SLIP FLOW OVER BIOTEMPLATED SUPERHYDROPHOBIC SURFACES

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March 18, 2013

Personal Background

- Andres Bisono, Junior
- Home Country: Dominican Republic
- Experience:
  - Coop: Krones Inc. Franklin, WI. Spring/Summer 2013
- BS in Mechanical Engineering and Mechanics (2014)

Goal and Motivation

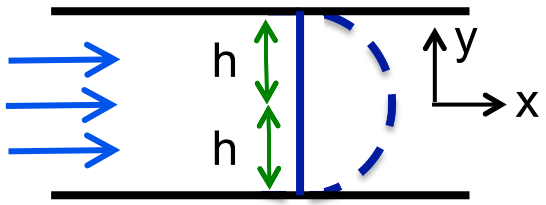
- Design, fabrication, and testing of superhydrophobic coatings based on biotemplated high aspect ratio nanostructures to reduce drag in fluid flows.
- Improve surface topology
- To achieve a **slip flow** characteristic at the solid-liquid interface
- Pressure drop reduction leads to the required pumping power

Application

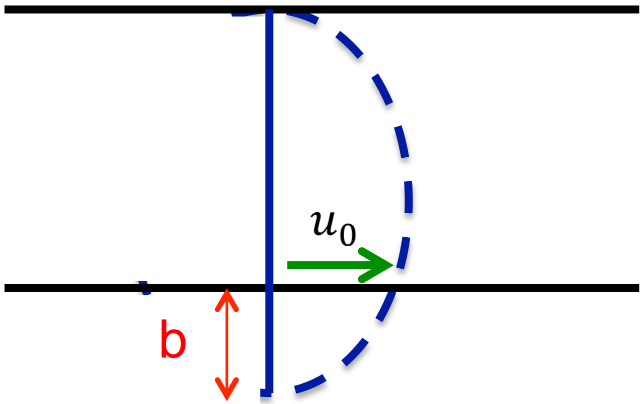
- Micro scale applications
- Lab on a chip
  - biological and chemical analysis

Theory / Slip Length

- No Slip



- Slip at bottom surface



Navier-Stokes eqn.:

$$\frac{d^2u}{dy^2} = \frac{1}{\mu}\frac{\partial p}{\partial x}$$

$$\frac{du}{dy} = \frac{1}{\mu}\left(\frac{\partial p}{\partial x}\right)y + c_1$$

$$u = \frac{1}{2\mu}\left(\frac{\partial p}{\partial x}\right)y^2 + c_1 y + c_2$$

$$\boxed{\begin{gathered} u = 0 \text{ for } y = +h \\ \text{and } u_0 = b\left|\frac{\partial u}{\partial y}\right| \text{ for } y = -h \end{gathered}}$$

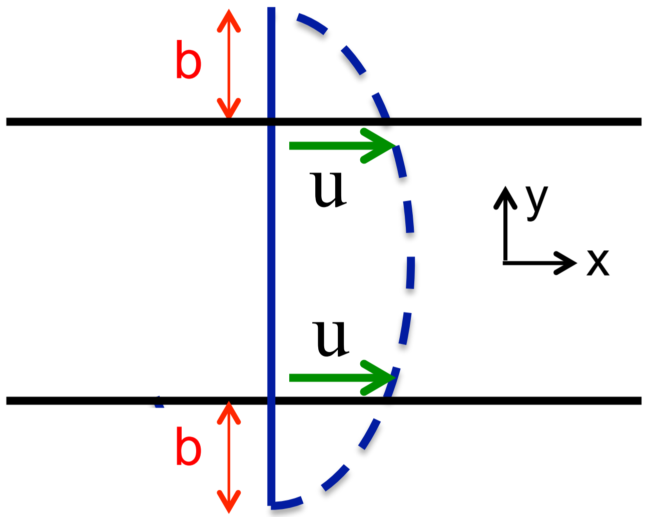
Volume flow rate passing between the plates:

$$\dot{Q} = \frac{wh^3}{4\mu}\left(-\frac{\partial p}{\partial x}\right)\left[\frac{1}{3} + \frac{b}{b+h}\right]$$

Negative pressure gradient, since pressure decreases in the direction of flow

Theory / Slip Length

- Slip both surfaces



$$u = b\left|\frac{\partial u}{\partial y}\right| \text{ for } y = +h$$

$$\text{and } u = -b\left|\frac{\partial u}{\partial y}\right| \text{ for } y = -h$$

Navier-Stokes eqn.:

$$u^* = -\frac{1}{2}{y^*}^2 - \frac{(\beta^- - \beta^+)}{(1+\beta^- + \beta^+)}y^* + \frac{1}{8}\left[\frac{3\beta^- + 3\beta^+ + 8\beta^-\beta^+ + 1}{\beta^- + \beta^+ + 1}\right]$$

$$u^* = \frac{u}{\frac{1}{\mu}\left(-\frac{\partial p}{\partial x}\right)H^2} \quad y^* = \frac{y}{H} \quad \beta = \frac{b}{H}$$

Volume flow rate passing between the plates:

$$\boxed{\dot{Q} = \frac{H^2W(6b+H)}{12\mu}\left(-\frac{\partial p}{\partial x}\right)}$$

Negative pressure gradient, since pressure decreases the direction of flow

Slip Flow at the Wall

- Non-slip condition
  - Caused by bond between interface molecules
- Nanostructure surfaces provide a slip flow characteristic
  - Prevent the contact between the fluid and the channel boundaries

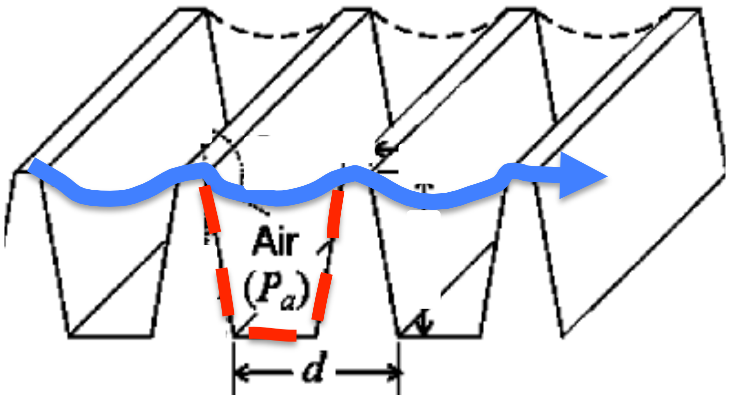


Figure 1: layer of air in between nonwetting surface structures. [3]

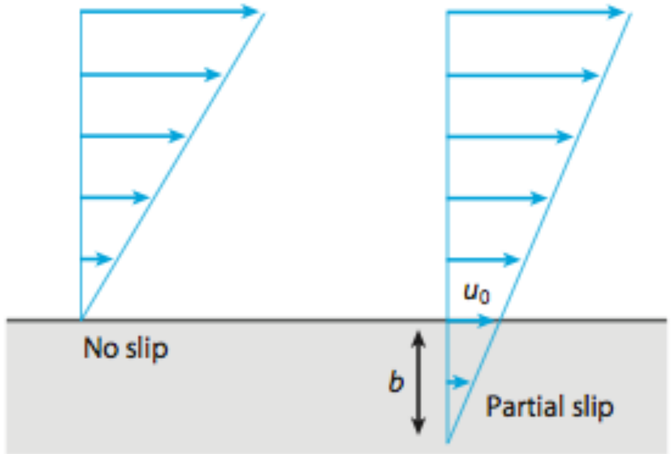
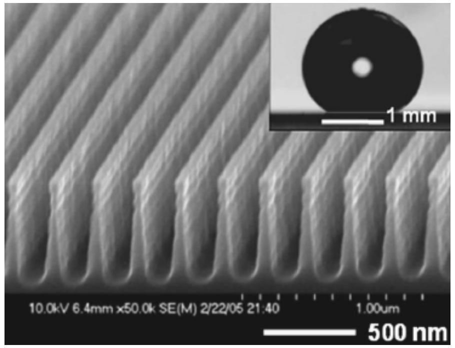


Figure 2: Schematic diagram of slip at a fluid-solid interface. [1]

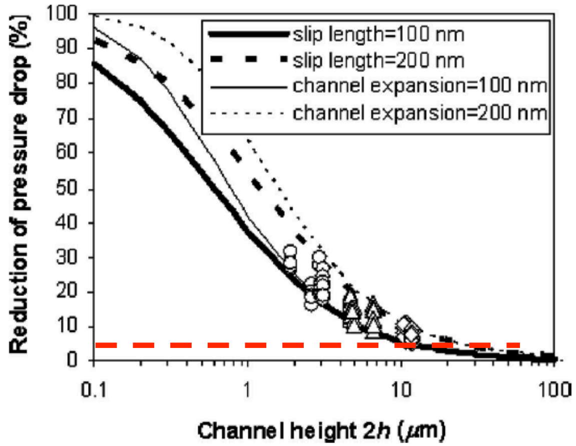
Slip Flow Over Superhydrophobic Nanostructures

Choi *et al.*, Phys. Fluids 18(2006)

- Silicon nanograting patterns slope angle were fabricated by interference lithography followed by a deep reactive ion etching DRIE

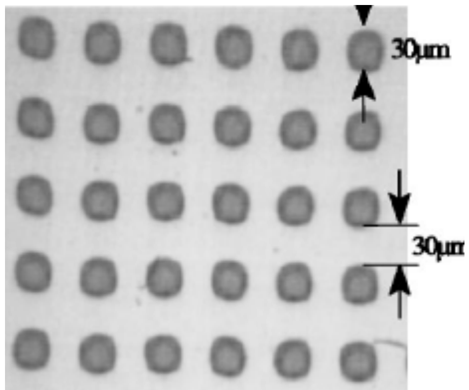


Si nanostructures

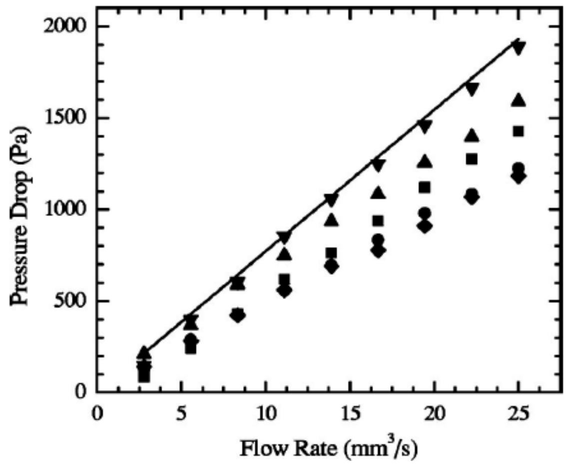


Ou *et al.*, Phys. Fluids, Vol. 16, No. 12, (2004)

- lithographically etched silicon surface
- rectangular microchannel having dimensions of width of **W** =2.54 mm, thickness **H**=127 um, and length **L** =50 mm



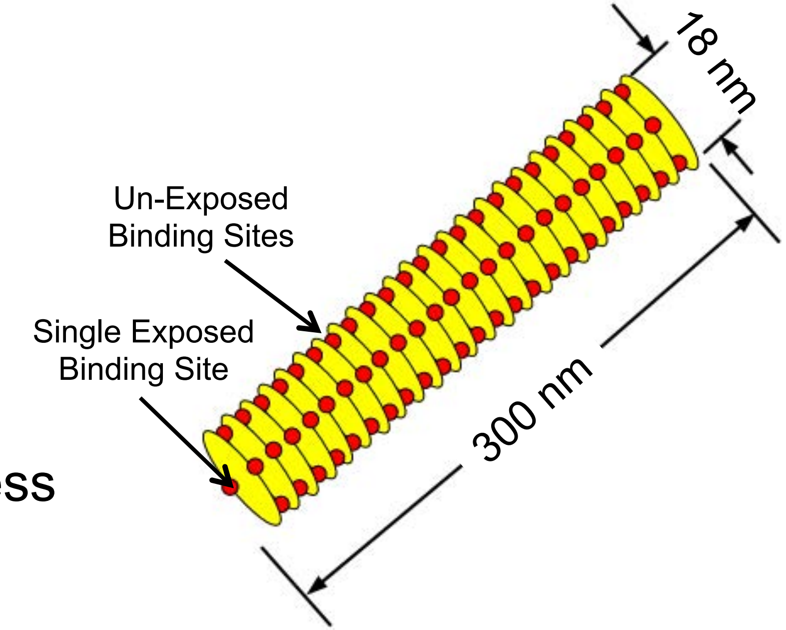
Silicon microposts



(-) theoretical, (▼) SI hydrophobic

The *Tobacco mosaic virus*

- Coated nanofabrication process to create superhydrophilic surfaces for a reduction in pressure drop through a channel.
- Characteristics:
  - rod-shaped
  - 300 nm long
  - 18 nm wide
- Benefits:
  - Increase surface porosity and roughness
  - Improve surface wettability
  - Extendable to large areas and complex geometries
  - Scalable and renewable nanomanufacturing method
  - Simple room temperature deposition

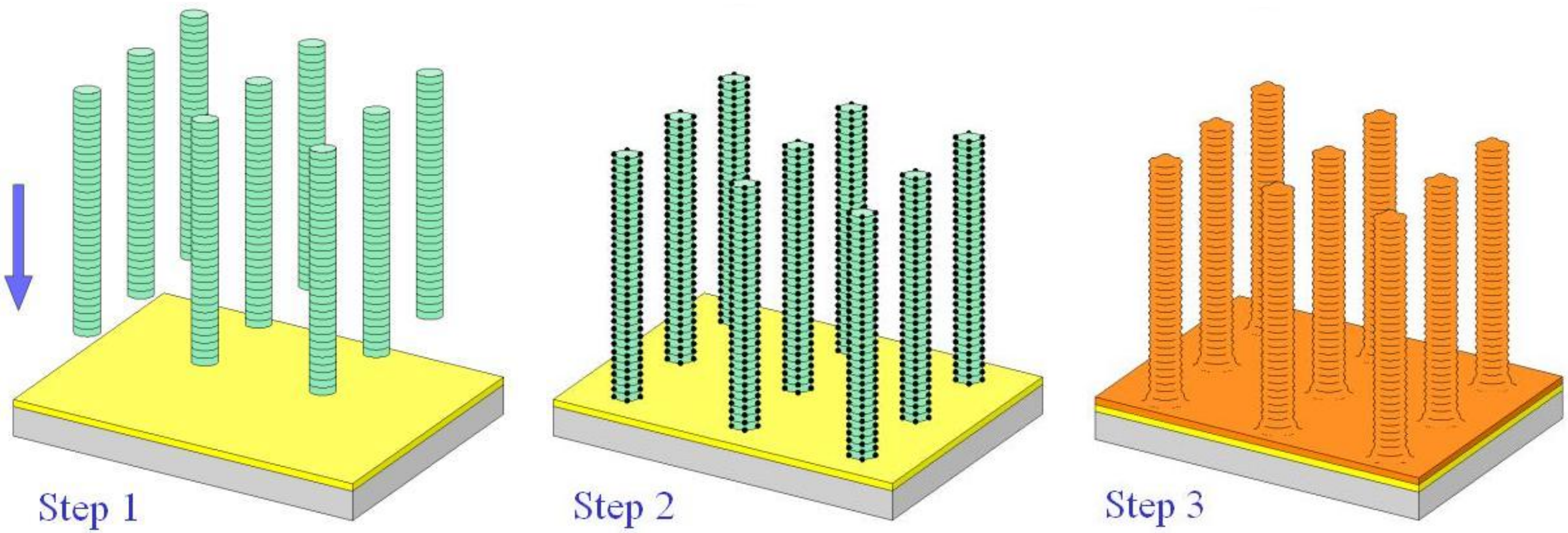


Solution-Based Assembly and Metallization

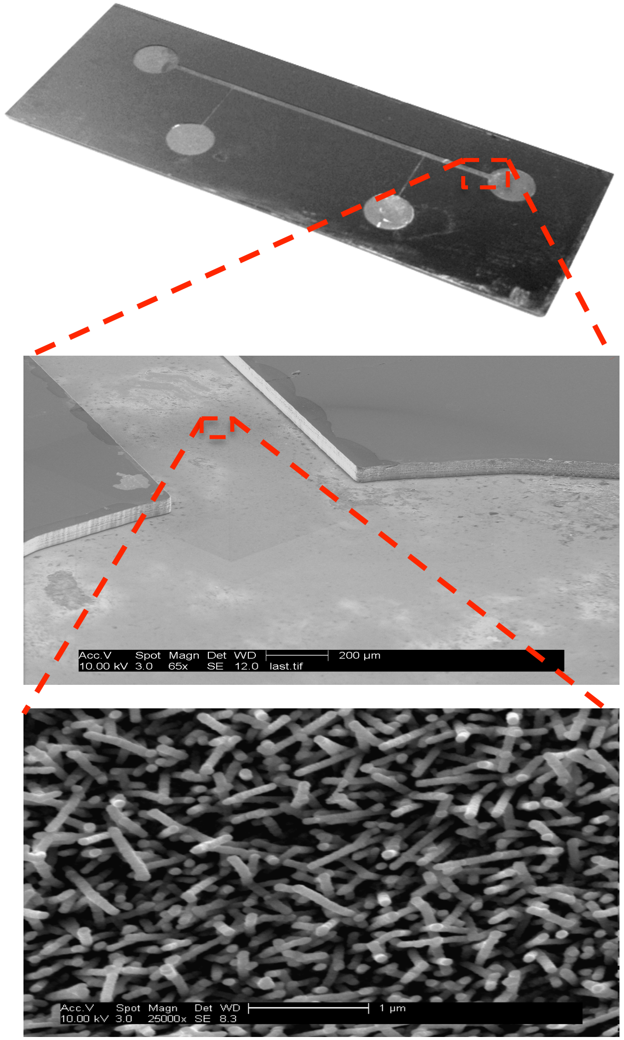
Step 1: Surface is immersed in a TMV solution (24 hours). The virus self assemble on the surface through the bottom end

Step 2: The virus surface is activated with a palladium catalyst

Step 3: The surface is immersed in an electroless plating solution and nickel is reduced onto the palladium catalyzed sites



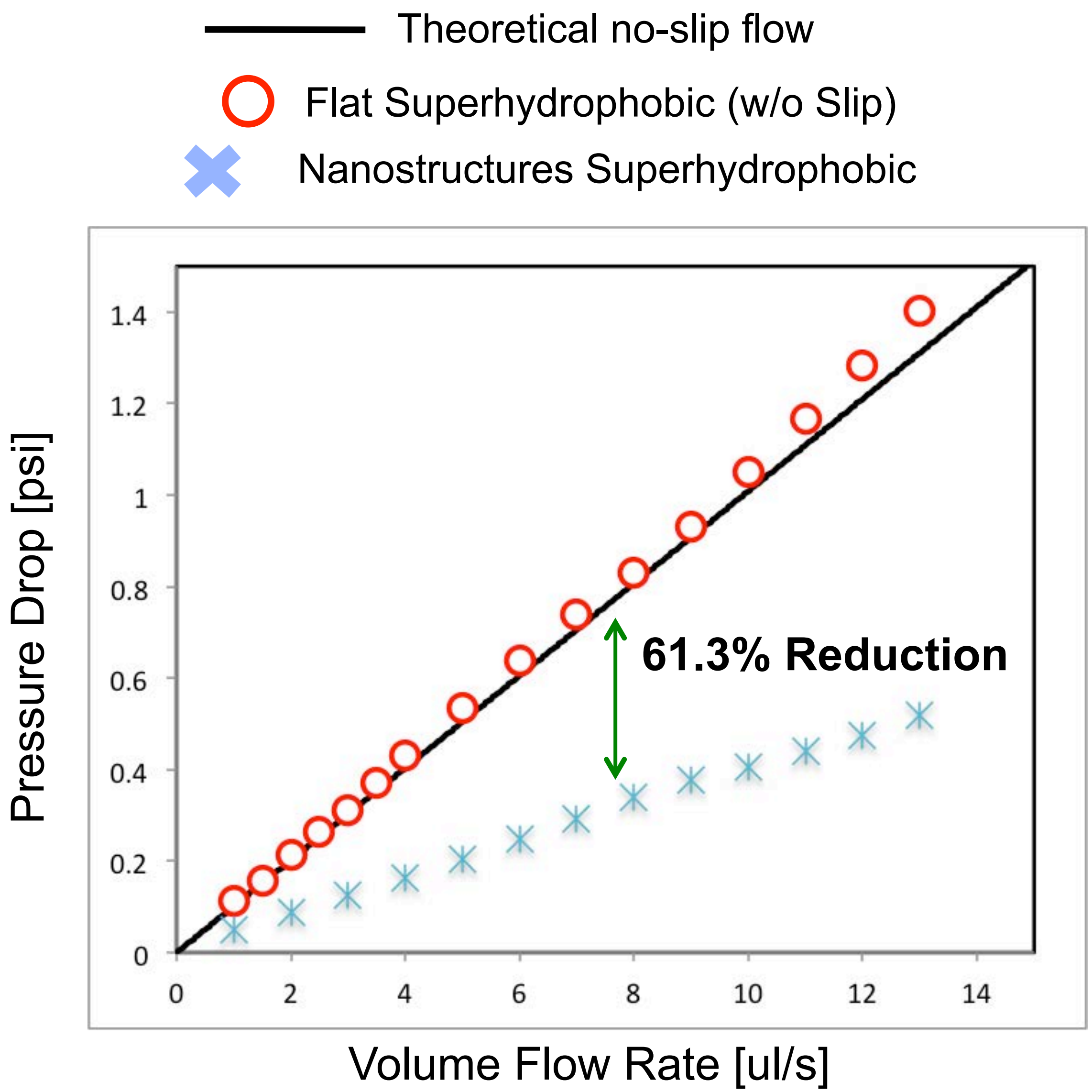
Prior Work



Fabrication:

- Silicon Micro machining
- Pyrex drilling
- Anodic bonding

Prior Work - Experimental Results



Prior Work - Summary

- Drag reductions:
  - Achieved = 61.3%
  - Literature ≈ 40% [1]

$$D_R = \frac{\Delta P_{no-slip} - \Delta P_{TMV}}{\Delta P_{no-slip}}$$

- Slip Length (b):
  - Achieved: b = 84.6 um
  - Literature: b = 0 - 100 um [1]

$$b = -\frac{1}{4}\frac{h(-12\dot{Q}\mu L + wh^3\Delta p)}{-3\dot{Q}\mu L + wh^3\Delta p}$$

Current Work Motivation

Drag Reduction having slip on both walls and assuming same achieved slip length

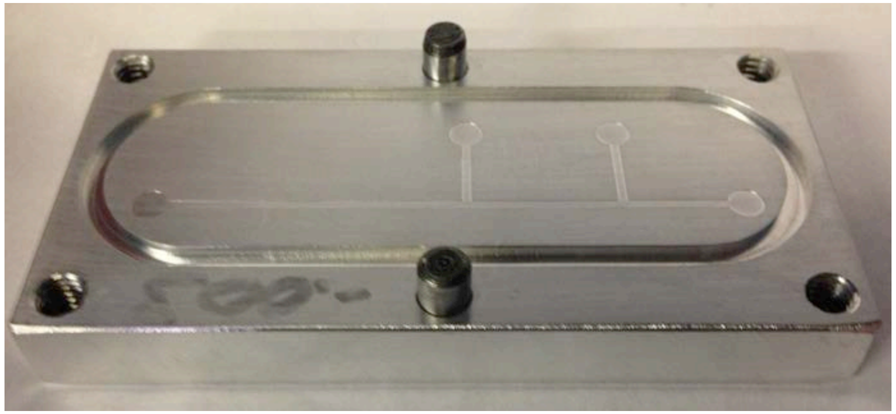
Slip Length (b): Achieved: b = 84.6 um

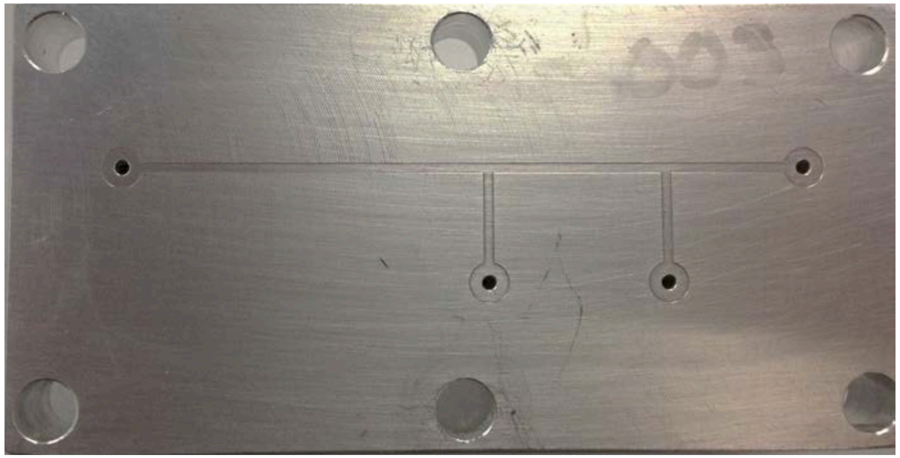
Pressure Drop: $$-\partial p = \frac{12\mu L\dot{Q}}{H^2W(6b+H)}$$

Drag Reduction: $$D_R = \frac{\Delta P_{no-slip} - \Delta P_{TMV}}{\Delta P_{no-slip}}$$

- Potentially to be achieved = 83.3%

Fabrication of Nanostructured Microchannel





Fabrication of Nanostructured Microchannel

- <u>Advantages:</u>
- Simple macro fabrication
- Ability to coat device on both sides
- Proof TMV adapt to any material and surface

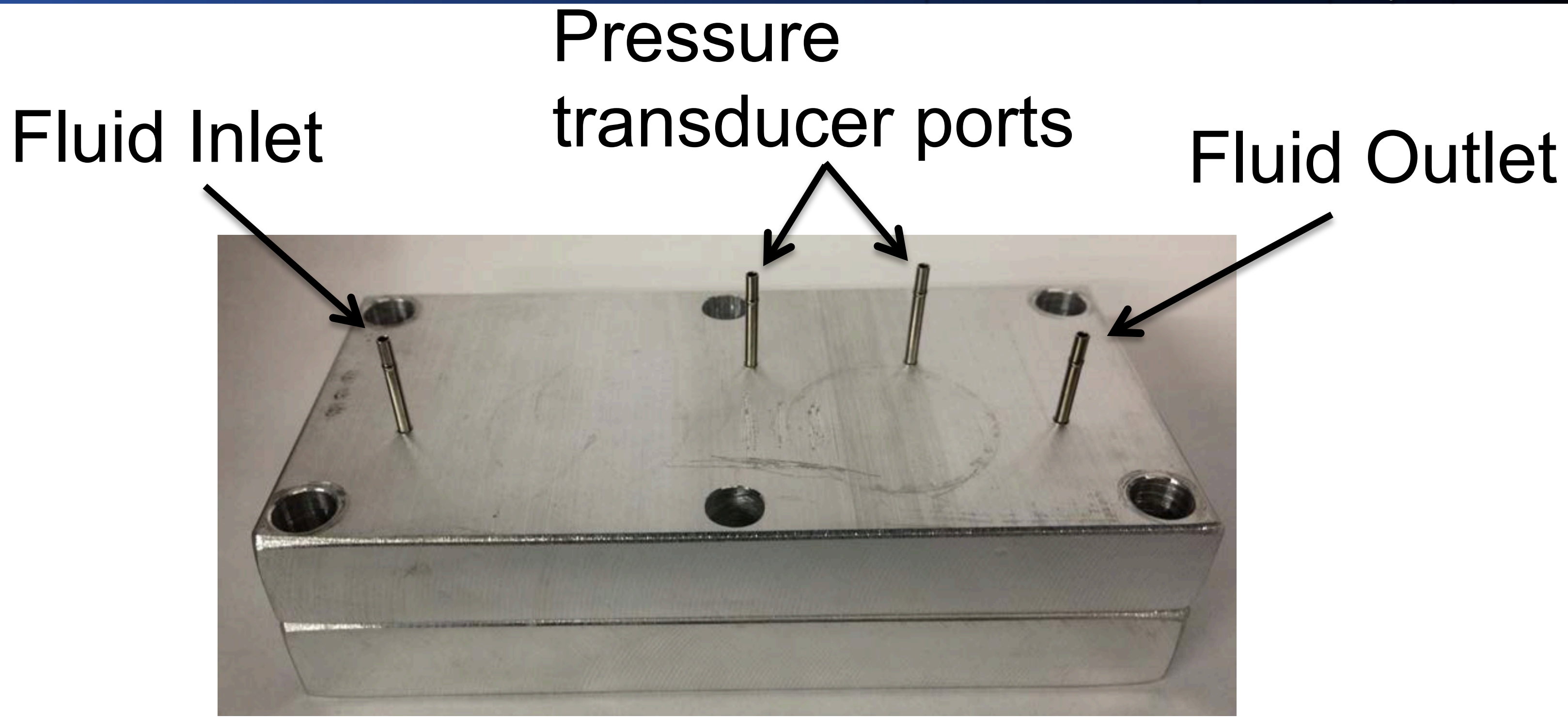
(Noah Gross research shows it is possible to coat aluminum)

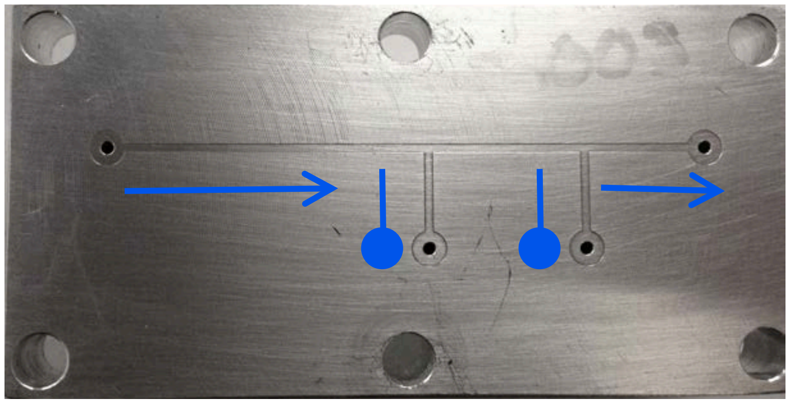
- Pyrex Drilling and Anodic Bonding not needed

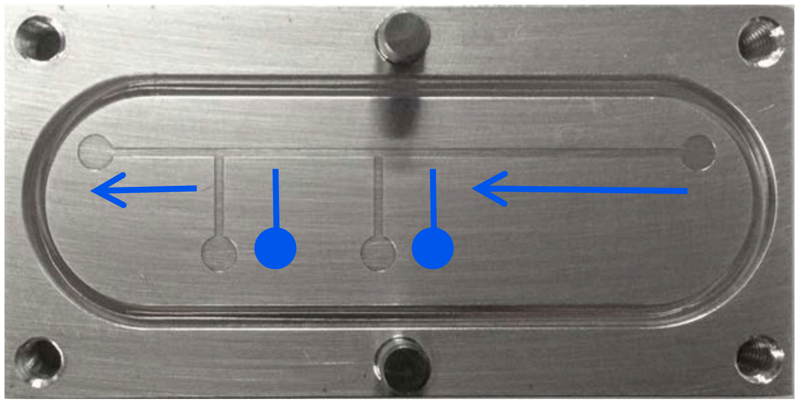
Hydrophobic Coating

- iCVD Teflon
- Silane
  1. Bath coating
  2. Vapor coating

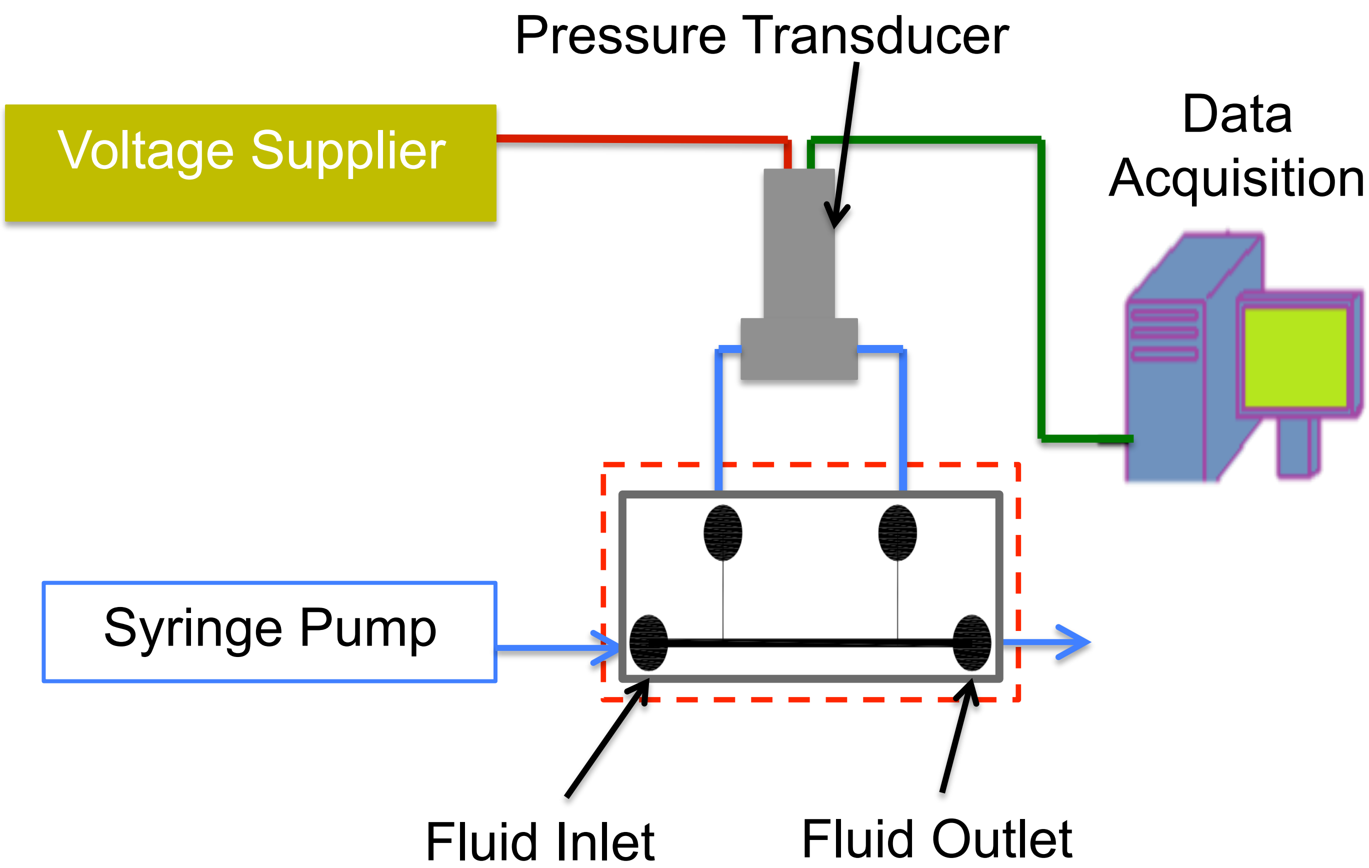
Experiment





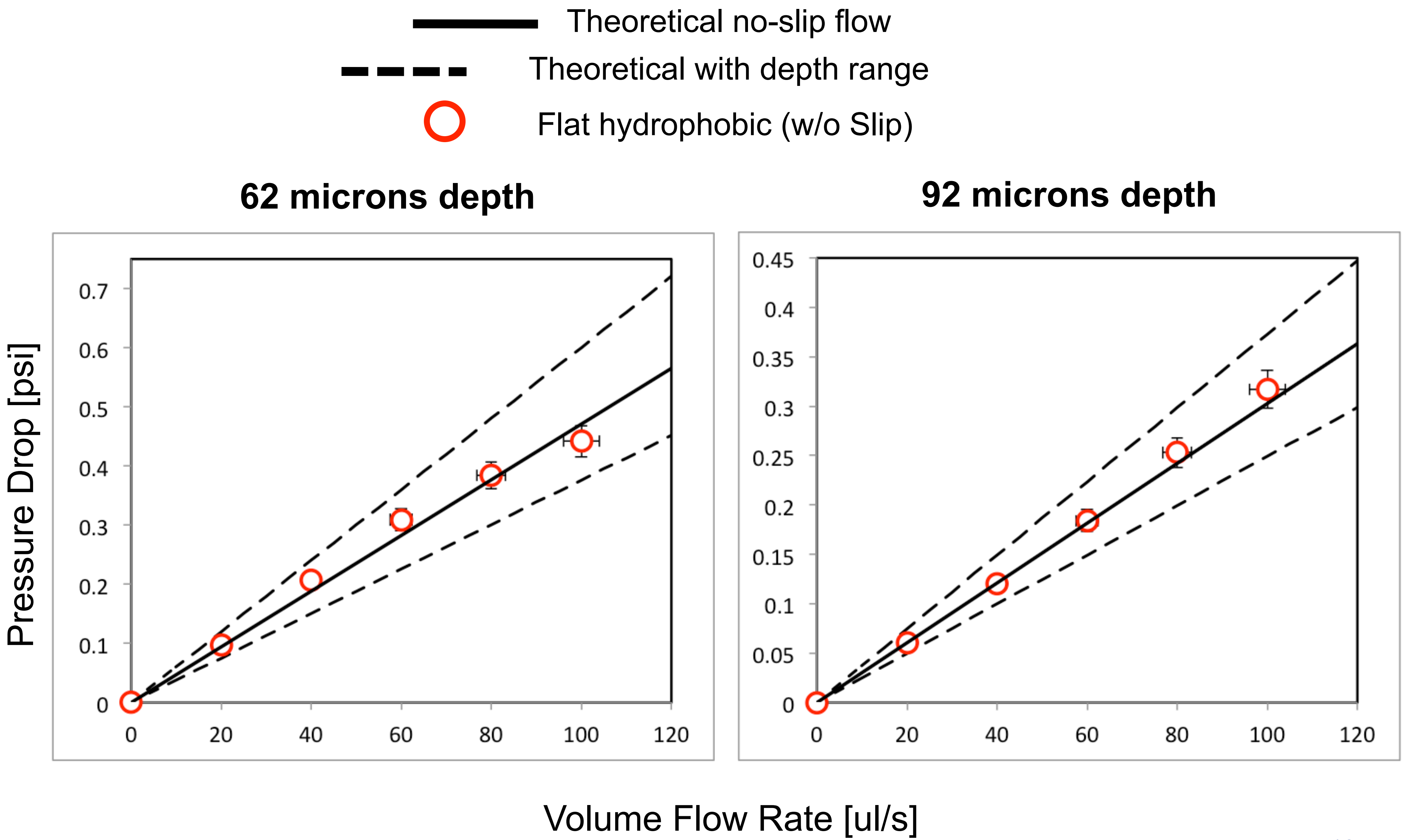


Schematic of experimental setup



$$\dot{Q} = \frac{H^2 W (6b + H)}{12\mu} \left(-\frac{\partial p}{\partial x} \right)$$

Experimental Results



Future Work

- Examine the TMV behavior when coating aluminum and other metals, instead of using gold coating before TMV deposition.
- Effects of different Reynolds Number and Pressure.
- Maximum pressure drop supported by the TMV structures before their contact angle do not improve the medium.

References

[1] Rothstein. 2009. Slip on Superhydrophobic Surfaces. 14:52

[2] Munson, Young and Okiishi. 2012. Fundamentals of Fluid Mechanics. (7th edition) Wiley

[3] Choi, Ulmanella, Kim, Ho, and Kim. 2006. Effective Slip and Friction Reduction in Nanograted Superhydrophobic Microchannels. 087105

[4] Kashaninejad, Chan, Nam-Trung. 2011. Fluid Mechanics of Flow Through Rectangular Hydrophobic Microchannels. 58140

Thank You