Challenges in using nano-textured surfaces to reduce pressure drop through microchannels

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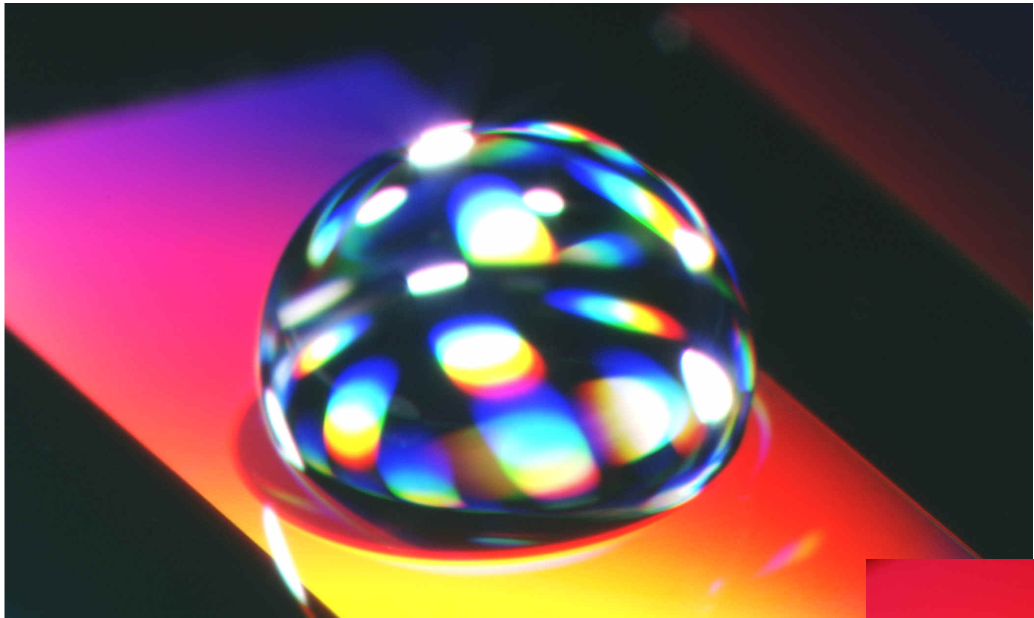
Superhydrophobic Surfaces



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Some possible applications

Lab-on-a-chip	Chemical and bio-sensors, micro reactors, genetic analysis, combinatorial chemistry
Electrical power cells	Novel reserve microbattery, fuel cell membranes
Microfluidics	Controllable “friction” channels , microfluidic mixers, pumps
Thermal management	On-chip hot spot mitigation, tunable thermal sinks
Drag reduction	Drag reduction, drag control, underwater steering and propulsion
Optics	Dynamic wavelength selective filters, tunable diffraction grating

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Thermal Management

Thermal management challenges in the electronics industry today.

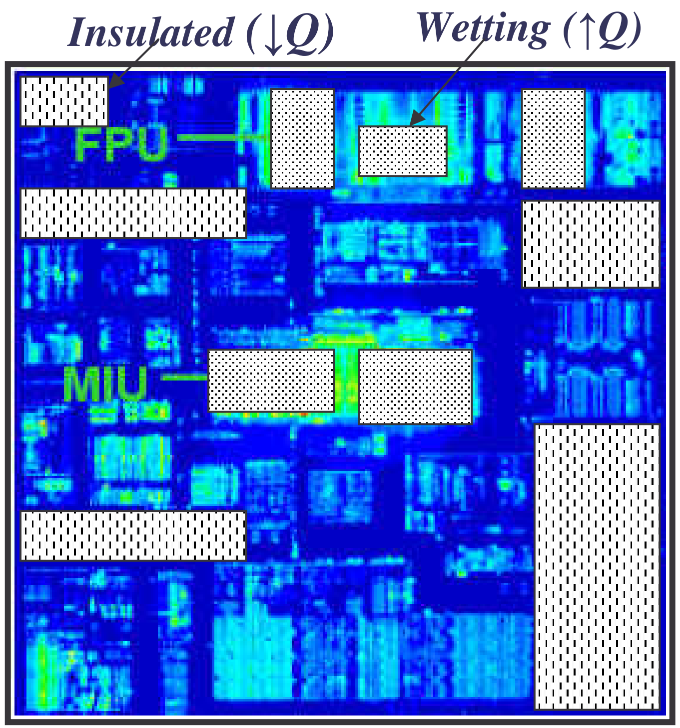
- **<u>Integrated circuits (MPU's, GPU's, ASIC's, etc.)</u>**
  - **Power levels are increasing to afford higher performance offsetting the trend of lower capacitances and voltages due to shrinking chip geometries.**

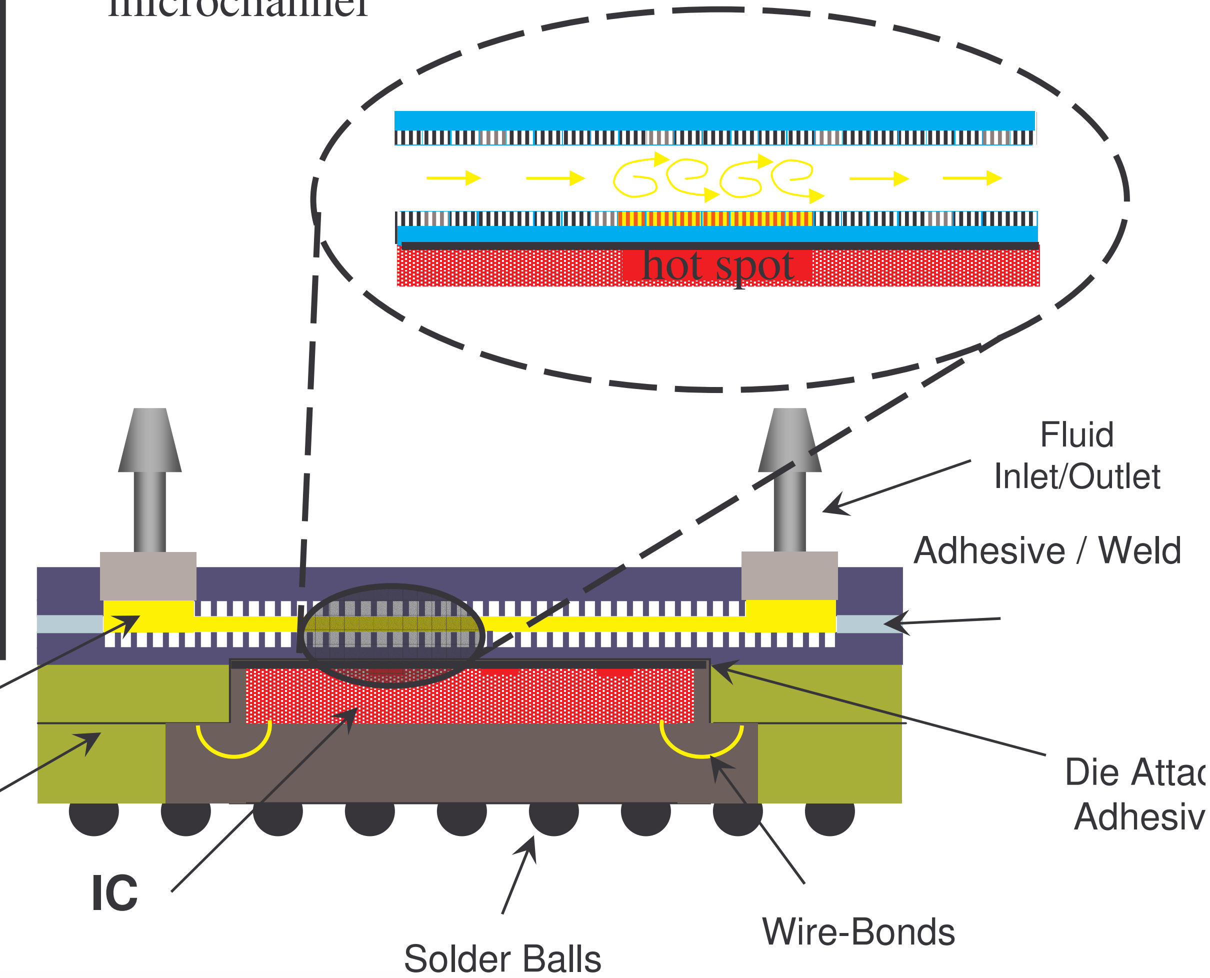
$$P \propto fCV^2$$

$f \rightarrow$ frequency
C $\rightarrow$ effective switching capacitance
V $\rightarrow$ supply voltage

  - **ITRS and iNEMI project heat fluxes of 100+ W/cm^2 in 10 years.**
  - **Power is the #1 limitation beyond the 65 nm generation. (Nassif, IBM)**
  - **Intel shifts its processor design strategy after hitting the thermal wall. (NY Times, 2004)**
  - **On-die power distribution, e.g. "hot spots", are a major concern.**
    - **Local heat fluxes >300 W/cm^2 are being realized.**
    - **Temperature gradients of 30°C on 22x22 mm silicon devices have been observed (Deeney, HP). This is a major issue with regards to chip operability and reliability.**
  - **Cooling solutions must be capable of dealing not only with static power dissipation, but also large dynamic variations.**

Thermal Management





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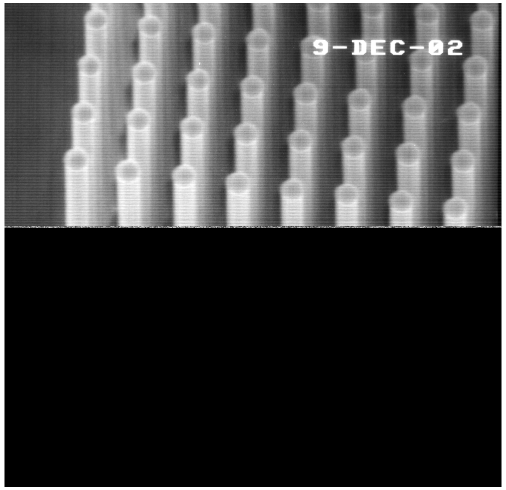
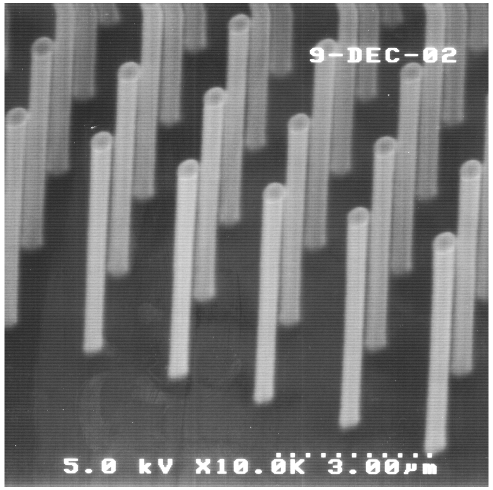
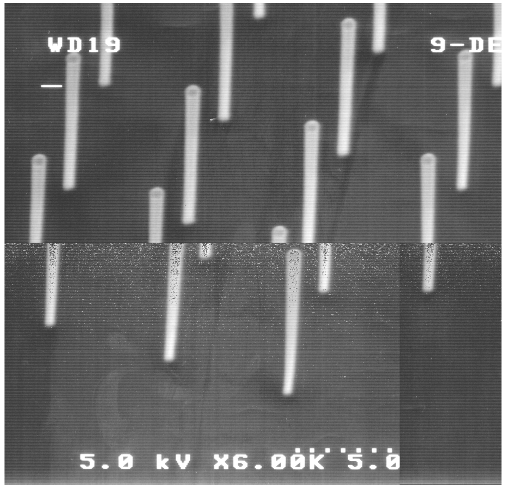
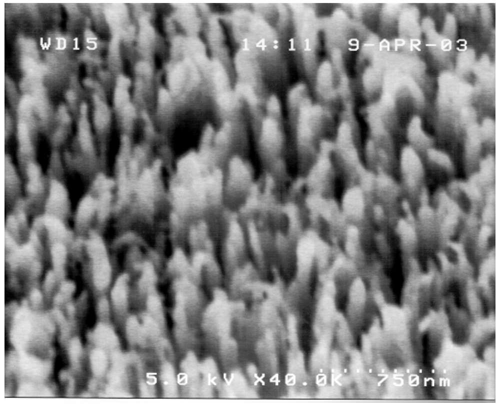
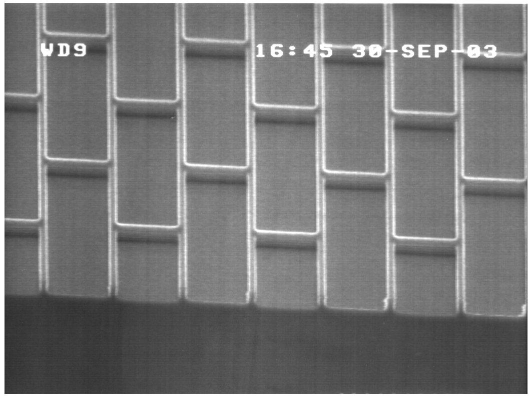
Superhydrophobic Surfaces

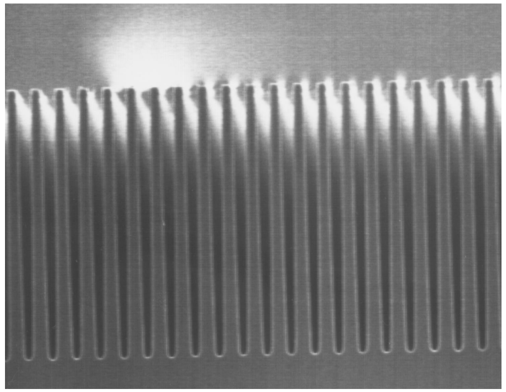












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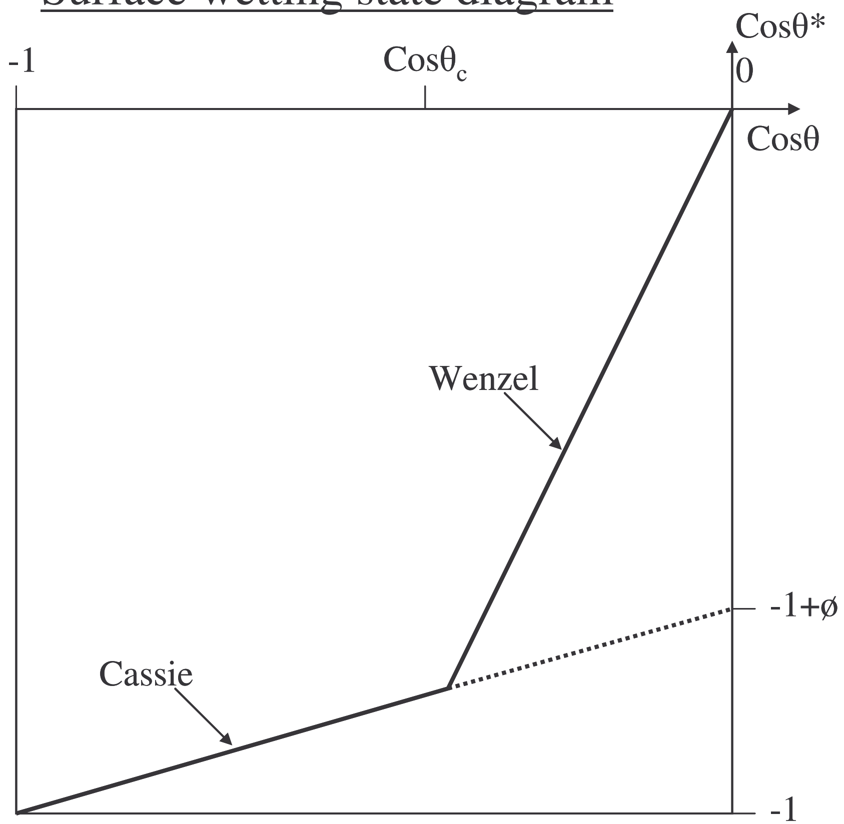
Superhydrophobic Surfaces

Surface wetting state diagram



Lafuma & Quéré (2003)

Cassie regime of wetting

$$\cos\theta^* = -1 + \phi(1 + \cos\theta)$$

$\theta^* \rightarrow$ apparent contact angle

$\phi \rightarrow$ ratio of contact area to projected area

$\theta \rightarrow$ contact angle

Cassie & Baxter. (1944)

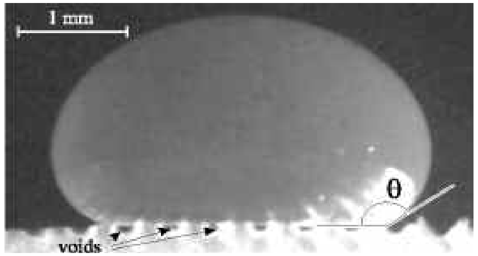
Wenzel regime of wetting

$$\cos\theta^* = r\cos\theta$$

$\theta^* \rightarrow$ apparent contact angle

$r \rightarrow$ ratio of true area to projected area

$\theta \rightarrow$ contact angle

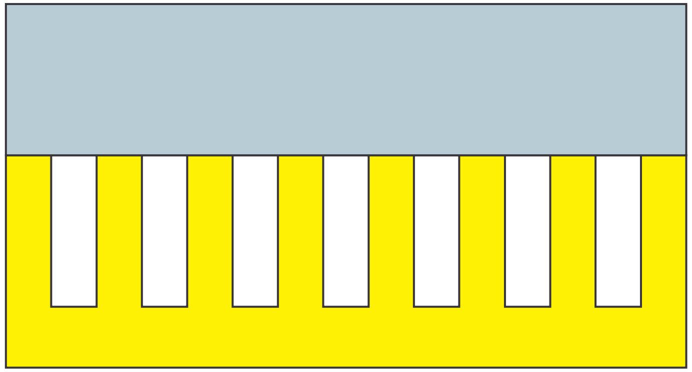


Gogte *et. al.* (2005)

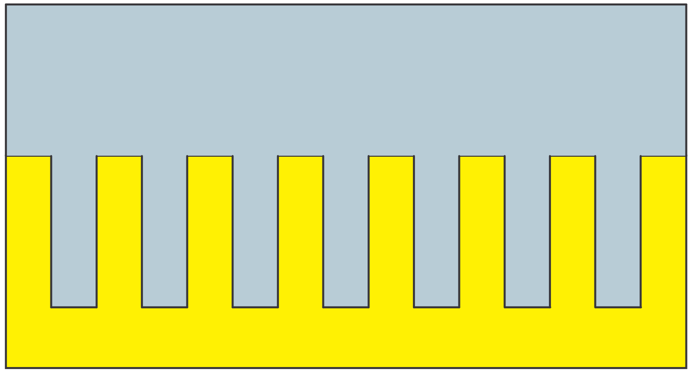
Superhydrophobic Surfaces

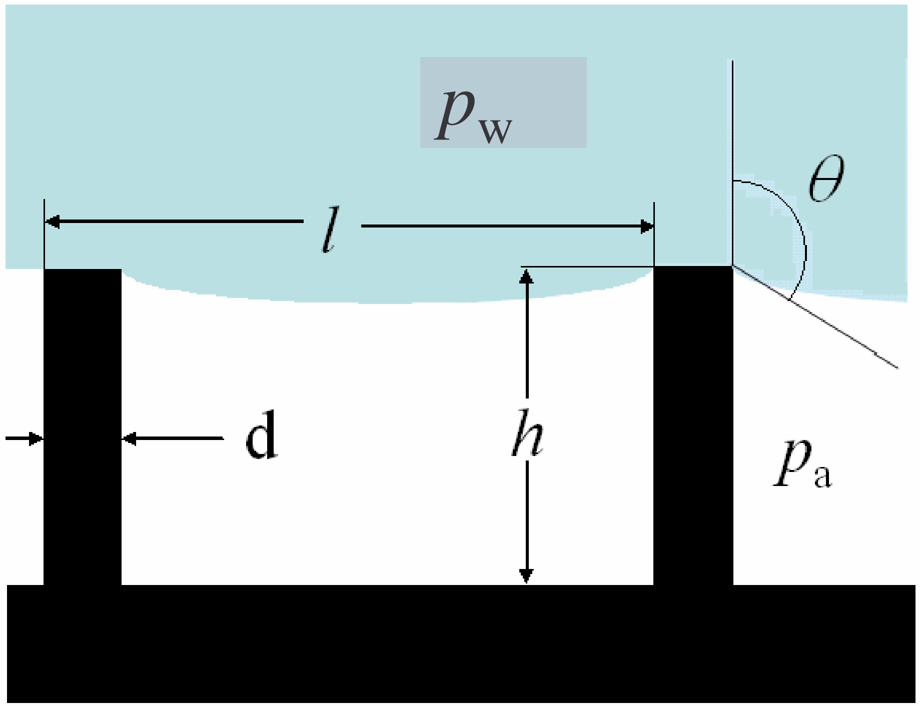
Irreversible wetting transition

Cassie regime of wetting



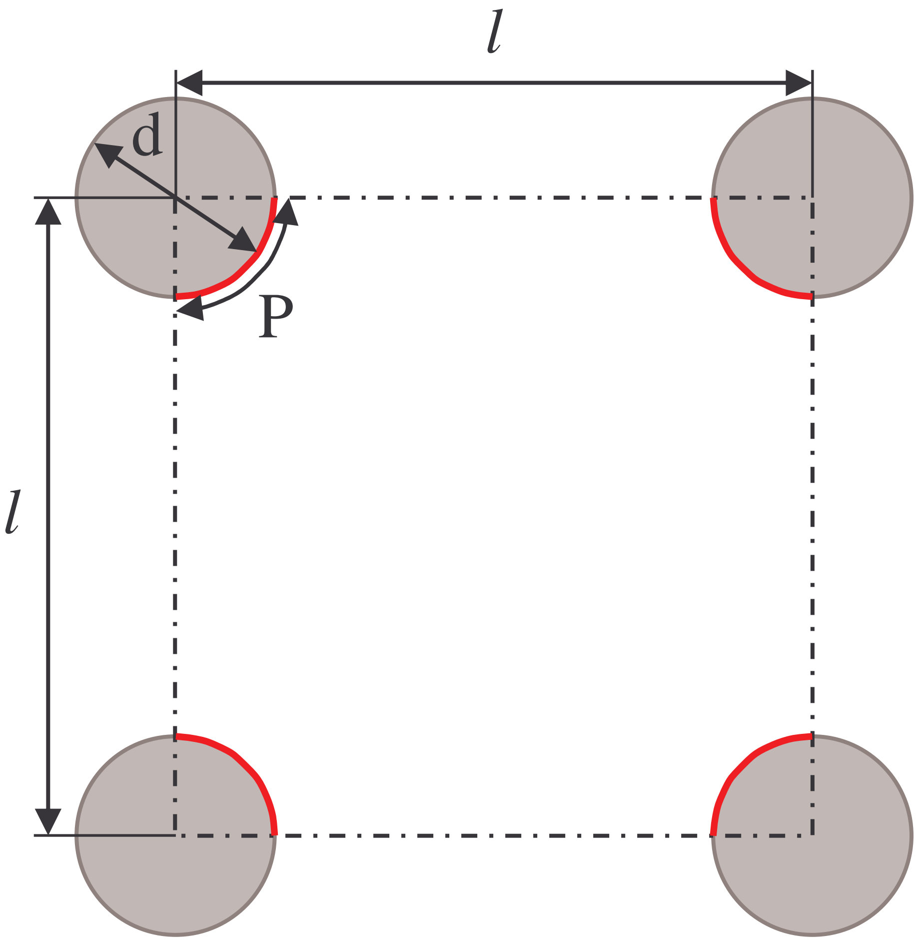
Wenzel regime of wetting





$$\Delta p = p_w + p_a$$

Interfacial Pressure Stability

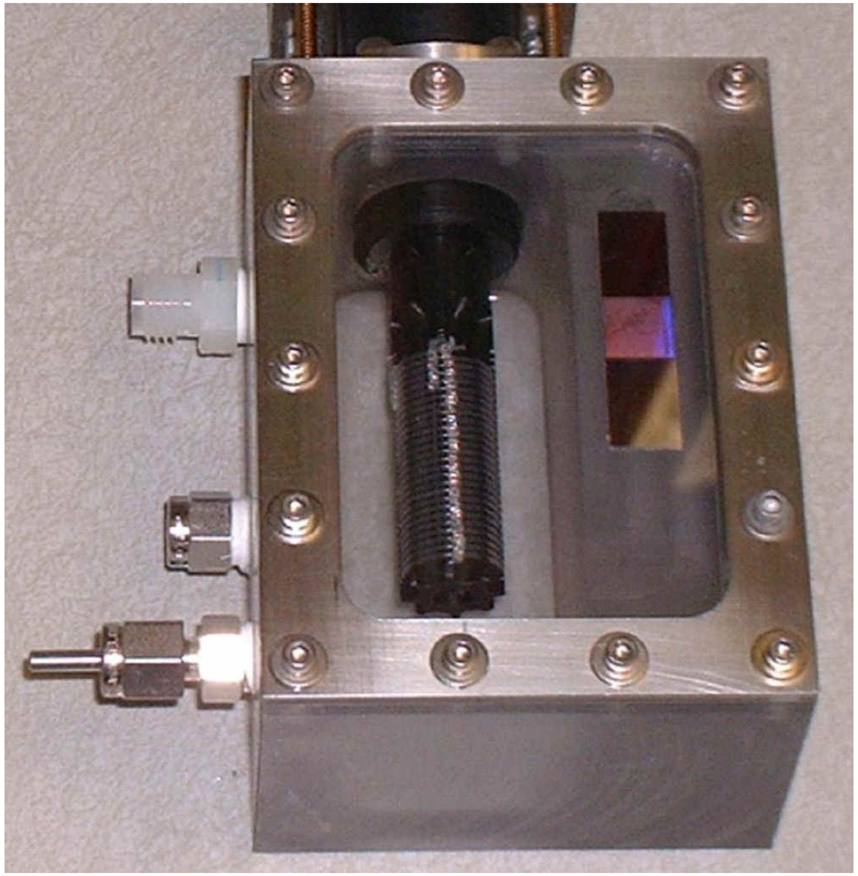


$$A\Delta p = -P\gamma\cos\theta$$

$$\left(l^2 - \frac{\pi d^2}{4}\right)\Delta p = -\pi d\gamma\cos\theta$$

$$\Delta p = -\frac{\pi d\gamma\cos\theta}{\left(l^2 - \frac{\pi d^2}{4}\right)}$$

Interfacial Pressure Stability



Roughness geometry
d = 200 nm
l = 2 µm
h = 7.5 µm

Interfacial chemistry
θ = 110° (PTFE)
γ_{LV} = 72.75 mN/m (Water)

Critical pressure differential
$\Delta p_c \approx 4$ kPa

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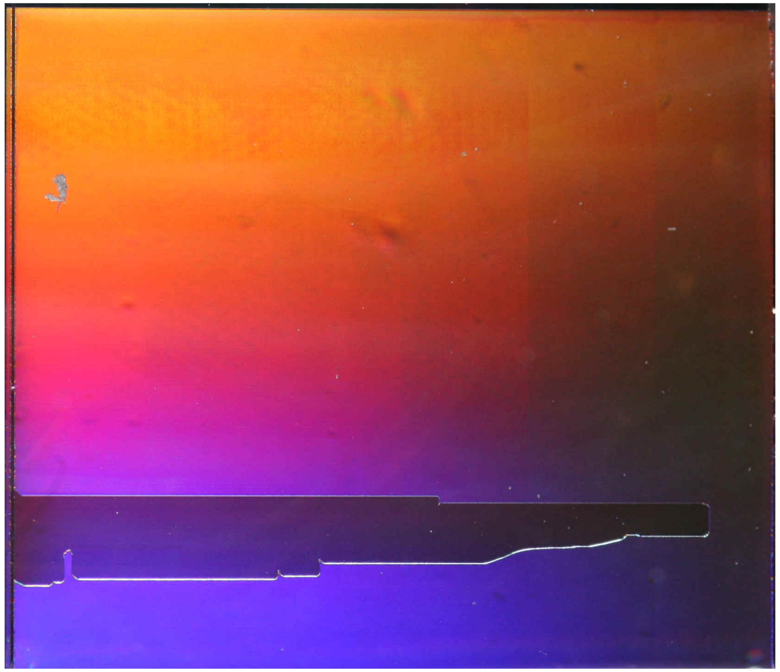
Interfacial Pressure Stability

p_w=9.2 kPa $p_w/\Delta p_c$=2.3

seconds after onset of wetting



168 seconds later

Air layer is a trapped volume, thus progression of wetting likely dictated by the diffusion of air into water.

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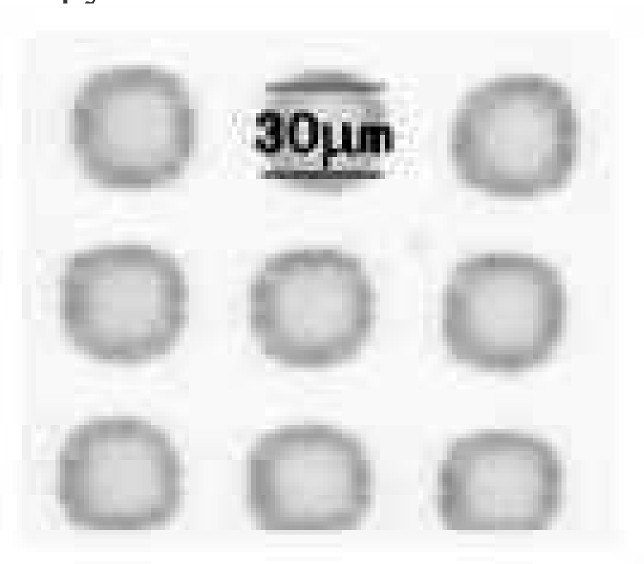
Superhydrophobic Microchannel Experiment

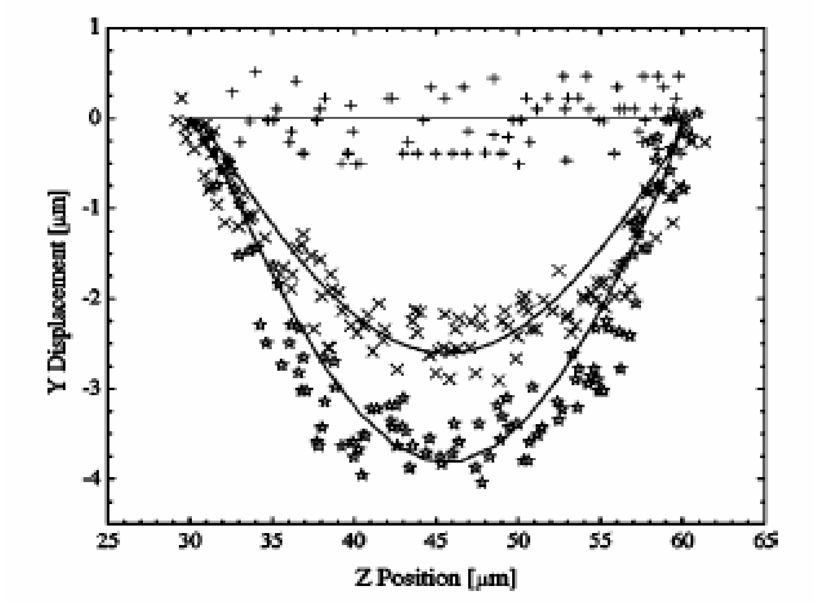
Ou *et. al.* (2004), "Laminar drag reduction in microchannels using ultrahydrophobic surfaces."

•Achieved drag reduction of up to 40% on structured superhydrophobic surfaces

•Identified & measured the deflection of the surface tension interface using confocal microscopy



Plan view image of post structures studied by Ou and colleagues.



Air/water interface deflection under pressure as measured by confocal microscopy.

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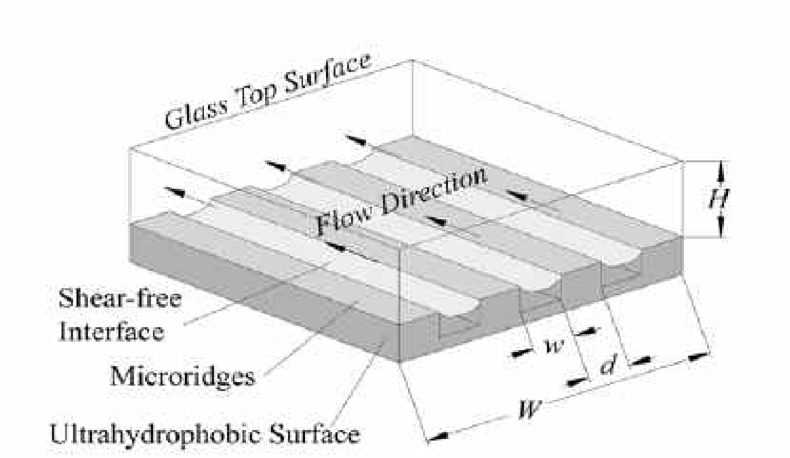
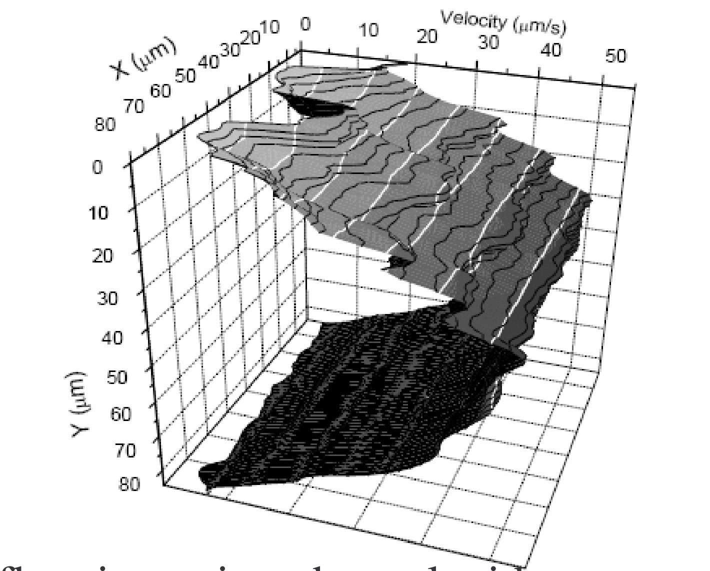
Superhydrophobic Microchannel Experiment

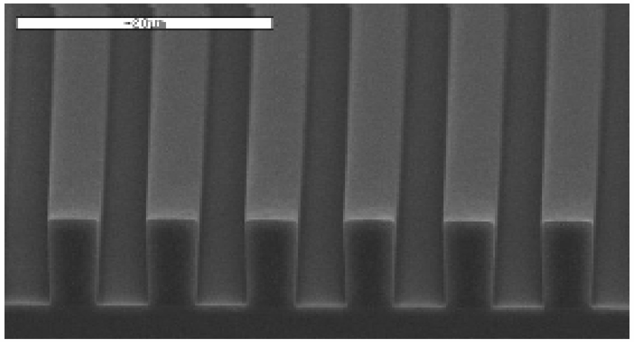
Ou & Rothstein (2005), “Drag Reduction and μ-PIV Measurements of the Flow Past Ultrahydrophobic Surfaces”





Woolford *et. al.* (2005), “Laminar fully-developed flow in a microchannel with patterned ultrahydrophobic walls.”

•Observed drag reduction of up to 30%



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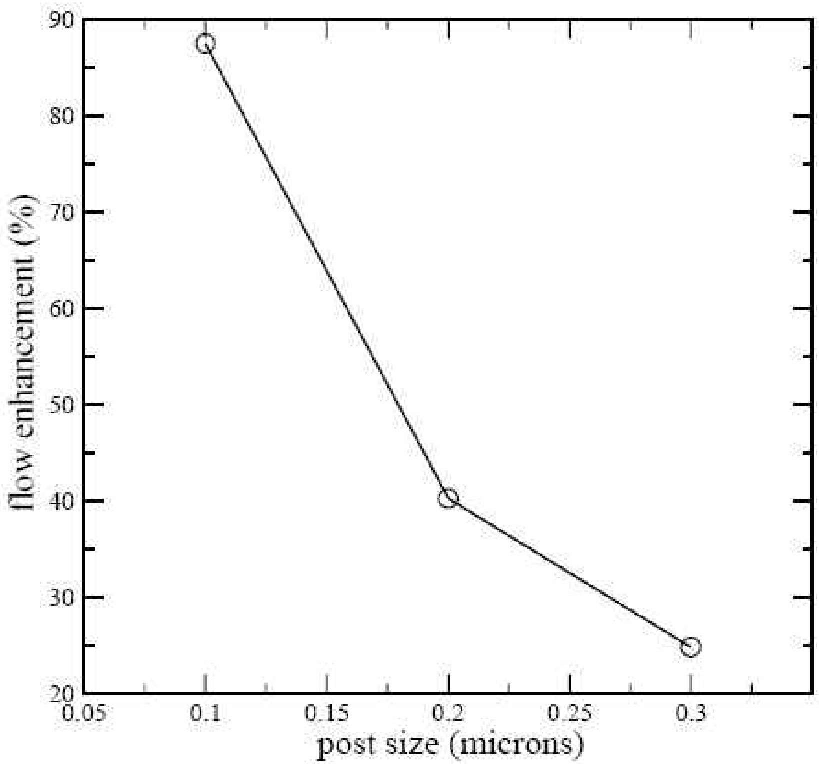
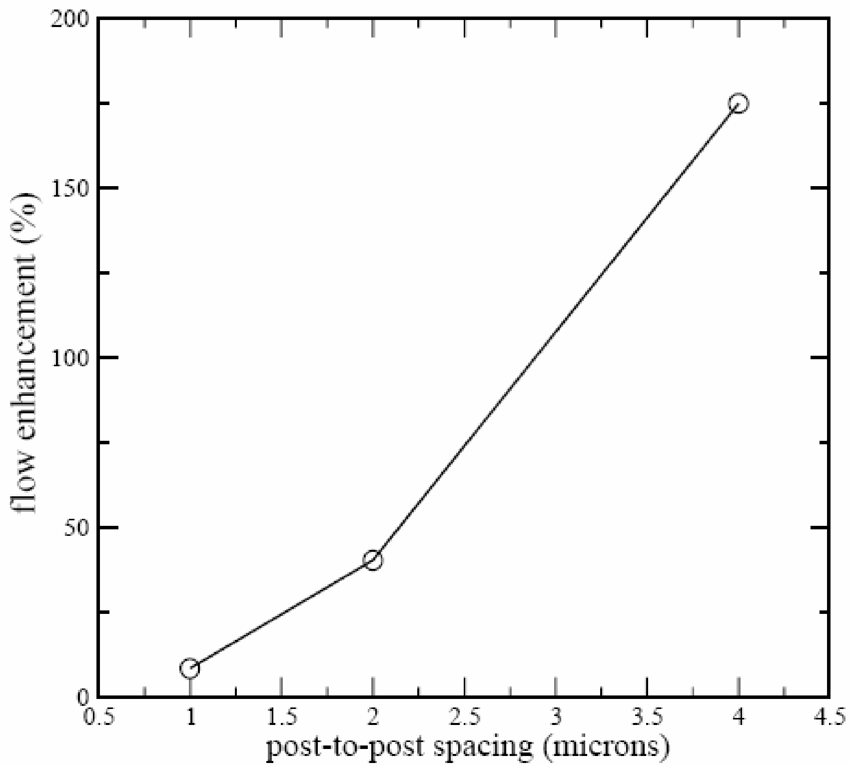
Superhydrophobic Microchannel Simulation

Salamon et. al., 2005. "Numerical Simulation of Fluid Flow in Microchannels with Superhydrophobic Walls"



Flow enhancement as a function of post spacing. d=200 nm

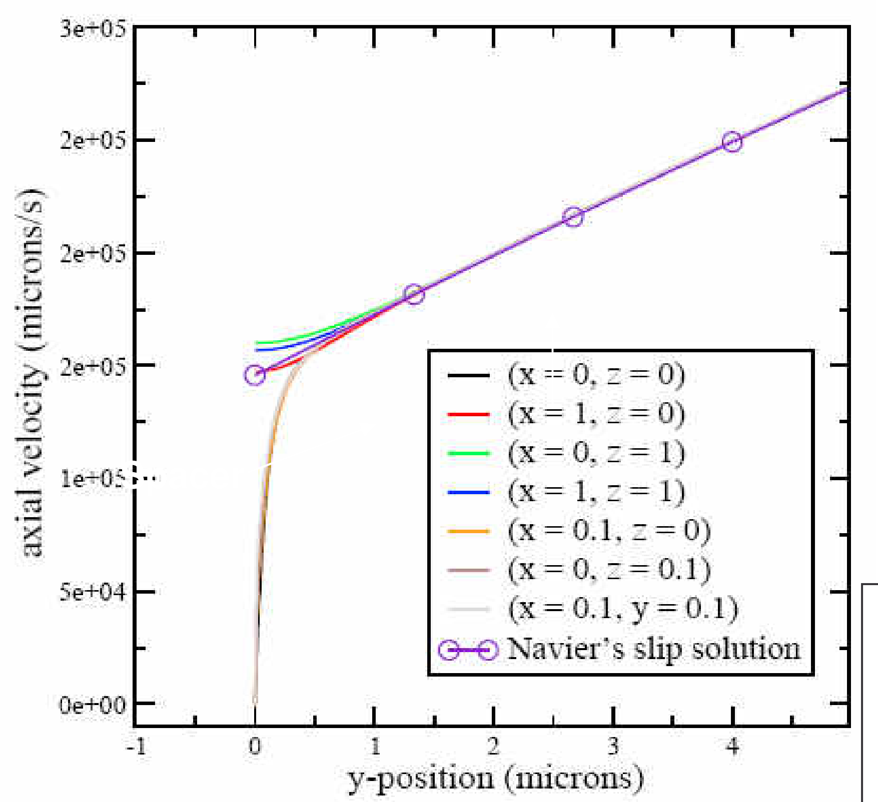


Flow enhancement as a function of post size. l=2 µm

Simulation predicts drag reduction of 40% for the superhydrophobic surfaces currently being investigated.

Superhydrophobic Microchannel

Application of the Navier slip hypothesis. ⟶ $$v_x\big|_{y=0} = b\left.\frac{dv_x}{dy}\right|_{y=0}$$



Two superhydrophobic walls

$$v_x(y) = \left(-\frac{\Delta p}{\Delta L}\right)\left(\frac{H^2}{2\mu}\right)\left(\frac{b}{H} + \frac{y}{H} - \frac{y^2}{H^2}\right)$$

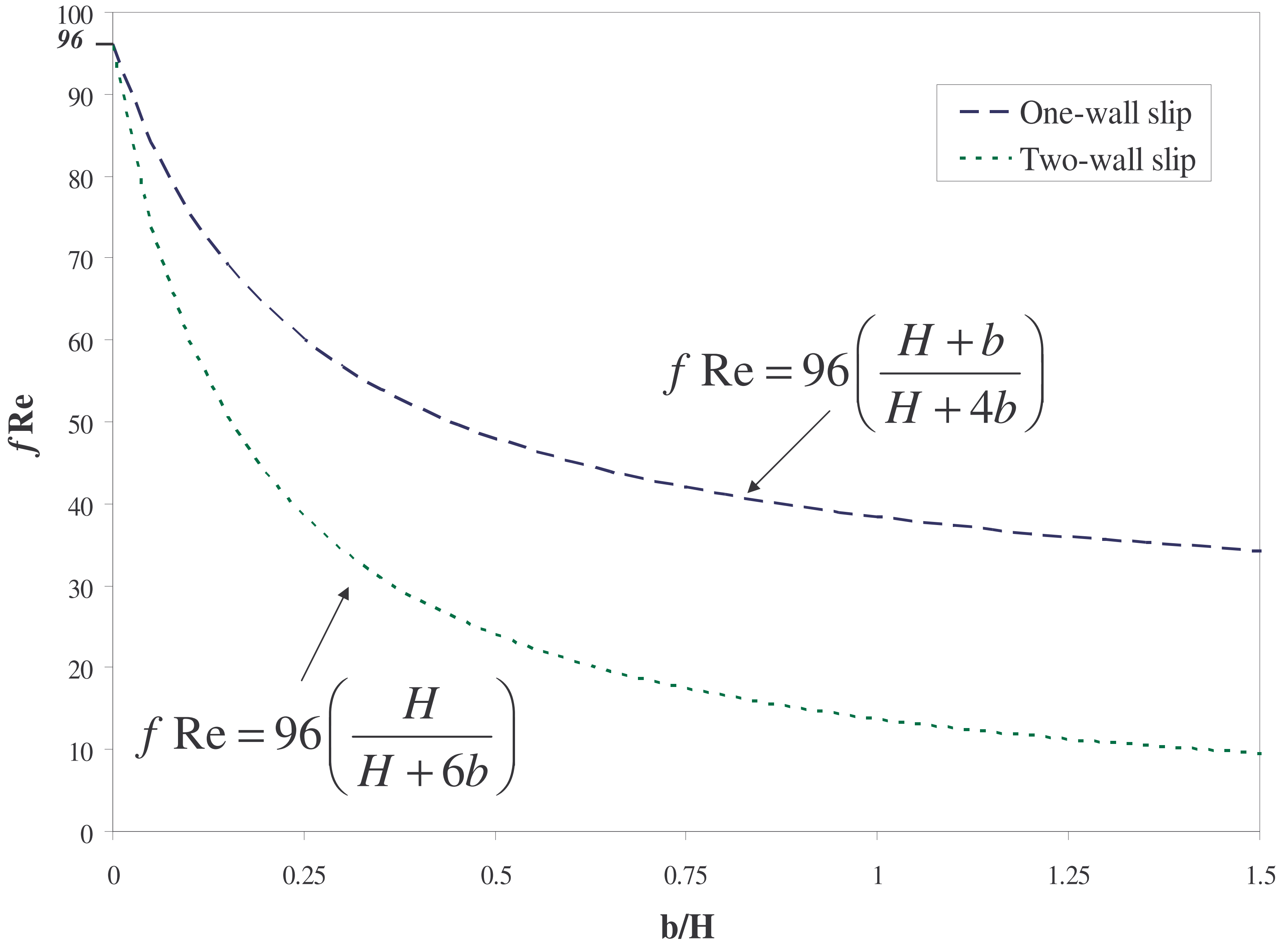
$$Q = \left(-\frac{\Delta p}{\Delta L}\right)\left(\frac{H^3}{2\mu}\right)\left(\frac{b}{H} + \frac{1}{6}\right)$$

One superhydrophobic wall

$$v_x(y) = \left(-\frac{\Delta p}{\Delta L}\right)\left(\frac{1}{\mu}\right)\left(-\frac{y^2}{2} - \left\{\frac{bH + H^2/2}{H+b}\right\}y\right)$$

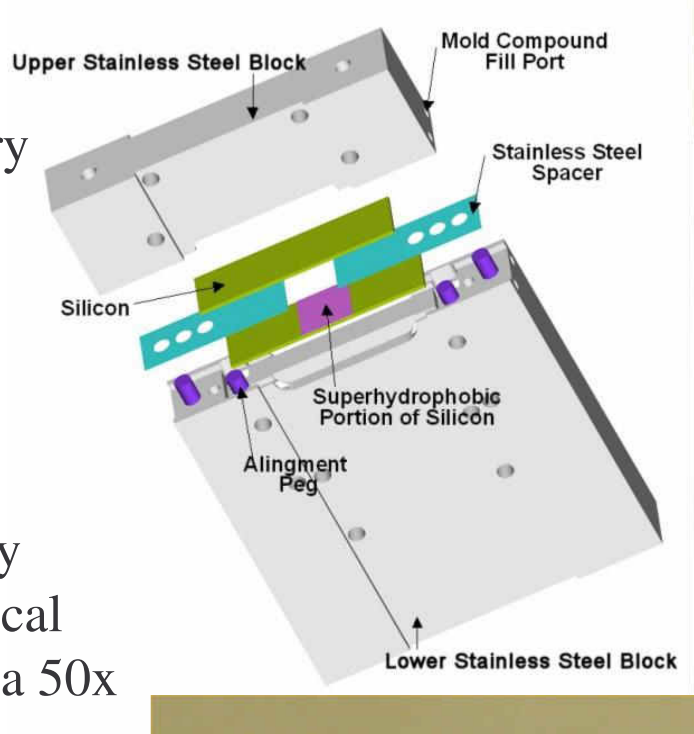
$$Q = \left(-\frac{\Delta p}{\Delta L}\right)\left(\frac{H^3}{12\mu}\right)\left(\frac{H+4b}{H+b}\right)$$

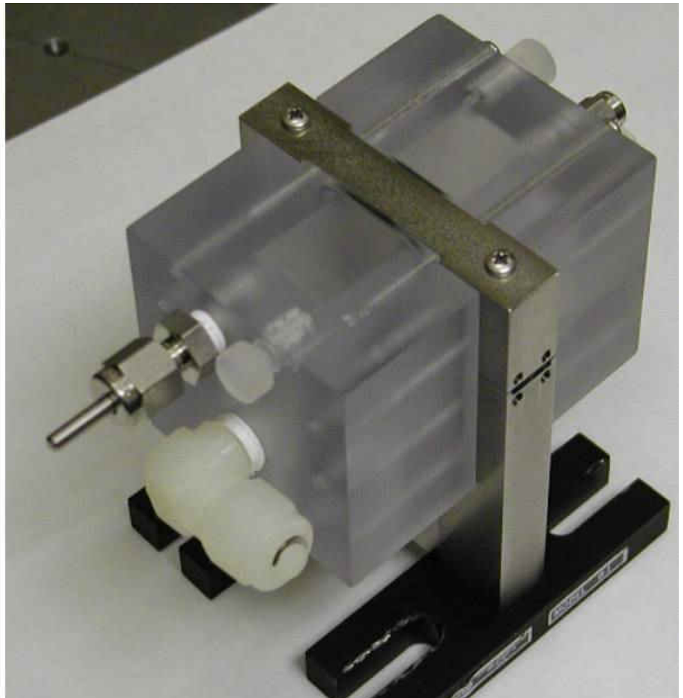
Superhydrophobic Microchannel



Superhydrophobic Microchannel

Parallel-plane geometry
Height = 86 μm
Width = 9.93 mm
Length = 9.91 mm





Dimensions accurately measured using a optical positioning stage and a 50x objective

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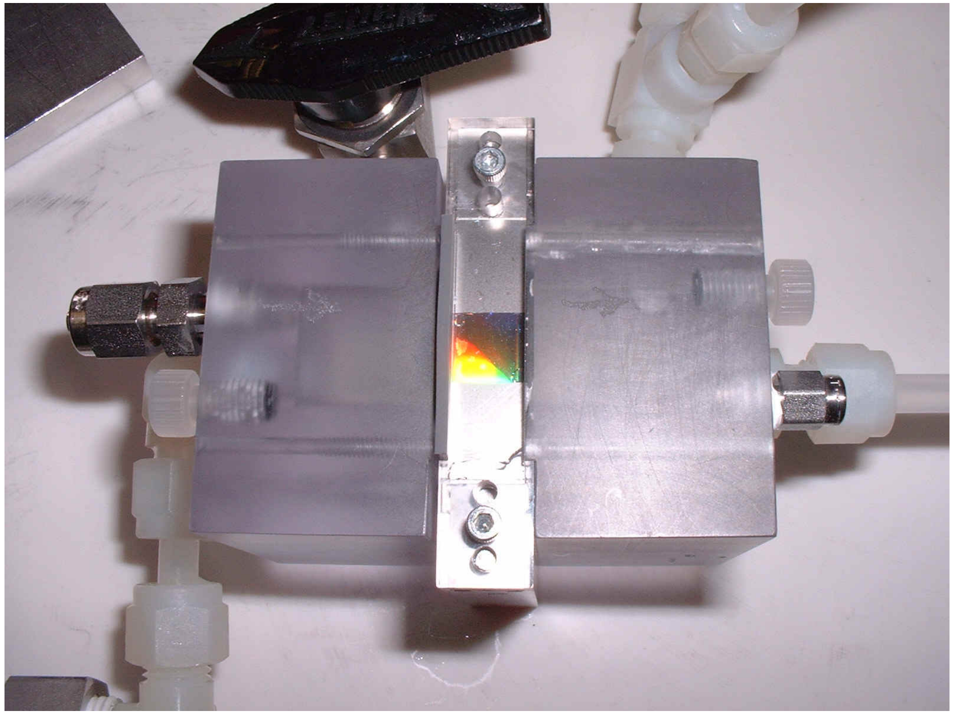
Superhydrophobic Microchannel

Polycarbonate "top plate" designed to allow optical access in order to:

- **Confirm experimental procedure**
- **Observe bubble formation and behavior**
- **Observe the wetting behavior of the nanograss surface under flow conditions**
- **Provide a possible means for future optical measurements**



Assembled test section w/ optical access

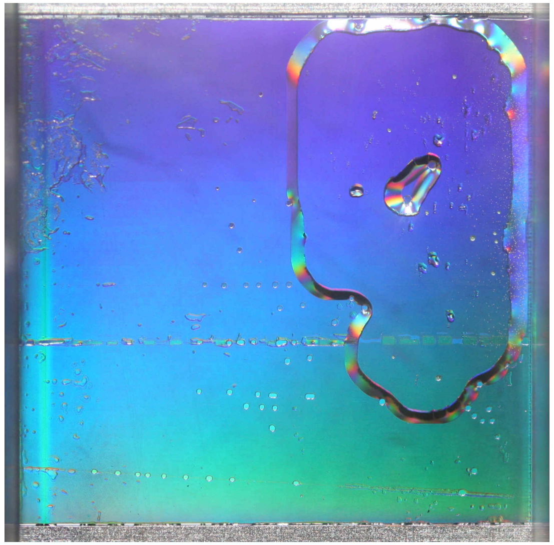


Image of an air bubble on the nanograss surface under static conditions.

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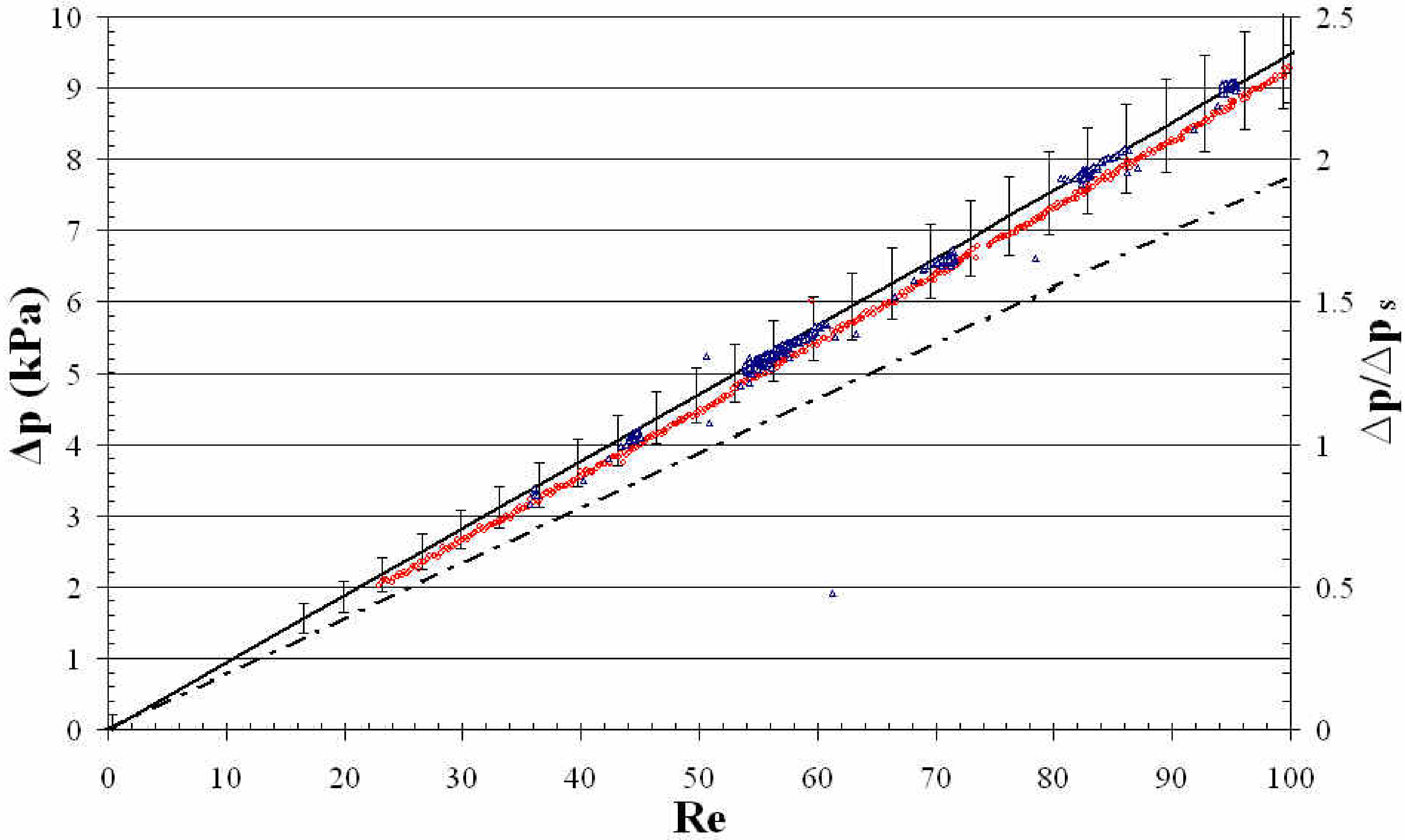
Superhydrophobic Microchannel



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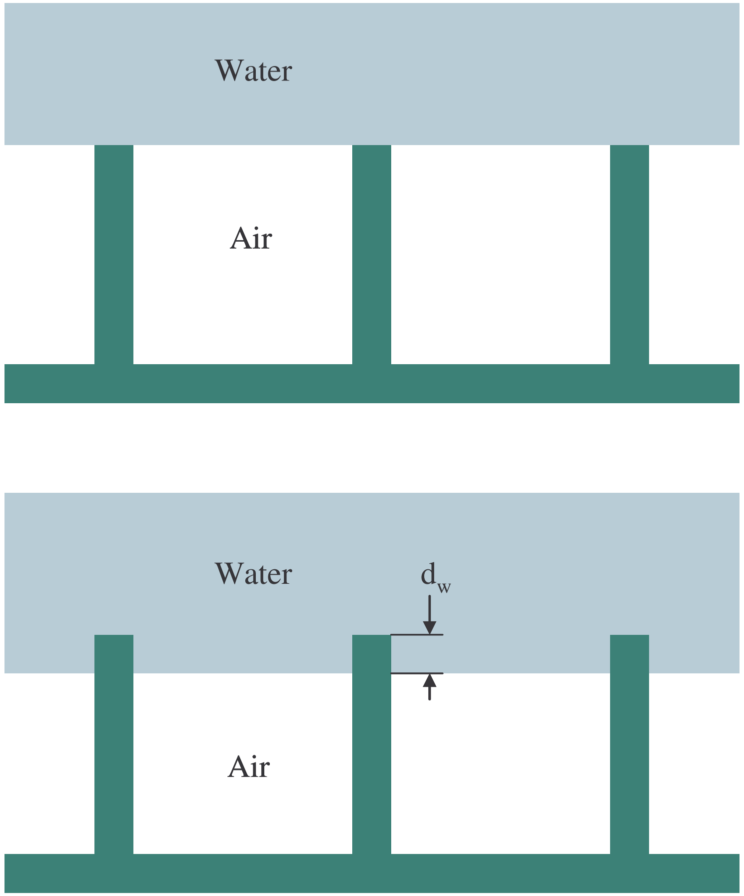
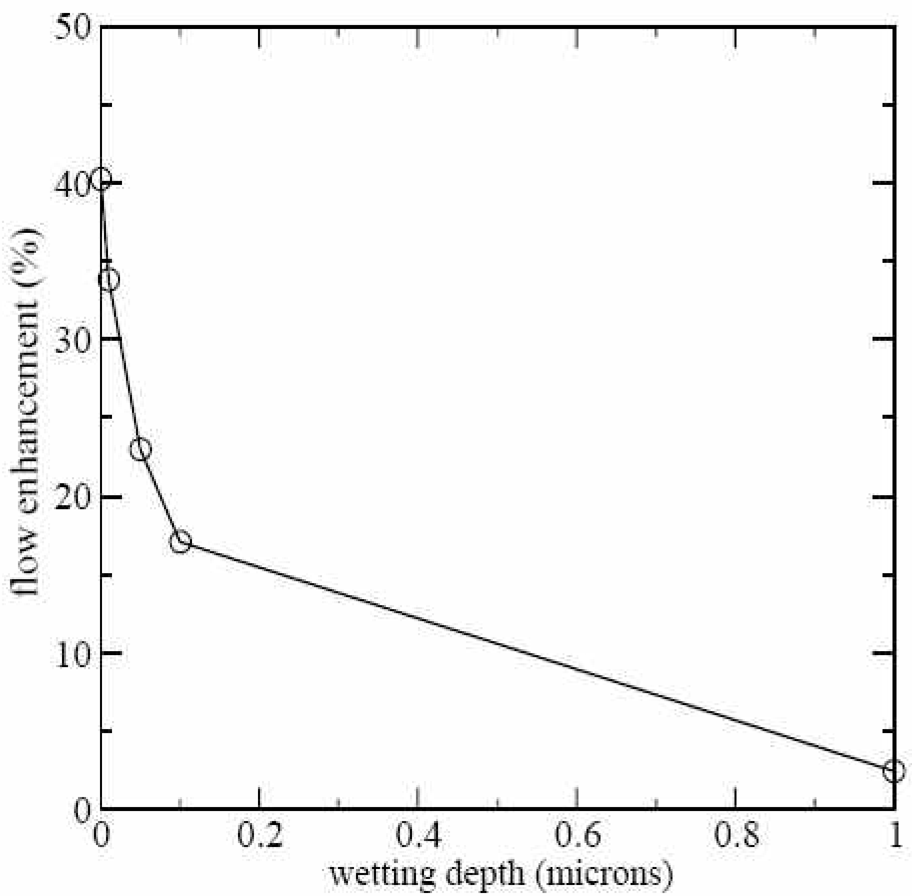
Superhydrophobic Microchannel





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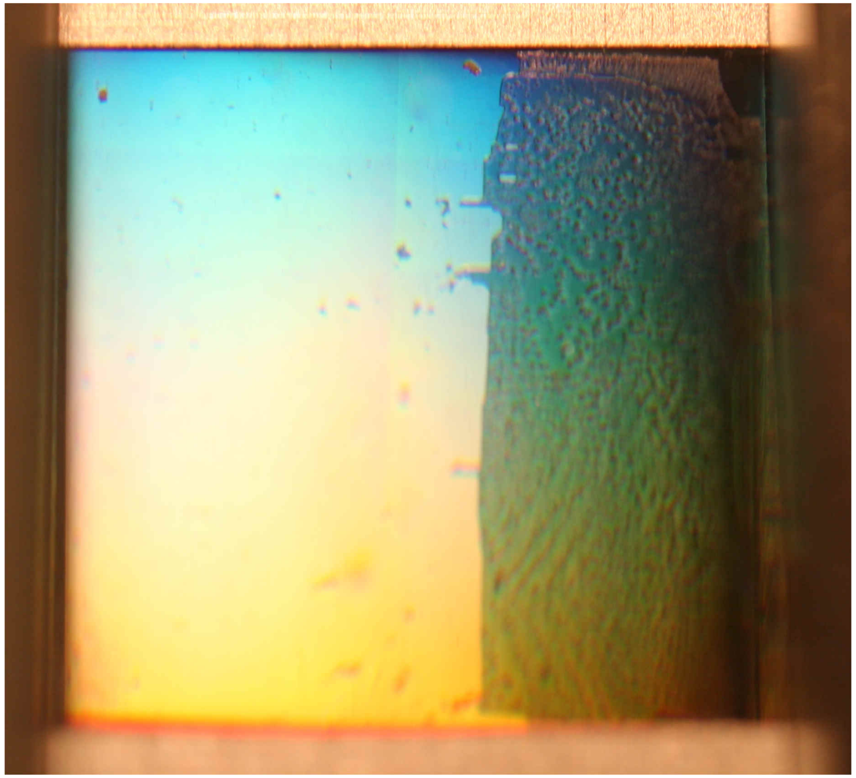
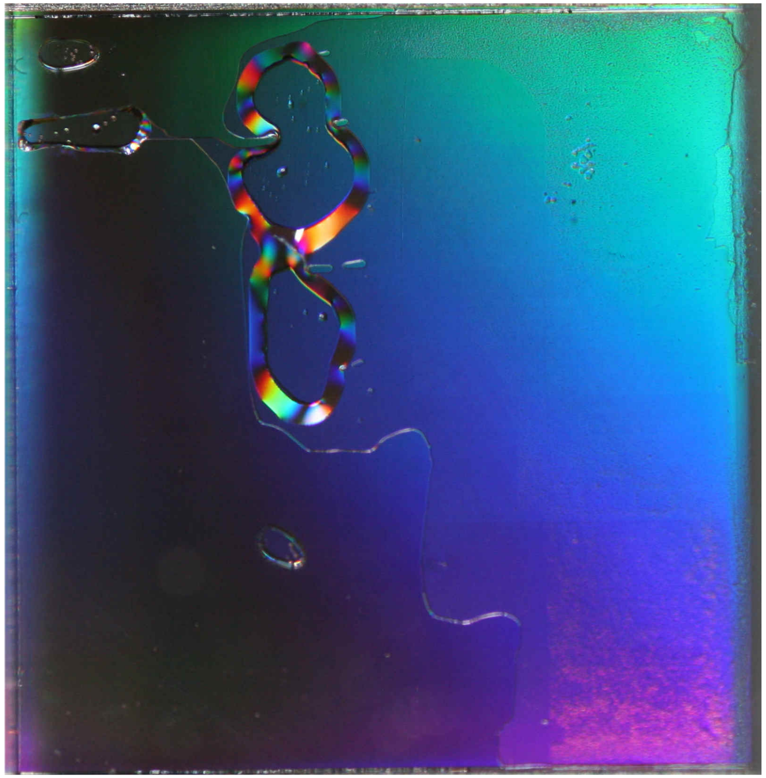
Dynamic Wetting



Re = 444; dp=20.7 kPa;
dp/dpc=5.175



Bubble formed in channel, occluding flow

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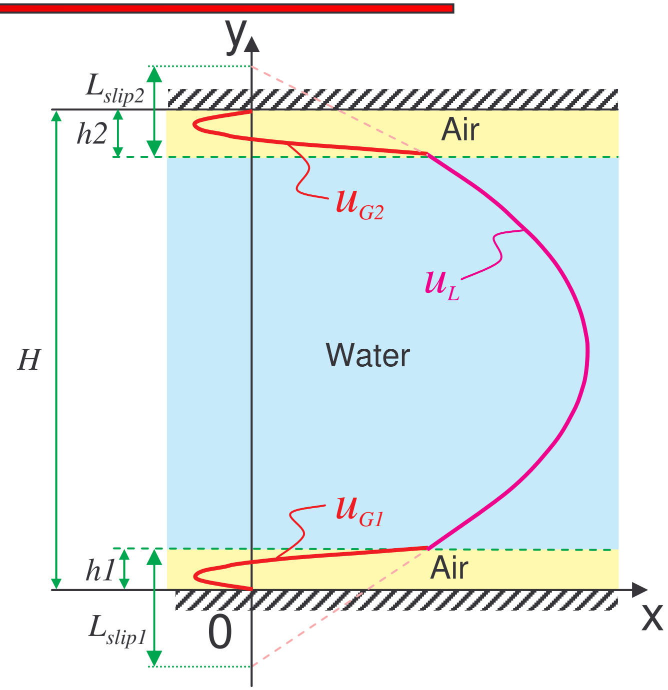
Two Wall Velocity Profile Solution

PROBLEM:

- **Flow of Water between 2 Superhydrophobic walls. No slip BC at top (y=H) and bottom (y=0). Water layer sits between 2 layers of Gas trapped in a nanograss coating**
- **Velocity and shear matched at liquid - air interfaces**
- **The pressure driven movement of the water induces recirculating flow in the gas layers**



3 Governing Momentum Equations: $$\left.\frac{dP}{dx}\right|_{L,G1,G2} = \mu_{L,G1,G2}\frac{d^2u_{L,G1,G2}}{dy}$$

Nomenclature:

A,B	**Integration Constants**
H	**Total Height of Flow Area (m)**
$L_{slip1,2}$	**Slip Lengths (m)**
P	**Pressure (Pa)**
h1,h2	**Height of Gas Layers (m)**
$u_{L,1,2}$	**Flow Velocity (m/s)**
$\mu_{L,1,2}$	**Viscosity (Pas)**

Subscripts:

G1,G2	**Property of Gas (Air) Layers**
L	**Property of Liquid Layer**

Note: $\left.\frac{dP}{dx}\right|_{L}$ **prescribed,** $\left.\frac{dP}{dx}\right|_{G1}$ **and** $\left.\frac{dP}{dx}\right|_{G2}$ **are unknown**

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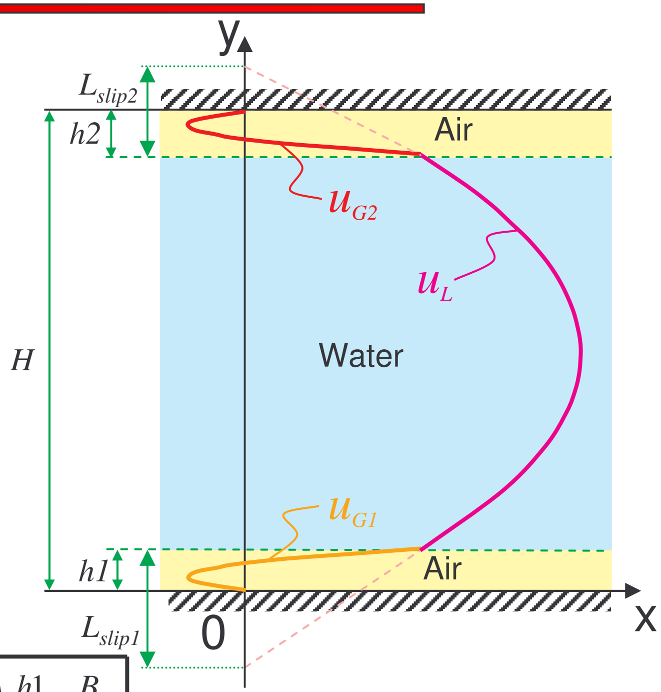
Two Wall Velocity Profile Solution

Integrate each of the three Momentum Equations Twice:

$$u_{L,G1,G2} = \frac{dP_{L,G1,G2}}{dx}\frac{y^2}{2\mu_{L,G1,G2}} - \frac{A_{L,G1,G2}\,y}{\mu_{L,G1,G2}} - \frac{B_{L,G1,G2}}{\mu_{L,G1,G2}}$$



Boundary Conditions:

1. $@y=0,\ u_{G1}=0$
2. $@y=H,\ u_{G2}=0$
3. $@y=h1,\ u_{G1}=u_L$
4. $@y=h1,\ \mu_{G1}\dfrac{du_{G1}}{dy}=\mu_L\dfrac{du_L}{dy}$
5. $@y=H\text{-}h2,\ u_{G2}=u_L$
6. $@y=H\text{-}h2,\ \mu_{G2}\dfrac{du_{G2}}{dy}=\mu_L\dfrac{du_L}{dy}$
7. $\int_0^{h1} u_{G1}\,dy = 0$
8. $\int_{H-h2}^{H} u_{G2}\,dy = 0$

Simultaneous Equations:

Solve for: A_L, A_{G1}, A_{G2}, B_L, B_{G1}, B_{G2}, $\dfrac{dP_{G1}}{dz}$, $\dfrac{dP_{G2}}{dz}$

1. $0=\dfrac{-B_{G1}}{\mu_{G1}}$

2. $0=\dfrac{dP_{G1}}{dx}\dfrac{H^2}{2\mu_{G2}}-\dfrac{A_{G2}H}{\mu_{G2}}-\dfrac{B_{G2}}{\mu_{G2}}$

3. $\dfrac{dP_{G1}}{dx}\dfrac{h1^2}{2\mu_{G1}}-\dfrac{A_{G1}h1}{\mu_{G1}}-\dfrac{B_{G1}}{\mu_{G1}}=\dfrac{dP_L}{dz}\dfrac{h1^2}{2\mu_L}-\dfrac{A_Lh1}{\mu_L}-\dfrac{B_L}{\mu_L}$

4. $\mu_{G1}\left(\dfrac{dP_{G1}}{dx}\dfrac{h1}{\mu_{G1}}-\dfrac{A_{G1}}{\mu_{G1}}\right)=\mu_L\left(\dfrac{dP_L}{dx}\dfrac{h1}{\mu_L}-\dfrac{A_L}{\mu_L}\right)$

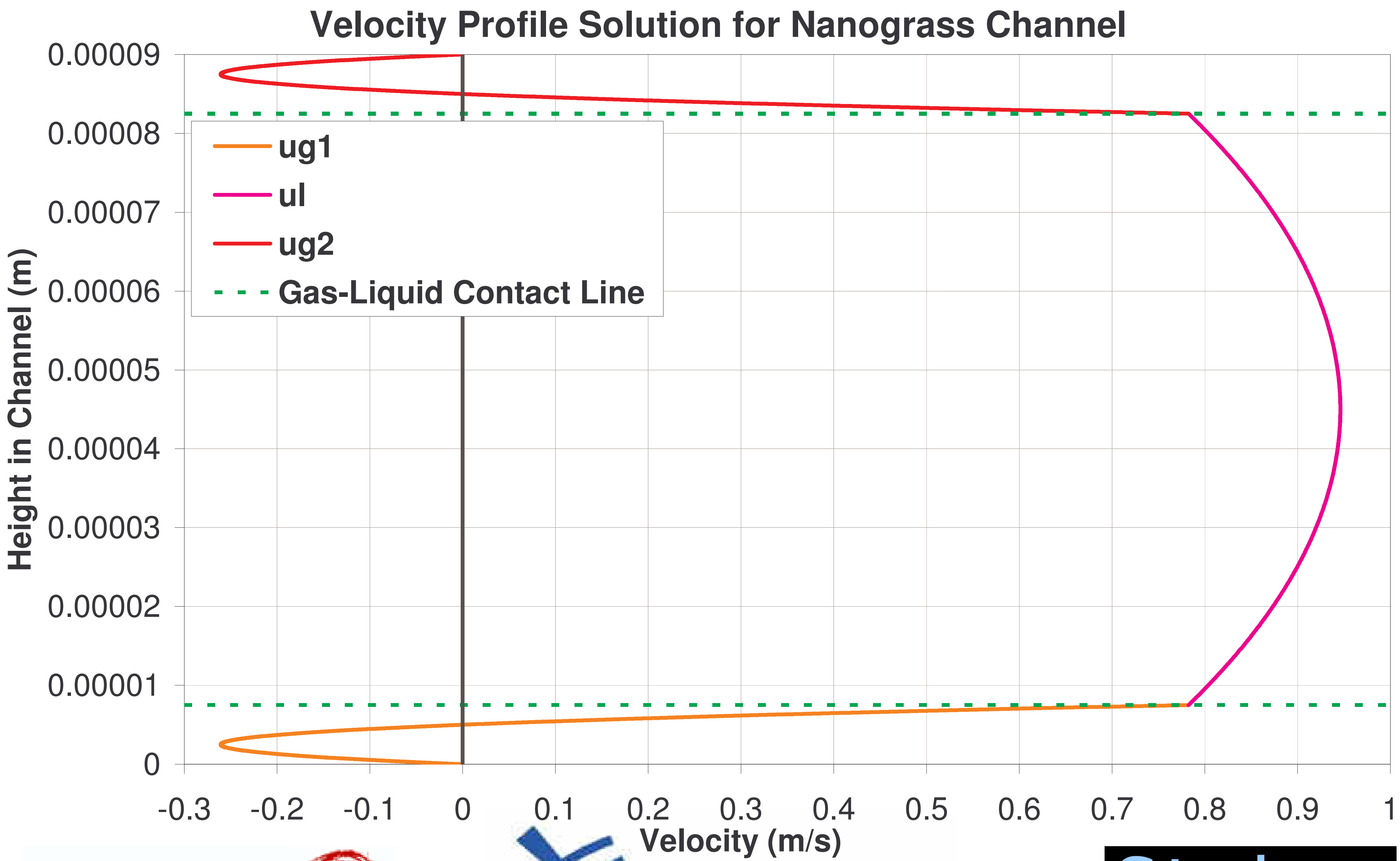
5. $\dfrac{dP_{G2}}{dx}\dfrac{(H-h2)^2}{2\mu_G}-\dfrac{A_G(H-h2)}{\mu_G}-\dfrac{B_G}{\mu_G}=\dfrac{dP_L}{dx}\dfrac{(H-h2)^2}{2\mu_L}-\dfrac{A_L(H-h2)}{\mu_L}-\dfrac{B_L}{\mu_L}$

6. $\mu_{G2}\left(\dfrac{dP_{G2}}{dx}\dfrac{(H-h2)}{\mu_{G2}}-\dfrac{A_{G2}}{\mu_{G2}}\right)=\mu_L\left(\dfrac{dP_L}{dx}\dfrac{(H-h2)}{\mu_L}-\dfrac{A_L}{\mu_L}\right)$

7. $\dfrac{dP_{G1}}{dx}\dfrac{h1^3}{6\mu_{G1}}-\dfrac{A_{G1}h1^2}{2\mu_{G1}}-\dfrac{B_{G1}h1}{\mu_{G1}}=0$

8. $\dfrac{dP_{G2}}{dz}\dfrac{(H-h2)^3}{6\mu_{G2}}-\dfrac{A_{G2}(H-h2)^2}{2\mu_{G2}}-\dfrac{B_{G2}(H-h2)}{\mu_{G2}}=0$

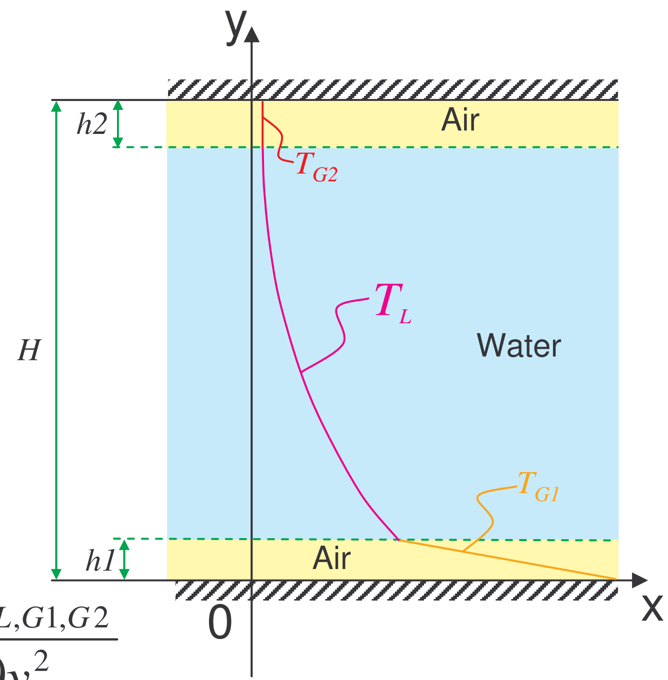
Two Wall Velocity Profile Solution



Two Wall Temperature Profile Solution

PROBLEM:

- A Constant Heat Flux is Applied to the $y=0$ surface
- The $y=H$ surface is assumed adiabatic
- Where the air and water layers meet their temperatures are equal
- The heat that leaves one layer equals the heat entering the next layer



Energy Equation: $$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}$$

Since $v=0$, Reduces to: $$u_{L,G1,G2}\frac{\partial T_{L,G1,G2}}{\partial x}=\alpha_{L,G1,G2}\frac{\partial^2 T_{L,G1,G2}}{\partial y^2}$$

Nomenclature:

A,B,C,D,E	Constants
H	Total Height of Flow Area (m)
$L_{slip1,2}$	Slip Lengths (m)
P	Pressure (Pa)
T	Temperature
$T_{InletSurf}$	Inlet Surface Temp
c_p	Specific Heat Capacity (J/kgK)
$h1,h2$	Height of Gas Layers (m)
$k_{L,1,2}$	Thermal Conductivity (w/mK)
$\alpha_{L,1,2}$	$\frac{k}{\rho c_p}$
$u_{L,1,2}$	Flow Velocity (m/s)
$\mu_{L,1,2}$	Viscosity (Pas)
ρ	Density (kg/m^3)

Subscripts:

$G1,G2$	Property of Gas Layers
L	Property of Liquid Layer
m	Mean value

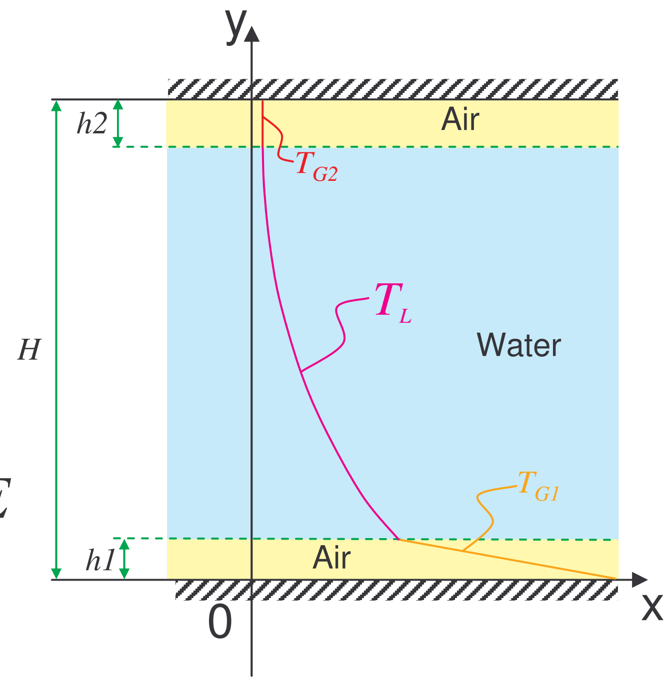
Two Wall Temperature Profile Solution

Velocity Profile is of the form: $u(y) = Ay^2 + By + C$

Differential Equation is of the form: $u\dfrac{\partial T}{\partial x} = \alpha \dfrac{\partial^2 T}{\partial y^2}$

Substituting in the velocity profile and integrating twice wrt y gives:

$$T_{L,G1,G2}(y) = \frac{1}{\alpha}\frac{dT_m}{dx}\left(\frac{Ay^4}{12} + \frac{By^3}{6} + \frac{Cy^2}{2}\right) + Dy + E$$



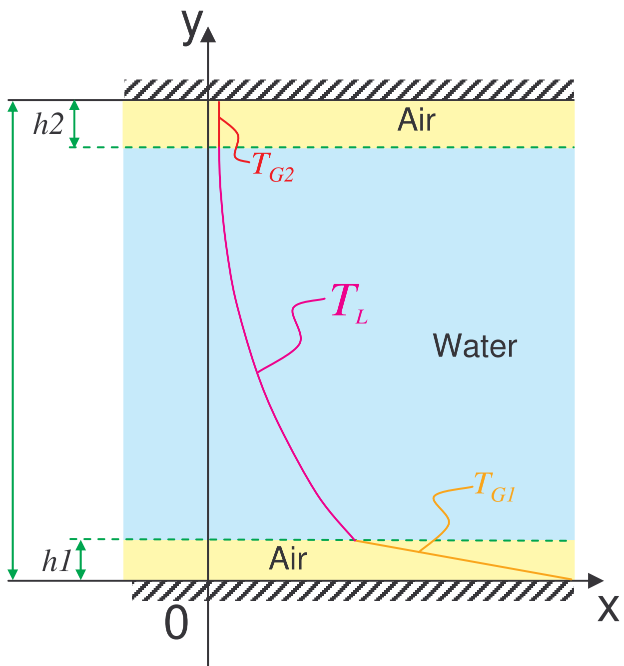
Note that $\dfrac{dT_m}{dx}$ is constant for constant heat flux case

The values of A, B and C are known from the velocity profile solution. D and E are integration constants and must be solved for.

This means that six boundary conditions are required as there are three Temperature Profile Equations

Two Wall Temperature Profile Solution

$$T_{L,G1,G2}(y) = \frac{1}{\alpha}\frac{dT_m}{dx}\left(\frac{Ay^4}{12} + \frac{By^3}{6} + \frac{Cy^2}{2}\right) + Dy + E$$



Boundary Conditions:

New B.C. No.1

$$T_{G1} = \frac{dT_m}{dx}x + T_{InletSurf}$$

1. $\boxed{@\ y = 0, -k_{G1}\frac{dT_{G1}}{dy} = \dot{q}}$

2. $@\ y = h1, T_{G1} = T_L$

3. $\boxed{@\ y = h1, -k_L\frac{dT_L}{dy} = -k_{G1}\frac{dT_{G1}}{dy}}$

4. $@\ y = H - h2, T_{G2} = T_L$

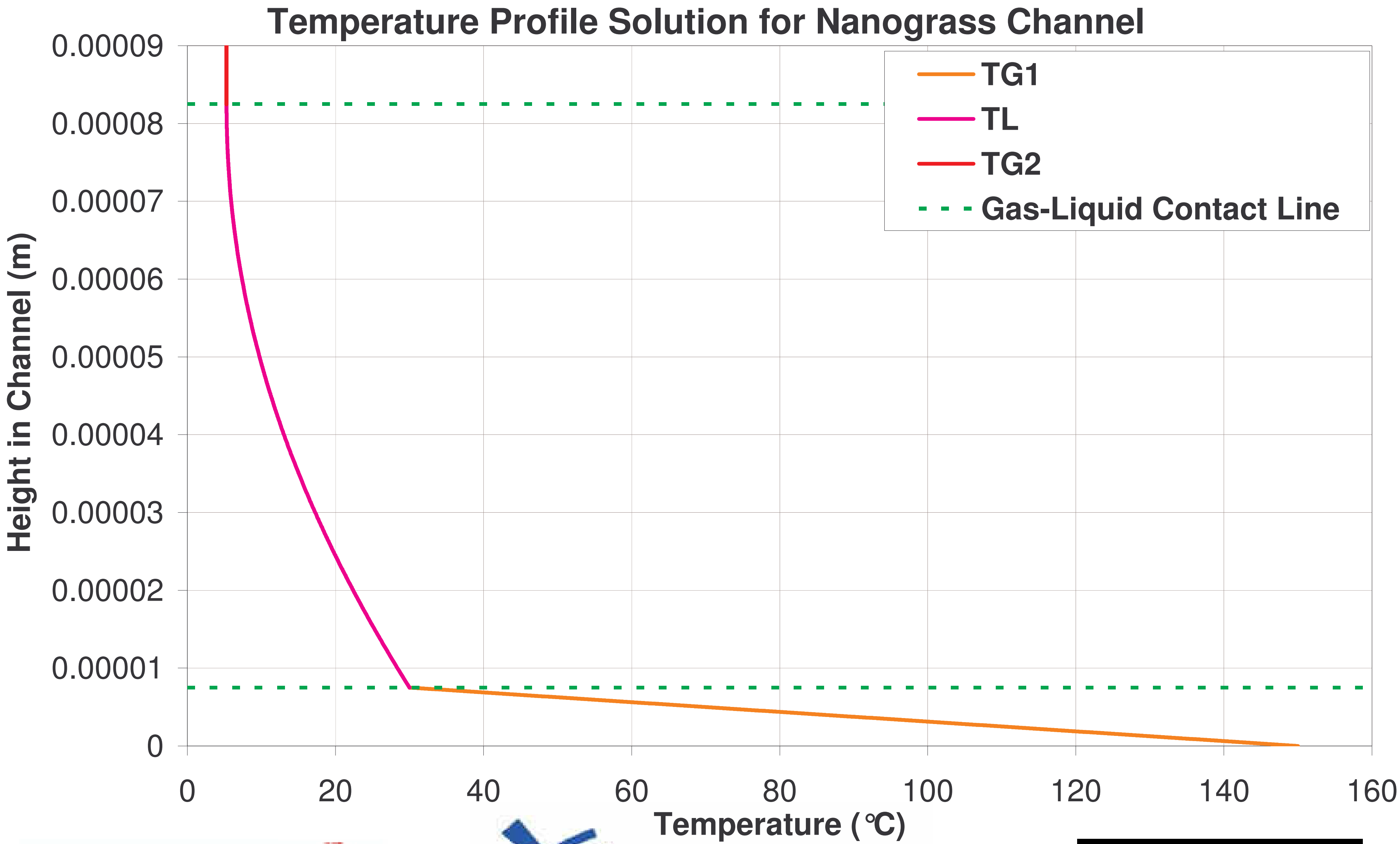
5. $\boxed{@\ y = H - h2, -k_L\frac{dT_L}{dy} = -k_{G2}\frac{dT_{G2}}{dy}}$

6. $\boxed{@\ y = H, -k_{G2}\frac{dT_{G2}}{dy} = 0}$

4 Equations define the D variables, while only 2 define the E variables. Unknowns to be solved for are D_L, D_{G1}, D_{G2}, E_L, E_{G1}, E_{G2}.No solution is possible with these boundary conditions.

Since the surface, liquid and gas temperature gradients in the flow direction are constant and equal (Constant heat flux case assumed), a temperature can be assigned to the wall at y=0

Two Wall Temperature Profile Solution



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