LAboratory PLAsma and Conversion of Energy

Self-propelled droplets for the transport of heat

LAPLACE – GREPHE (Toulouse, FRANCE)
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Self-propelled droplets for the transport of heat

Introduction

1. **Motion driven by surface tension forces**
   1. Hydrodynamic theory and model
   2. Results and analysis
2. **Water vapor condensation using wettability gradient surface**
   1. Model
   2. Experimental setup
   3. Experimental results

Conclusion

Introduction

- The change of state is widely used in thermal transfer enhancement techniques
- Evacuation of the dispersed phase using a wettability gradient
- Very broad application domain: microbiology, microfluidics, microelectronics, microgravity systems…

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Motion driven by surface tension forces

Hydrodynamic theory and model

- Minimization of free surface energy: $\theta_d(x,t) = \theta(x_G)$
- Conservation of volume: $V\left(R(x_G,t),\theta(x_G,t)\right) = \text{constant}$
- Momentum balance:

$$F_\theta(x_G,t) + F_\mu(x_G,t) - mg\sin\alpha = 0$$

  - With the Subramanian et al.[1] viscous force:

$$F_v(x_G,t) = 6\pi\mu U(x_G,t)R(x_G,t)\left(g(\theta(x_G,t),1-\varepsilon) - g(\theta(x_G,t),0)\right)$$

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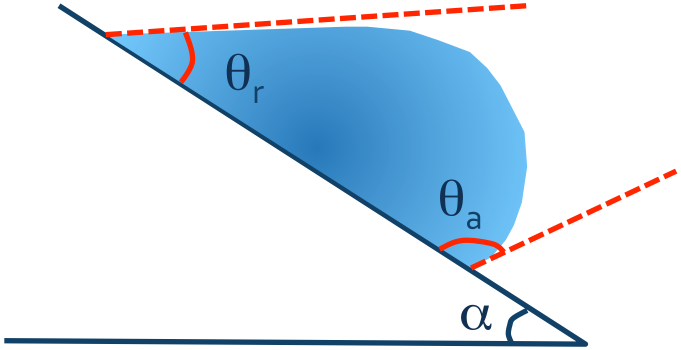
1. R. S. Subramanian, N. Moumen and J. B. McLaughlin, Langmuir **21**,11844 (2005)

Motion driven by surface tension forces

Hydrodynamic theory and model

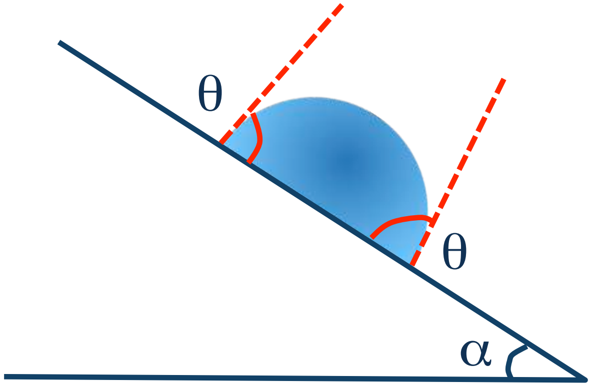
- $R \gg L_{cap}$



- The droplet slides when:

$$\begin{cases} \theta_r > \theta_{rear} \\ \theta_{front} > \theta_a \end{cases}$$

- $R \ll L_{cap}$



- Same angle everywhere

$$\theta_{front} = \theta_{rear} = \theta$$

- Gradient allows to satisfy two relationships simultaneously.

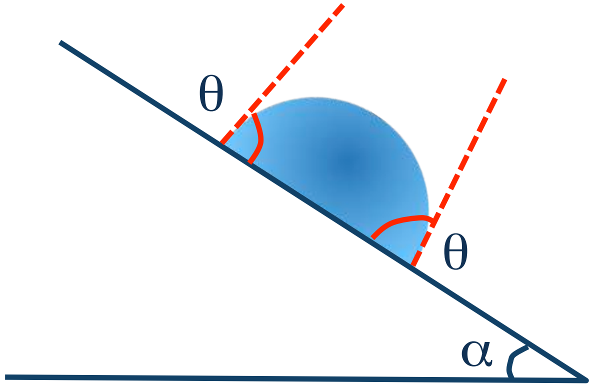
$$\theta_r \geq \theta \geq \theta_a$$

Motion driven by surface tension forces

Hydrodynamic theory and model

A small droplet having a spherical cap shape on a wettability gradient surface is “deformed” because the local contact angles along the triple line are different than the Young's contact angles

- $R << L_{cap}$



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- Gradient allows to satisfy two relationships simultaneously.

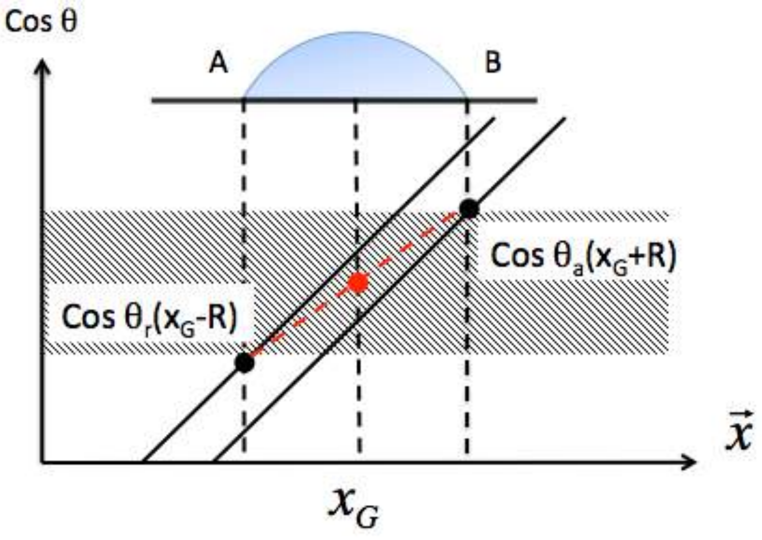
$$\theta_r \geq \theta \geq \theta_a$$

Motion driven by surface tension forces
Hydrodynamic theory and model

- Because the real contact angle is not equal to the static contact angle, the contact line is unbalanced:

$$F_\theta(x_G,t)=\gamma_{lv}R(x_G,t)\int_0^{2\pi}(\cos\theta_s(x)-\cos\theta(x_G,t))\cos\phi\,d\phi$$

With: $x = x_G + R(x_G,t)\cos\phi$



- By analogy with the droplet on the inclined plate: continuity of the static contact angle between θ_a and θ_r

$$\cos\theta_s(x,t)=\frac{\cos\theta_a(x_G+R(x_G,t))-\cos\theta_r(x_G-R(x_G,t))}{2R(x_G,t)}x+b(x_G,t)$$

Motion driven by surface tension forces

Hydrodynamic theory and model

Finally the driving force related to the wettability gradient with contact angle hysteresis:

$$F_\theta(x_G,t) = \frac{\gamma_{lv} R(x_G,t)\pi}{2}\left[\cos\theta_a(x_G + R(x_G,t)) - \cos\theta_r(x_G - R(x_G,t))\right]$$

With: $\theta_a = \theta_s(x) + \frac{CAH(x)}{2}$ and $\theta_r = \theta_s(x) - \frac{CAH(x)}{2}$

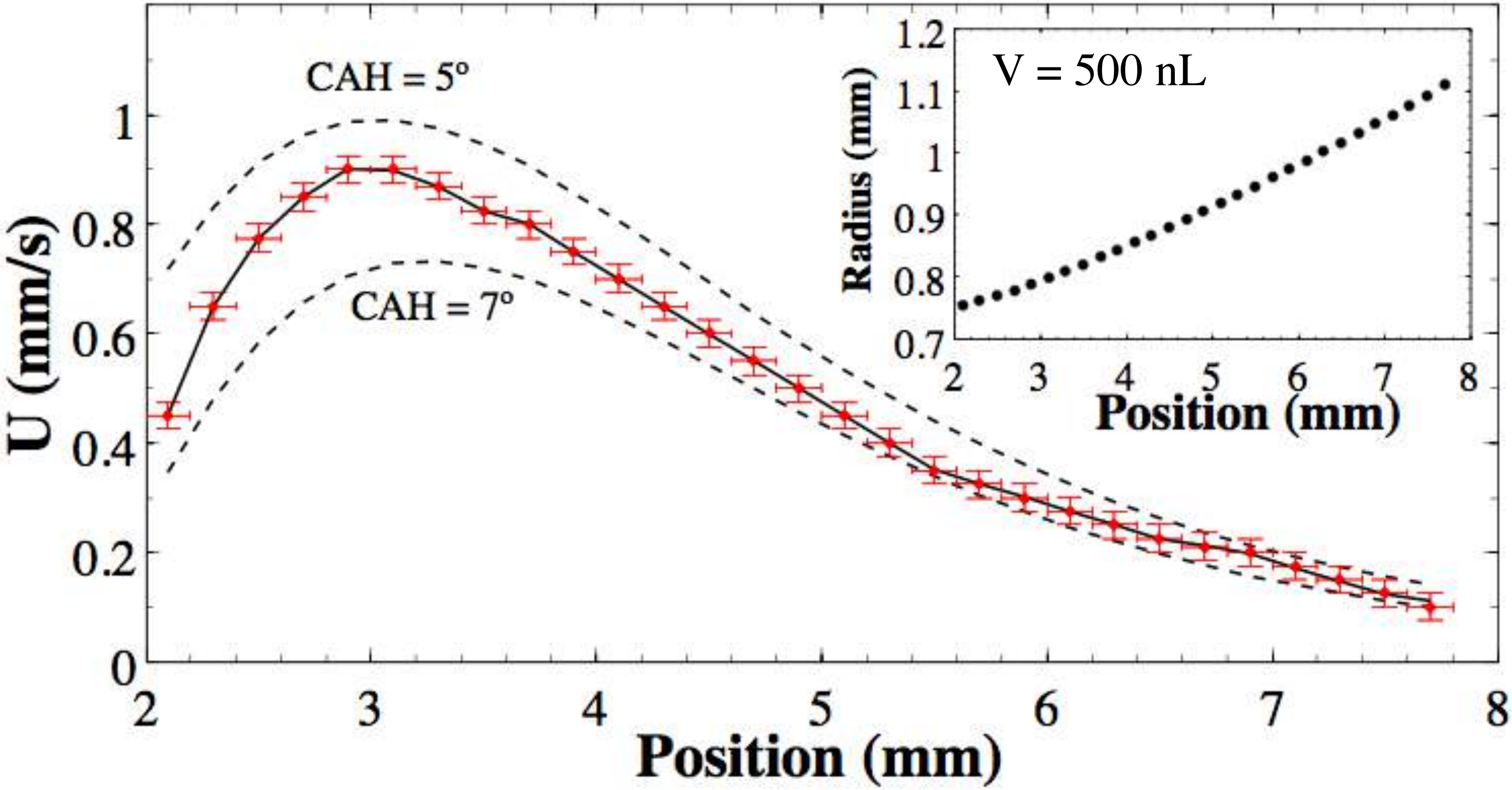
$$\boxed{F_\theta(x_G,t) = \frac{\gamma_{lv} R(x_G,t)\pi}{2}\left[\cos\left(\theta + \frac{CAH}{2}\right)_{x_G+R(x_G,t)} - \cos\left(\theta - \frac{CAH}{2}\right)_{x_G-R(x_G,t)}\right]}$$

Validity criterion of the model: the droplet maintains its spherical cap shape,

$$\boxed{F_\theta(x_G,t) << 4\pi\gamma_{lv} R(x_G,t)\frac{1-\cos\theta(x_G,t)}{\sin\theta(x_G,t)}}$$

Motion driven by surface tension forces

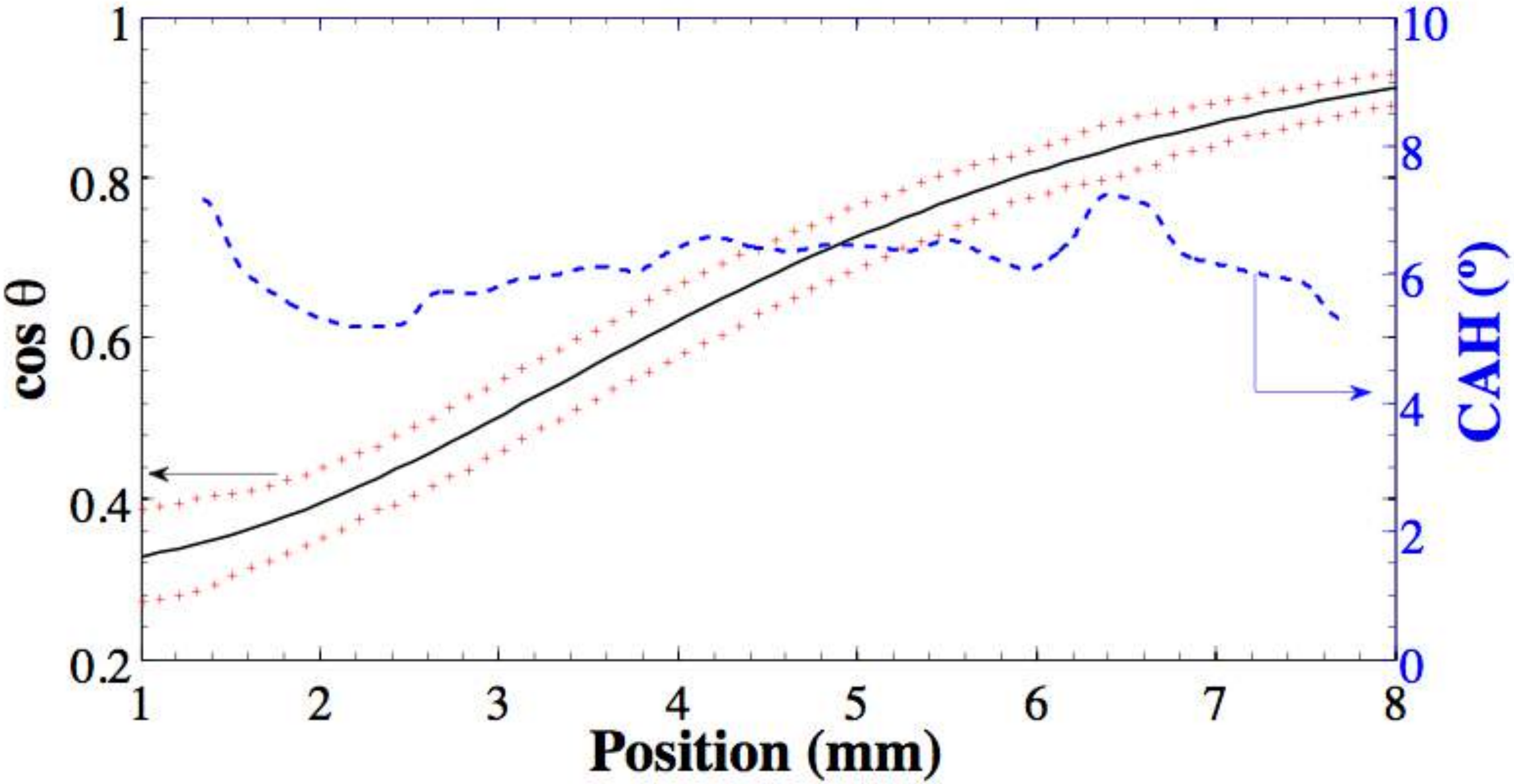
Results and analysis



1. N. Moumen, R.S. Subramanian et J.B. McLaughlin, Langmuir **22**, 2682 (2006)

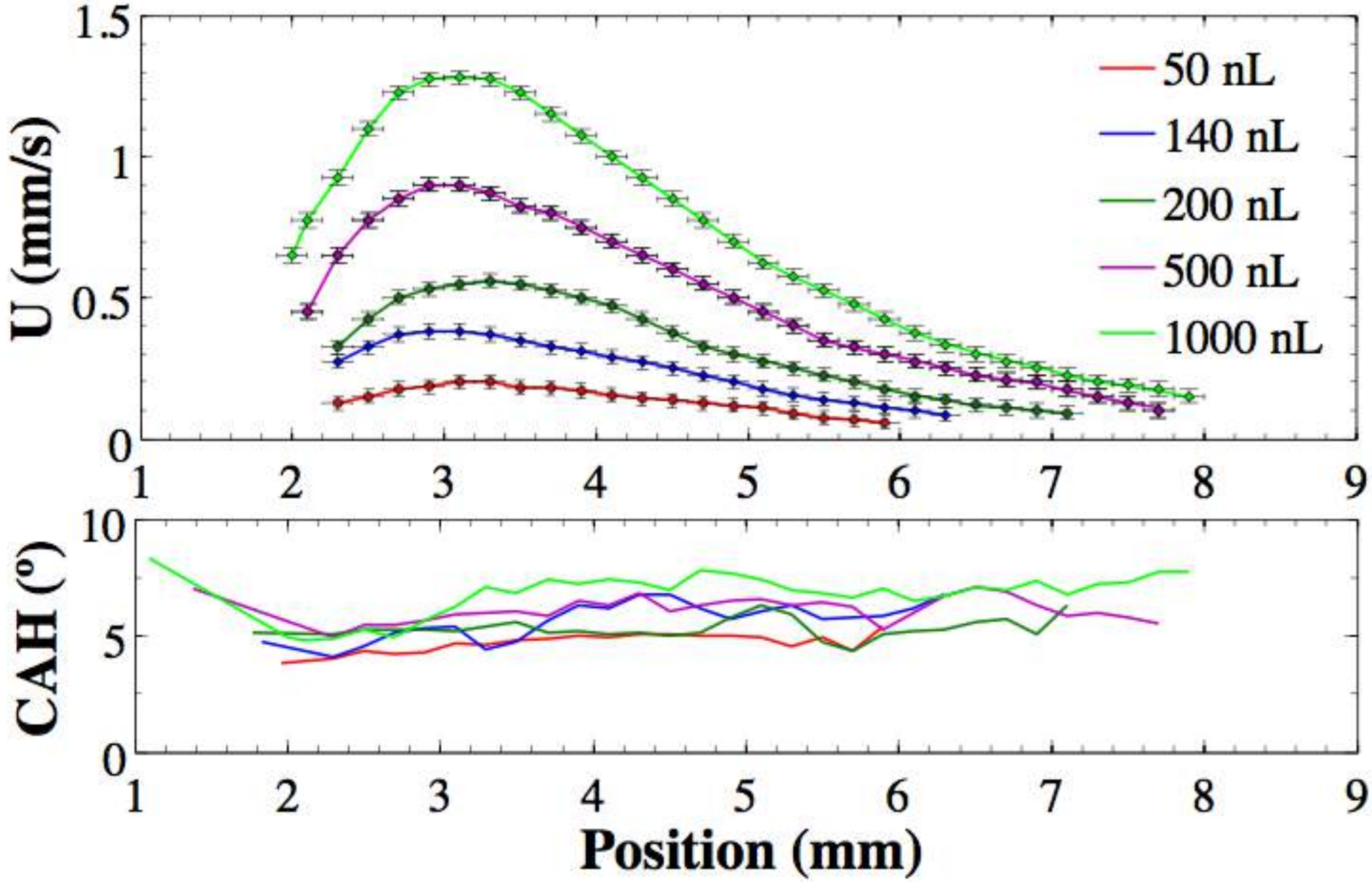
Motion driven by surface tension forces

Results and analysis



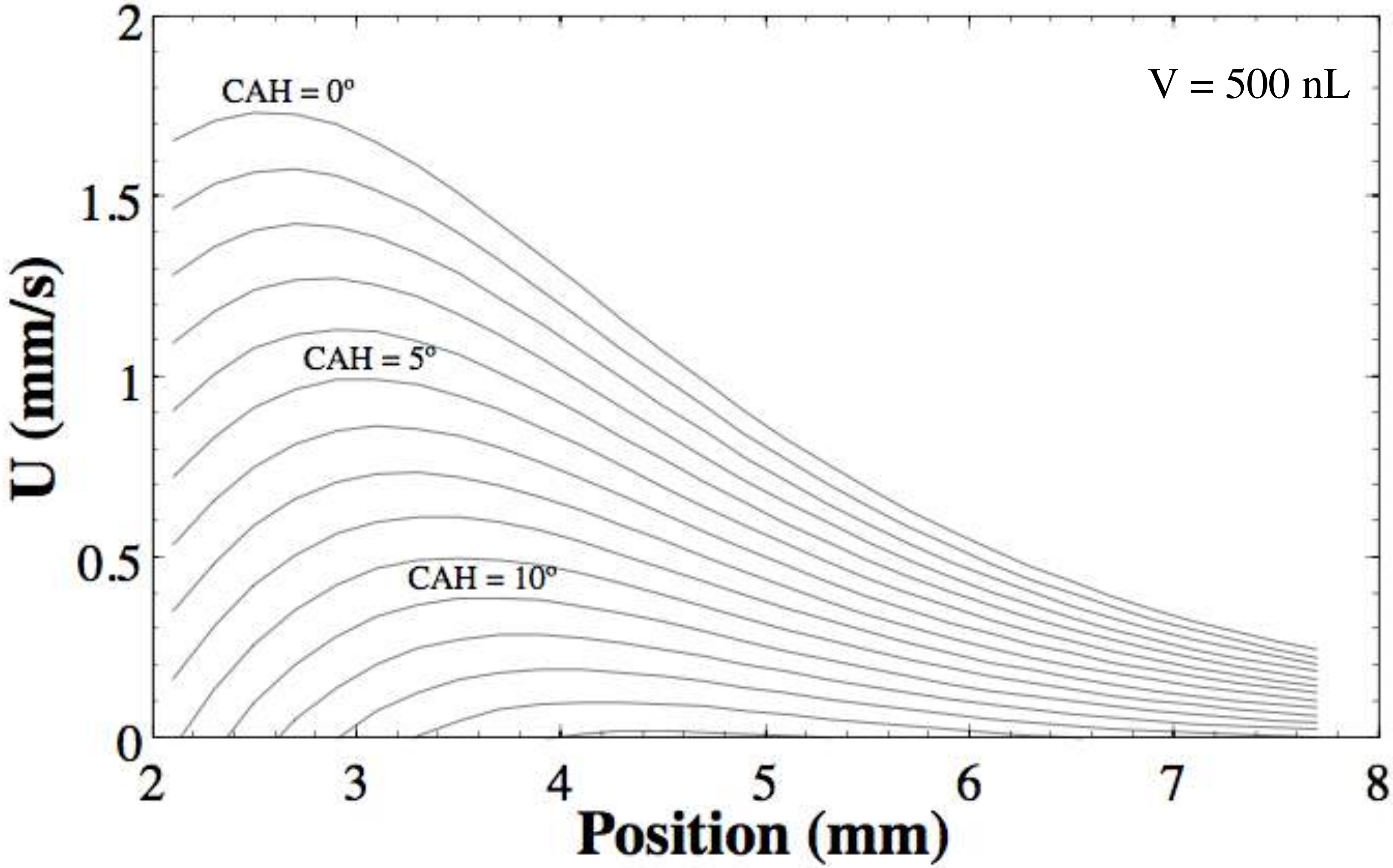
Motion driven by surface tension forces

Results and analysis



Motion driven by surface tension forces

Results and analysis



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Water vapor condensation

Extension of the hydrodynamic model to take into account heat and mass transfer

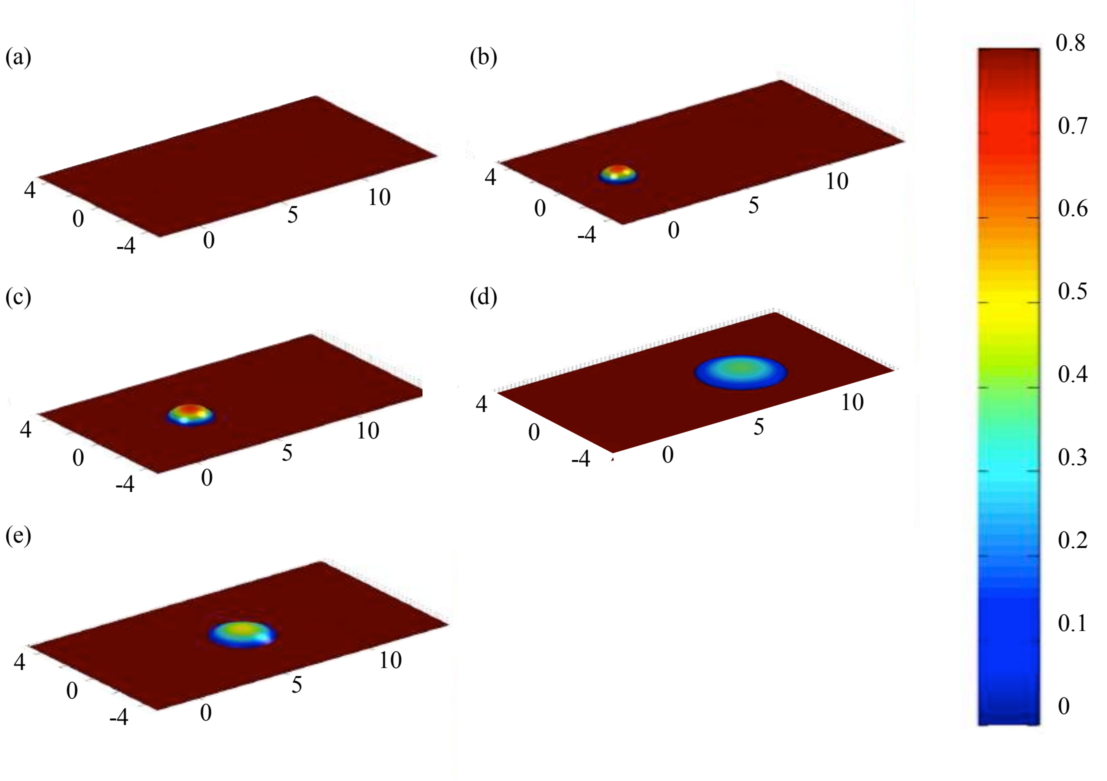
$$\frac{dr_c}{dt}=\underbrace{\frac{8\Delta T}{\rho_l h_{lv}\left(2-3\cos\theta+\cos^3\theta\right)}\frac{\left(1-\frac{r_{c,\min}}{r_c}\right)}{\frac{r_c\theta}{k_l\sin\theta}+\frac{4}{h_{\text{int}}\left(1-\cos\theta\right)}}}_{\text{growth due to heat transfer}}-\underbrace{\frac{r_c\sin^3\theta}{\left(2-3\cos\theta+\cos^3\theta\right)}\frac{d\theta}{dx}\frac{dx}{dt}}_{\text{spreading due to wettability gradient}}$$

$$\frac{dx_G}{dt}=\frac{\pi\gamma_{lv}r_c\left(\cos\theta_a\left(x_G+r\right)-\cos\theta_r\left(x_G-r\right)\right)}{2\left(6\pi\mu r_c[g(\theta,1-\varepsilon)-g(\theta,0)]+\frac{\phi}{h_{lv}}\right)}$$

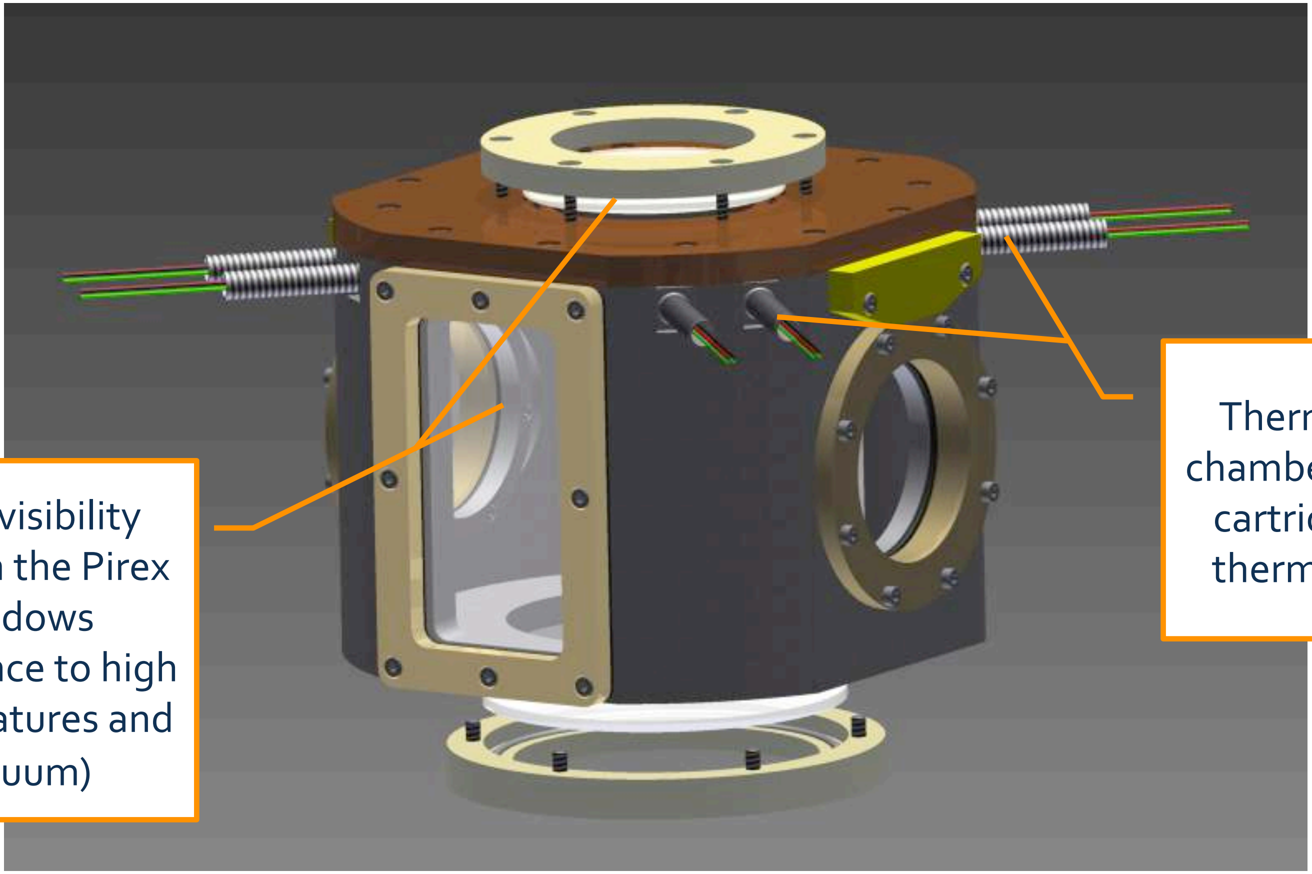
Water vapor condensation

Hydrodynamic model results taking into account heat and mass transfer

Simulation of growth by condensation and movement of a tetraethylene glycol droplet due to wettability gradient.



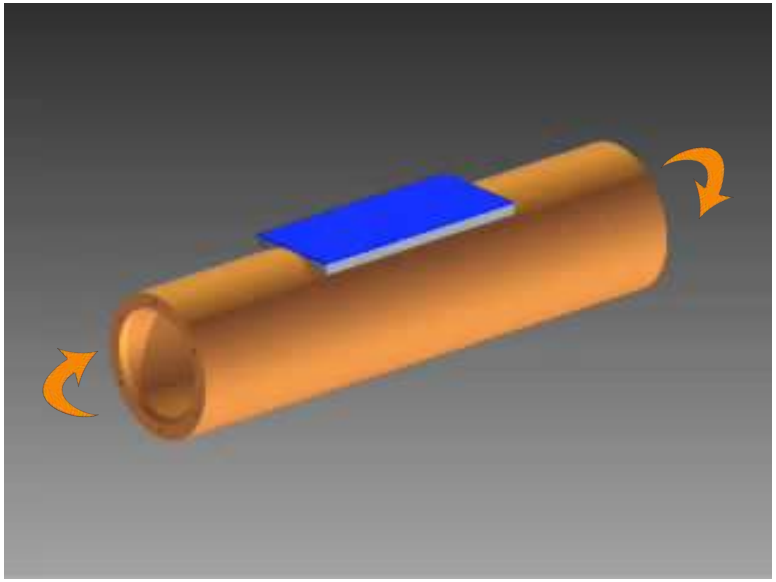
Experimental setup
Chamber



Good visibility through the Pirex windows (resistance to high temperatures and vacuum)

Thermostated chamber : heating cartridges with thermocouples

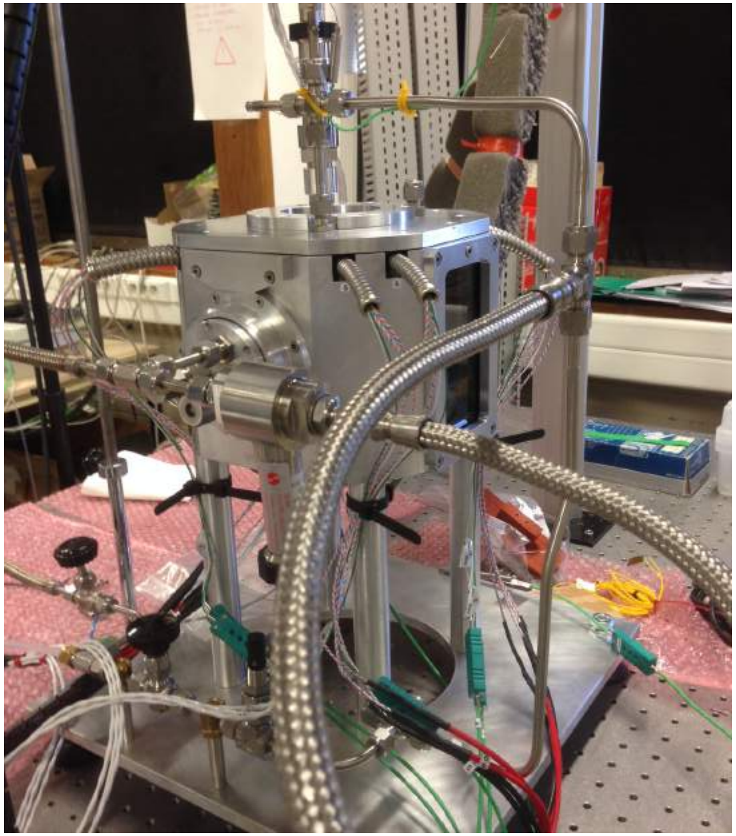
Experimental setup
Sample holder

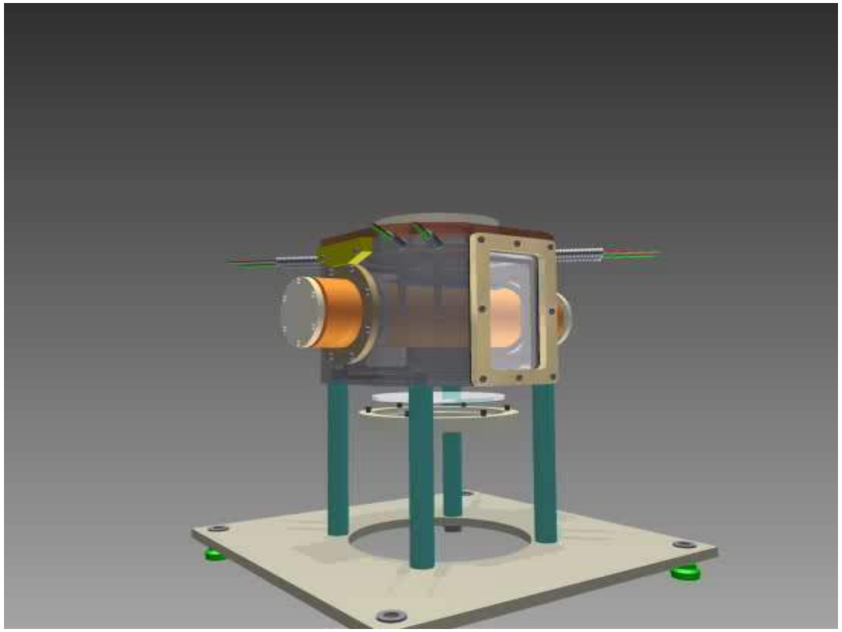


- Sample aspiration system avoids the parasite nucleation and irregularities on the surface
- Facilitates the switching of the sample
- Sample holder : insulating material (λ=0,3 W/(K.m))
- Rotation of the cylinder : study of the gravity effects on boiling

Experimental setup

Cell test picture and overview:





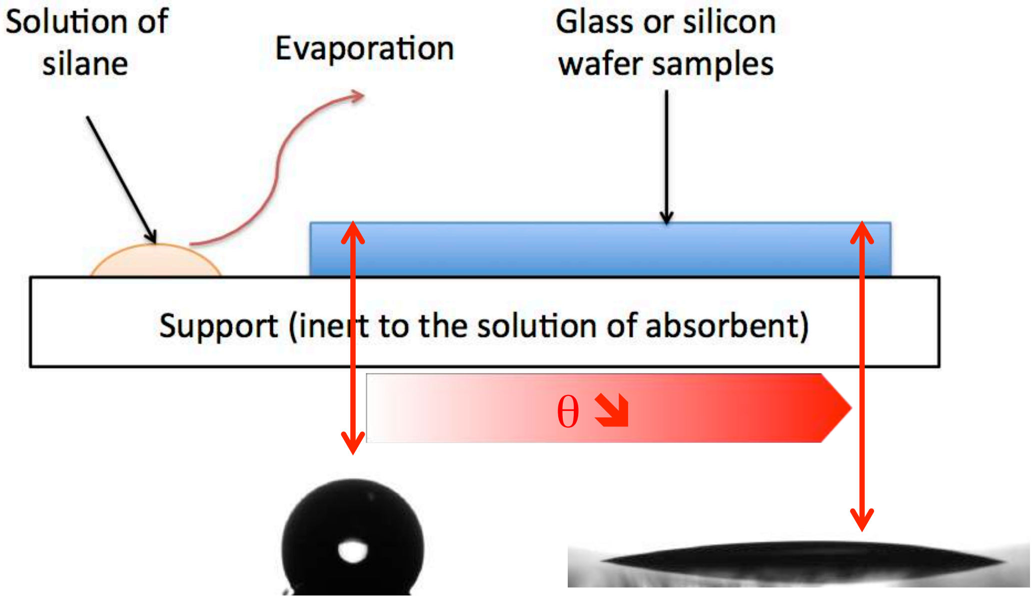
Surface treatment

Chemichal deposition

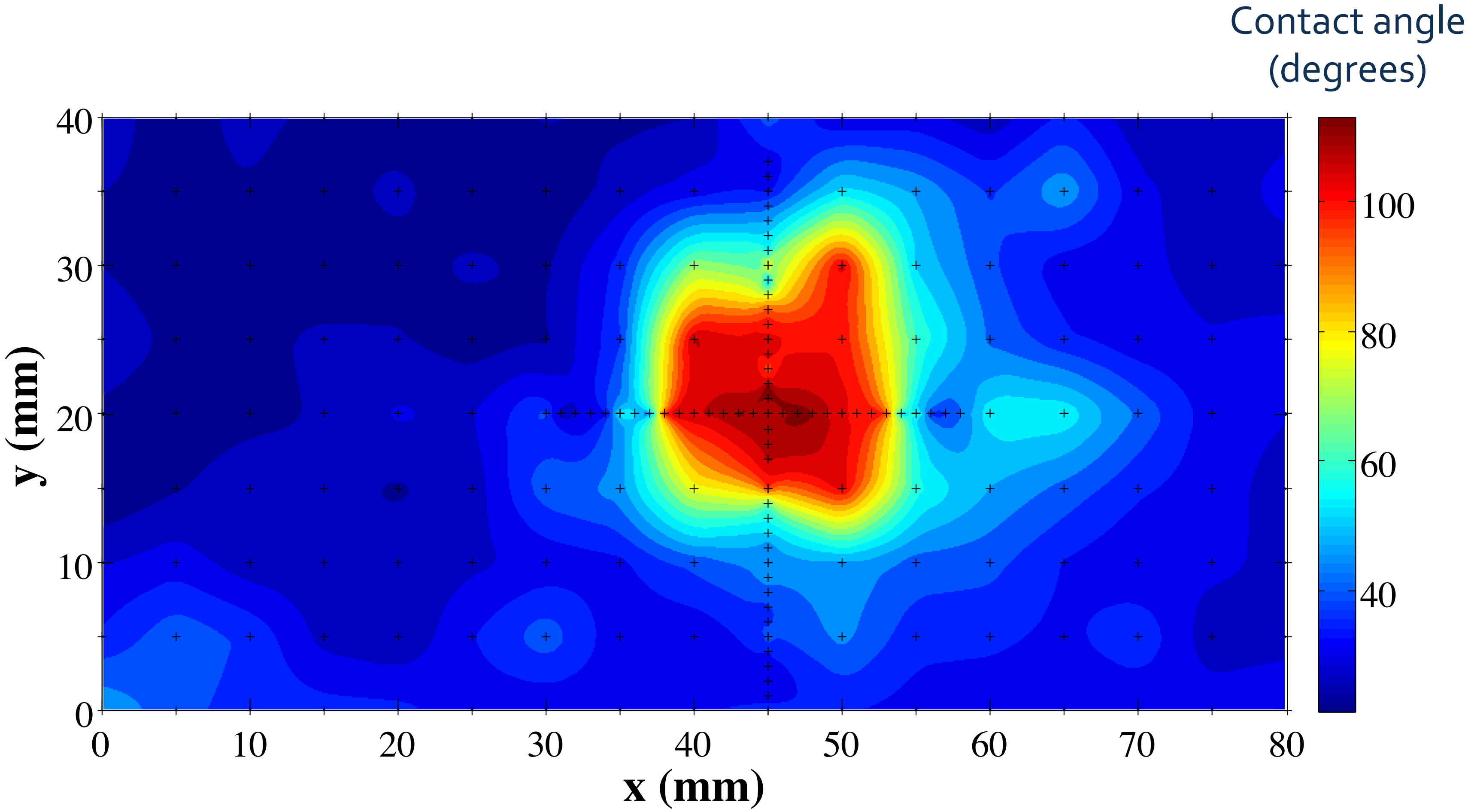
- The chemical deposition is used to produce gradients surface tension on solid surfaces. It is based on Pr. M. K. Chaudhury silanization method.

- This surface treatment, allows the sample to react with vapors of a volatile R-$SiCl_3$ by using the diffusion-controlled process.

- As the silane evaporated and diffused in the vapor phase, it generated a gradient of concentration that decreased along the length of the sample.

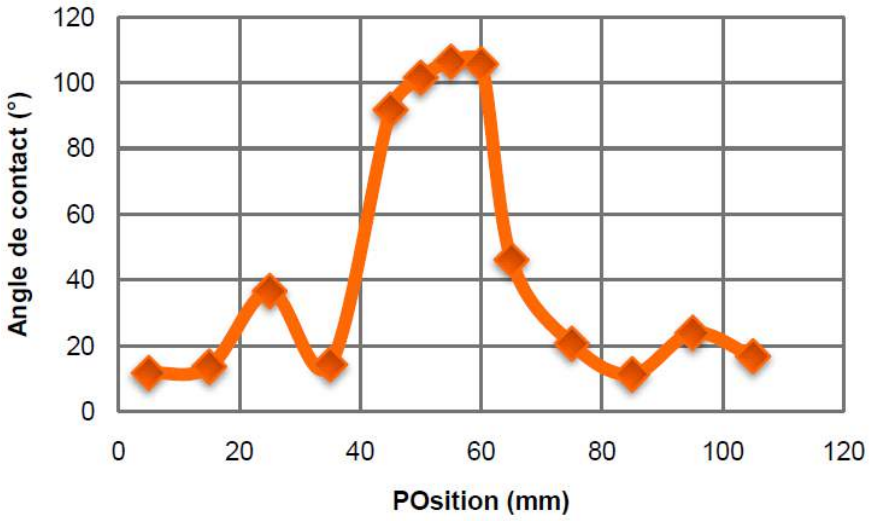


Contact angle distribution

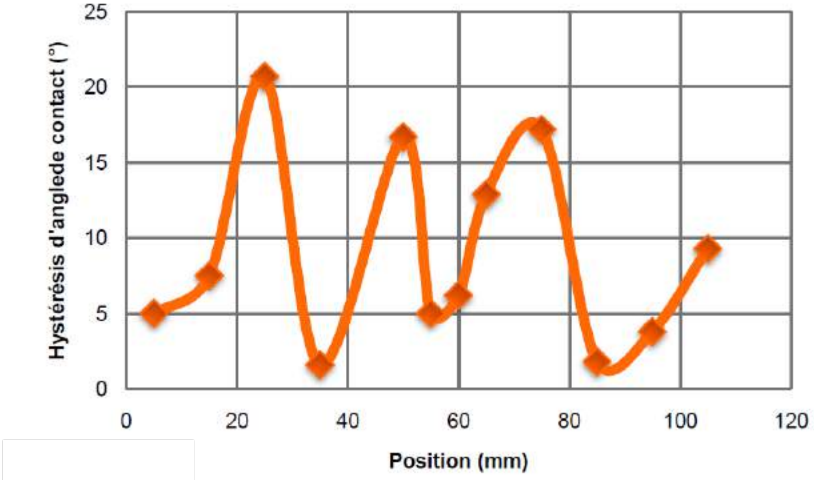


Surface characterization

Contact angle

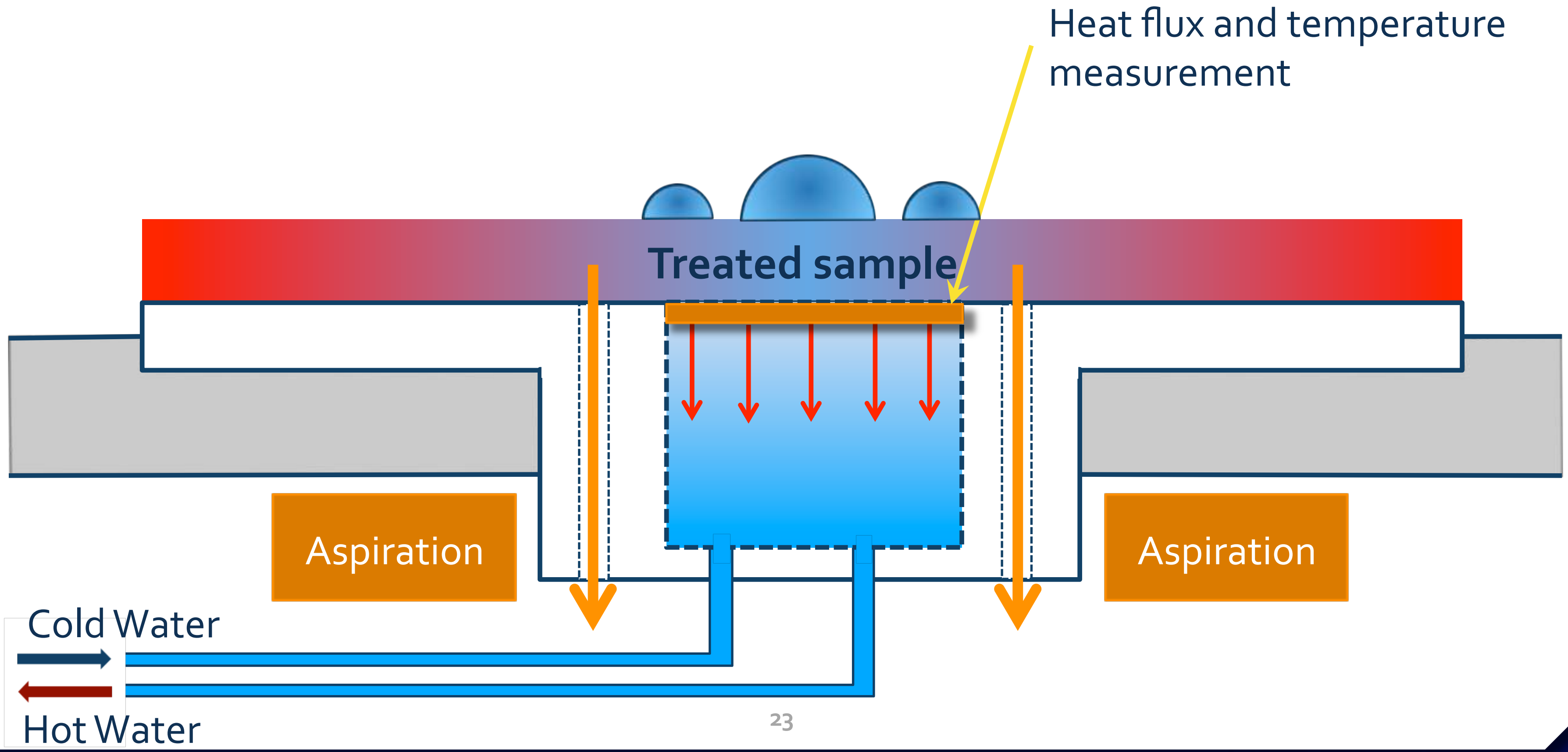


Hysteresis



Experimental setup

Sample holder



Heat flux and temperature measurement

Treated sample

Aspiration

Aspiration

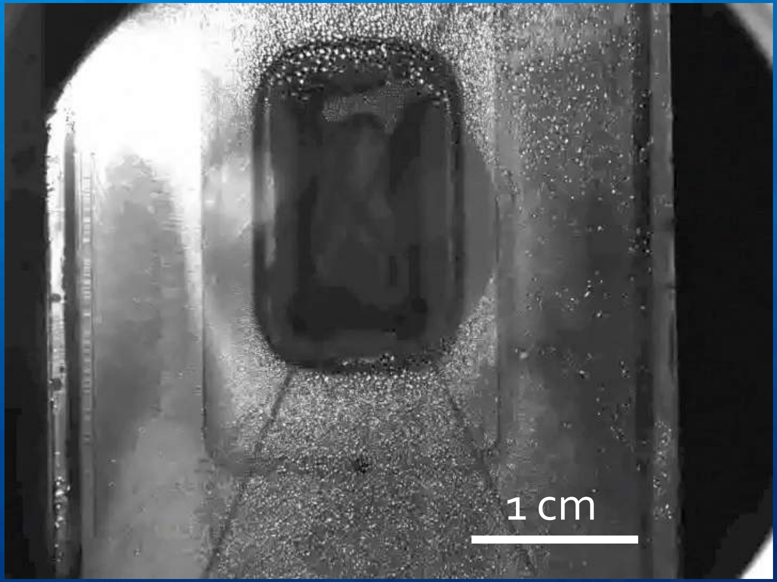
Cold Water

Hot Water

Experimental results

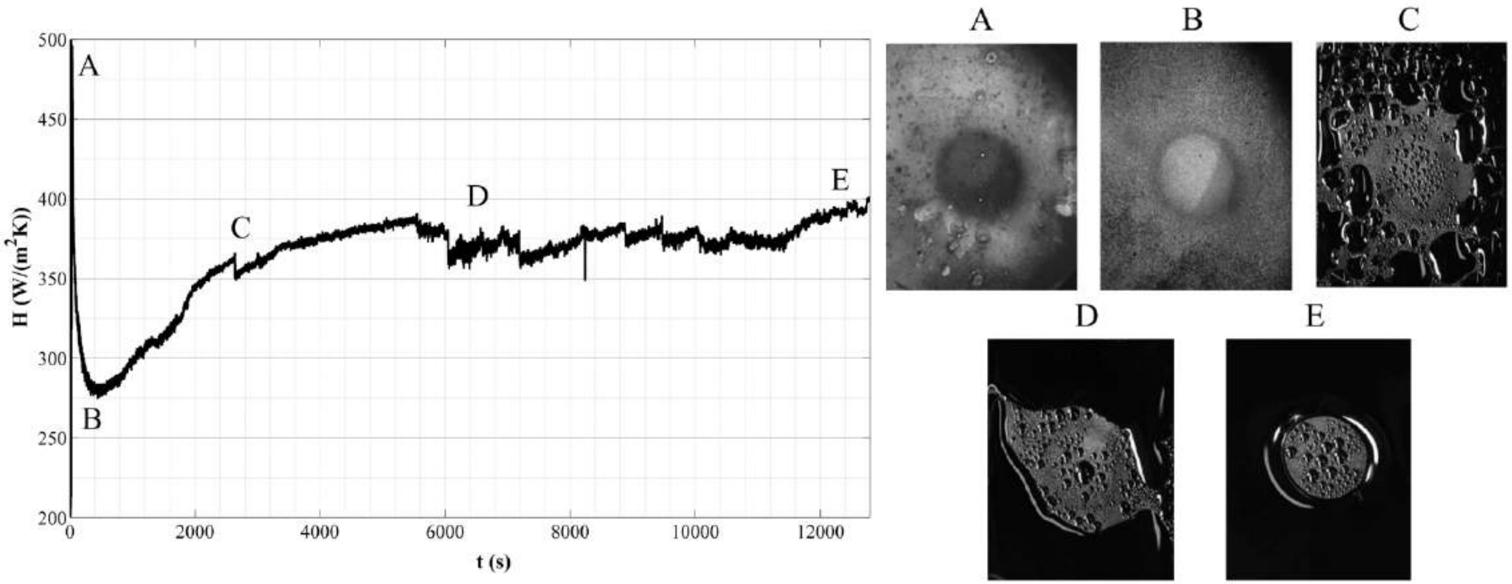
Example of water vapor condensation on a treated glass surface:

- Radial gradient of wettability made by silanization technique
- $\Delta\theta = 95°$ in 12 mm
- 5h recording



Experimental results

Heat transfer coefficient



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- The contact angle hysteresis is the result of different chemical heterogeneities and roughness of the surface.
- The hysteresis has a very important effect on the velocity profile of a droplet on a wettability gradient.
- Local variations of the hysteresis must be taken into account if we want to reproduce accurately the dynamic behavior.
- Wettability gradients represent an interesting passive technique of heat transfer enhancement.

Ongoing

- Optimisation of the wettability gradient
- Applications to thermal two-phase systems
  - Condensation: inclination effect and quantification of the thermal transfers
  - Coupling with capillary grooves to evacuate condensates (for microgravity applications)
  - Boiling: effect of the gradient of wettability on a bubble

Many thanks to the
European Space Agency
for the funding
(Microgravity Application Program MANBO)

Thank you for your attention…