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Experimental and Numerical Investigation of Two Phase Flow in a Model of Nanoporous Medium

LowPerm 2015

Les rencontres scientifiques d'IFP Energies Nouvelles

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([1] : IMFT, [2] : LAAS, [3] : LMDC)

June 9th - 11th 2015

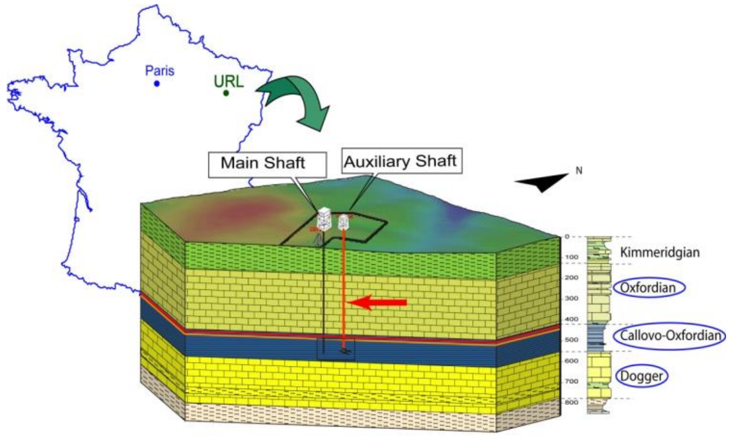
1. **Motivation / Context**

2. Fabrication and procedure

3. Two phase flow in dead end nanochannels

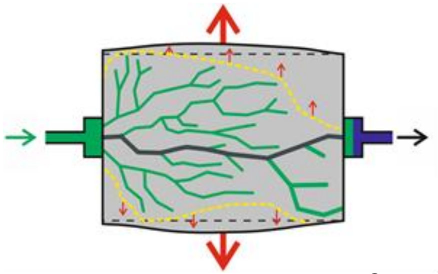
Conclusion

Repository Issue of Long Life Radioactive Wastes



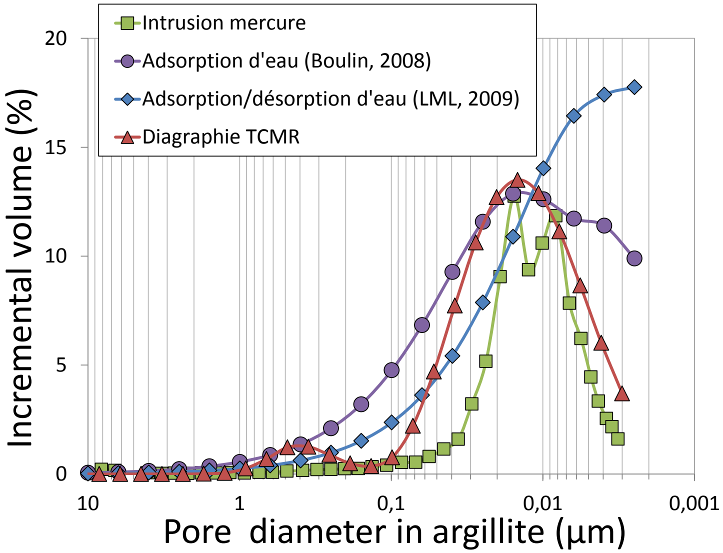
ANDRA's project of repository of long life radioactive wastes

- Specificities of this deep repository:
  - **Gas generation** (mainly H_2 from corrosion of metallic component)



Drainage experiment of BGS

  - Typical pore size : **few tens of nanometre**



JC Robinet - ANDRA

- Issues:
  - Influence of gas generation on fluid flow around repository galleries?

Goals : specificities due to nanometer scale

- **Validation of hydraulic law**
  - Kinetics of imbibition

- **Effect of high capillary pressure**
  - Flow and mechanical deformation

$$P_c = \frac{2\gamma}{a} = 72\ bar$$

a =20 nm, γ= 72mN/m (water)

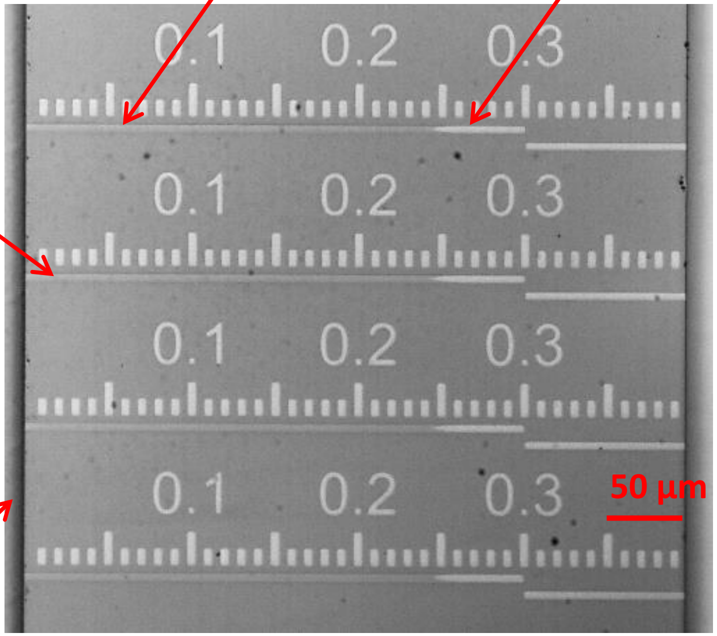
- **Modification of physical properties:**
  - Dissolution properties
  - Cavitation
  - Rarefied gas

Our approach : Nano-fabrication

- **Classical use of model system: [1]**
  - Controlled geometry
  - Phase visualisation
  - Parallelization of experiments
  - High reproducibility

- **Emergence of nanofluidics**

  < 200 nm [2]



Picture of two phase flow in dead end nano channel (depth = 54 nm)

[1] P. Lenormand et al., *J. Fluid Mech.* (1988)
[2] C. Duan et al., *Biomicrofluidics* (2013)

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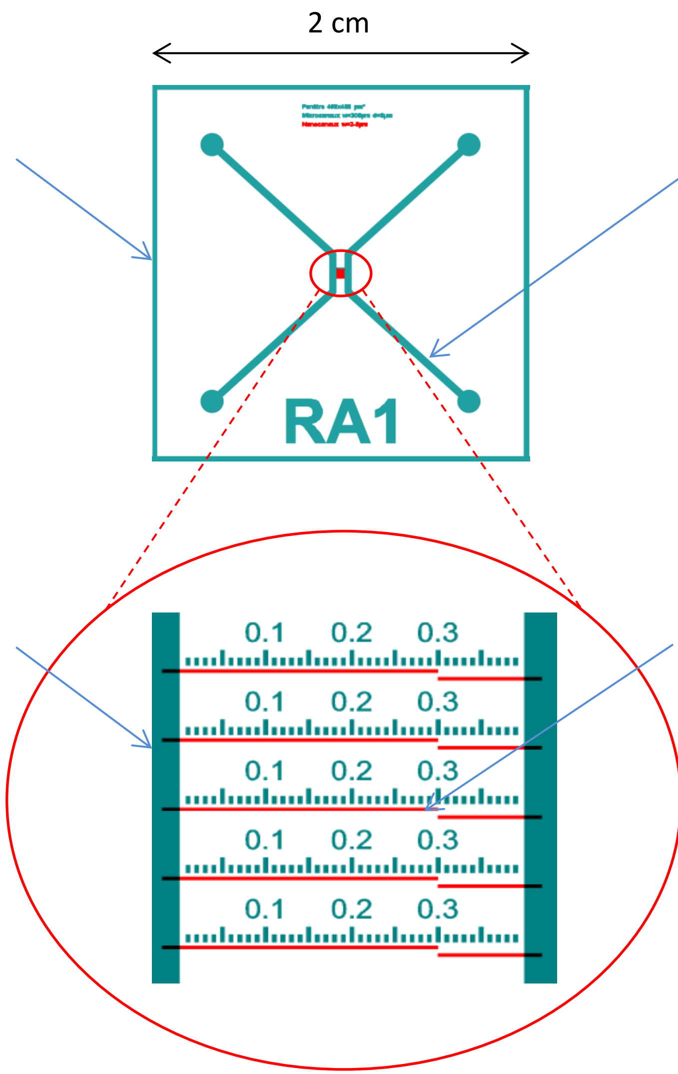
Nano-fabricated chip

Silicon/glass chip (anodic bonding)

Microchannels : fluid deliver (etched by RIE)

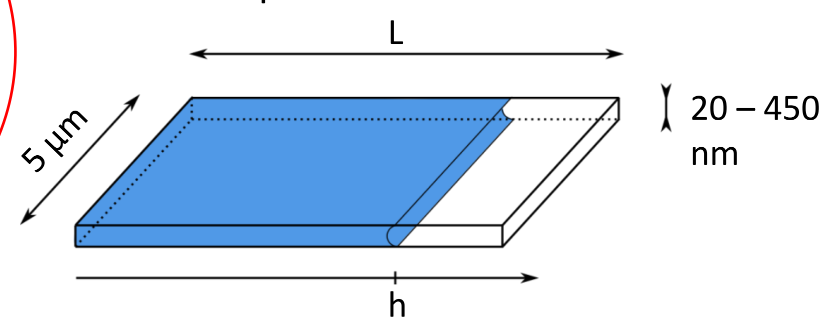
- Width : 300 µm
- Depth : 50 µm



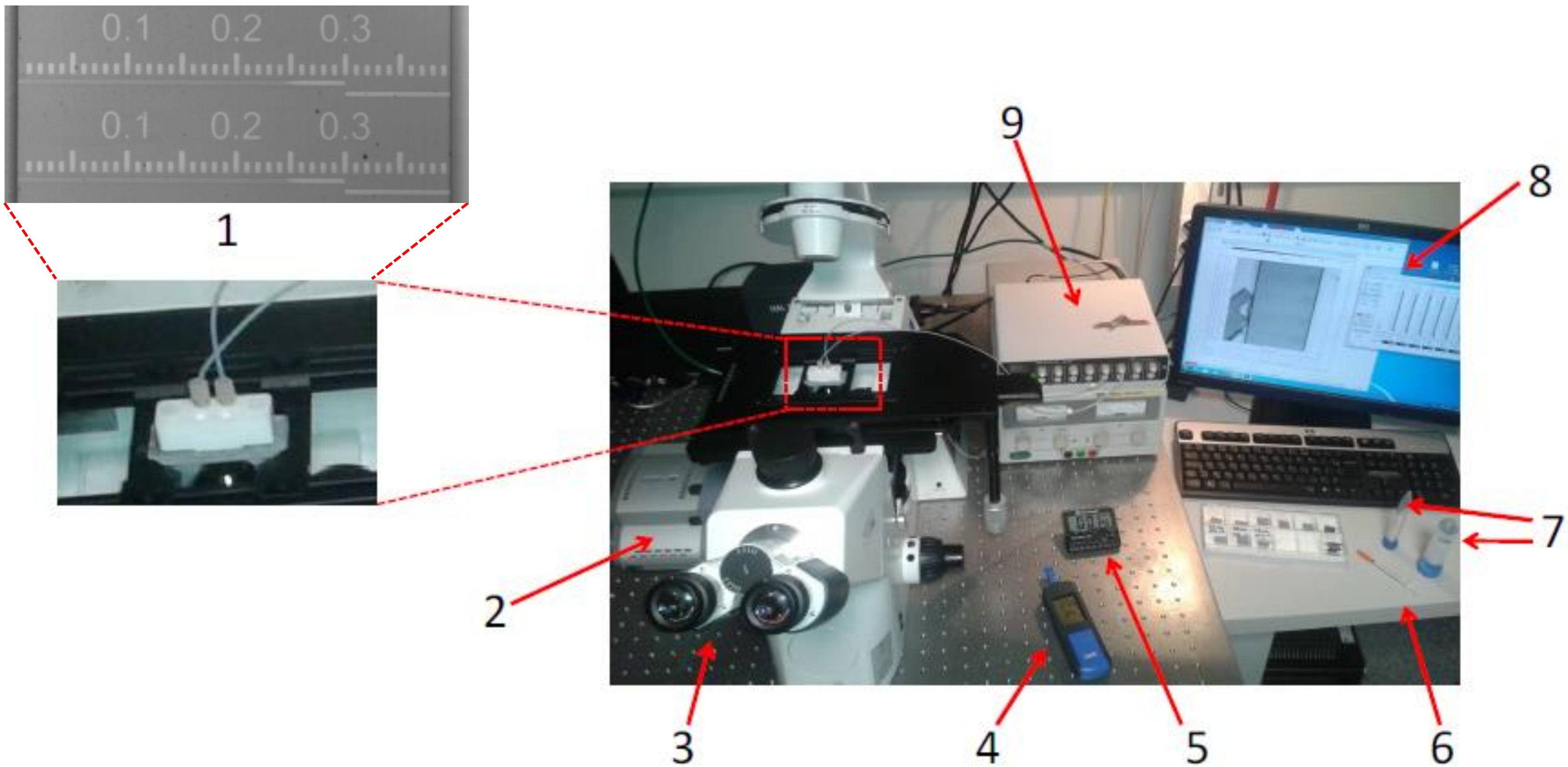
Microchannels

Nanochannels (etched by smooth RIE)

- Width : 5 µm
- Depth : **20 to 450 nm**



Experimental Procedure



1. Experimental support
2. Video camera
3. Inversed microscopy

4. Thermo and moisture meter
5. Chronometer
6. Needle

7. Sample
8. Control screen
9. Pressure deliver

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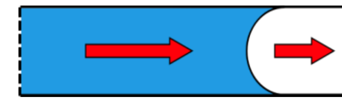
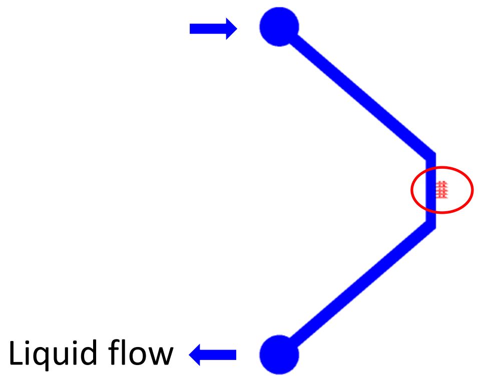
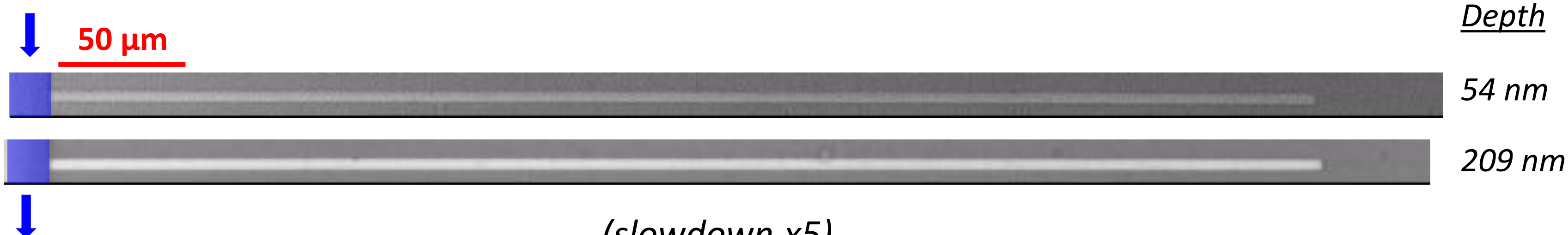
Imbibition in dead end nanochannels

- **Beginning of imbibition** => gas pressurization



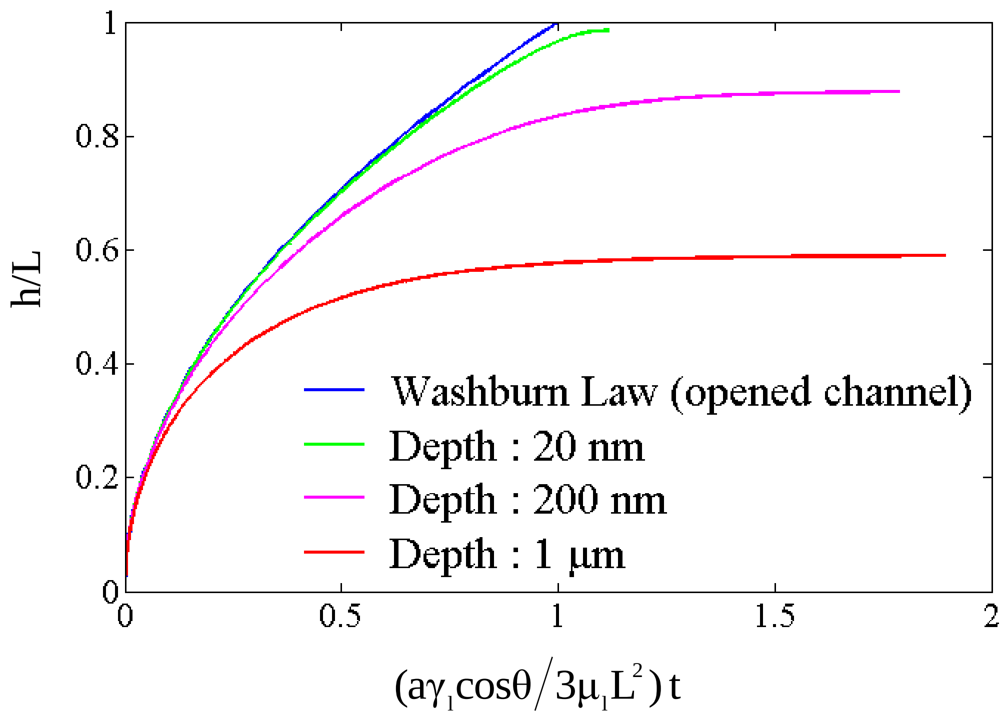




(slowdown x5)

=> Meniscus dynamics is less affected at nanometer scale by gas pressurization effect

Imbibition in dead end nanochannels



h: meniscus position

a: channel depth

L: channel length

γ_l: surface tension

μ_l: liquid viscosity

θ: contact angle

$$\alpha = \frac{p_0}{p_{cap}}$$

Washburn law:

$$h = \sqrt{\frac{a\gamma_l \cos\theta}{3\mu_l} t}$$

Imbibition in dead end channel : (with gas compression) [1]

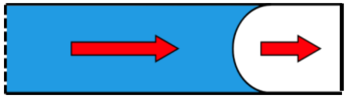
$$t(h) = \frac{h^2}{2(1+\alpha)} - \frac{\alpha h}{(1+\alpha)^2} - \frac{\alpha}{(1+\alpha)^3} \ln[1-(1+\alpha)h]$$

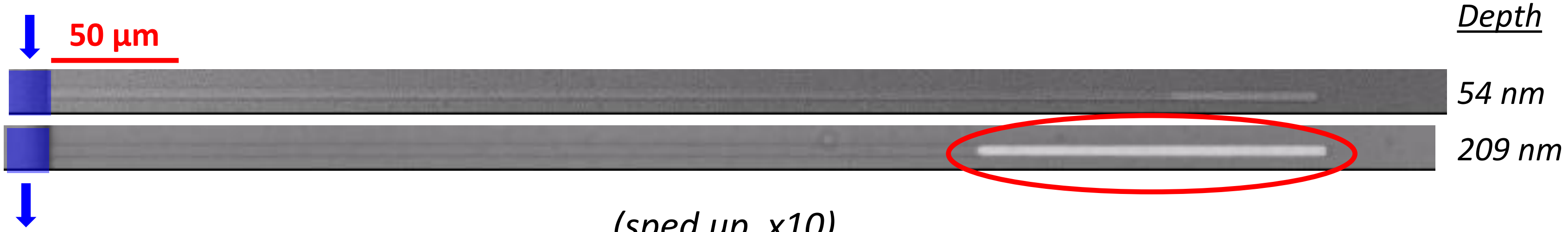
=> Gas compression has low influence on filling kinetics for the smallest depth

[1] V.N. Phan et al., *Langmuir*, 2010

Imbibition in dead end nanochannels

- **End of imbibition** => gas dissolution





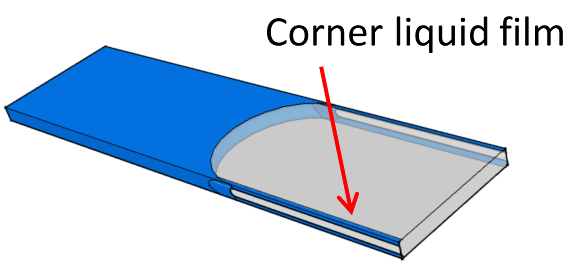
(sped up x10)

- Gas dissolution is faster for the lowest depths :

  => Higher gas concentration : c_{eq}(gas)=H*P_{gaz}

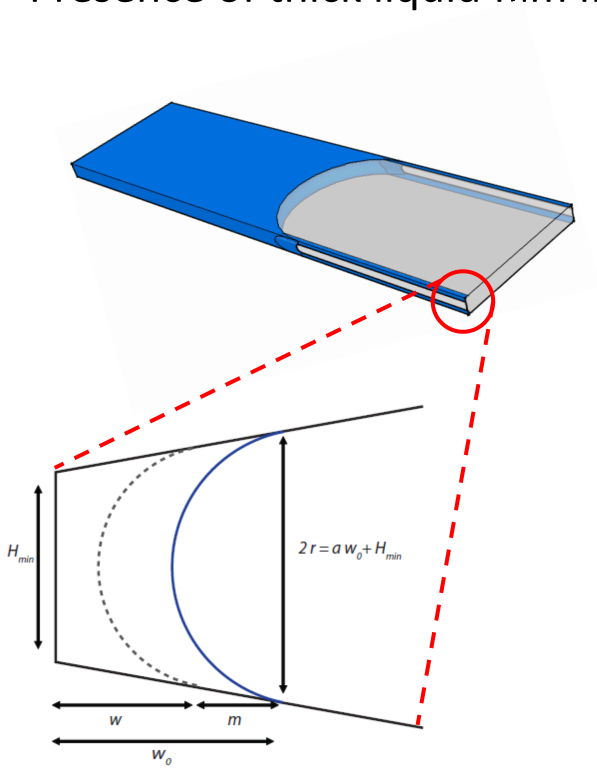
- Channel can be filled from the end !

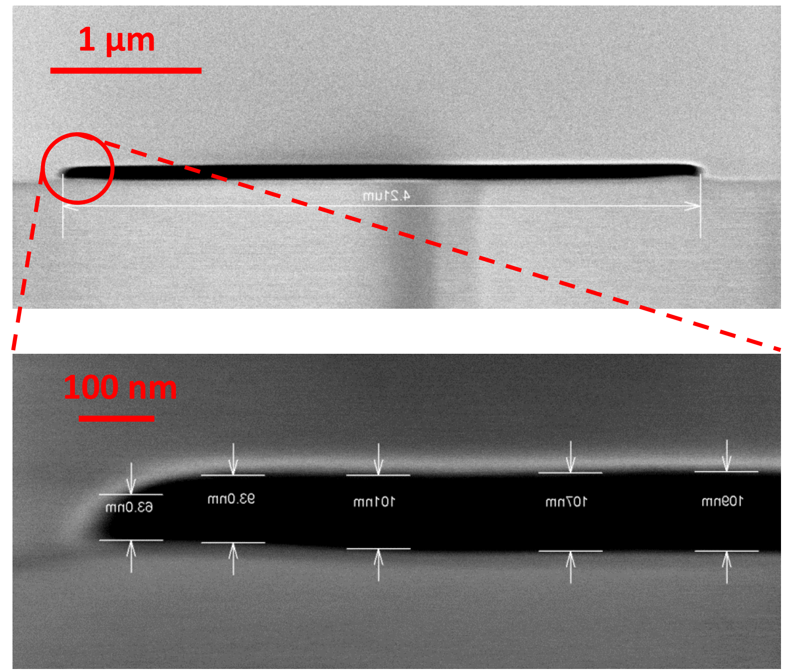
  => end of channel is supplied by corner liquid films



Imbibition in dead end nanochannels

- Presence of thick liquid film if walls are not strictly parallel [1]

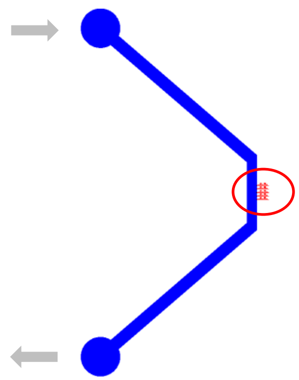




SEM imaging of nanochannels

[1] E. Keita , *Thesis*, 2014

Evaporation in dead end nanochannels



Depth

209 nm

54 nm

Evaporation in nanochannel (real time)

Liquid pocket

⇒ Presence of gas bubble modifies the kinetics of evaporation (similar in [1])

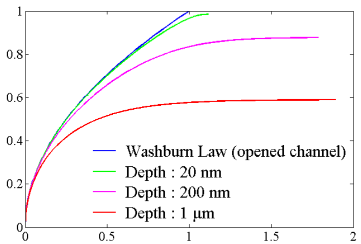
⇒ Evaporation from inside the liquid appears only for depth lower than 104 nm (with ethanol) (same observation as[2])

[2] C. Duan et al., *Proc. Natl. Acad. Sci. U. S. A. (2012)*
[1] O. Vincent et al., *PRL (2014)*

Conclusion

Two phase flow at nanometer scale presents particularities

High gas pressurization



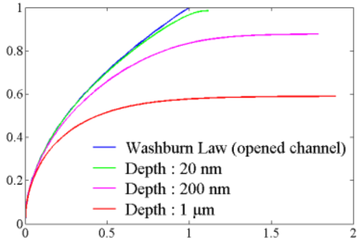
Filling from the end

Bubbles appearance

Conclusion

Two phase flow at nanometer scale presents particularities

High gas pressurization

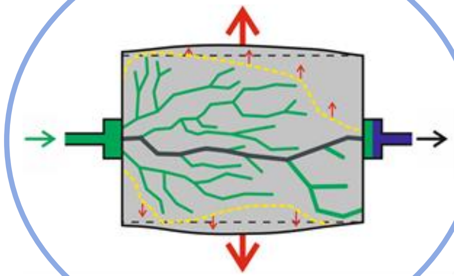


Filling from the end

Bubbles appearance

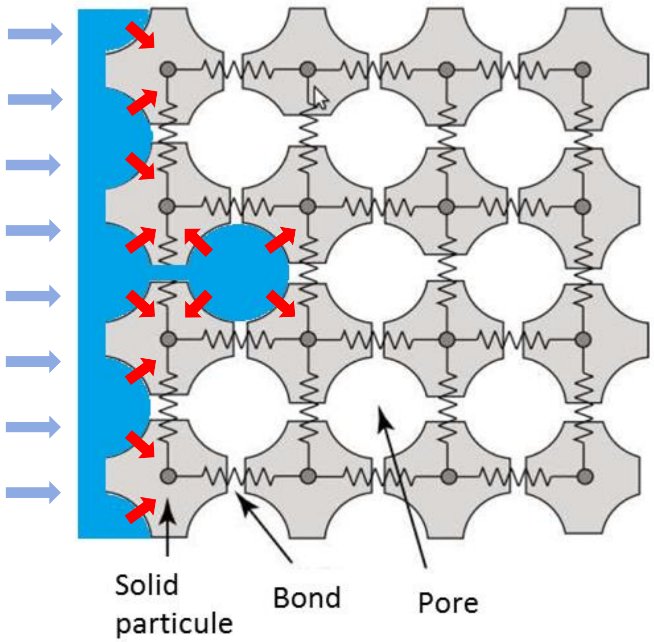
Pore size effect on crystallization

Fluid structure interaction

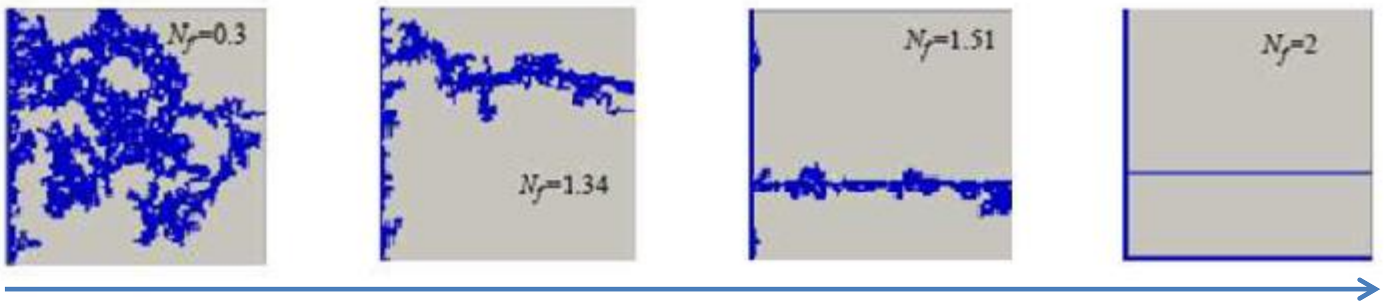


Perspective: deformable medium

- Approach of [1] and [2]
  - Simulation on pore network coupling:
    - Flow pore network (resolve by invasion percolation algorithm)
    - Spring network (elastic deformation)



- Goal = study the impact of deformation on invasion pattern

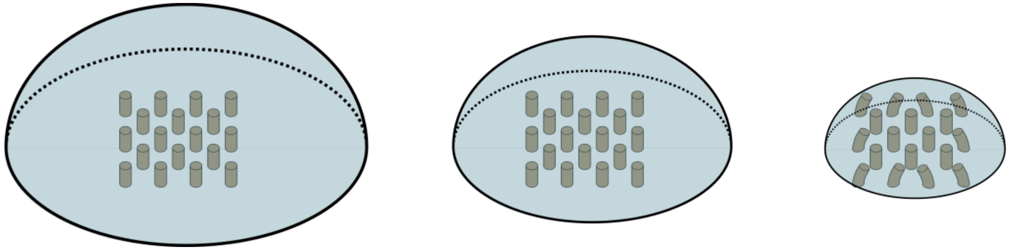


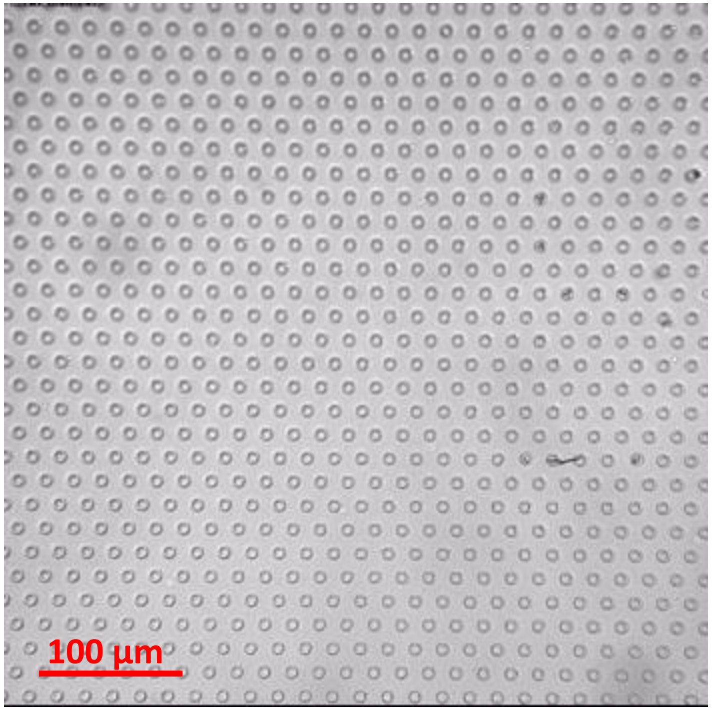
$$N_f = \frac{\gamma}{\lambda E^* a \sqrt{\varepsilon_0}}$$

[1] Holtzman & Juanes, *Physical Review E. (2010)*
[2] P. Lefort, *PhD Thesis (2014)*

Perspective: deformable medium

- Evaporation of a droplet in a network of pillars





=> Bending and collapse of pillars by capillarity

Thank you for your attention