

INVESTIGATION AND MODELING OF SHEAR FLOW BOILING IN MICROGRAVITY: THE RUBI EXPERIMENT

Luc Favre, Basile Gigon, Julien Sebilliau, Catherine Colin, Sébastien Tanguy



April 8th 2026, Journées du GDR TransInter, Aussois, France

OUTLINE

1. Introduction & Context
2. The RUBI experiment
3. Bubble departure diameter
4. Bubble dynamics
5. Bubble growth
6. Conclusion

INTRODUCTION & CONTEXT

WHY DO WE STUDY BOILING ?

WHY DO WE STUDY BOILING ?



Pasta cooking optimization -
©Kitchenaid

WHY DO WE STUDY BOILING ?



Pasta cooking optimization -
©Kitchenaid

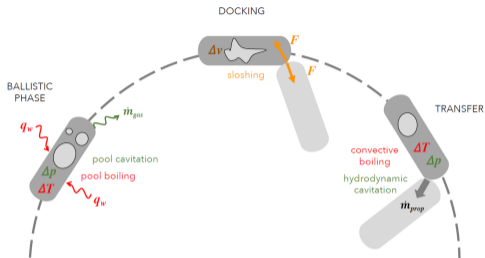


Boiling crisis on heated rods - ©CEA

WHY DO WE STUDY BOILING ?



Pasta cooking optimization -
©Kitchenaid



Fuel boil-off in space [Simonini *et al.*, 2024]



Orbital depot concept - ©ETA
Space

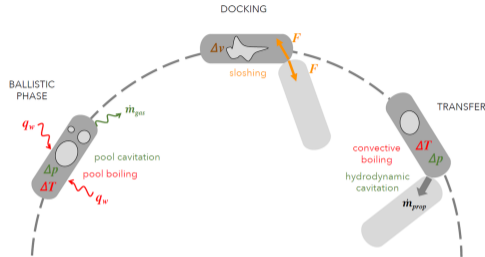


Boiling crisis on heated rods - ©CEA

WHY DO WE STUDY BOILING ?



Pasta cooking optimization -
©Kitchenaid



Fuel boil-off in space [Simonini *et al.*, 2024]



Orbital depot concept - ©ETA
Space

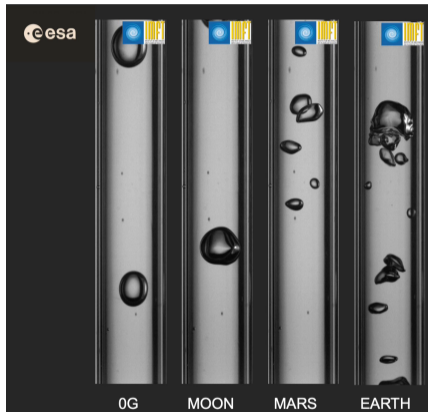


Boiling crisis on heated rods - ©CEA

Fields of application

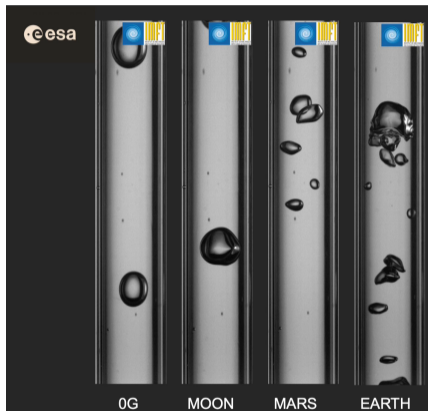
- **Nuclear industry:** boiling crisis (fuel rods), fluid induced vibrations (vapor generator tubes)
- **Space:** Fuel tank management (long missions), electronics cooling (satellites)
- **Evaporators:** heat pumps, air conditioning, etc.

BOILING IN MICROGRAVITY

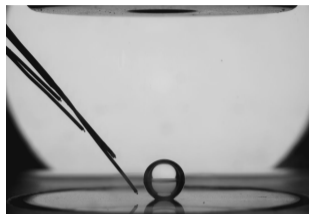


Gas-liquid flow under variable gravity

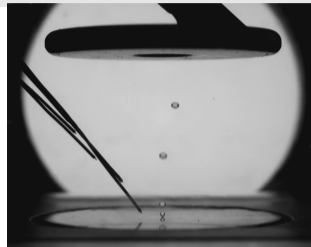
BOILING IN MICROGRAVITY



Gas-liquid flow under variable gravity



Zero-gravity boiling (ISS)



Earth gravity boiling

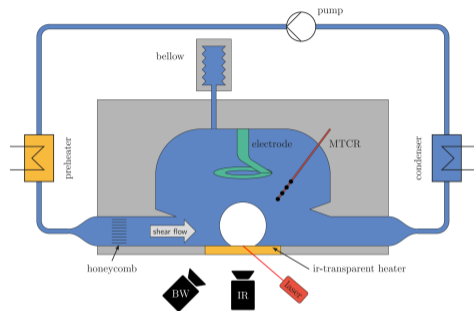
Multi-scale phenomenon

- Fuel tank size with multiple bubbles $\sim m$
- Bubble size $\sim mm$
- Contact line region $\sim \mu m$ to nm

⇒ **Microgravity = larger time-space resolution for measurements + clean spherical shape**

THE RUBI EXPERIMENT

THE REFERENCE MULTISCALE BOILING INVESTIGATION (RUBI)

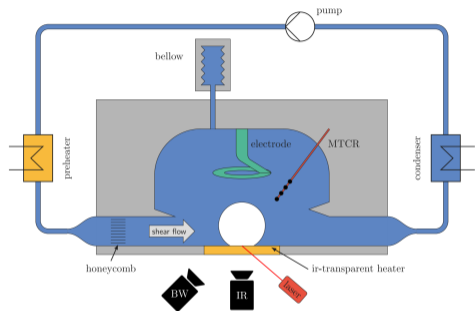


Sketch of the RUBI experiment

RUBI experiment details

- International collaboration (TUD, ULB, UniPi, etc.)
- Operated in ISS from 2019 to 2021: 3440 × 3 exp.
- Explored various P , T_{liq} , q_w , t_{wait} , Q_{liq} , etc.

THE REFERENCE MULTISCALE BOILING INVESTIGATION (RUBI)



RUBI experiment details

- International collaboration (TUD, ULB, UniPi, etc.)
- Operated in ISS from 2019 to 2021: 3440 × 3 exp.
- Explored various P , T_{liq} , q_w , t_{wait} , Q_{liq} , etc.

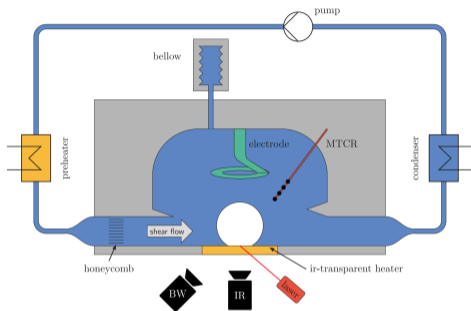


Launch to ISS (SpaceX)



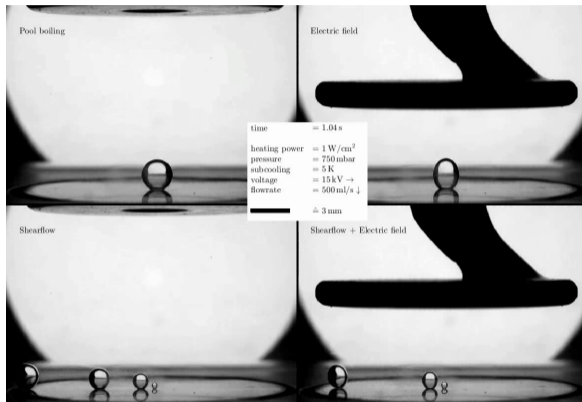
Installation in the Fluid Science Laboratory

THE REFERENCE MULTISCALE BOILING INVESTIGATION (RUBI)



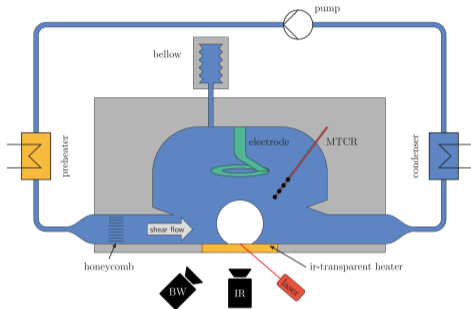
RUBI experiment details

- International collaboration (TUD, ULB, UniPi, etc.)
- Operated in ISS from 2019 to 2021: 3440 × 3 exp.
- Explored various P , T_{liq} , q_w , t_{wait} , Q_{liq} , etc.



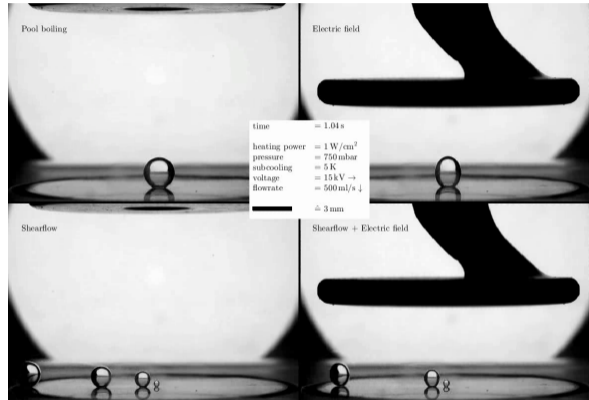
Typical visualizations in RUBI

THE REFERENCE MULTISCALE BOILING INVESTIGATION (RUBI)



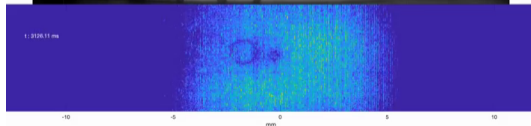
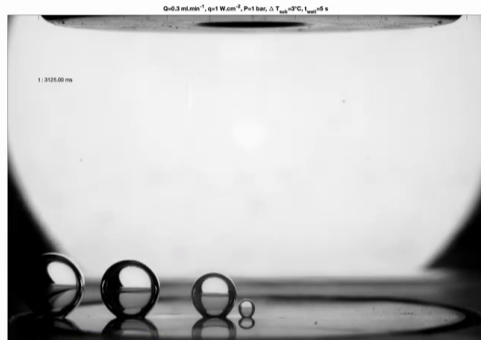
RUBI experiment details

- International collaboration (TUD, ULB, UniPi, etc.)
- Operated in ISS from 2019 to 2021: 3440×3 exp.
- Explored various P , T_{liq} , q_w , t_{wait} , Q_{liq} , etc.



Unique and valuable data for fundamental investigation of wall boiling physics, modeling and simulation

EXAMPLE: TYPICAL EXPERIMENT OF SHEAR FLOW BOILING



$$q_w = 1.5 \text{ W/cm}^2, T_l = T_{sat} - 5 \text{ K}, P = 500 \text{ mbar}, t_{wait} = 1 \text{ s},$$
$$Q_{liq} = 500 \text{ mL/min}$$

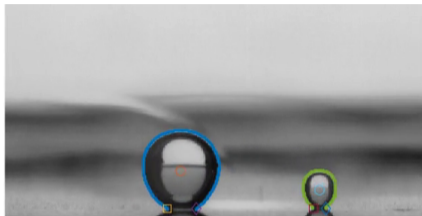
Bubble behavior

- 1) Static growth on nucleation site
- 2) Sliding phase, departure from nucleation site
- 3) Coalescence and jump, lifts off the wall

⇐ HSV camera: black and white (BW) images (bubble contours)

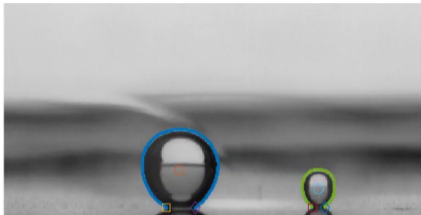
⇐ Infrared camera: thermography (IR) for wall temperature and heat flux

SHEAR FLOW CASES BW IMAGE PROCESSING

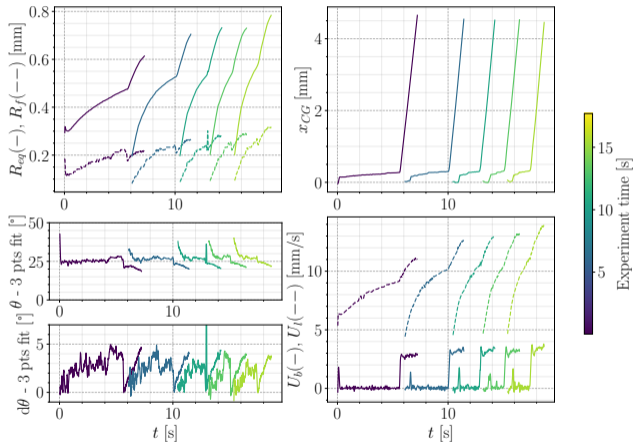


Bubble tracking algorithm

SHEAR FLOW CASES BW IMAGE PROCESSING

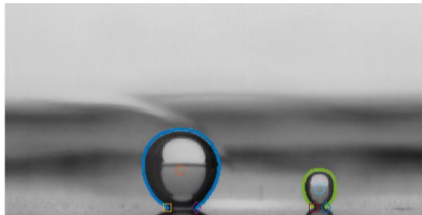


Bubble tracking algorithm

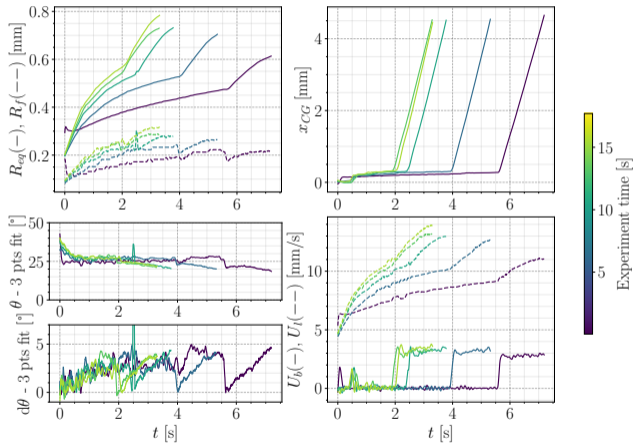


$$T_{liq} = T_{sat} - 10K, \quad q_w = 1W/cm^2, \quad t_{wait} = 10s, \quad P = 1.0bar, \\ Q_{liq} = 300mL/min$$

SHEAR FLOW CASES BW IMAGE PROCESSING

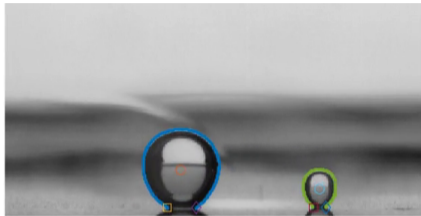


Bubble tracking algorithm

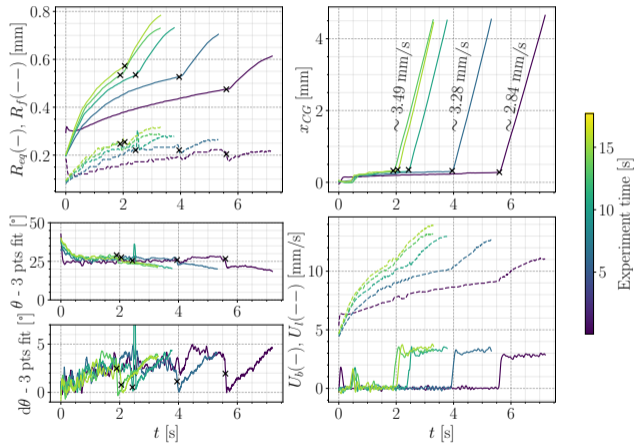


$$T_{liq} = T_{sat} - 10K, \quad q_w = 1W/cm^2, \quad t_{wait} = 10s, \quad P = 1.0bar, \\ Q_{liq} = 300mL/min$$

SHEAR FLOW CASES BW IMAGE PROCESSING

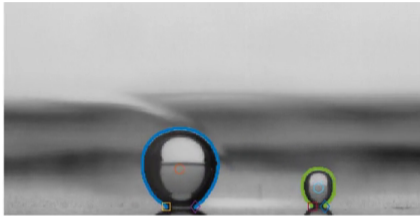


Bubble tracking algorithm



$$T_{liq} = T_{sat} - 10K, \quad q_w = 1W/cm^2, \quad t_{wait} = 10s, \quad P = 1.0bar, \\ Q_{liq} = 300mL/min$$

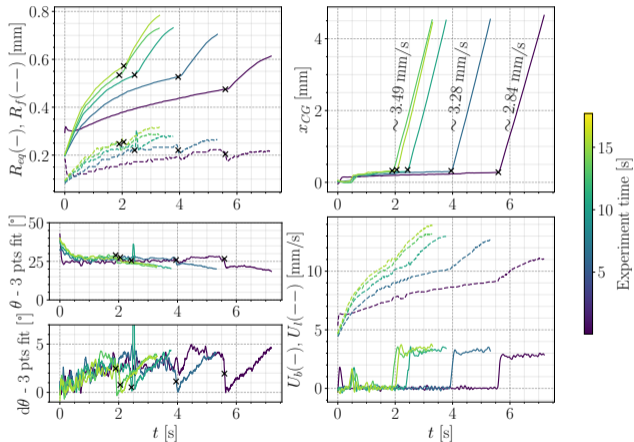
SHEAR FLOW CASES BW IMAGE PROCESSING



Bubble tracking algorithm

Post-processing results & observations

- Retrieving of V_b , R_{eq} , x_{GC} , y_{GC} , R_f , θ_a , θ_r , etc. for 157 runs with IR available
- Constant sliding velocity, slower than liquid
- Bubble growth \nearrow with experiment time: constant heating \nearrow thermal boundary layer
- Sliding: faster bubble growth \rightarrow why?
- Departure diameter: behavior with flow conditions?



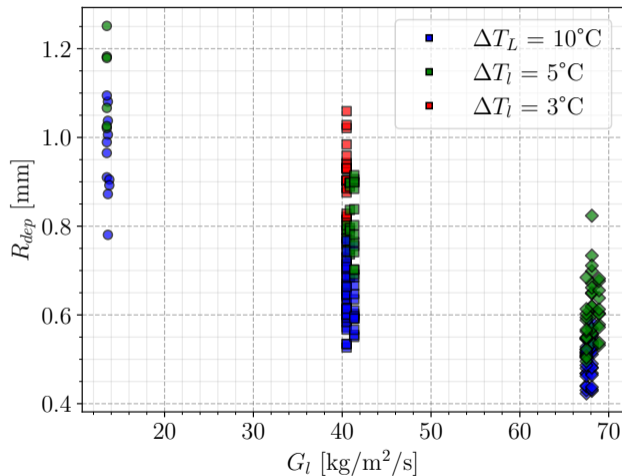
$$T_{liq} = T_{sat} - 10K, \quad q_w = 1W/cm^2, \quad t_{wait} = 10s, \quad P = 1.0bar, \\ Q_{liq} = 300mL/min$$

BUBBLE DEPARTURE DIAMETER

DEPARTURE DIAMETER: INFLUENCE OF OPERATING CONDITIONS

Finding main dimensionless parameters?

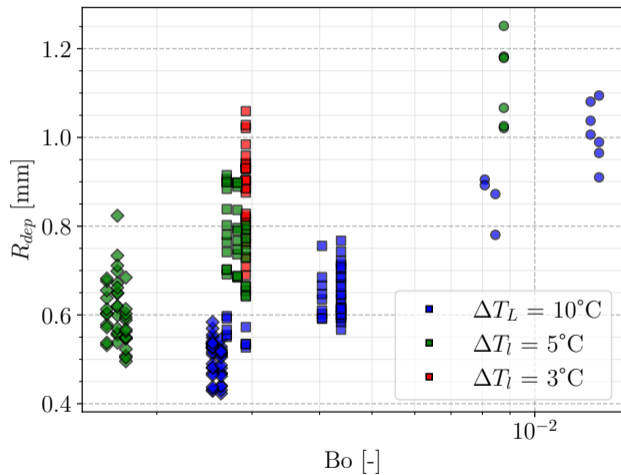
- Most influent: liquid mass flow G_l , but large scattering



DEPARTURE DIAMETER: INFLUENCE OF OPERATING CONDITIONS

Finding main dimensionless parameters?

- Most influent: liquid mass flow G_l , but large scattering
- Include heat flux: $Bo = \frac{q_w}{G_l h_{lv}}$



DEPARTURE DIAMETER: INFLUENCE OF OPERATING CONDITIONS

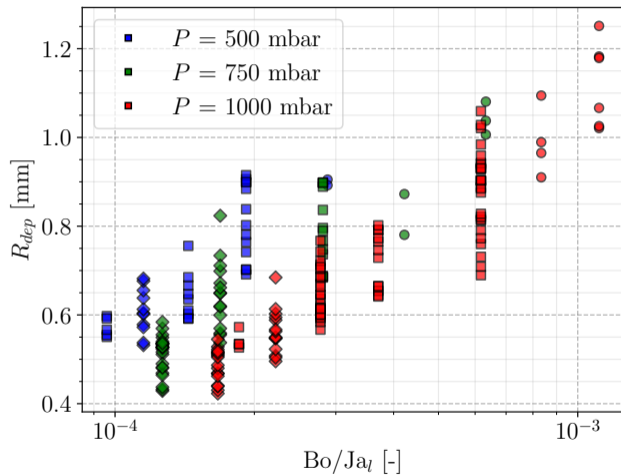
Finding main dimensionless parameters?

- Most influent: liquid mass flow G_l , but large scattering

- Include heat flux: $Bo = \frac{q_w}{G_l h_{lv}}$

- Add subcooling effect: $Ja_l = \frac{\rho_l c_{p,l} \Delta T_l}{\rho_v h_{lv}}$

$$\Rightarrow Bo/Ja_l = \frac{\rho_v}{\rho_l} \frac{q_w}{G_l c_{p,l} \Delta T_l}$$



DEPARTURE DIAMETER: INFLUENCE OF OPERATING CONDITIONS

Finding main dimensionless parameters?

- Most influent: liquid mass flow G_l , but large scattering

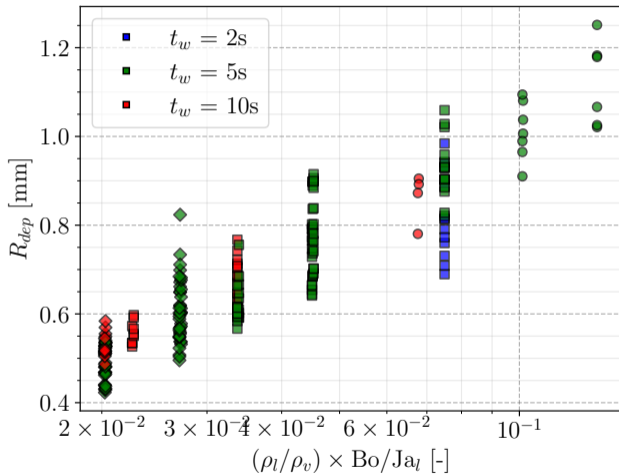
- Include heat flux: $Bo = \frac{q_w}{G_l h_{lv}}$

- Add subcooling effect: $Ja_l = \frac{\rho_l c_{p,l} \Delta T_l}{\rho_v h_{lv}}$

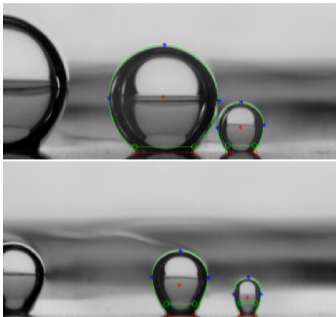
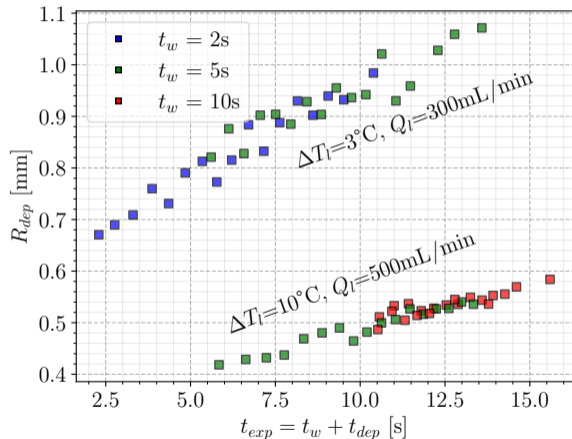
$$\Rightarrow Bo/Ja_l = \frac{\rho_v}{\rho_l} \frac{q_w}{G_l c_{p,l} \Delta T_l}$$

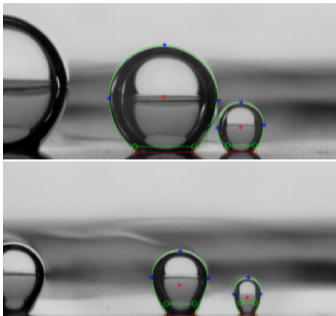
$$\Rightarrow \text{Regroup pressures: } \frac{\rho_l}{\rho_v} \frac{Bo}{Ja_l}$$

⇒ Effect of t_w ? Requires δ_{TBL} estimation

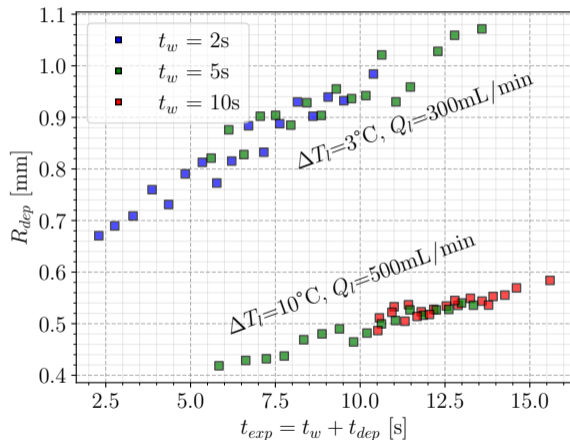


○: $Q_l=100$ mL/min - □: $Q_l=300$ mL/min - ◇: $Q_l=500$ mL/min

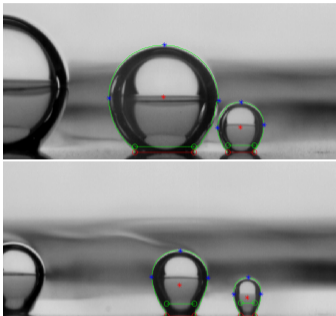
EFFECT OF WAIT TIME ON R_{dep} Top: $\Delta T_l = 3^\circ\text{C}$ case - Bottom: $\Delta T_l = 10^\circ\text{C}$ case R_{dep} as function of total exp. time $t_w + t_{dep}$

EFFECT OF WAIT TIME ON R_{dep} Top: $\Delta T_l = 3^\circ\text{C}$ case - Bottom: $\Delta T_l = 10^\circ\text{C}$ caseGathering close cases with various t_w

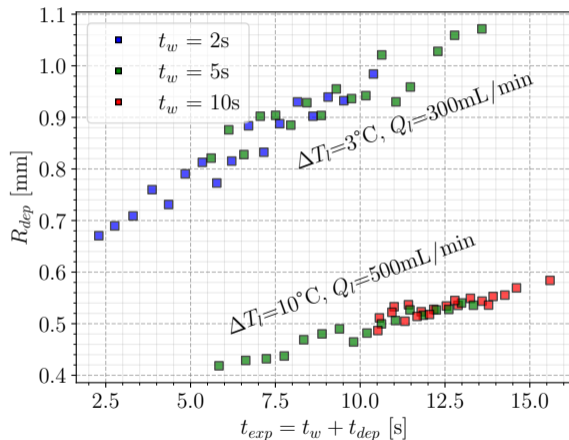
- Same R_{dep} for same t_{exp} , but $\neq t_w$
→ Total time t_{exp} more important than t_w alone

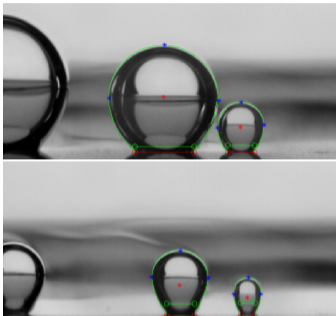


R_{dep} as function of total exp. time $t_w + t_{dep}$

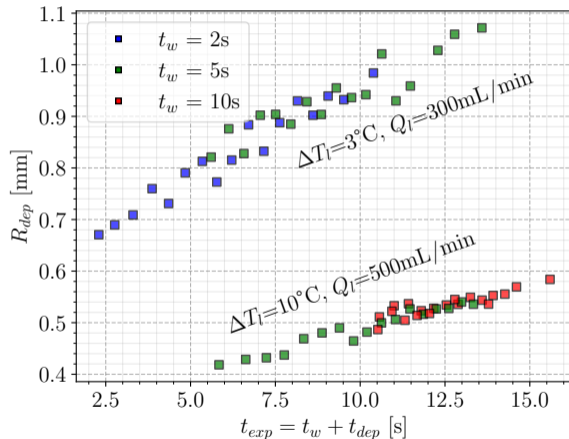
EFFECT OF WAIT TIME ON R_{dep} Top: $\Delta T_l = 3^\circ\text{C}$ case - Bottom: $\Delta T_l = 10^\circ\text{C}$ caseGathering close cases with various t_w

- Same R_{dep} for same t_{exp} , but $\neq t_w$
→ Total time t_{exp} more important than t_w alone
- ⇒ TBL $\delta_{TBL}(t_{exp}) \sim$ same with previous bubbles ?

 R_{dep} as function of total exp. time $t_w + t_{dep}$

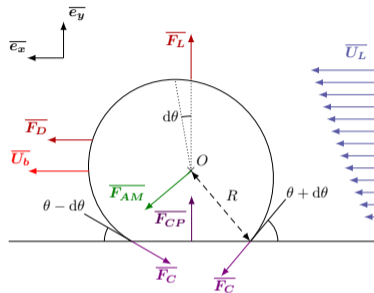
EFFECT OF WAIT TIME ON R_{dep} Top: $\Delta T_l = 3^\circ\text{C}$ case - Bottom: $\Delta T_l = 10^\circ\text{C}$ caseGathering close cases with various t_w

- Same R_{dep} for same t_{exp} , but $\neq t_w$
→ Total time t_{exp} more important than t_w alone
- ⇒ TBL $\delta_{TBL}(t_{exp}) \sim$ same with previous bubbles?
- ⇒ Proper model of bubble growth + single phase simulations for δ_{TBL} estimation

 R_{dep} as function of total exp. time $t_w + t_{dep}$

BUBBLE DYNAMICS

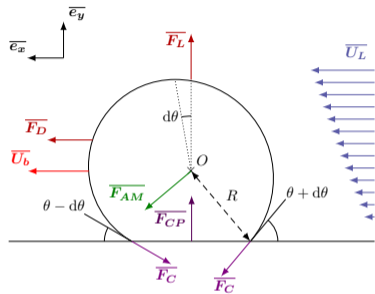
STUDY OF BUBBLE DYNAMICS: FORCE BALANCE APPROACH



Application to BW image data

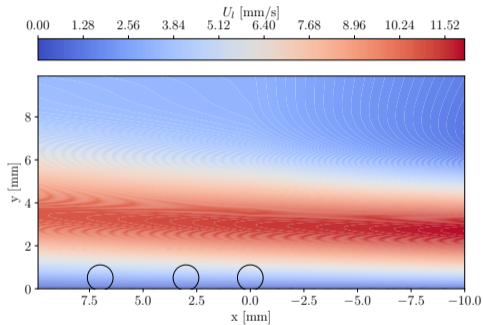
- Forces : capillary, drag, lift, contact pressure, added mass
- Drag: [Shi *et al.*, 2021], AM: [Favre *et al.*, 2023]

STUDY OF BUBBLE DYNAMICS: FORCE BALANCE APPROACH

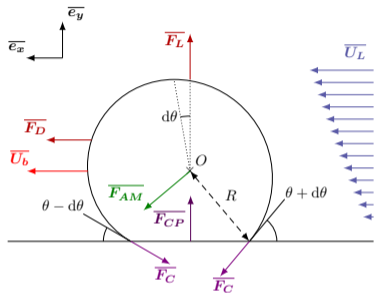


Application to BW image data

- Forces : capillary, drag, lift, contact pressure, added mass
- Drag: [Shi *et al.*, 2021], AM: [Favre *et al.*, 2023]

Liquid axial velocity field, $Q_l = 100$ mL/min

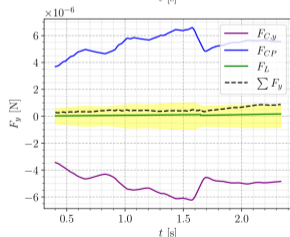
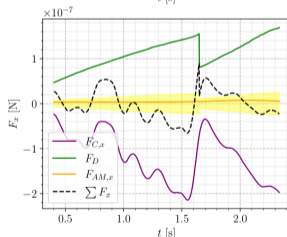
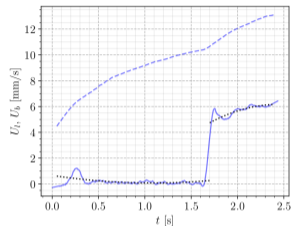
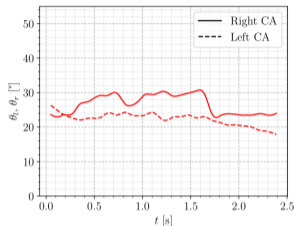
STUDY OF BUBBLE DYNAMICS: FORCE BALANCE APPROACH



Application to BW image data

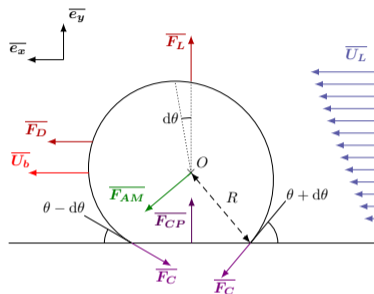
- Forces : capillary, drag, lift, contact pressure, added mass
- Drag: [Shi *et al.*, 2021], AM: [Favre *et al.*, 2023]

⇒ Verify force balance // and \perp to the wall \approx OK



$$P = 0.5\text{bar}, q_w = 1\text{W/cm}^2, T_{liq} = T_{sat} - 10\text{K}, Q_{liq} = 300\text{mL/min}, t_{wait} = 10\text{s}$$

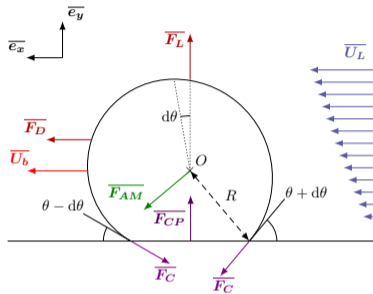
BUBBLE DRAG COEFFICIENT CALCULATION



Calculation process

- Very sensitive to θ , $d\theta$ value
- End of bubble sliding: largest $d\theta$
- $$C_D = \frac{8\dot{R}}{|U_{rel}|} \left(\frac{\rho_v}{\rho_l} \frac{U_b}{U_{rel}} - C_{AM,x} \right) + \frac{2\sigma f_{C,x}(\theta, d\theta)}{\rho_l R |U_{rel}| U_{rel}}$$

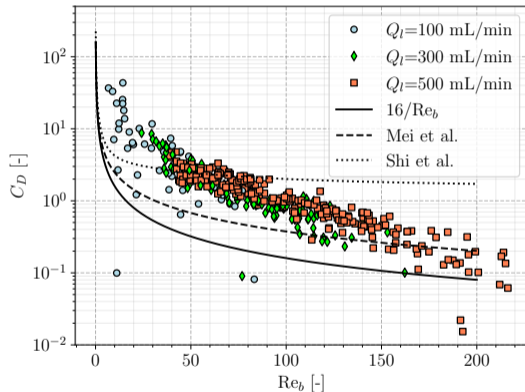
BUBBLE DRAG COEFFICIENT CALCULATION



Calculation process

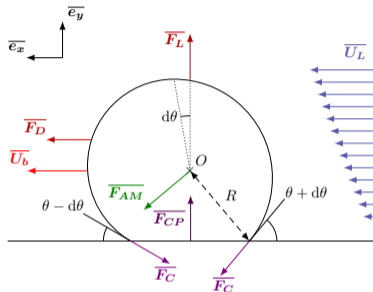
- Very sensitive to θ , $d\theta$ value
- End of bubble sliding: largest $d\theta$

$$C_D = \frac{8\dot{R}}{|U_{rel}|} \left(\frac{\rho_v}{\rho_l} \frac{U_b}{U_{rel}} - C_{AM,x} \right) + \frac{2\sigma f_{C,x}(\theta, d\theta)}{\rho_l R |U_{rel}| U_{rel}}$$



Estimated C_D values, compared with [Mei, 1992] and [Shi, 2020]

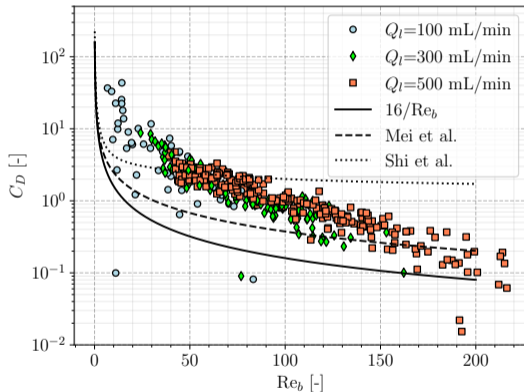
BUBBLE DRAG COEFFICIENT CALCULATION



Calculation process

- Very sensitive to θ , $d\theta$ value
- End of bubble sliding: largest $d\theta$

$$C_D = \frac{8\dot{R}}{|U_{rel}|} \left(\frac{\rho_v}{\rho_l} \frac{U_b}{U_{rel}} - C_{AM,x} \right) + \frac{2\sigma f_{C,x}(\theta, d\theta)}{\rho_l R |U_{rel}| U_{rel}}$$

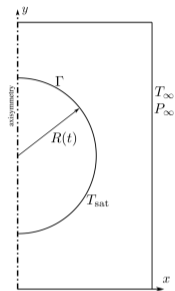


Estimated C_D values, compared with [Mei, 1992] and [Shi, 2020]

Important effect of shear ($Sr = \gamma D_b / U_{rel} \in [1, 4]$) + wall + truncated sphere + $d\theta$ uncertainty

BUBBLE GROWTH

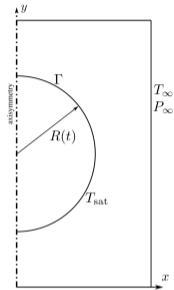
STUDY OF BUBBLE GROWTH BEHAVIOR



Theoretical case of [Scriven, 1959]

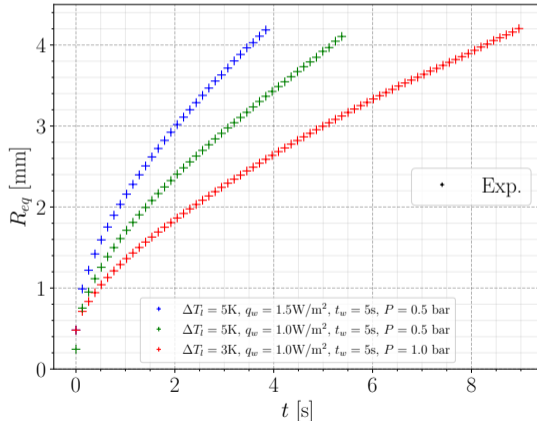
- Pure heat-diffusion
- $T_{\infty} > T_{sat}$, uniform at $t = 0$
- $R(t) = \underbrace{f(\text{Ja})}_{k_{gr}} \text{Ja} (\alpha_l t)^{0.5}$
- $\text{Ja} = \frac{\rho_l c_p l (T_w - T_{sat})}{\rho_v h_{lv}}$
- Generic law: $R = k \times t^n$

STUDY OF BUBBLE GROWTH BEHAVIOR



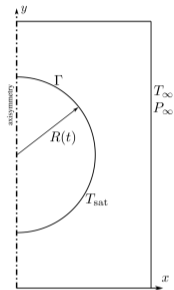
Theoretical case of [Scriven, 1959]

- Pure heat-diffusion
- $T_\infty > T_{sat}$, uniform at $t = 0$
- $R(t) = \underbrace{f(\text{Ja})}_{k_{gr}} \text{Ja} (\alpha_l t)^{0.5}$
- $\text{Ja} = \frac{\rho_l c_p l (T_w - T_{sat})}{\rho_v h_{lv}}$
- Generic law: $R = k \times t^n$



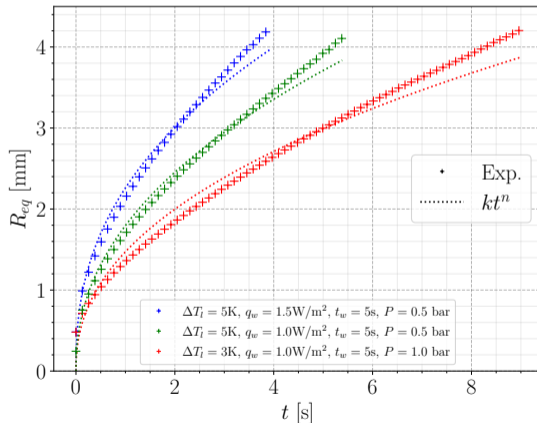
Bubble growth fitting : pool boiling cases

STUDY OF BUBBLE GROWTH BEHAVIOR



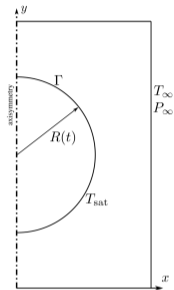
Theoretical case of [Scriven, 1959]

- Pure heat-diffusion
- $T_\infty > T_{sat}$, uniform at $t = 0$
- $R(t) = \underbrace{f(\text{Ja})}_{k_{gr}} \text{Ja} (\alpha_l t)^{0.5}$
- $\text{Ja} = \frac{\rho_l c_p l (T_w - T_{sat})}{\rho_v h_{lv}}$
- Generic law: $R = k \times t^n$



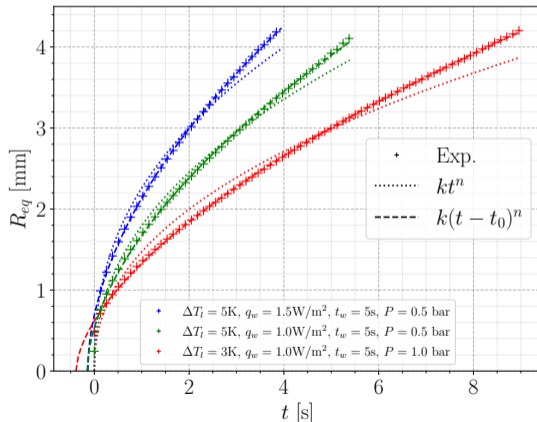
Bubble growth fitting : pool boiling cases

STUDY OF BUBBLE GROWTH BEHAVIOR



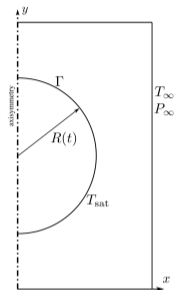
Theoretical case of [Scriven, 1959]

- Pure heat-diffusion
- $T_\infty > T_{sat}$, uniform at $t = 0$
- $R(t) = \underbrace{f(\text{Ja})}_{k_{gr}} \text{Ja} (\alpha_l t)^{0.5}$
- $\text{Ja} = \frac{\rho_l c_p l (T_w - T_{sat})}{\rho_v h_{lv}}$
- Generic law: $R = k \times t^n$



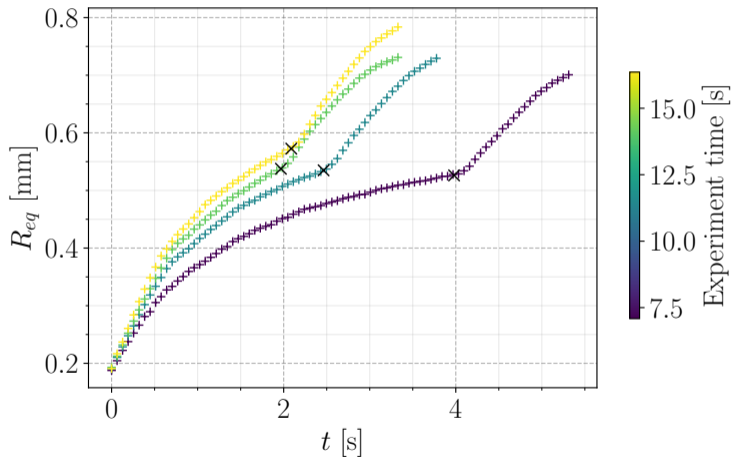
Bubble growth fitting : pool boiling cases

STUDY OF BUBBLE GROWTH BEHAVIOR



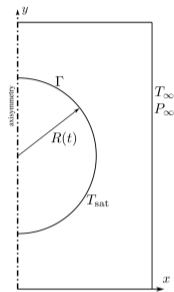
Theoretical case of [Scriven, 1959]

- Pure heat-diffusion
- $T_\infty > T_{sat}$, uniform at $t = 0$
- $R(t) = \underbrace{f(\text{Ja})}_{k_{gr}} \text{Ja} (\alpha_l t)^{0.5}$
- $\text{Ja} = \frac{\rho_l c_{p,l} (T_w - T_{sat})}{\rho_v h_{lv}}$
- Generic law: $R = k \times t^n$



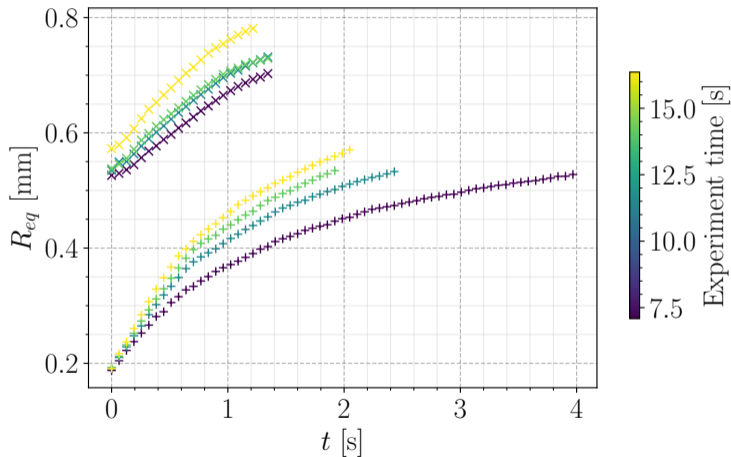
Bubble growth fitting : shear flow cases

STUDY OF BUBBLE GROWTH BEHAVIOR



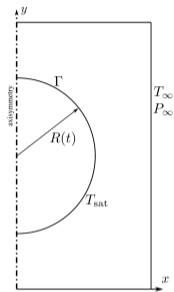
Theoretical case of [Scriven, 1959]

- Pure heat-diffusion
- $T_\infty > T_{sat}$, uniform at $t = 0$
- $R(t) = \underbrace{f(\text{Ja})}_{k_{gr}} \text{Ja} (\alpha_l t)^{0.5}$
- $\text{Ja} = \frac{\rho_l c_{p,l} (T_w - T_{sat})}{\rho_v h_{lv}}$
- Generic law: $R = k \times t^n$



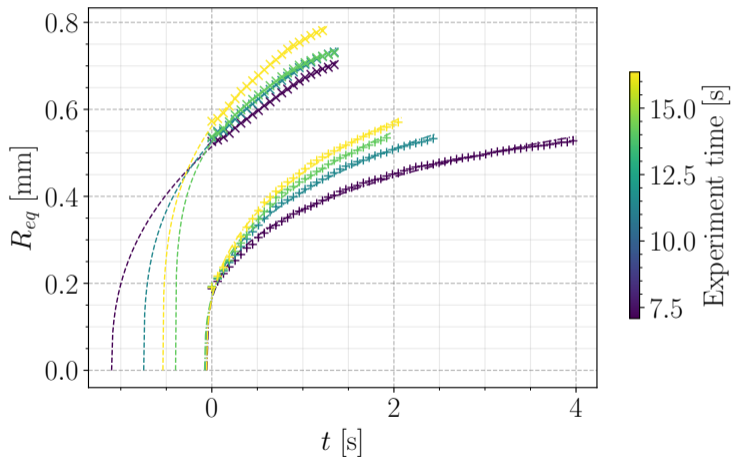
Splitting static and sliding phases

STUDY OF BUBBLE GROWTH BEHAVIOR



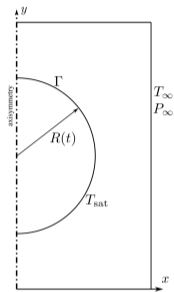
Theoretical case of [Scriven, 1959]

- Pure heat-diffusion
- $T_\infty > T_{sat}$, uniform at $t = 0$
- $R(t) = \underbrace{f(\text{Ja})}_{k_{gr}} \text{Ja} (\alpha_l t)^{0.5}$
- $\text{Ja} = \frac{\rho_l c_{p,l} (T_w - T_{sat})}{\rho_v h_{lv}}$
- Generic law: $R = k \times t^n$



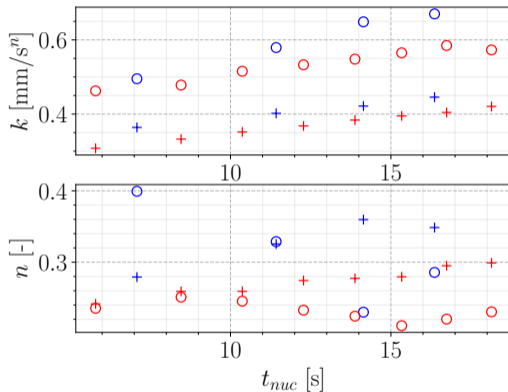
Splitting static and sliding phase

STUDY OF BUBBLE GROWTH BEHAVIOR



Theoretical case of [Scriven, 1959]

- Pure heat-diffusion
- $T_\infty > T_{sat}$, uniform at $t = 0$
- $R(t) = \underbrace{f(\text{Ja})}_{k_{gr}} \text{Ja} (\alpha_l t)^{0.5}$
- $\text{Ja} = \frac{\rho_l c_p l (T_w - T_{sat})}{\rho_v h_{lv}}$
- Generic law: $R = k \times t^n$



- + Static
- Sliding
- + 300 mL/min
- + 500 mL/min

$k \nearrow$ with t and sliding, few impact of Q_l | $n \searrow$ with Q_l , non monotonous impact of sliding or t

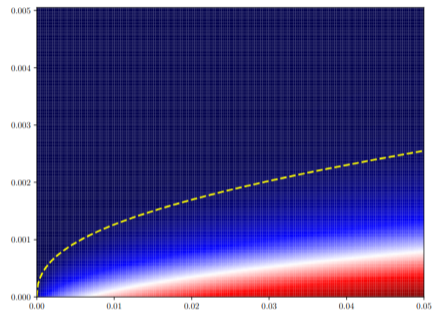
Deviation from Scriven $n < 0.5$, k dep. on δ_{TBL} , $U_{rel} \rightarrow$ find proper law

CONCLUSION

CONCLUSIONS & PERSPECTIVES

Conclusions

- Detection of R_{dep} , well correlated to $\frac{\rho_l}{\rho_v} \frac{Bo}{Ja_l}$
- TBL thickness at $t_w + t_{dep}$ impacts growth law and R_d : to be calculated (transient Graetz pb.)
- C_D calculation: deviation because of large shear + sensitivity to $d\theta$?



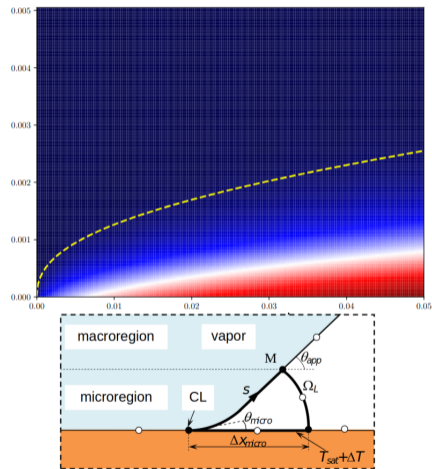
CONCLUSIONS & PERSPECTIVES

Conclusions

- Detection of R_{dep} , well correlated to $\frac{\rho_l}{\rho_v} \frac{Bo}{Ja_l}$
- TBL thickness at $t_w + t_{dep}$ impacts growth law and R_d : to be calculated (transient Graetz pb.)
- C_D calculation: deviation because of large shear + sensitivity to $d\theta$?

Perspectives

- Treatment of IR images : linking growth and T_w at TCL
 - Use of \mathcal{DIVA} code (S. Tanguy *et al.*): DNS + Boiling + Wall conduction
 - Microregion (MR) modeling of [Mathieu, 2002] implemented for axisymmetric cases [Torres *et al.*, 2024]
- ⇒ Comp. of MR models with pool boiling cases: (Ja_w, θ)
- ⇒ 3D to simulate shear flow boiling cases ?

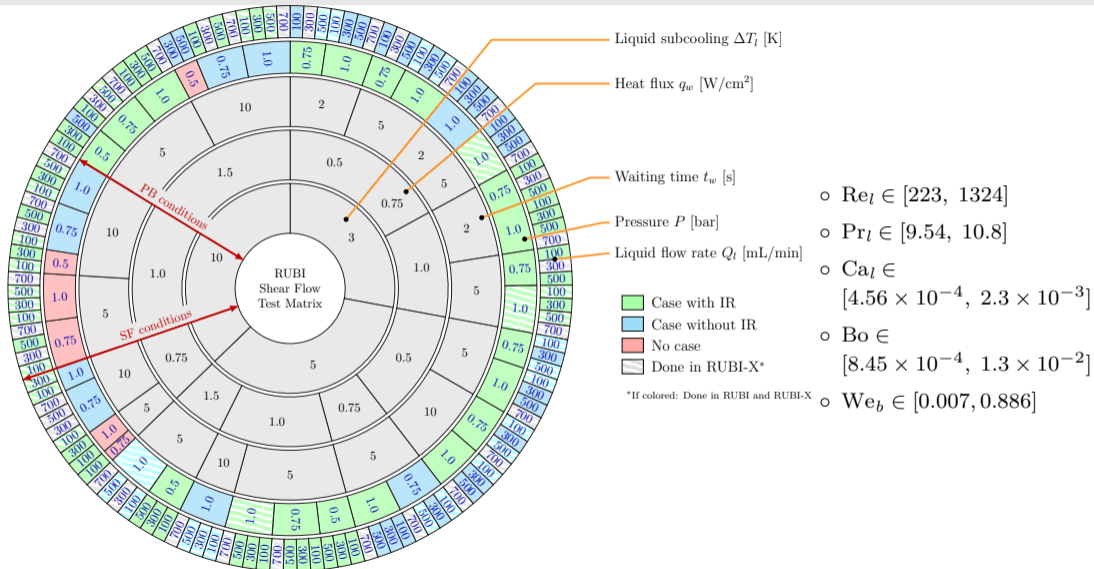


Thank you very much for your attention !

Questions / Contact: luc.favre@imft.fr or favre.luc05@gmail.com

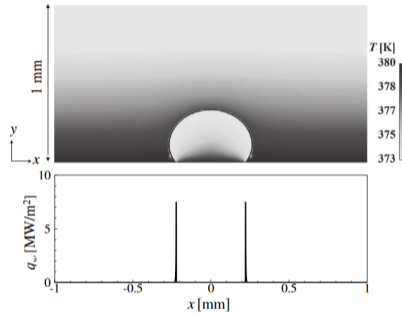


RUBI SHEAR FLOW TEST MATRIX



DIVA code (S. Tanguy, A. Urbano, L. Torres)

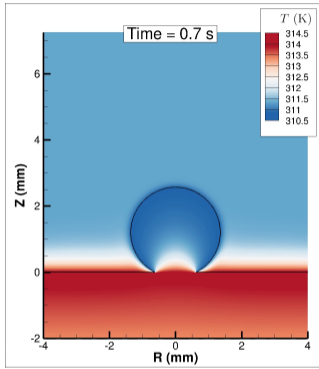
- Direct Numerical Simulation
- Incompressible + boiling phase change
- Coupled with heat conduction solving in the wall
- **Microregion modeling**



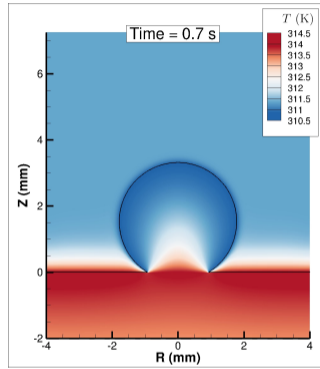
(a) $Ja = 21$, contact line regime

Simulation of boiling in contact line regime

[Urbano *et al.*, 2018]

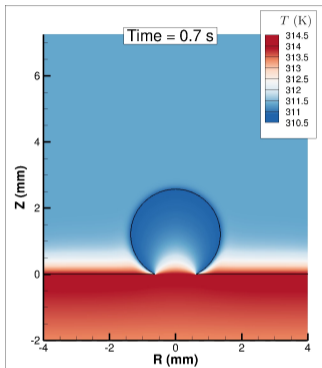


Without microregion model

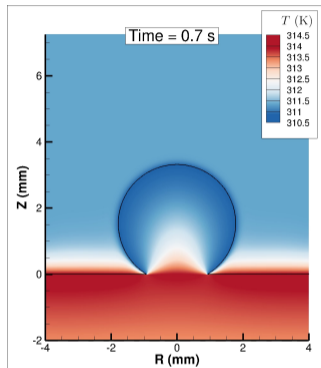


With microregion model

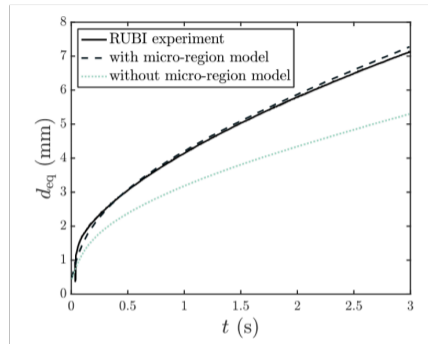
- o Strong impact of microregion modeling: large contribution to bubble growth
- o Next steps: Further comparison with other recent models (e.g. [Janecek & Nikolayev, 2012])



Without microregion model



With microregion model



Comparison with RUBI experiment

- o Strong impact of microregion modeling: large contribution to bubble growth
- o Next steps: Further comparison with other recent models (e.g. [Janecek & Nikolayev, 2012])