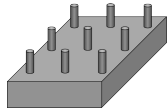
Pitch \rightarrow

$$\frac{\delta}{L} = -\frac{1}{\pi} \log \left[\cos\left(\frac{\pi\phi}{2}\right) \right]$$

Gas fraction \leftarrow



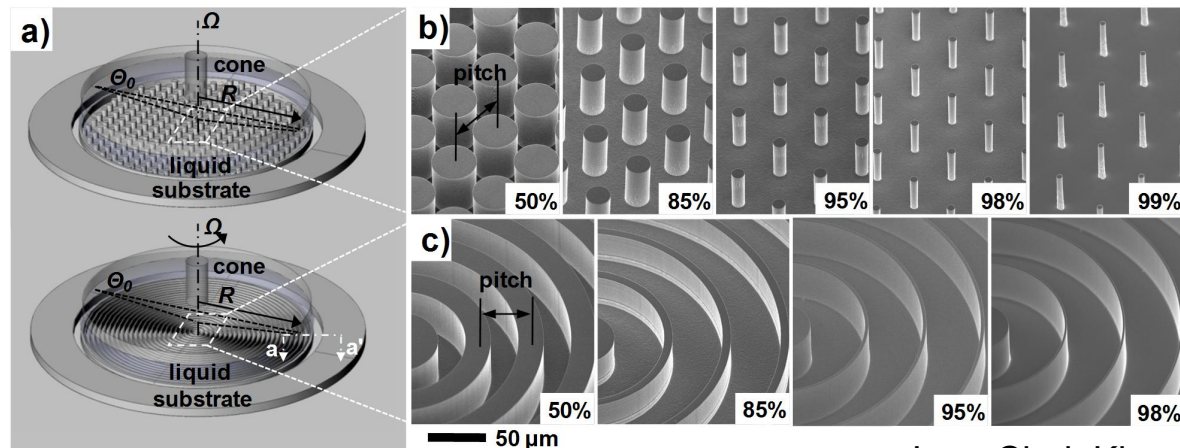
Scaling law on posts at a high gas fraction ($\phi > 0.7$) (Ybert et al. PoF 2007)



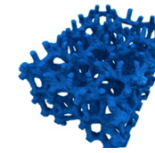
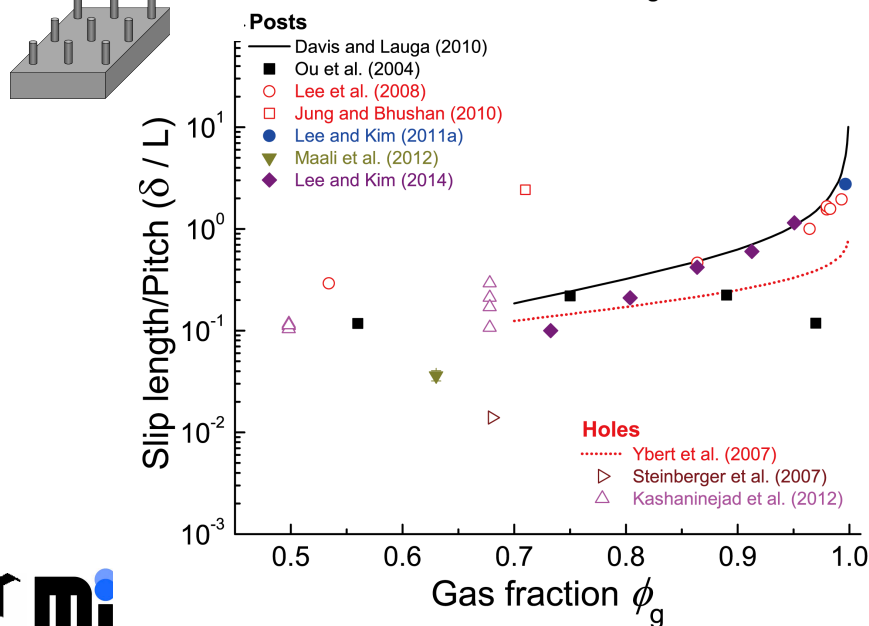
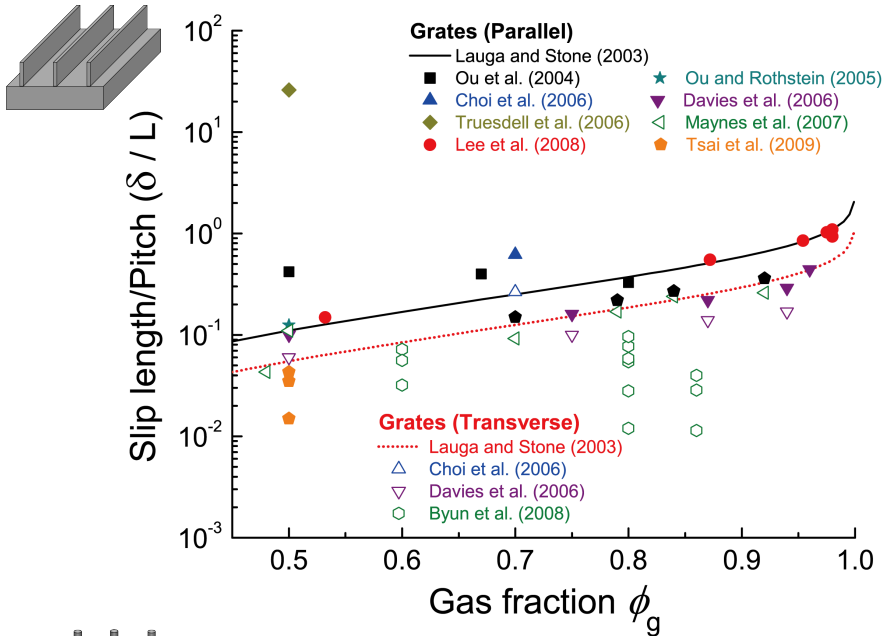
$$\frac{\delta}{L} = \frac{0.325}{\sqrt{(1-\phi)}} - 0.44$$

Coefficients (empirical) \leftarrow

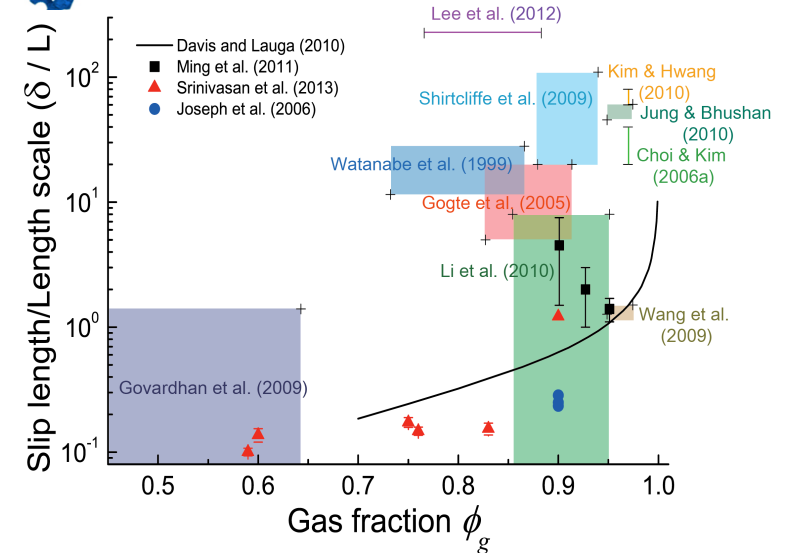
- According to the theories, **pitch** and **gas fraction** are two important surface parameters determining slip length
- Since previous experimental reports deviated from the theoretical predictions, we performed experiments to test the theories



The slip length data of laminar flows in the literature



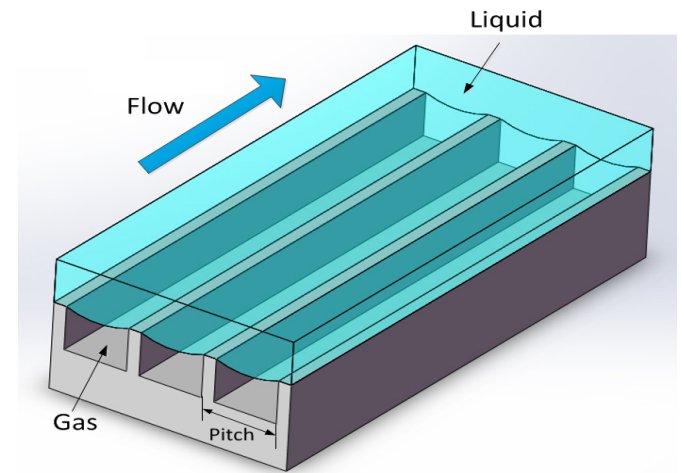
Random microstructures



These unreasonable data in early years explain the difficulties of experiments and the misguided anticipation of SHPo drag reduction

- The slip on SHPo surfaces and drag reduction in laminar flows are understood today

- We will use grating structures aligned to the water flow
- Slip length $\sim 100 \mu\text{m}$ has been obtained (Lee, Choi, Kim, *PRL* 2008)

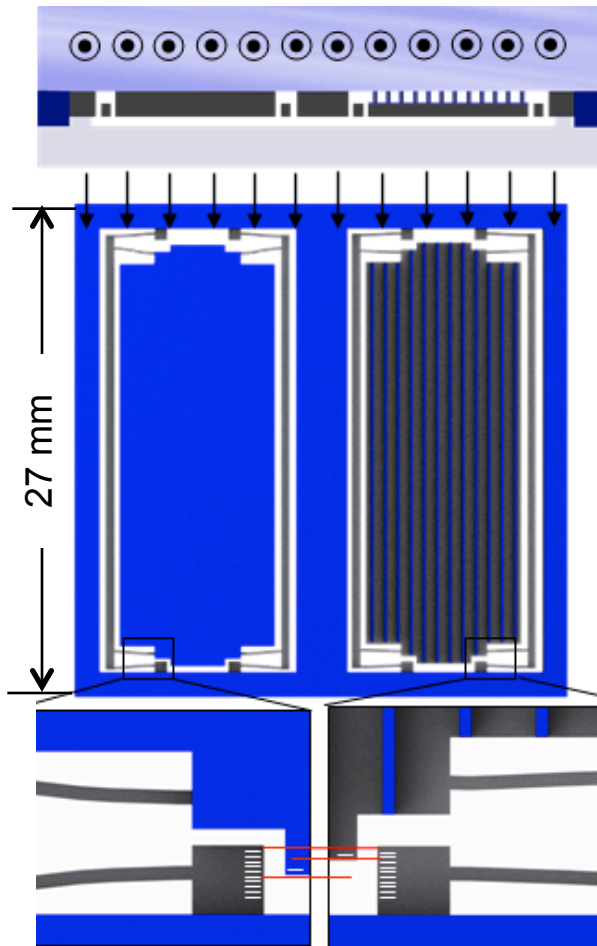


- How about in turbulent flows, especially boundary layer flows (e.g., boat traveling in open water)?

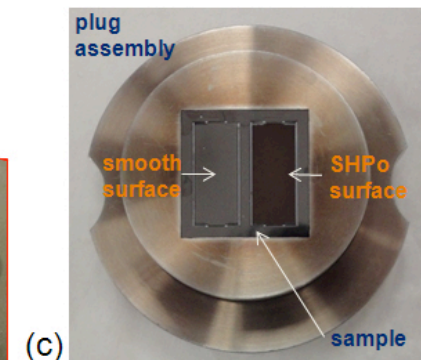
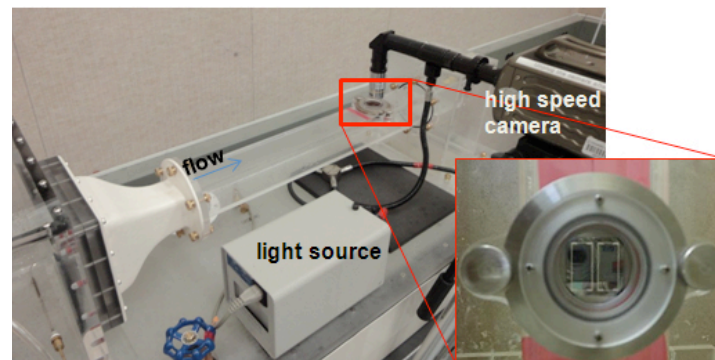
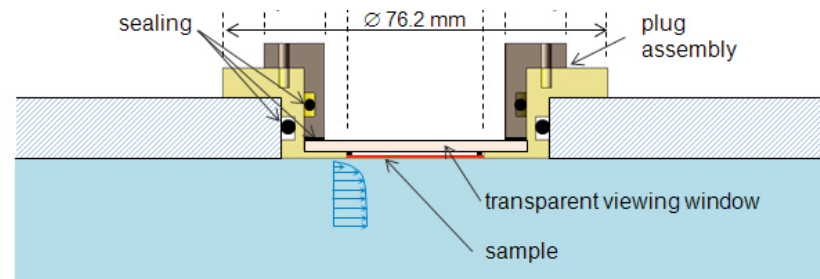
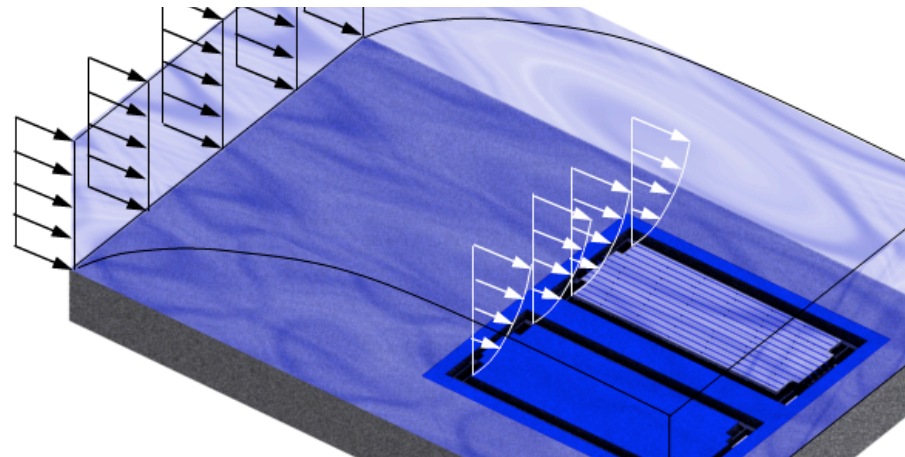
Drag reduction in turbulent boundary layer flows



-- Measured differentially

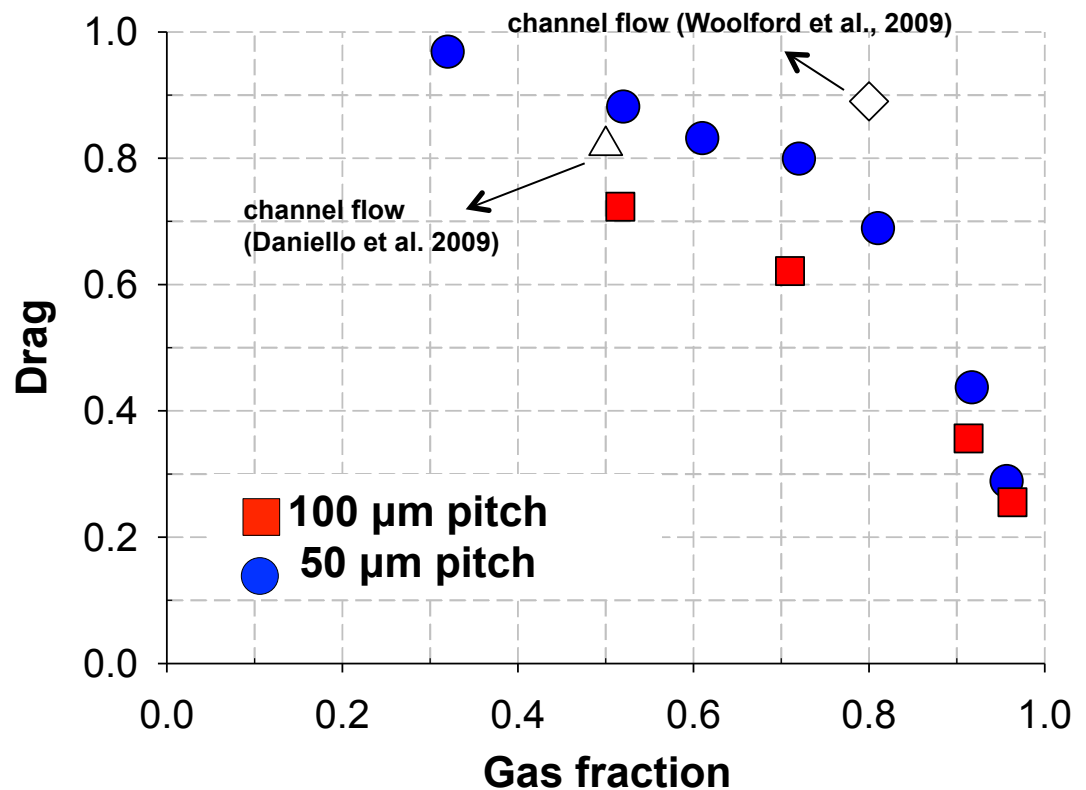


A pair of 1" floating plates carved out of a silicon wafer



A SHPo surface is dragged
less than a smooth counterpart
in a turbulent flow

Hyungmin Park, Guangyi Sun
and Chang-Jin "CJ" Kim (UCLA)



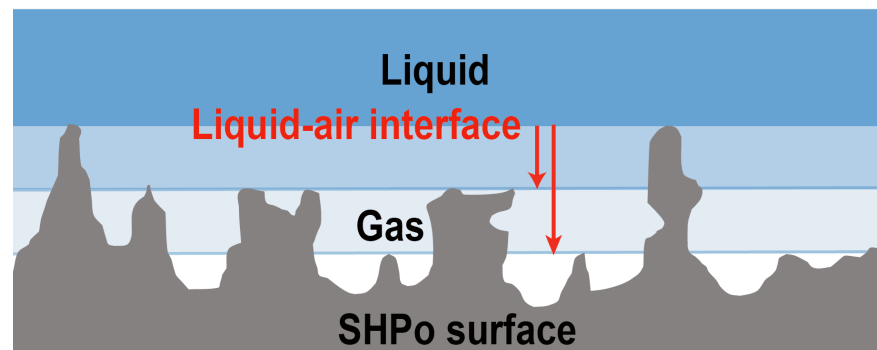
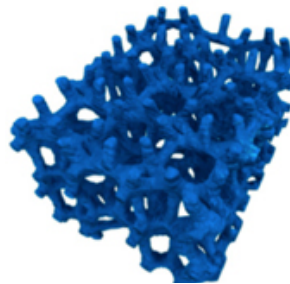
Drag on SHPo surface as low as 25% of that on the
smooth surface obtained, i.e., 75% reduction!

Dream or reality?

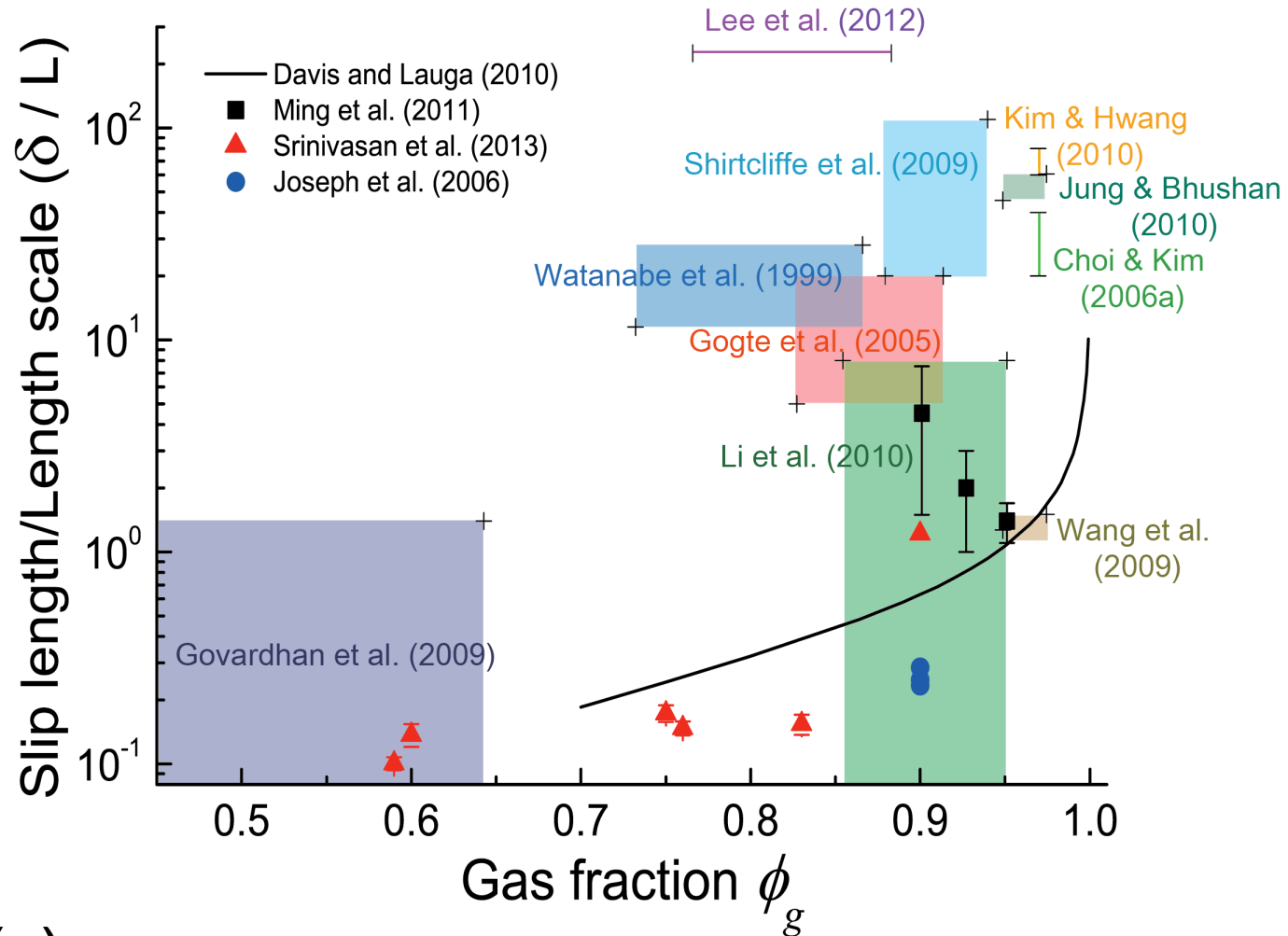
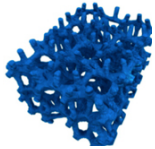
- Despite many publications reporting successful drag reduction in laboratory conditions (e.g., water channel tests), no one has so far reported any drag reduction in a field condition (e.g., in open water)
- Frustrated with this disconnect between the lab success and field failure, some people even liken the drag reduction of fluid mechanics to the cold fusion of physics, implying the SHPo drag reduction is just a dream.
- We need to study fundament science to figure out the above disconnect and develop engineering solutions to make the SHPo drag reduction a reality.

Where is the problem?

- Currently, many experimental successes are being reported with random-roughness surfaces even though they defy the proven science
- These unreasonable successes add more episodes of “laboratory success not transpiring to field demo”, only deepening the doubt about the SHPo drag reduction
- One explanation of the unreasonable success is the very high gas fraction obtainable on rough surface in water channel (which is typically supersaturated with air) but not in open water (which is undersaturated with air)



Recall the slip length data of laminar flows



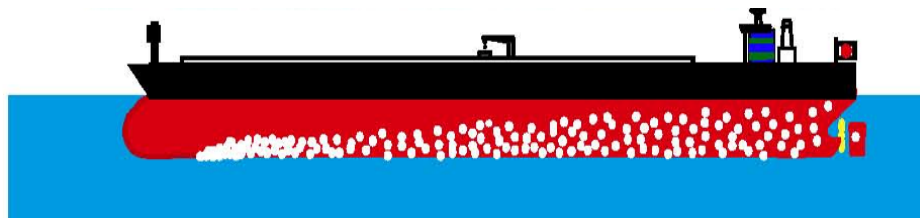
#2. Would the air layer persist?



Existing approaches



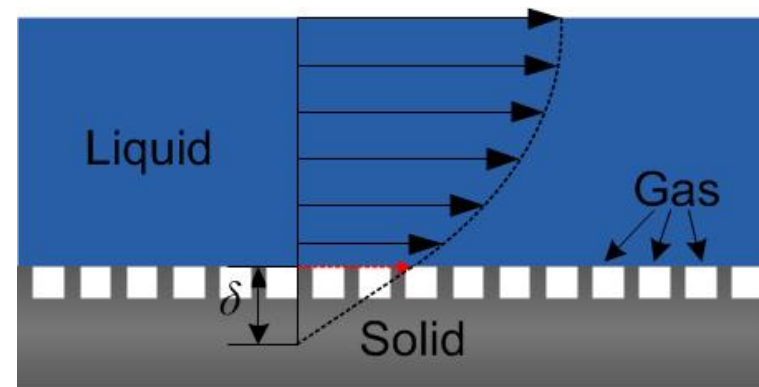
Ceccio, *Ann Rev Fluid Mech* 2010)



Center for Smart Control of Turbulence, Japan

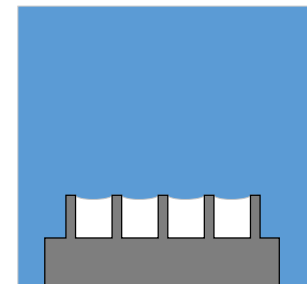
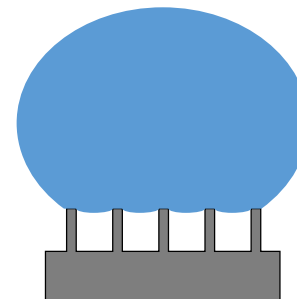
Air has to be provided continuously

SHPo surface



Air is trapped!?

True only in air



In-air vs. under water

Cassie state is frail under water

- Critical immersion depth: the maximum depth at which a SHPo surface can trap the air indefinitely
- Environmental fluctuation will cause wetting transition
 - Temperature, pressure, shock, etc.
- Underwater insect

Critical Immersion Depth

$$H_c = \frac{2\gamma \cos \theta_{adv}}{w\rho g} + \frac{k_H c - p_{atm}}{\rho g}$$

The habitat of
these underwater
insects is 10-15 cm

↙

> 15 m

↙

Negative term due to
environment fluctuation

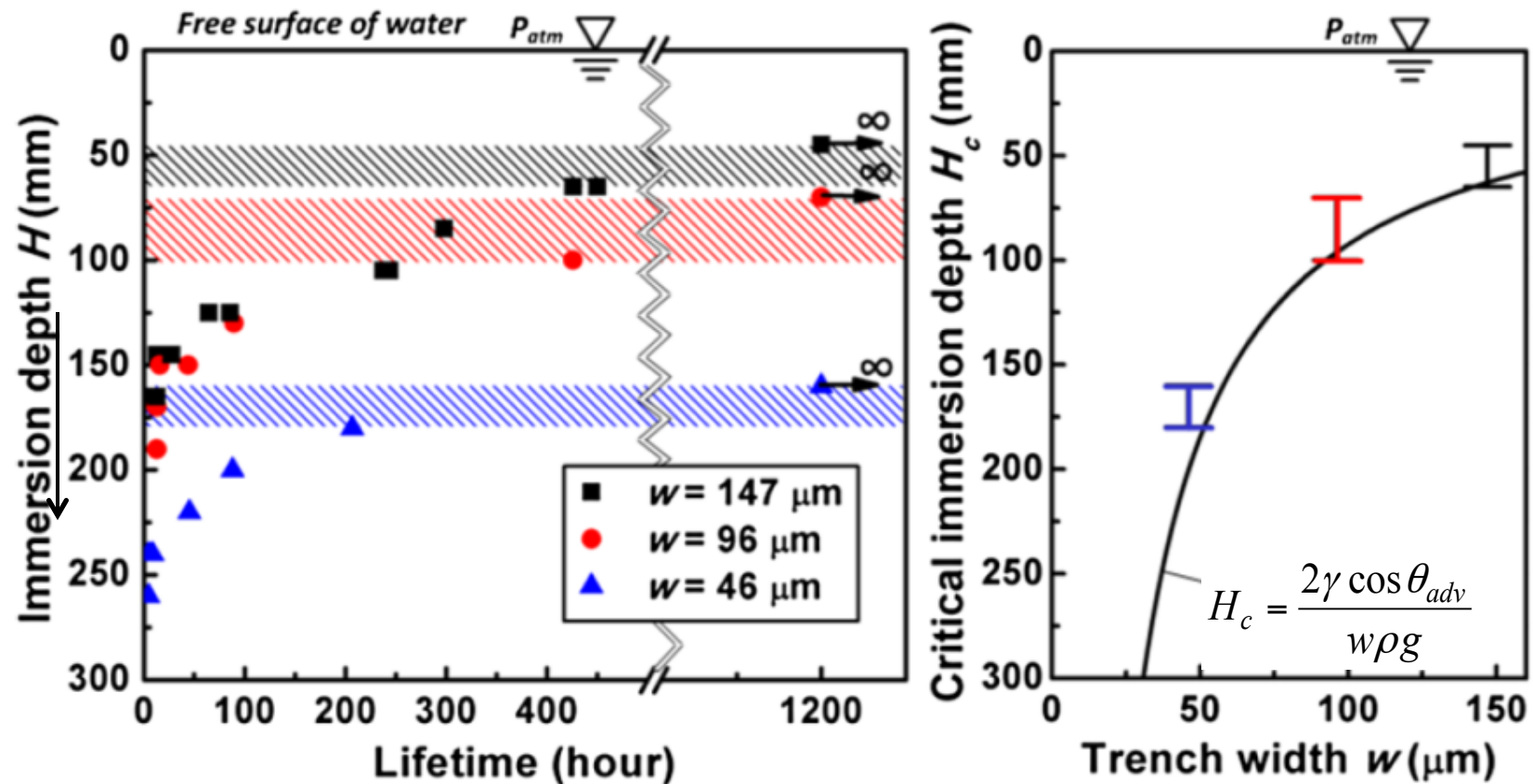
↓

Plastron



The air layer is lost in most underwater conditions

Lifetimes of different samples in different immersion depths



- Most watercrafts have hull immersed deeper than 1 m
→ Indefinite gas cannot be expected in drag reduction applications

Drag reduction on marine vessels

To obtain enough slip for a useful amount of drag reduction, pitch $w > \sim 20 \mu\text{m}$.



For $w \sim 20 \mu\text{m}$, H_c is $\sim 35 \text{ cm}$ even if no environment fluctuation. In practice, $H_c < \sim 10 \text{ cm}$.



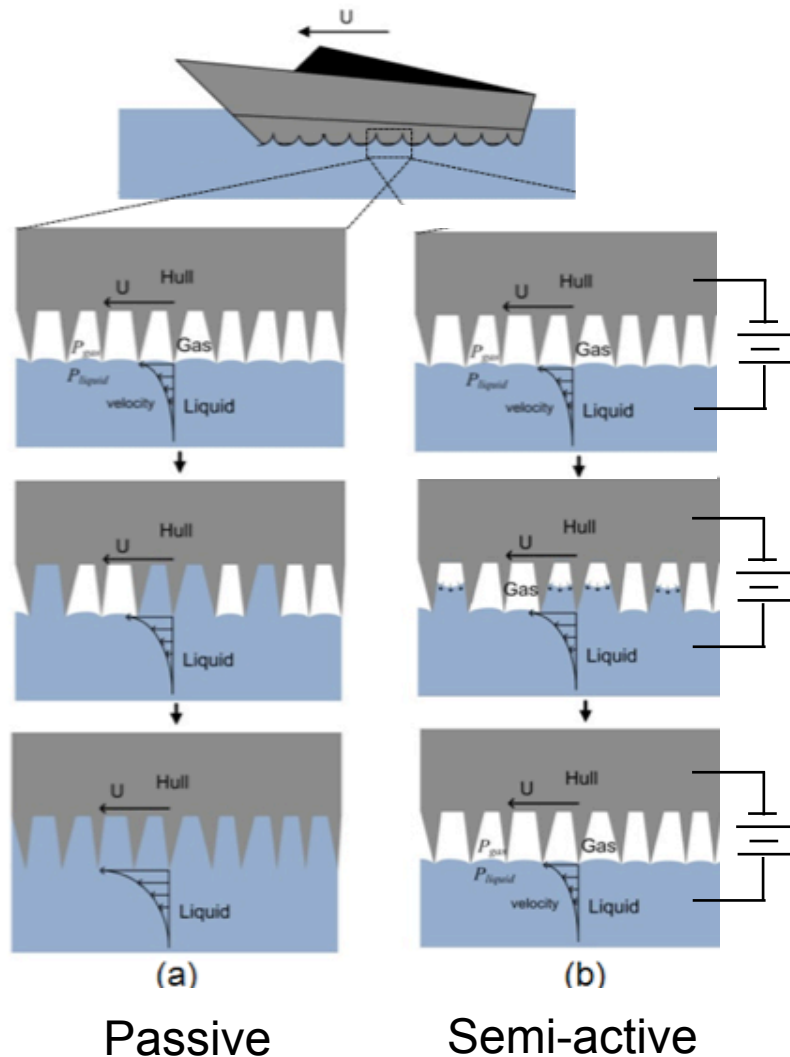
Drag reduction possible only in shallow immersion (cm's): not practical



Needs an engineering solutions, e.g., replenishing the lost gas.

Need an active method to replenish the lost air

Our solution: Self-limiting electrolysis



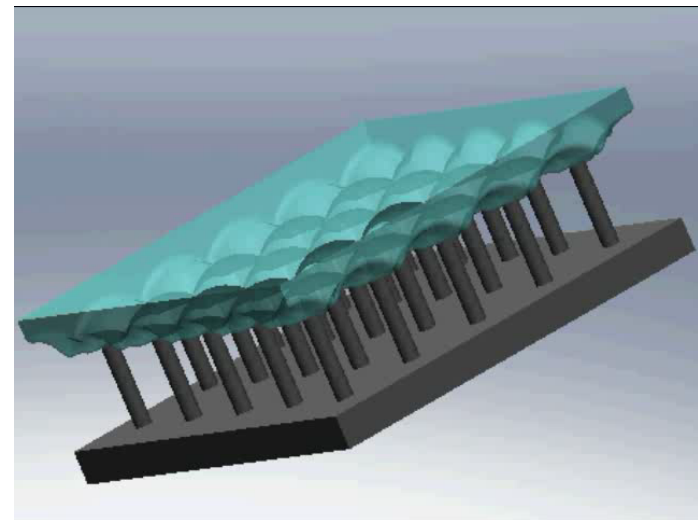
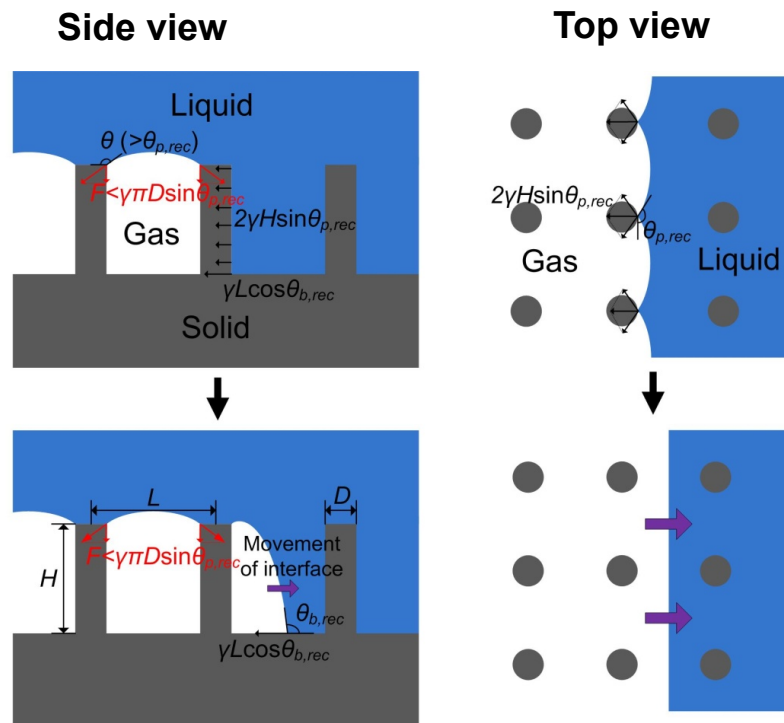
Once the air is lost, can we restore air by a simple and energy-efficient way?

Let's push the liquid out of the texture with a regenerated (e.g., by electrolysis) gas; see figure (b)

Figure (b) is possible if the surface microstructures are designed properly, as shown in the next slide.

Condition for gas film formation underwater

Gas should prefer to spread laterally than vertically off the surface

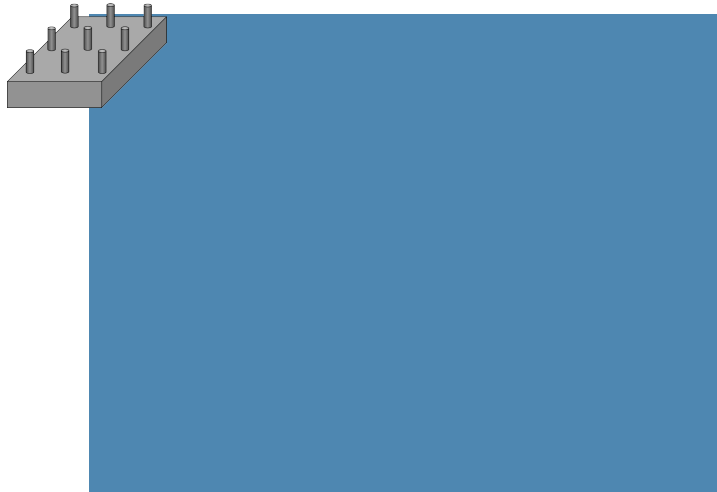


$$H / L < \frac{-\cos \theta_{b,rec}}{2 \sin \theta_{p,rec} (1 - \sqrt{\pi(1 - \phi) / \phi})}$$

Demonstration of gas film restoration underwater

Starting from fully wetted (i.e., worst case) condition

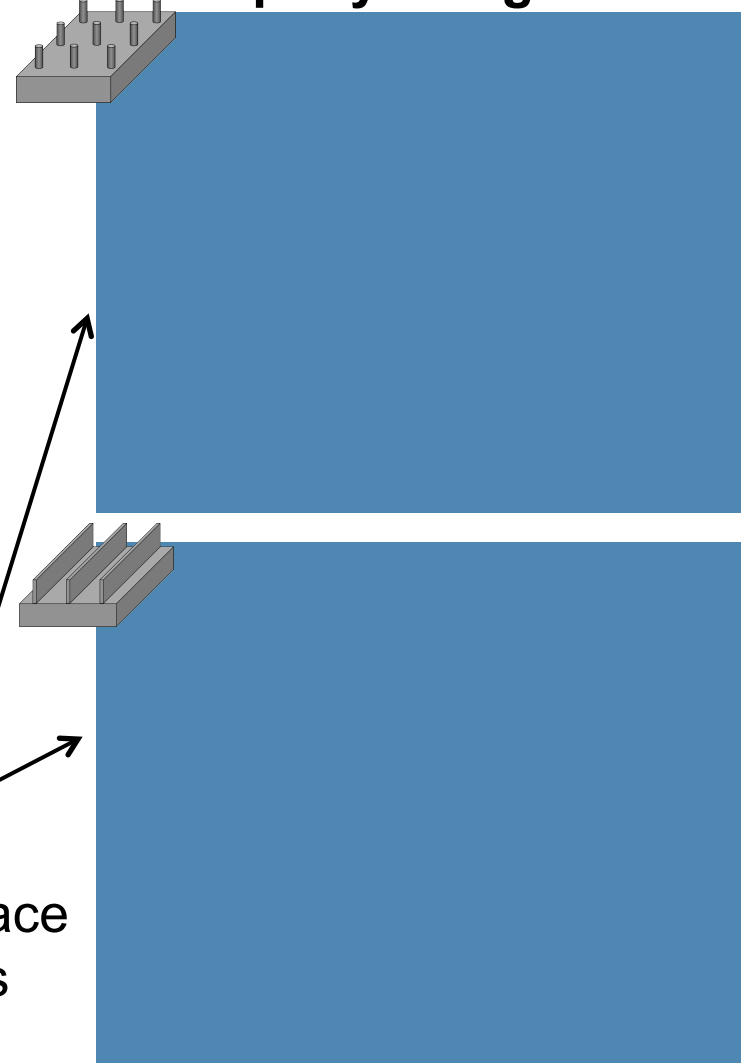
Control surface



Fails to form gas film

- Small bubbles leave off the surface
- Bubbles cover the top surfaces

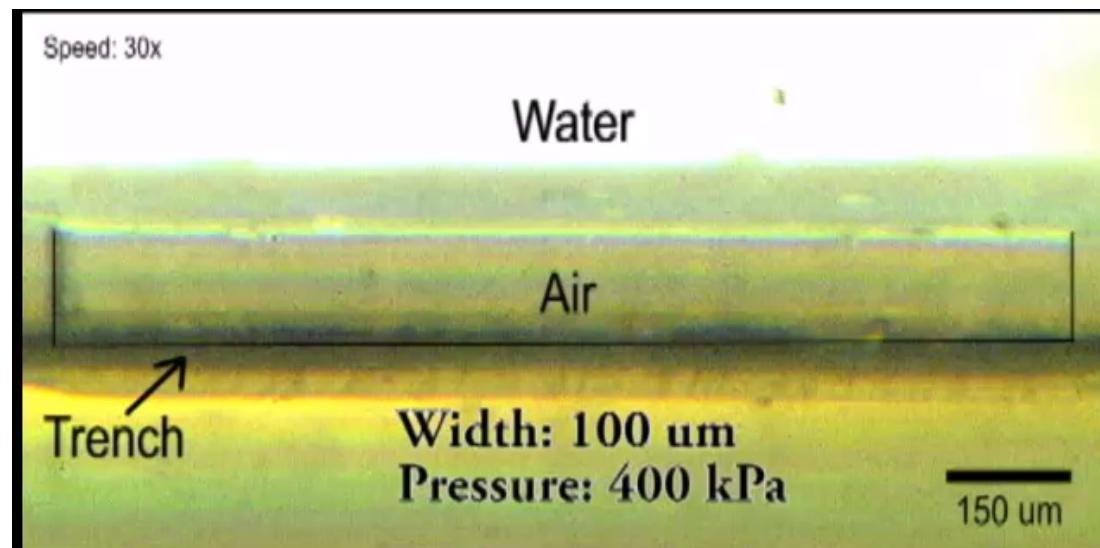
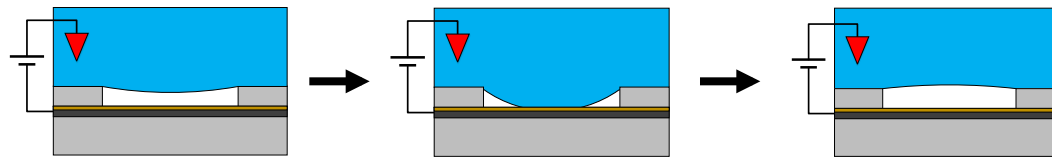
Properly designed



Succeeds to form gas film

- No bubble leaves the surface
- Gas film gradually spreads

Side view of wetting and recovery

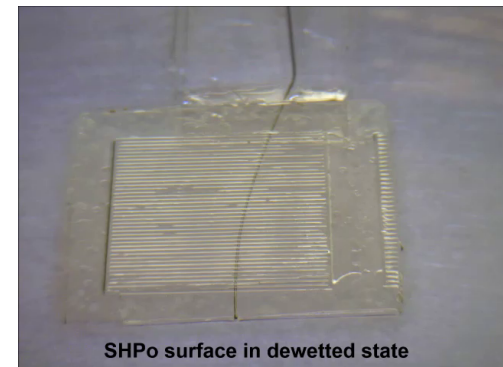


1. Initially, the trench underwater is filled with air
2. The chamber is quickly pressurized to simulate hydrostatic pressure
3. The air is slowly diffused out
4. When water reaches the bottom, gas is generated to refill the trench
5. Gas generation terminates when the gas fills up to the trench top

Conclusion for #2: using the semi-active surface that uses a minimal amount of energy in a self-regulated manner, one can maintain the plastron under realistic conditions

Overall: By combining #1 (large drag reduction by parallel-trench SHPo structures) and #2 (semi-active surface), we expect to obtain SHPo surfaces viable for practical marine applications.

Our current effort is to make drag reducing films through a mass manufacturing method.



Summary

If we play the game the right way based on firm scientific studies, we can apply microscale phenomena even to large-scale applications



Science
Engineering
Manufacturing
Economy
Luck

