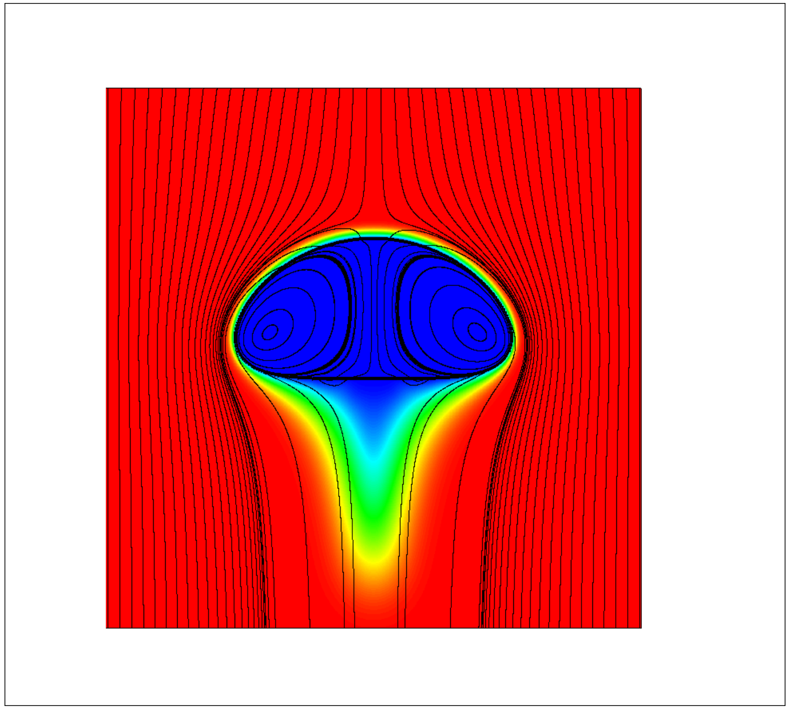
Direct Numerical Simulation of liquid-vapor phase change



Sébastien Tanguy

Fluid Mechanics Institute of Toulouse

And Catherine Colin, Annafederica Urbano, Gregory Huber…

Conservation laws and jump conditions

Conservation law	Jump conditions
$\nabla \cdot \vec{V} = 0$	$[\vec{V}]_\Gamma = \dot{m}\left[\frac{1}{\rho}\right]_\Gamma \vec{n}$
$\rho \frac{D\vec{V}}{Dt} = -\nabla p + \nabla \cdot (2\mu \boldsymbol{D}) + \rho \vec{g}$	$[p]_\Gamma = \sigma\kappa + 2\left[\mu \frac{\partial V_n}{\partial n}\right]_\Gamma - \dot{m}^2 \left[\frac{1}{\rho}\right]_\Gamma$
$\rho C_p \frac{DT}{Dt} = \nabla \cdot (k\nabla T)$	$[k\nabla T \cdot \vec{n}]_\Gamma = \dot{m}\left(L_{vap} + \left(C_{pliq} - C_{pvap}\right)(T_{sat} - T\big\|_\Gamma)\right)$
$\rho \frac{DY_1}{Dt} = \nabla \cdot (\rho D_m \nabla Y_1)$	$[\rho D_m \nabla Y_1 \cdot \vec{n}]_\Gamma = -\dot{m}[Y_1]_\Gamma$

Nucleate Boiling in the contact line regime: numerical simulation

- 2D axisymetric non-uniform mesh.
- Wall thermal conduction.
- Initial thermal boundary layer (Kays and Crawford, 1980).
- *Ja* = *21* (ΔT=7 K) , θ_{app} = *50°* , $\rho_{liq}/\rho_{vap} = 1604$

$$Ja = \frac{\rho_l Cp_l (T_{paroi} - T_{sat})}{\rho_v L_v}$$

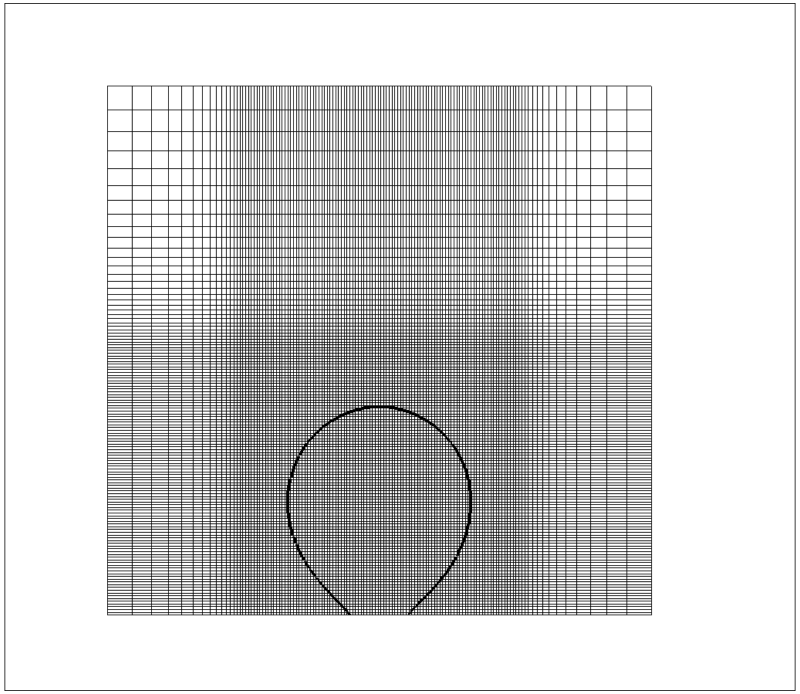
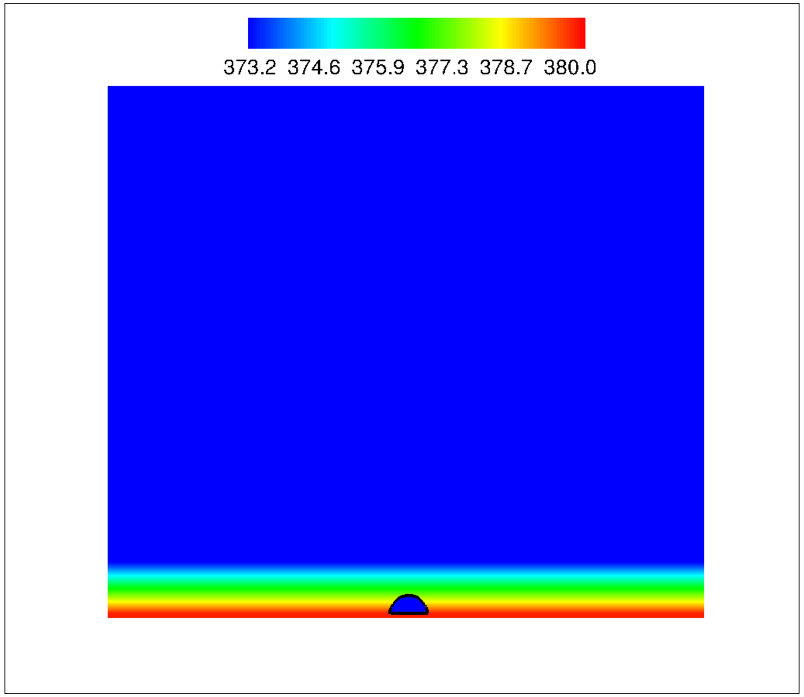
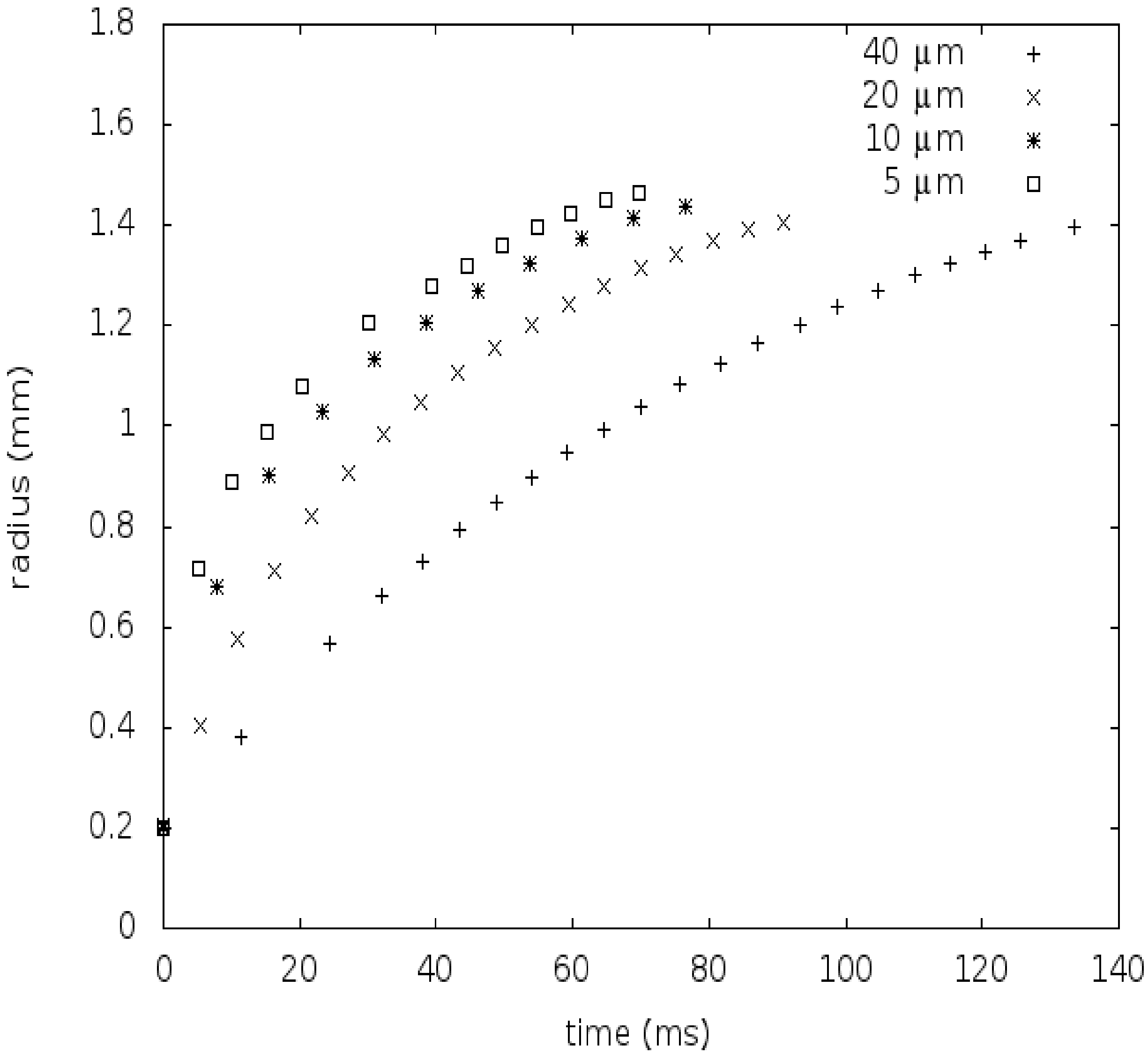


Figure : Example of a Non-uniform axisymetric mesh



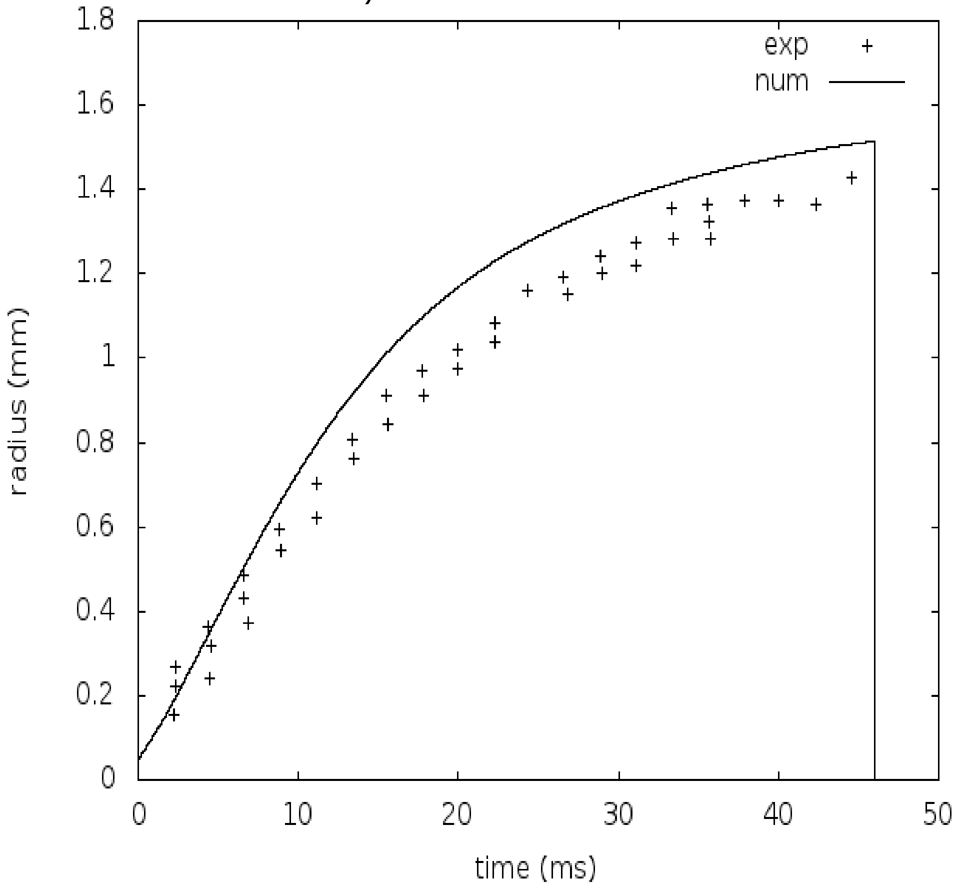
- Nucleate Boiling in the contact line regime: spatial convergence



Grid sensitivity study on the bubble radius

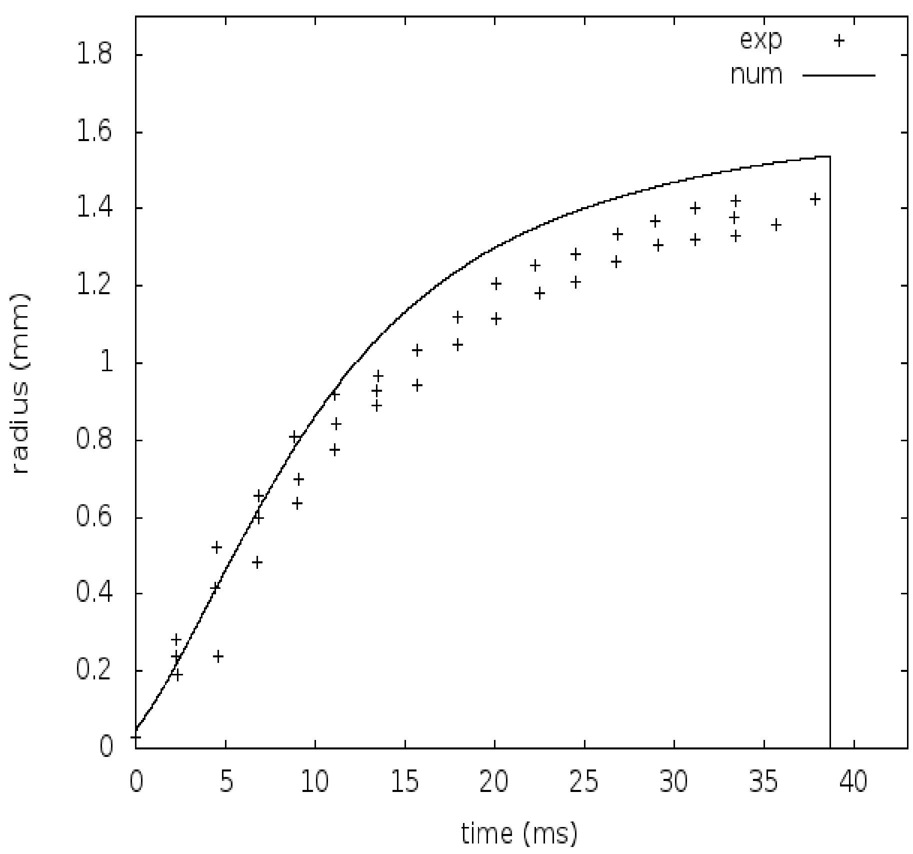
Nucleate Boiling in the contact line regime: Comparisons between simulations and experimental results

Ja = *21* , ΔT=7 K



Departure radius relative error: 5.94%
Departure period relative error: 4.90%

Ja = *25.5* , ΔT=8.5 K



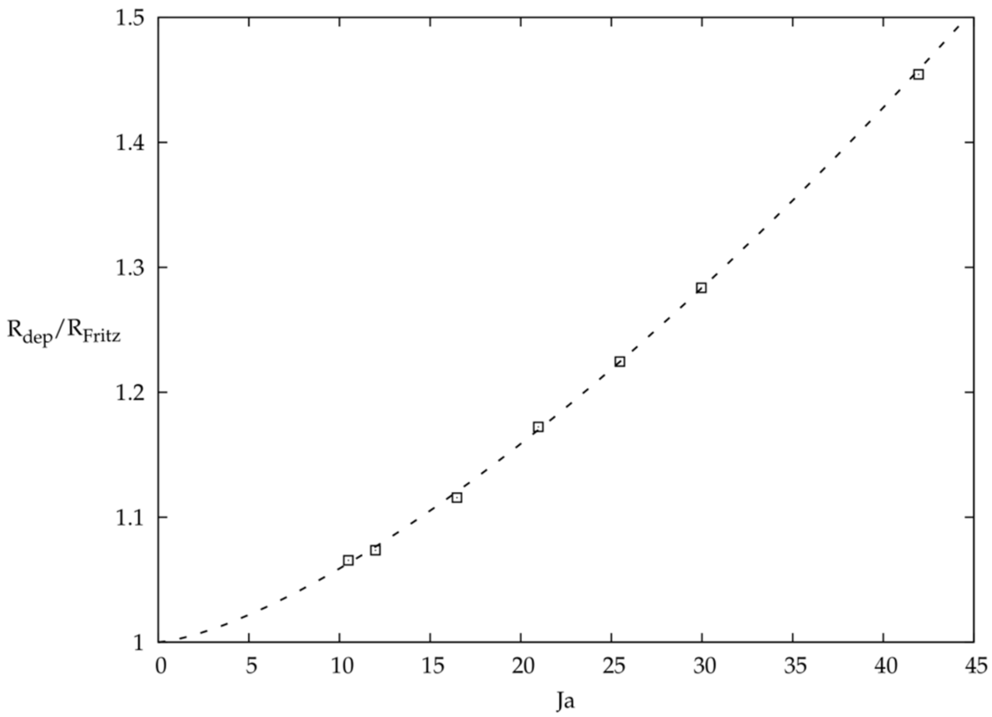
Departure radius relative error: 7.78%
Departure period relative error: 3.59%

Comparison between numerical results and experimental results (Son & Dhir, 1999).

- Nucleate Boiling : a simplified correlation on bubble radius departure

$$\frac{R_{dep}}{R_{Fritz}} = 1 + f\left(Ja, Pr, \theta_{micro}, \frac{\delta}{R_{fritz}}, \frac{\rho_l}{\rho_v} \ldots\right)$$

$$R_{Fritz} = 0.104\theta\sqrt{\frac{\sigma}{g(\rho_L - \rho_V)}}\ .$$



Variation of the dimensionless departure radius with the Jakob number

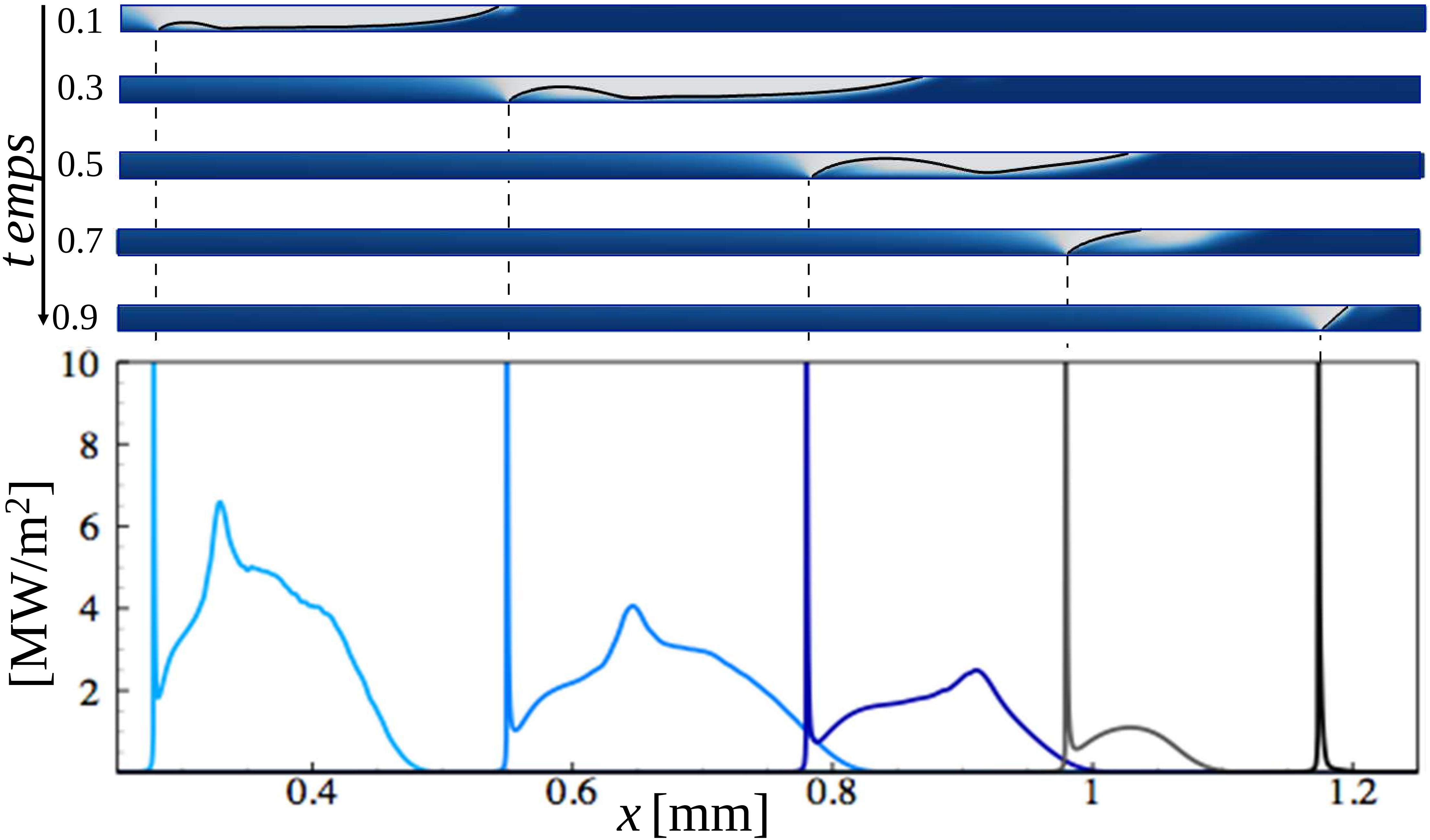
$$\frac{R_{dep}}{R_{Fritz}} = 1 + \alpha Ja^n$$

$\alpha = 0.00219$ and $n = 1.43$

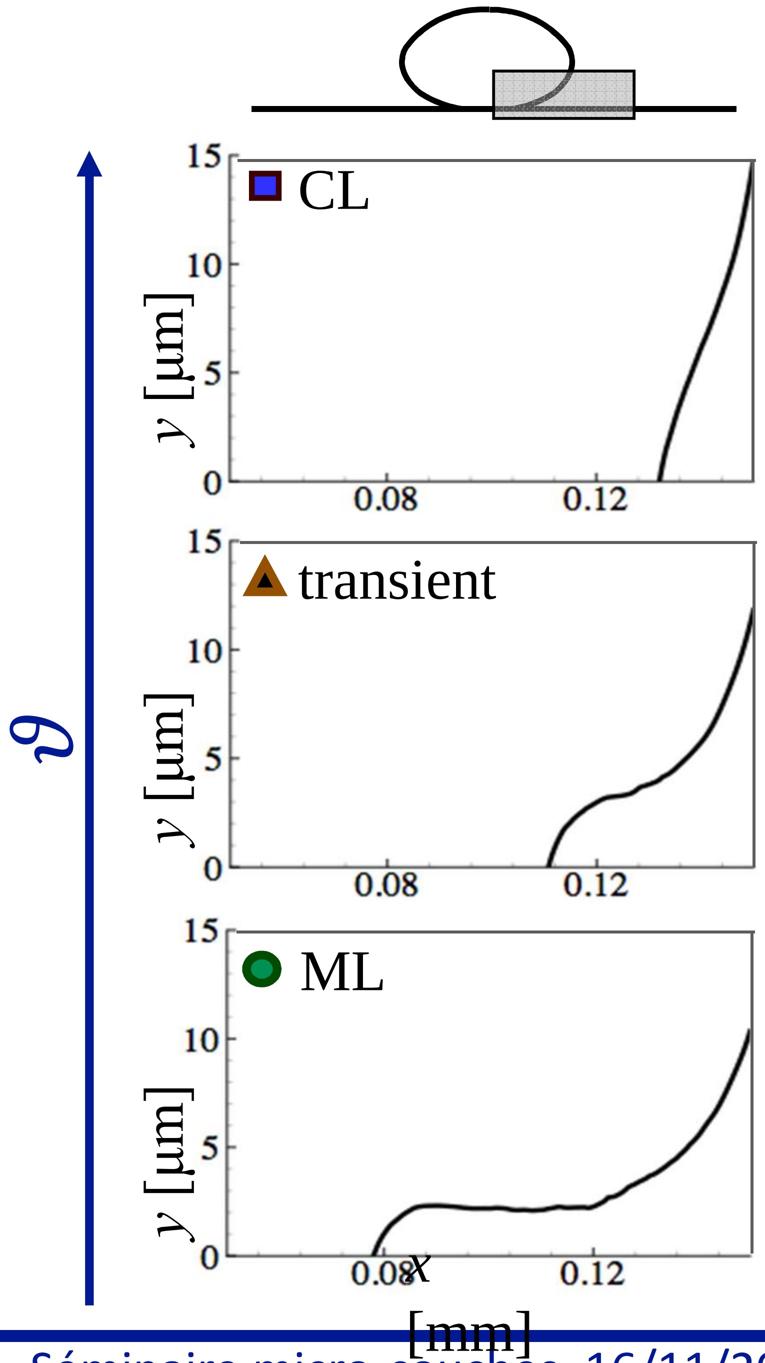
G. Huber, S. Tanguy, M. Sagan, C. Colin, Direct Numerical Simulation of Nucleate Pool Boiling at large microscopic contact angle and moderate Jakob number . IJHMT 2017

- Nucleate Boiling in the micro-layer regime some preliminary results

Microlayer formation has been observed by performing axisymetric numerical simulations with much more refined grids (4096x4096) for higher Jakob number

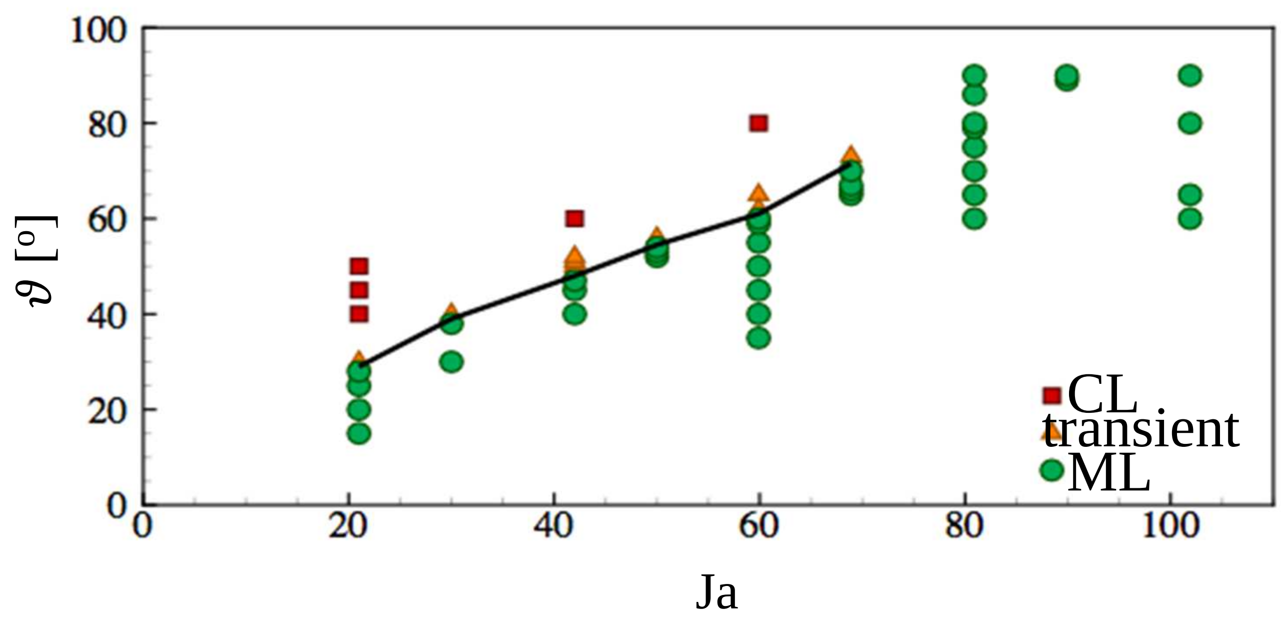


t emps
0.1
0.3
0.5
0.7
0.9
[MW/m^2]
10
8
6
4
2
0.4
0.6
0.8
1
1.2
x [mm]



Computational field
L= 2mm
Time computed: 0.04 ms

$20 < Ja < 100$
$15 < \vartheta < 90$



If Ja is increasing→ micro-layer appears for lower contact angle ϑ

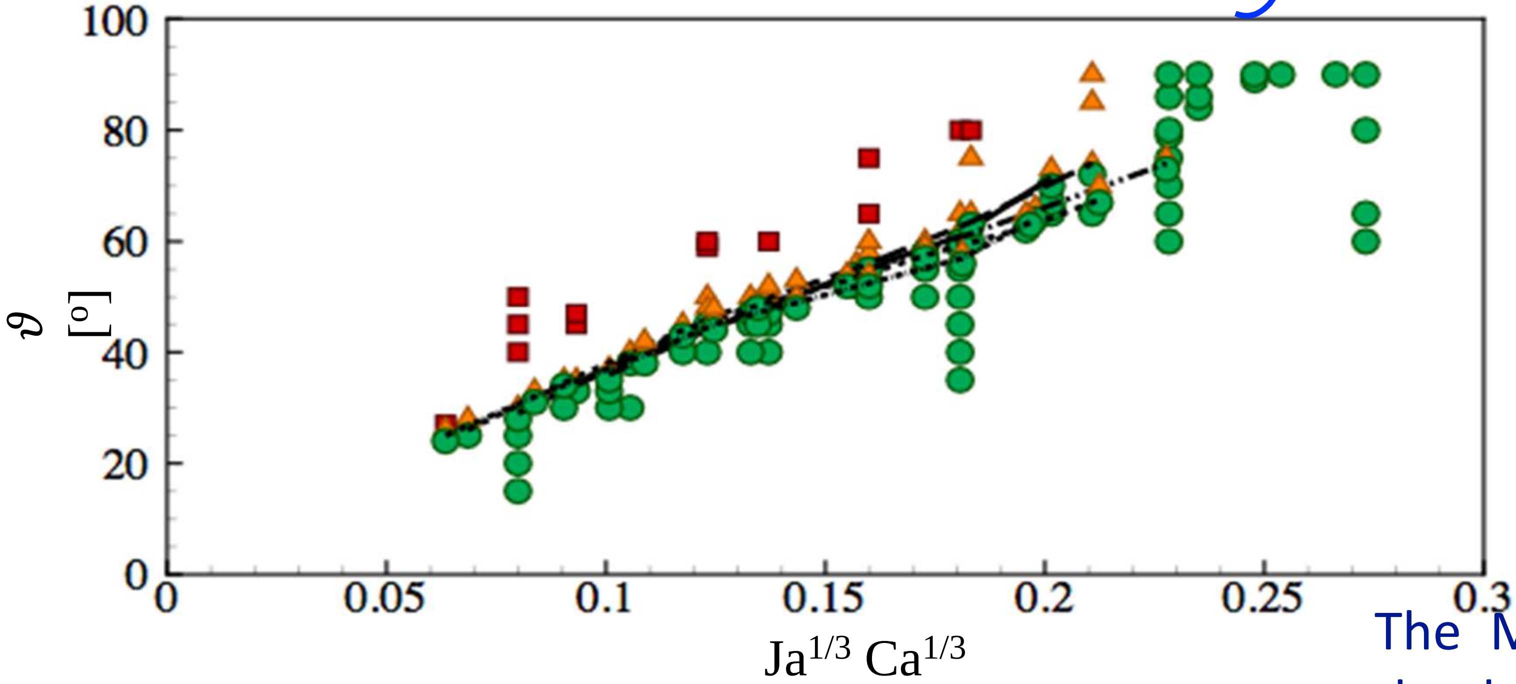
If Ja > 80 → we always observe a ML ($\vartheta \leq 90$ °)

$$\mathrm{Ca} = \frac{\mu_l\, v_{int}}{\sigma}$$

$$v_{int} \approx \frac{q_w}{L_{vap}\,\rho_v}$$

$$q_w = k_l \frac{(T_w - T_{sat})}{h_{KC}}$$

$$\mathrm{Ca} = \mathrm{Ja}\, \frac{\alpha_l}{h_{kc}} \frac{\mu_l}{\sigma}$$



$$\frac{\mathrm{Ja}\,\mathrm{Ca}}{(\theta - \theta_0)^3} > \frac{1}{A^3}$$

$A = 313$

$\vartheta_0 = 5\ °$

$$v_{int} > \frac{1}{A^{3/2}} \sqrt{\frac{\alpha_l}{h_{kc}} \frac{\mu_l}{\sigma} (\theta - \theta_0)^3}$$

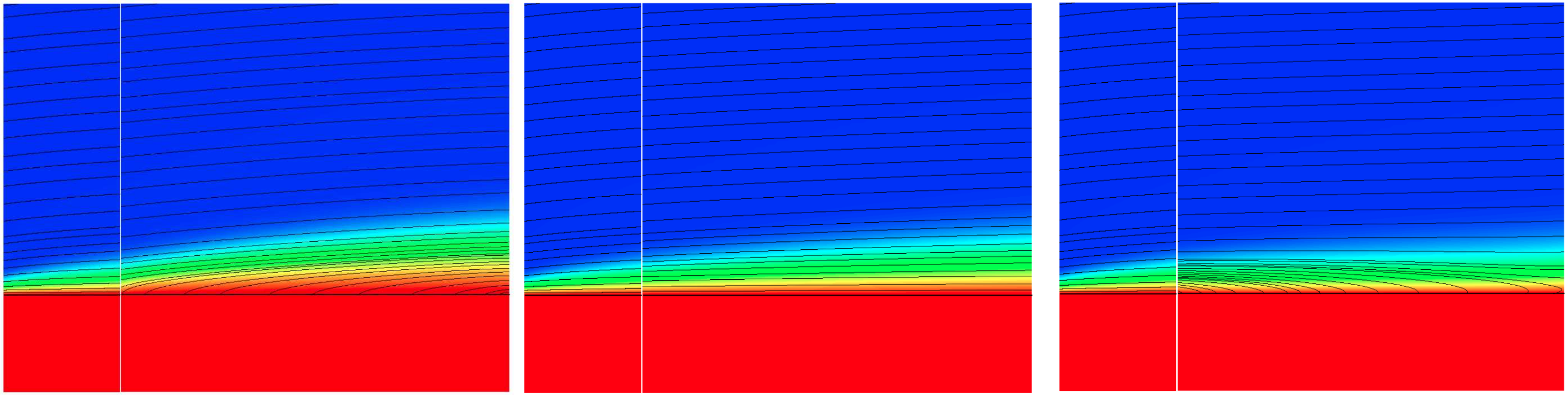
$$v_m^* = \frac{\alpha_l}{h_{kc}}$$

$$v_d^* = \frac{\mu_l}{\sigma} (\theta - \theta_0)^3$$

The Micro-Layer is formed if the bubble is growing faster than the maximum velocity of the contact line which depends on :

- Deweting velocity
- Phase change velocity

- Interaction of a superheated or subcooled laminar vapor flow with a static liquid surface (E-R Popescu PhD thesis)

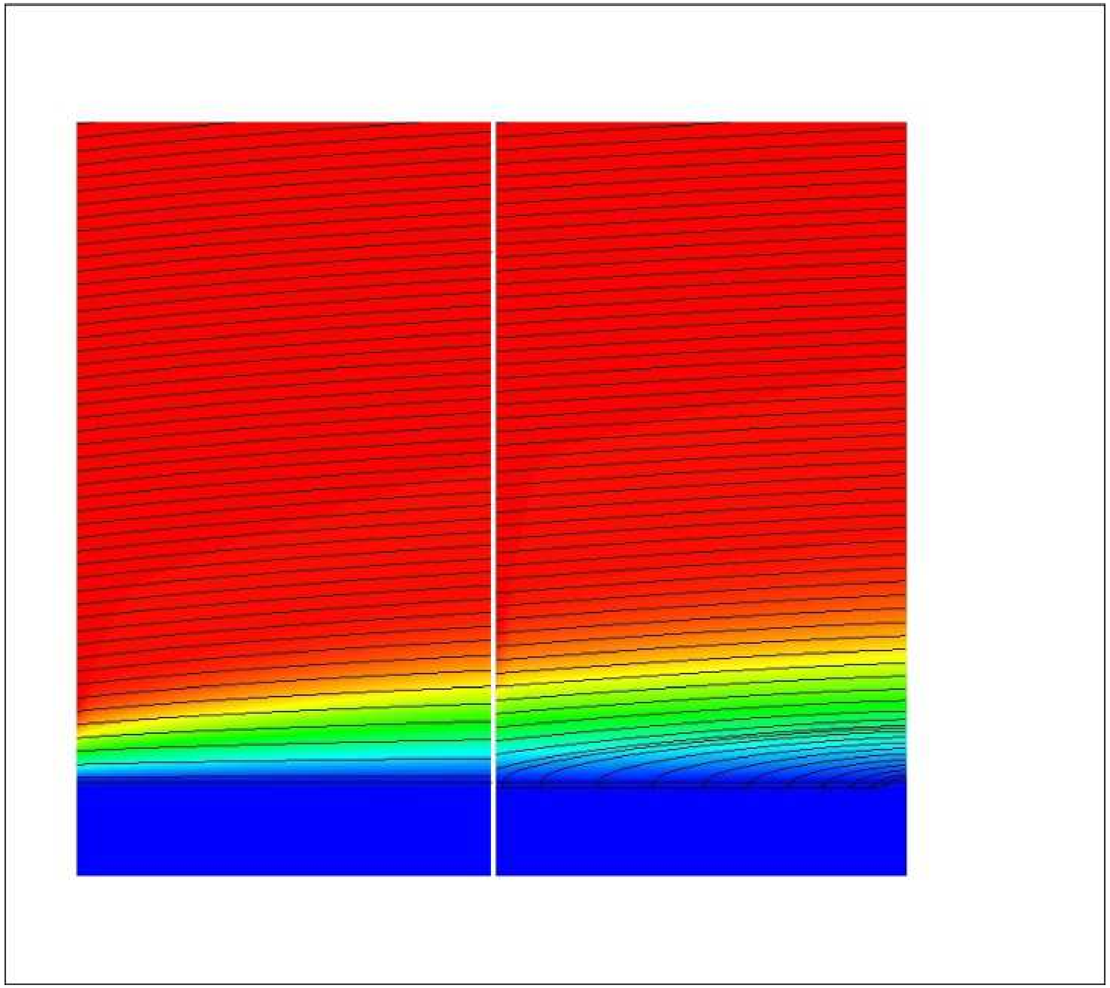


Vaporization: Superheated vapor flow

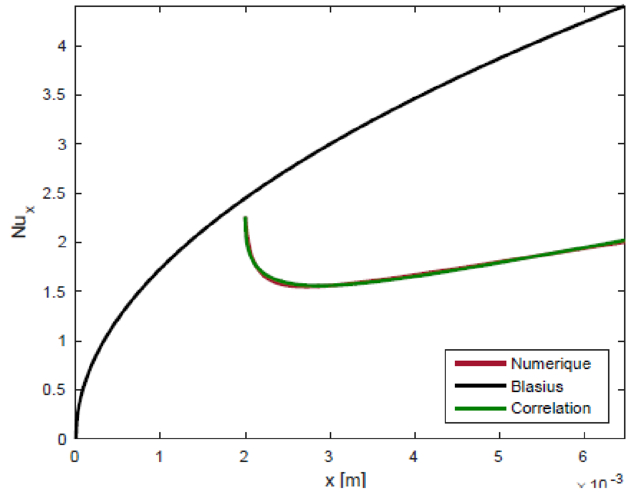
No phase change, classical developement of the boundary layer following Blasius and Polhausen theory

Condensation: Subcooled vapor flow

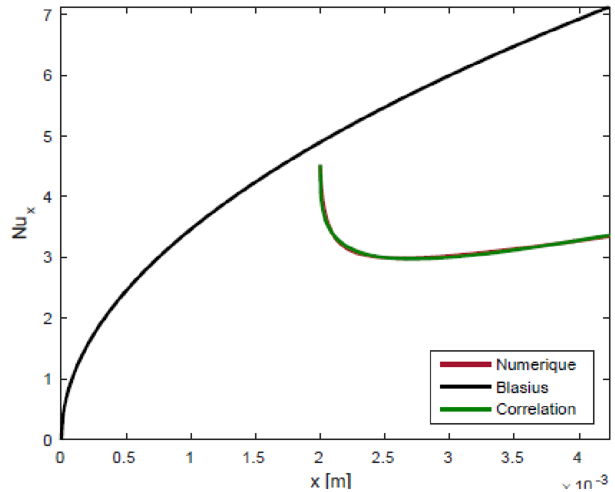
- Interaction of a superheated or subcooled laminar vapor flow with a static liquid surface (E-R Popescu PhD thesis)



2D Simulation on a 1024 x 1024 grid with a BlackBox MultiGrid solver for solving linear systems



$Re_{x_L} = 54$



$Re_{x_L} = 218$

- Interaction of a superheated or subcooled laminar vapor flow with a static liquid surface (E-R Popescu PhD thesis)

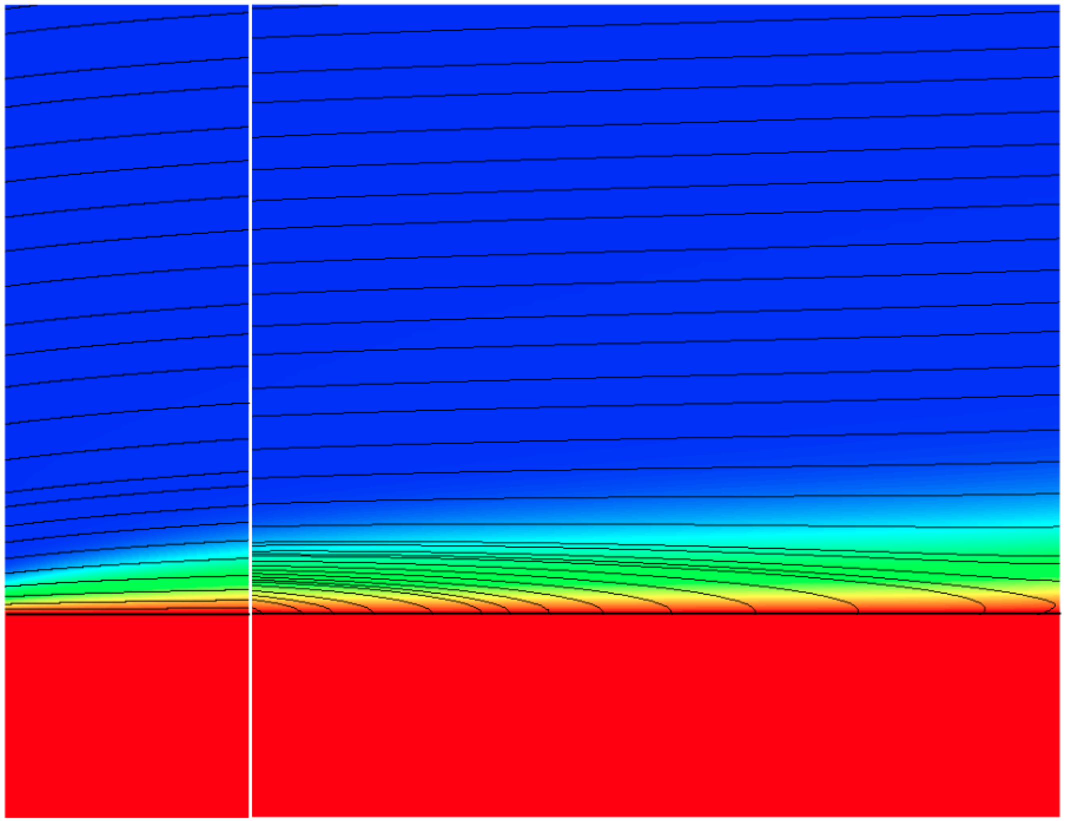
$$\boxed{Nu_x^{cp} = Nu_x^{Bl} - (\alpha(\frac{x}{x_L} - 1)^n + \beta)H(x - x_L)}$$

$$\beta = 0.0117 Re_{x_L}^{0.4874} Pr^{0.2368} (1 - e^{-1.392 Ja})(\frac{\rho_l}{\rho_g} - 1)^{0.7845} \quad (3)$$

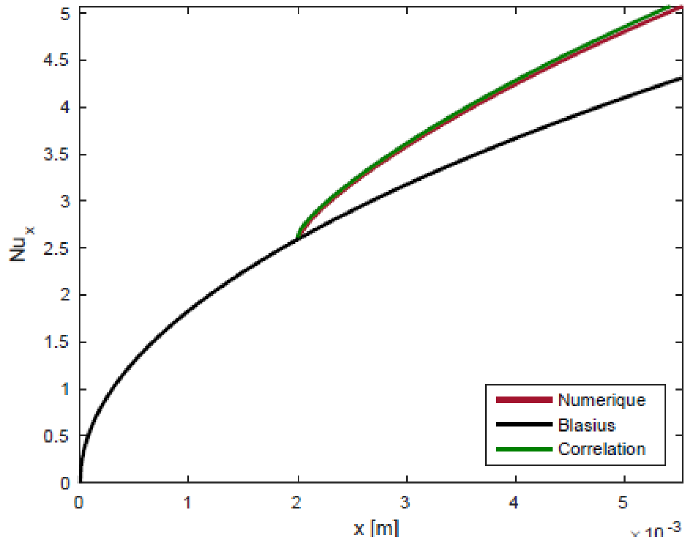
$$\alpha = 0.4033 Re_{x_L}^{0.5058} Pr^{0.3345} (1 - e^{-4.828 Ja^{0.8357}})(1 - e^{-0.1145(\frac{\rho_l}{\rho_g} - 1)^{0.78679}}) \quad (4)$$

$$n = 0.7769 Re_{x_L}^{-0.1215} Pr^{-0.07571} Ja^{-0.09389} \frac{\rho_l}{\rho_g}^{-0.1344} \quad (5)$$

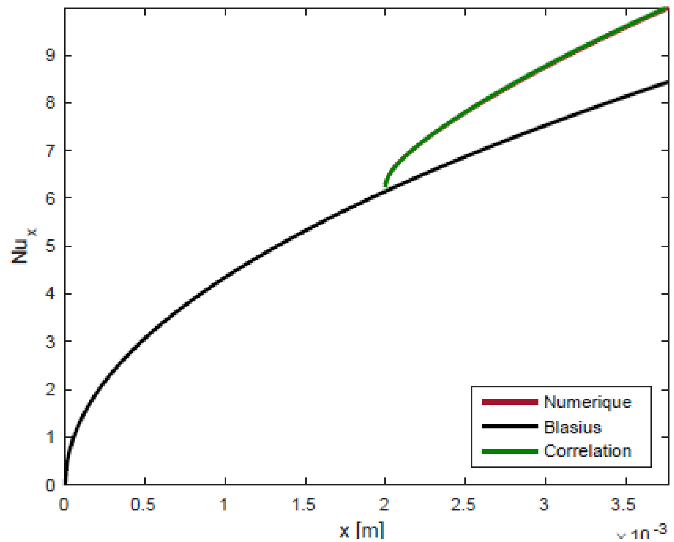
30. Work in Progress: Interaction of a superheated or subcooled laminar vapor flow with a static liquid surface (E-R Popescu PhD thesis)



2D Simulation on a 1024 x 1024 grid with a BlackBox MultiGrid solver for solving linear systems

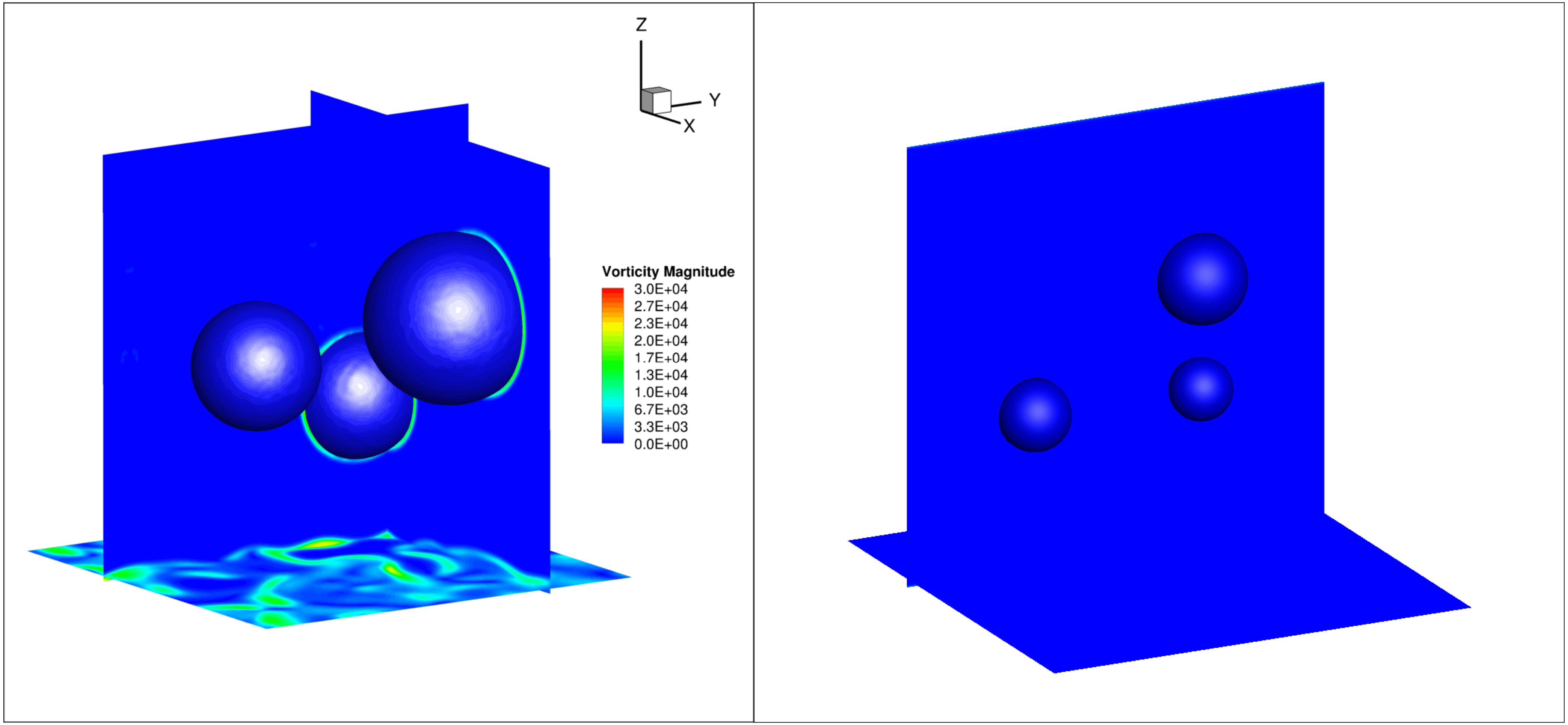


$Pr = 0.6$



$Pr = 8$

- Evaporation of droplets in a turbulent flow (R Alis PhD Thesis)



Parallel simulation on a 512 x 512 x 512 grid with a Black Box MultiGrid solver for solving linear systems

Final remarks

Conclusions

- Numerical simulation of Nucleate Boiling in the Contact Line regime
- Numerical simulation of Nucleate Boiling in the Micro-Layer regime
- Interaction between an external laminar superheated or subcooled vapor flow and a static liquid surface

Perspectives

- Evaporation of a sessile droplet with a contact line (Marangoni Convection)
- Multi-bubbles nucleate boiling
- Evaporation of droplets in a turbulent flow
- Interaction of a turbulent superheated vapor with a liquid pool

- 33. Thanks to funding Partners

- ANR for the financial support of L. Rueda Villegas PhD thesis on « the Direct Numerical Simulation of Leidenfrost effect » in the framework of the IDHEAS Project

- CNES for supporting the Phd Thesis of Michaël Sagan and the postdoc of Grégory Huber on « the Direct Numerical Simulation of Nucleate Boiling »

A1. Mathieu's micro region model for partially wetting fluid

Set of 5 coupled equations

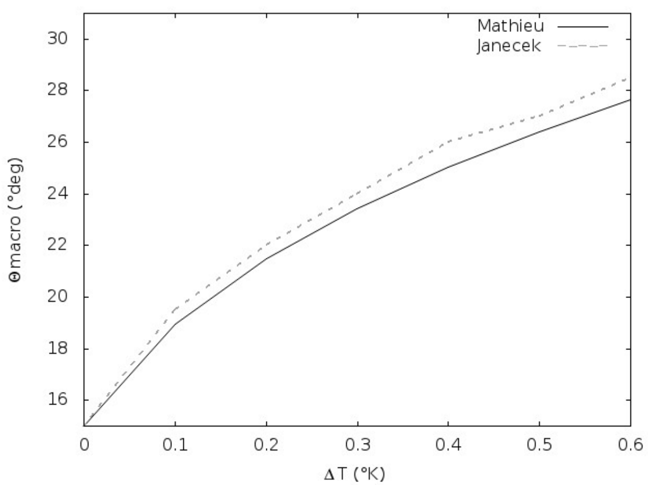
$$\frac{\partial x}{\partial s} = cos\theta \, ,$$

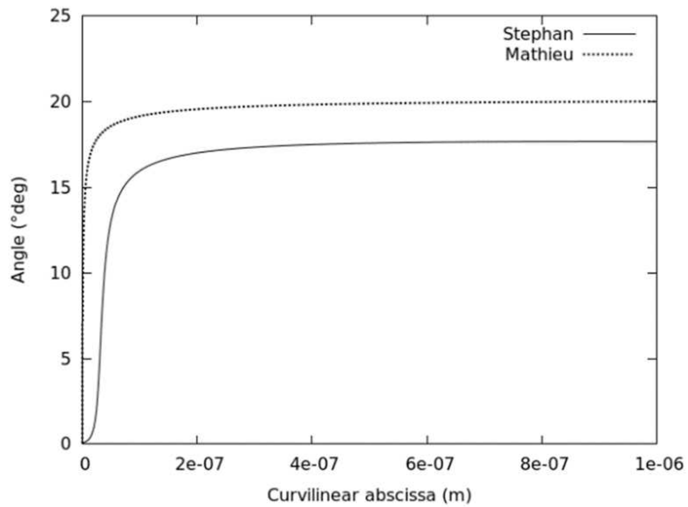
$$\frac{\partial y}{\partial s} = sin\theta \, ,$$

$$\frac{\partial \theta}{\partial s} = \frac{\Delta p}{\sigma} \, ,$$

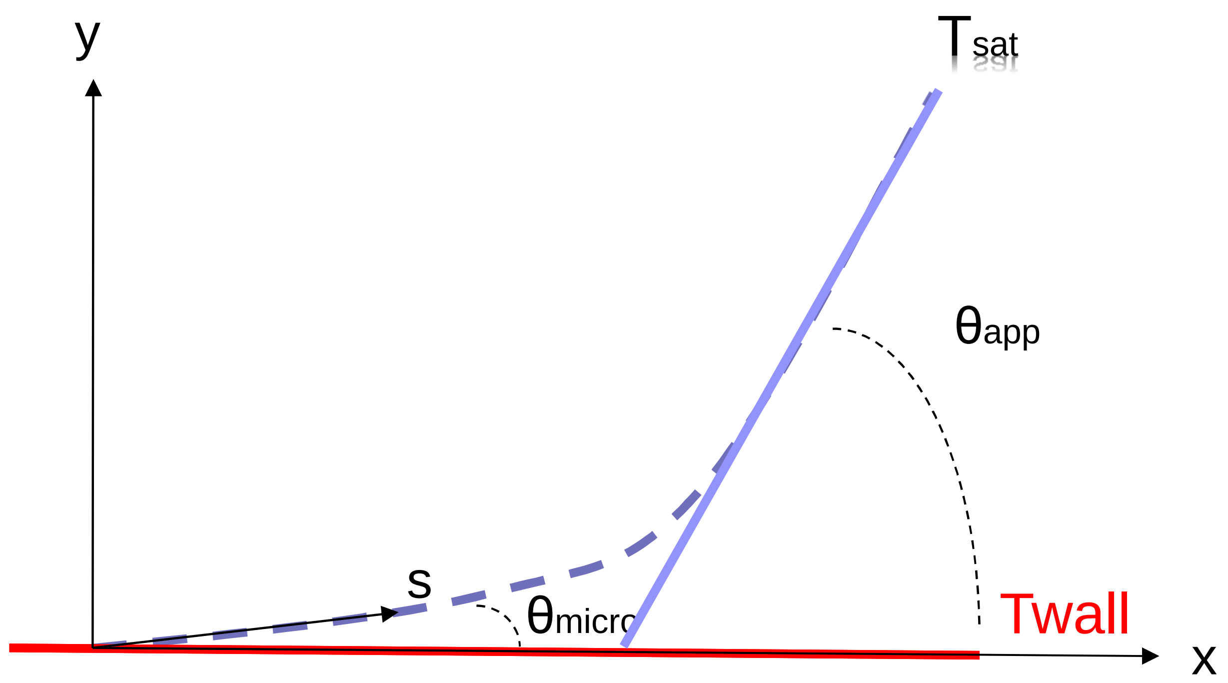
$$\frac{\partial (\Delta p)}{\partial s} = -\mu_l \frac{3Q}{\rho_l L_{vap} \theta^3} \, ,$$

$$\frac{\partial Q}{\partial s} = k_l \frac{\Delta T}{r\theta + kR_i} \, , \qquad r = \frac{y + l_s}{sin\theta} \qquad R_i = \frac{T_{sat}\sqrt{2\pi R_g T_{sat}}}{2\rho_v L_{vap}^2} \qquad T_{sat} = T_{sat,0}\left(1 + \frac{\Delta p}{\rho_l L_{vap}}\right)$$

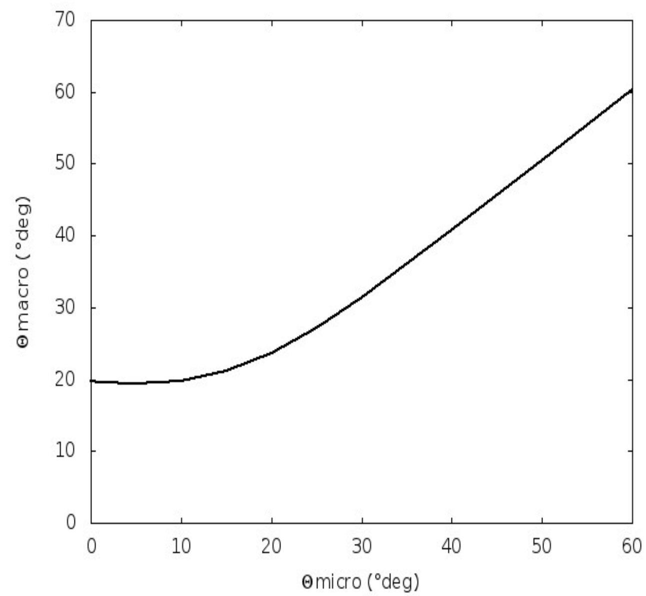


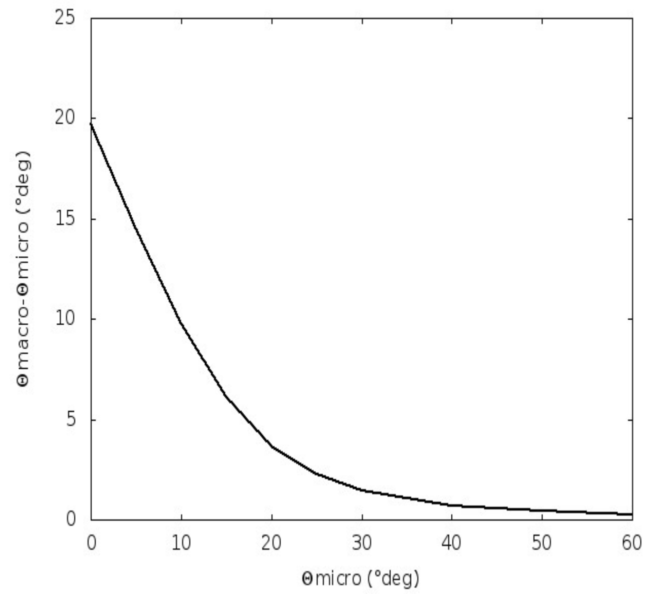


- A2. Nucleate Boiling in the contact line regime: Micro region model or not micro region model ?



$$\Delta T = 7K, \theta_{app} = 50° \Leftrightarrow \theta_{mic} = 49{,}66°$$





- A3. Nucleate Boiling : Micro region or not micro region ?