Numerical Simulation of Bubble Growth under Low Pressure

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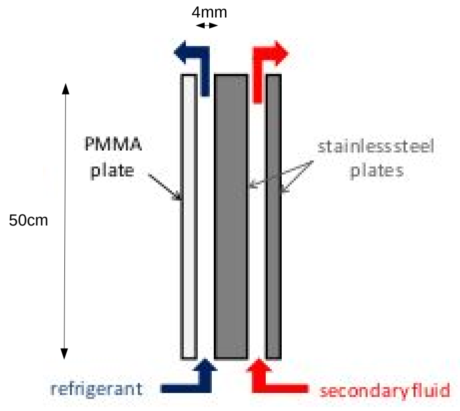
Context

- Air conditioning at room temperature
- Harmful working fluids
- Water as refrigerant
  - Ambient temperature → $P_{sat} \simeq 1\% P_{atm}$

$$\frac{\rho_l}{\rho_v} \to 10^5$$

Context

- Compact heat exchangers



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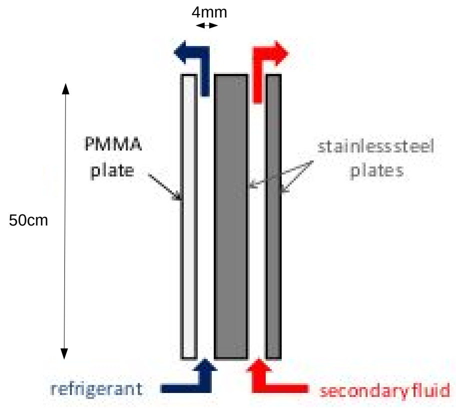

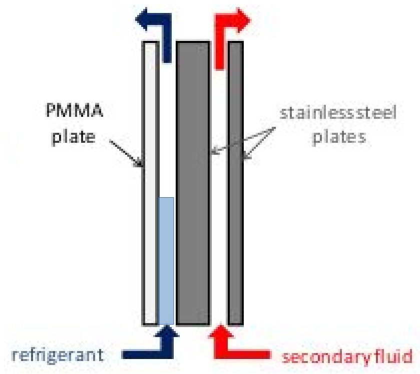

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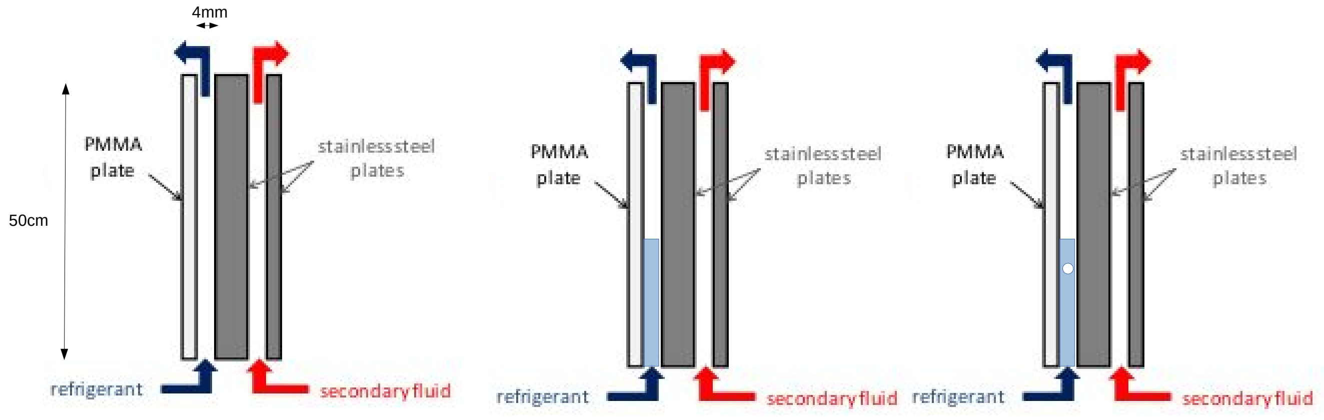

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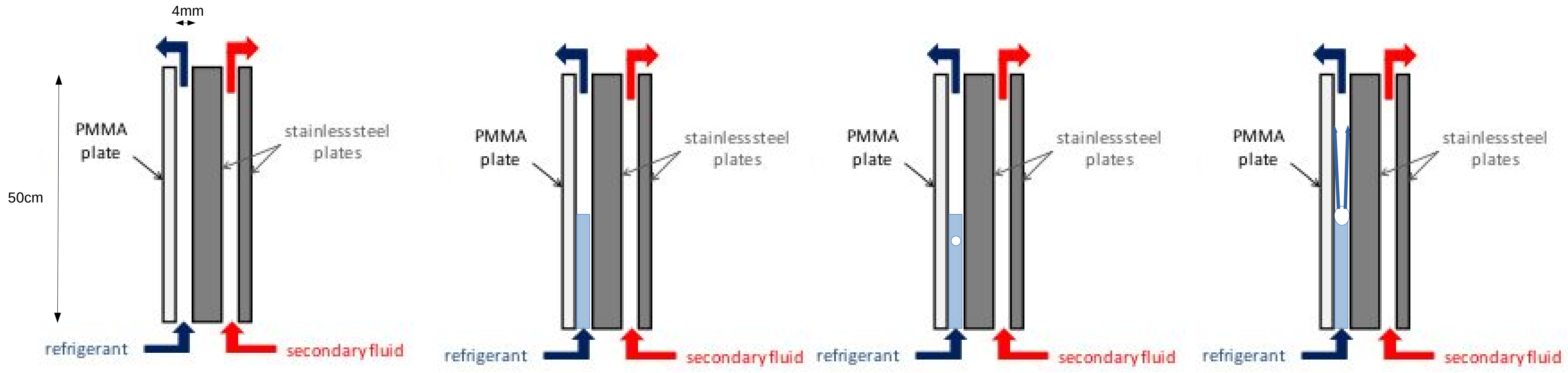

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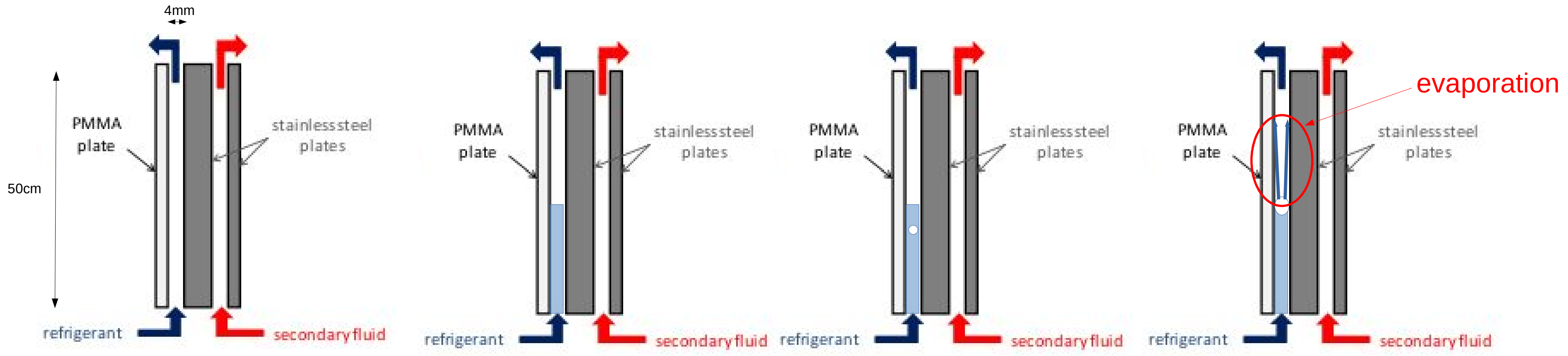
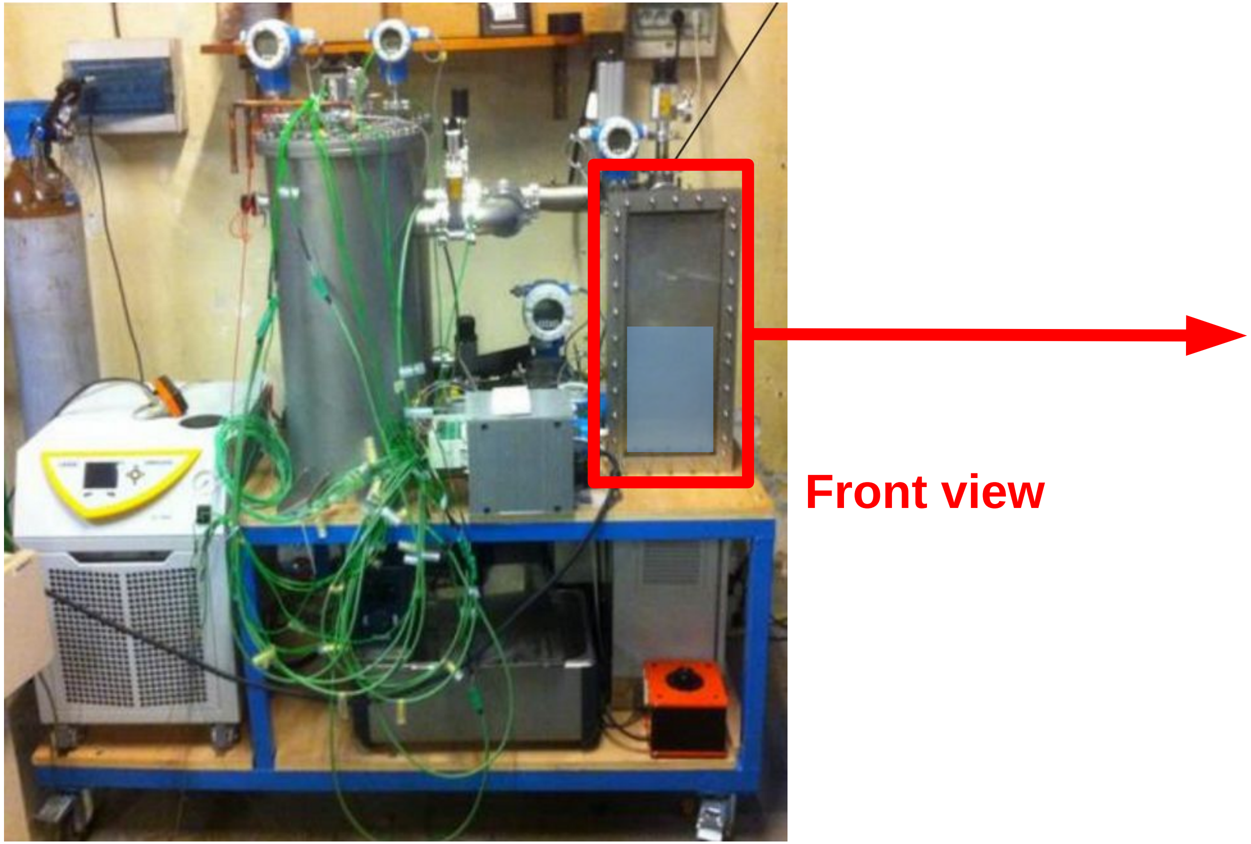
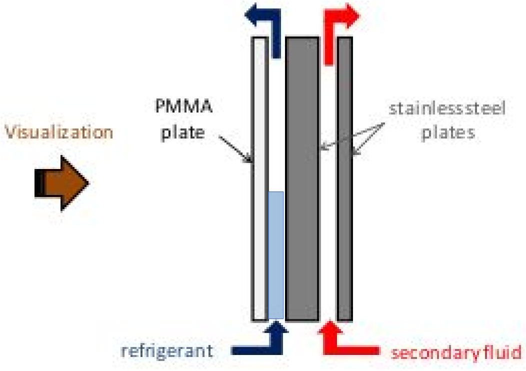


- Complex physics / short time scales
  - Usual correlations out of range
- Need for numerical simulation to support experiments

Experimental cell



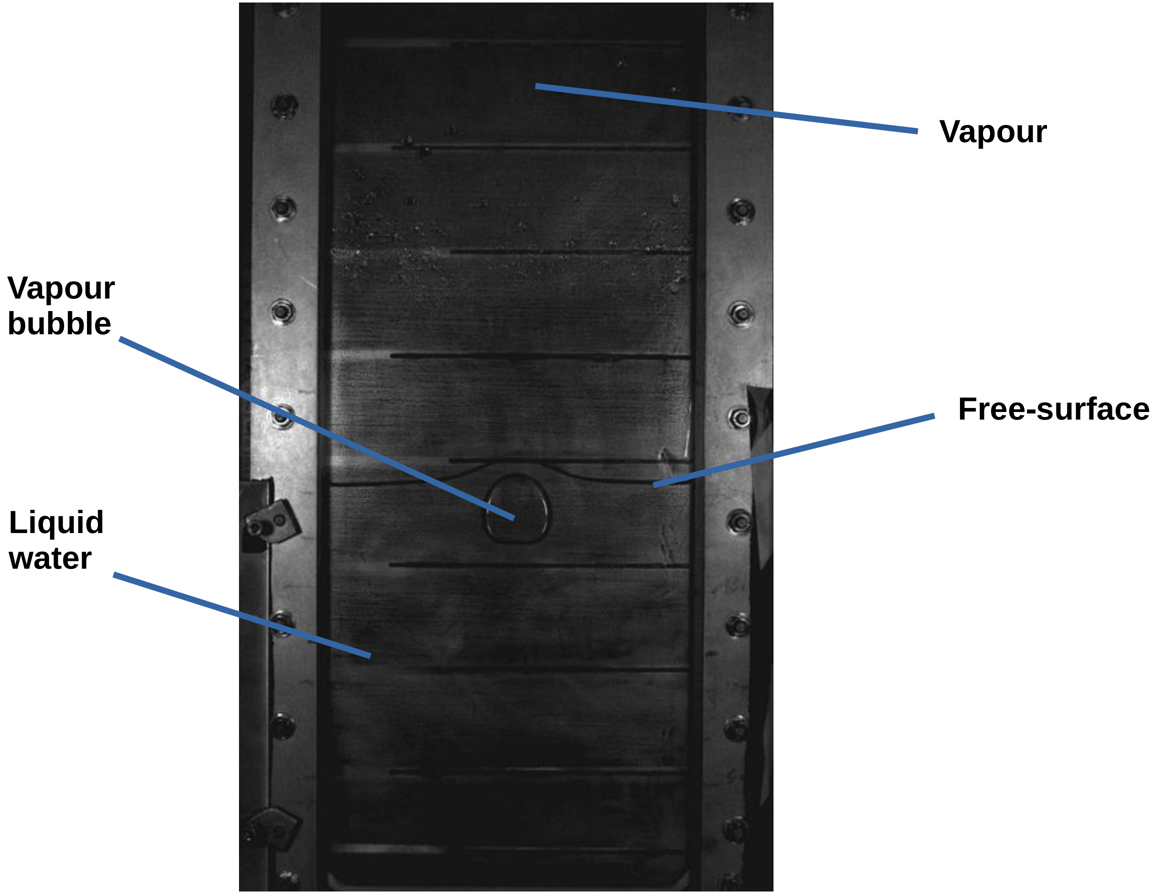
Front view



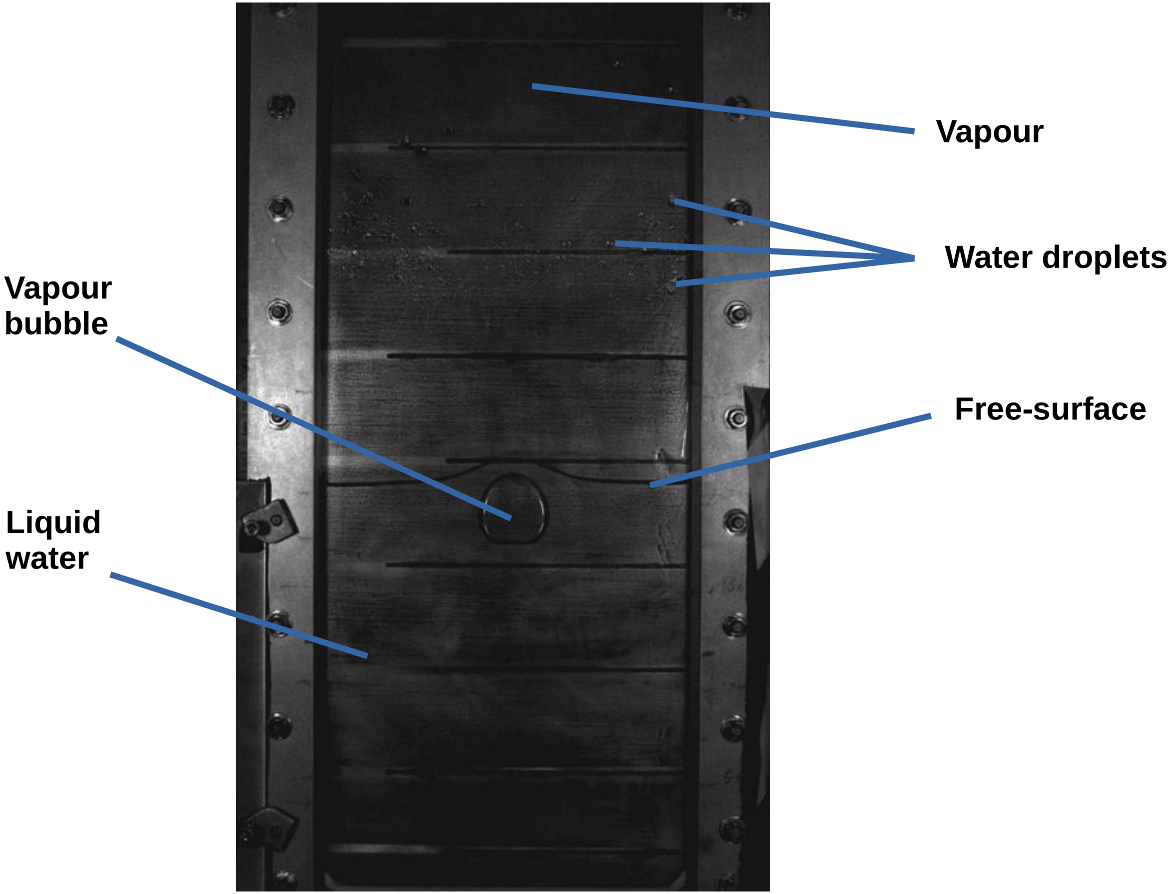
Side view

Experimental cell front view

Experimental cell front view



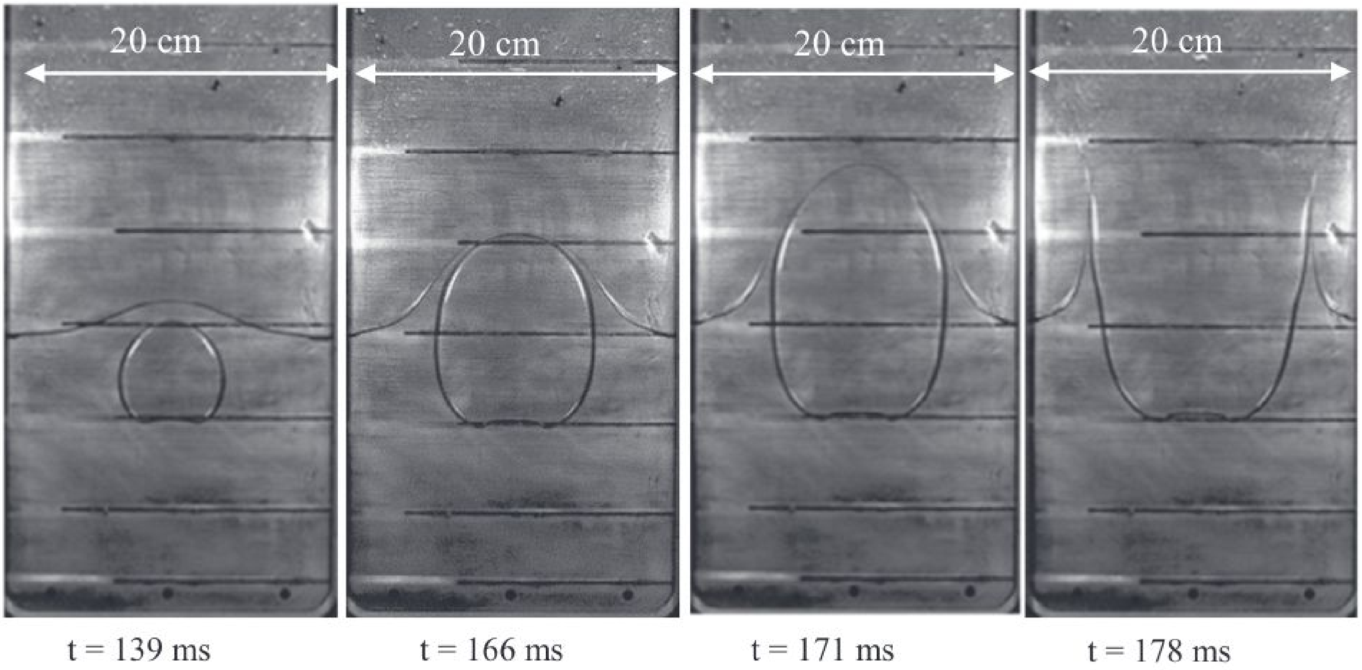
Experimental cell front view



Experimental cell front view

Duration ~ *40ms*

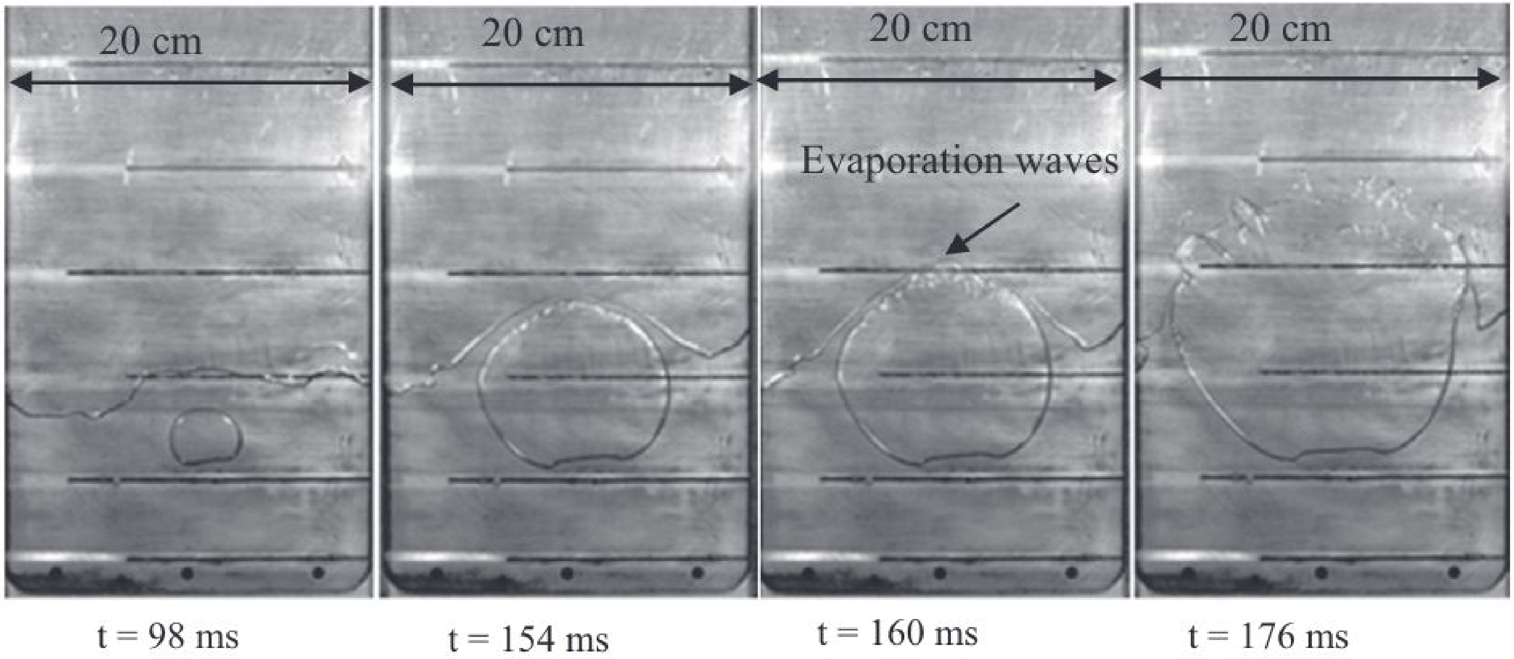
Experimental scenarios



(Co = 0.23, ΔP = 1.18 kPa, FR = 20%, P_{sat} = 1.46 kPa)

Giraud, Tréméac IJHMT 2019

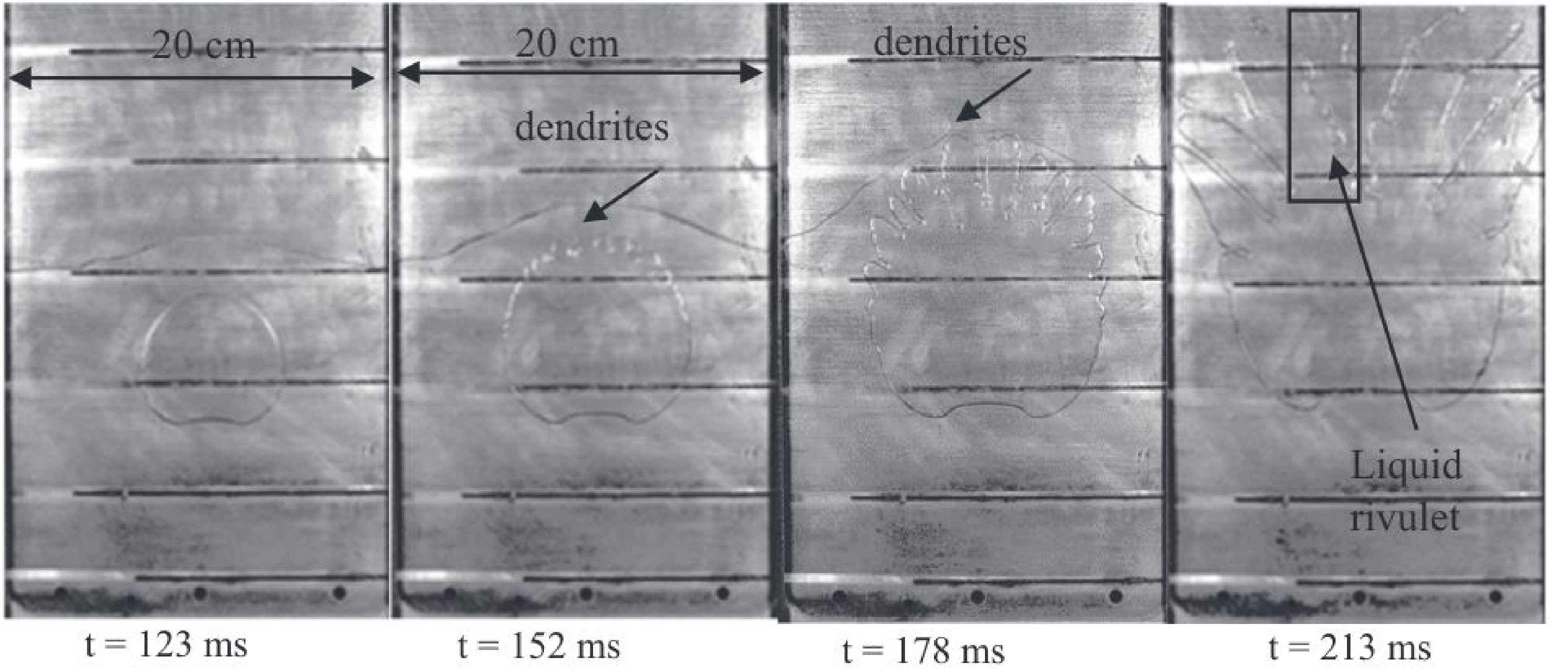
Experimental scenarios



(Co = 0.35, ΔP = 1.10 kPa, FR = 30%, P_{sat} = 0.88 kPa)

Giraud, Tréméac IJHMT 2019

Experimental scenarios



(Co = 0.69, ΔP = 1.18 kPa, FR = 20%, P_{sat} = 1.46 kPa)

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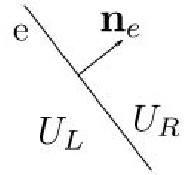
Numerical approach

- Two-fluid Direct Numerical Simulation
  - Mixing model
  - Compressible approach
    - Assumptions :
      - 2 densities, one for each fluid $\tilde{\rho}_g = \alpha\rho_g \qquad \tilde{\rho}_l = (1-\alpha)\rho_l$
      - 1 pressure, 1 velocity, 1 temperature for both fluids $\rho = \tilde{\rho}_g + \tilde{\rho}_l$
    - 2 mass, 1 momentum, 1 enthalpy conservation equations $\begin{cases} \partial_t\tilde{\rho}_g + div(\tilde{\rho}_g\mathbf{u}) &= 0 \\ \partial_t\tilde{\rho}_l + div(\tilde{\rho}_l\mathbf{u}) &= 0 \\ \partial_t\tilde{\rho}\mathbf{u} + div(\tilde{\rho}\mathbf{u}\otimes\mathbf{u} + \nabla p) &= S \end{cases}$

      → isobaric relation to close equations and obtain volume fraction
    - Barotropic Equation of State $p = f(\rho)$
  - Also includes viscous and thermal diffusion, surface tension effects

Numerical approach

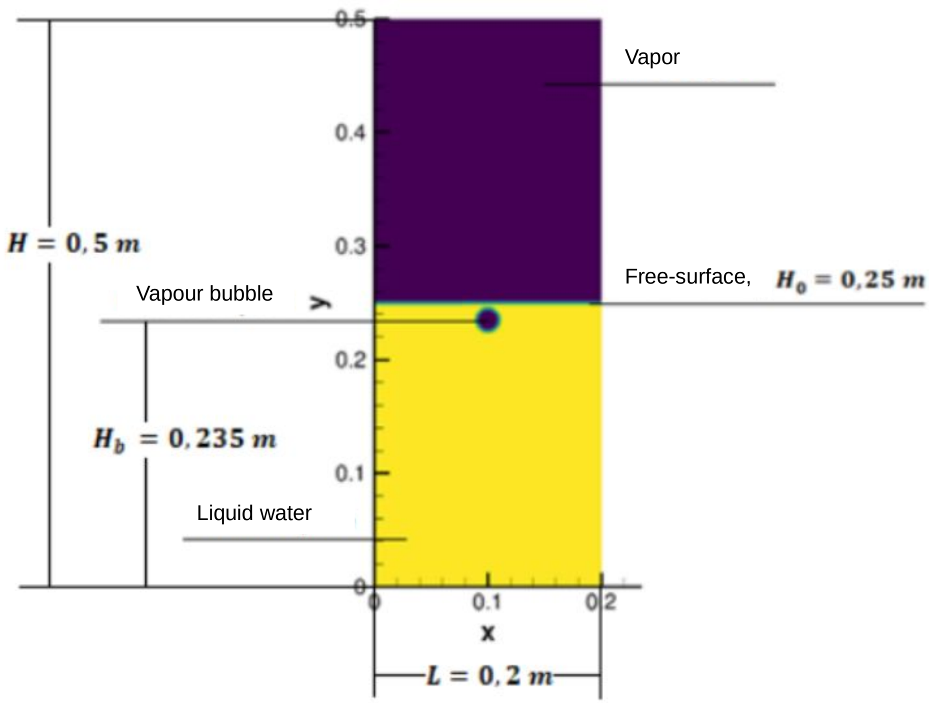
- Finite Volume approach $Q^{n+1} = Q^n - \frac{\Delta t}{\mathcal{V}} \sum_e F_e^n l_e + \Delta t S^n$
- Numerical flux at cell edge $F_e = v_e^+ U_L + v_e^- U_R + p_e \mathbf{n}_e$



  – Centered pressure $p_e = 1/2(p_R + p_L)$
  – Velocity upwind $v_e = 1/2(\mathbf{u}_L + \mathbf{u}_R) - \gamma_e(p_R - p_L)$
    - γ_e stabilizes the scheme
  – Based on semi-implicit low-Mach scheme [Grenier et al., *JCP 2013*]
    - Implicit continuity equation
      → **no time-step restriction** linked to sound speed
    - Explicit momentum equation
    - **High-density ratio** ($\mathcal{O}(10^5)$)

Numerical set-up

- Hypothesis
  - First approach → 2D computation
  - Short time scales → isothermal flow
- Initial conditions **?**
  - Lack of experimental data
    - visualisation only
  - Strong hypothesis for simulation
    - Motionless fluids
    - Bubble
      - Circular shape
      - Initial pressure



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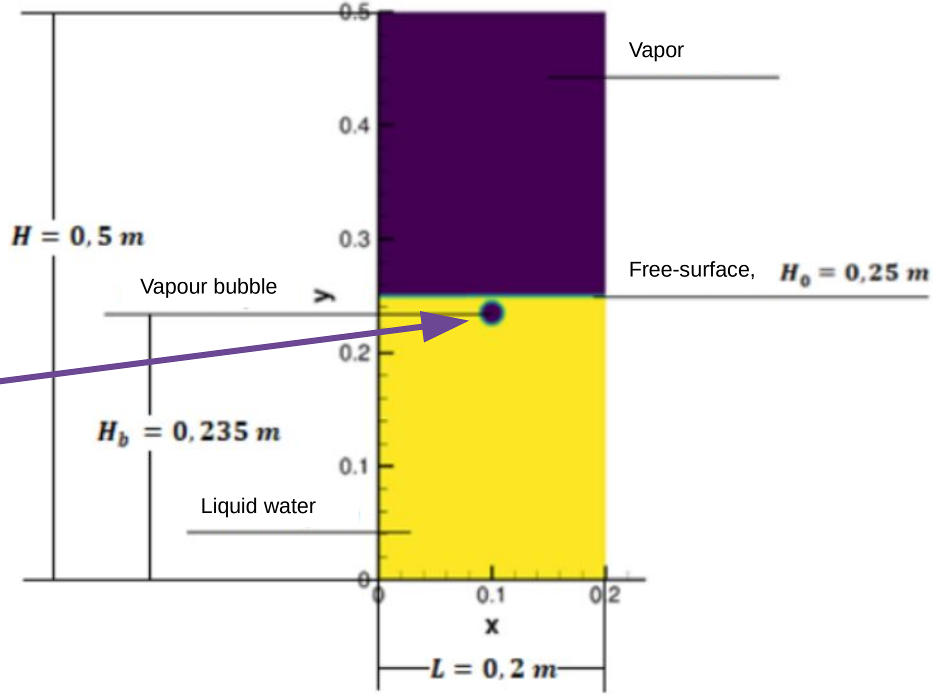
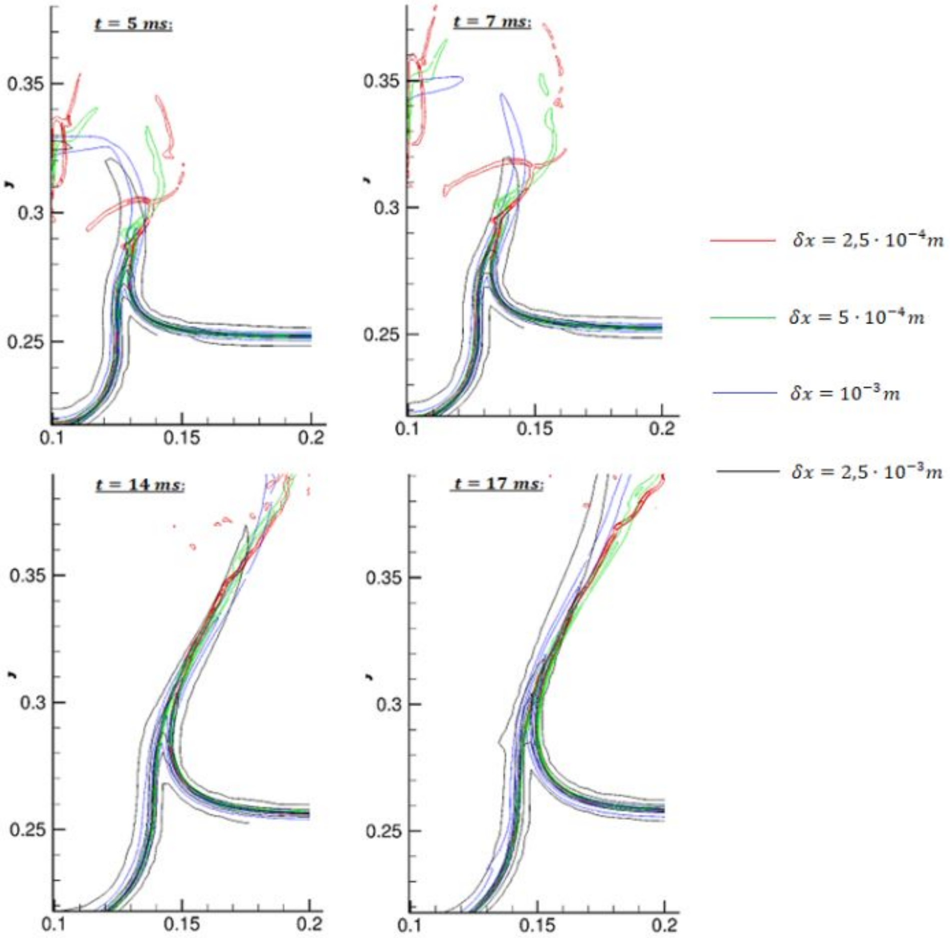


Preliminary study : space convergence

- Space convergence
  - Good jet description
  - Still under-resolved for filament rupture
  - $\delta x = 5\,10^{-4}\,m$ *(400x1000 cells)* selected for further study



$P_s = 0.85\,kPa$

$\rho_v = 0.0066 kg/m^{-3}$

$H_0 = 0.25\,m$

$\frac{H_b}{H_0} = 0.94 \qquad \frac{R_b}{H_0} = 0.04 \qquad \frac{\rho_b}{\rho_v} = 30$

Parametric study

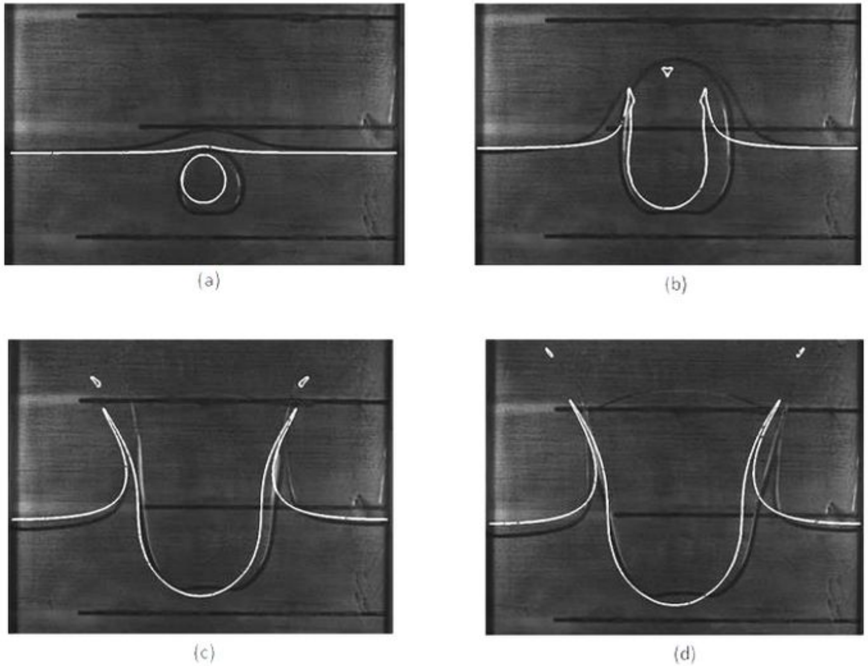
- Experimental conditions

$P_s = 0.98\, kPa \qquad \rho_v = 0.0076 kg/m^{-3} \qquad H_0 = 0.25\, m$

- CFD guess estimate for initial conditions

$\frac{H_b}{H_0} = 0.936 \qquad \frac{R_b}{H_0} = 0.04 \qquad \frac{\rho_b}{\rho_v} = 30$

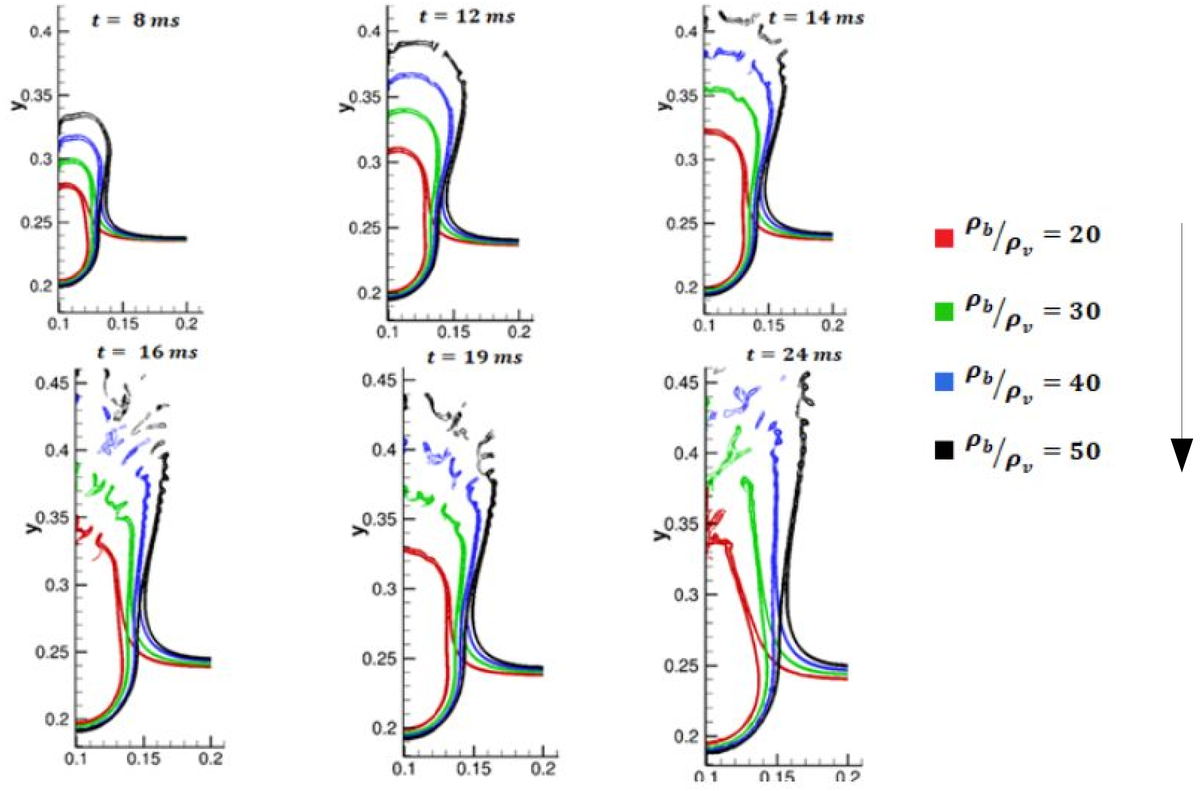
- Objective: find best initial conditions
  - Bubble location
  - Bubble radius
  - Bubble pressure
- Constraints: best match experimental data (HSV)
  - Bubble growth
  - Interfacial dynamics



CFD results (iso contours of volume fraction) superimposed on EFD visualisations

Impact of initial conditions on bubble dynamics

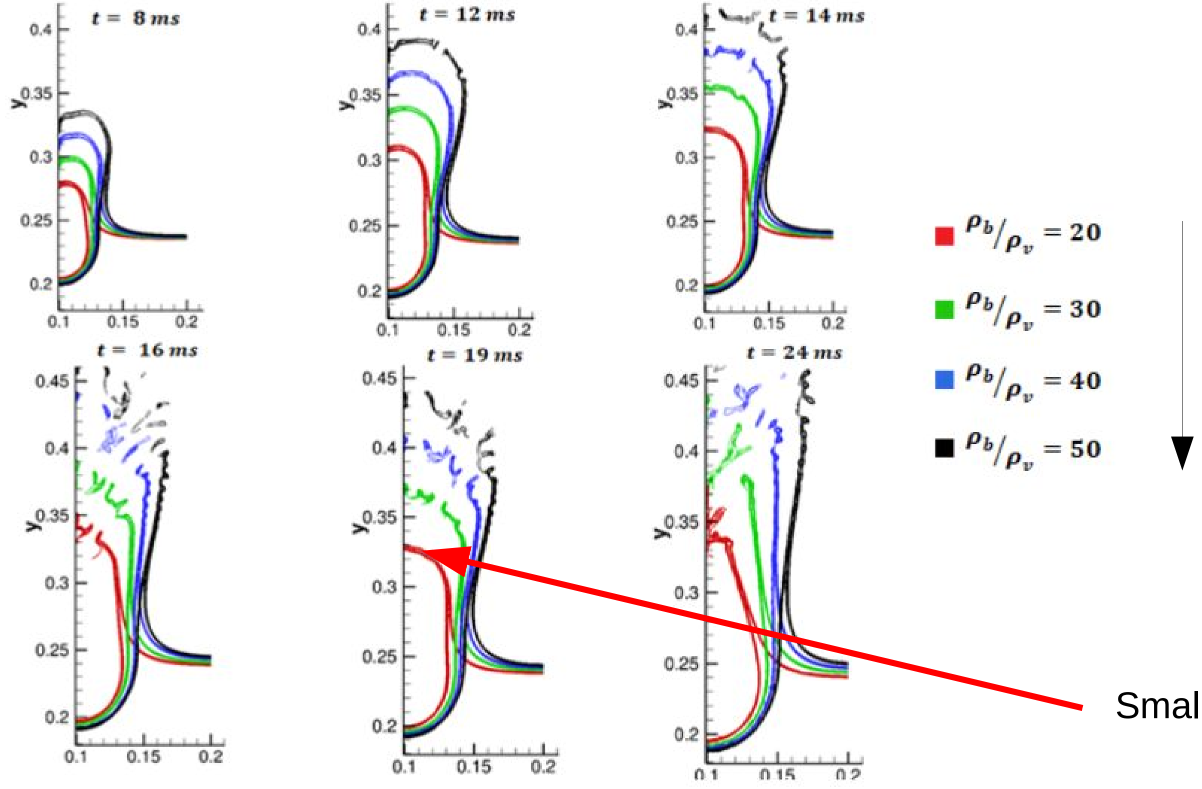
- Initial bubble density



- Final bubble area is higher
- Interface rupture is faster

Impact of initial conditions on bubble dynamics

- Initial bubble density

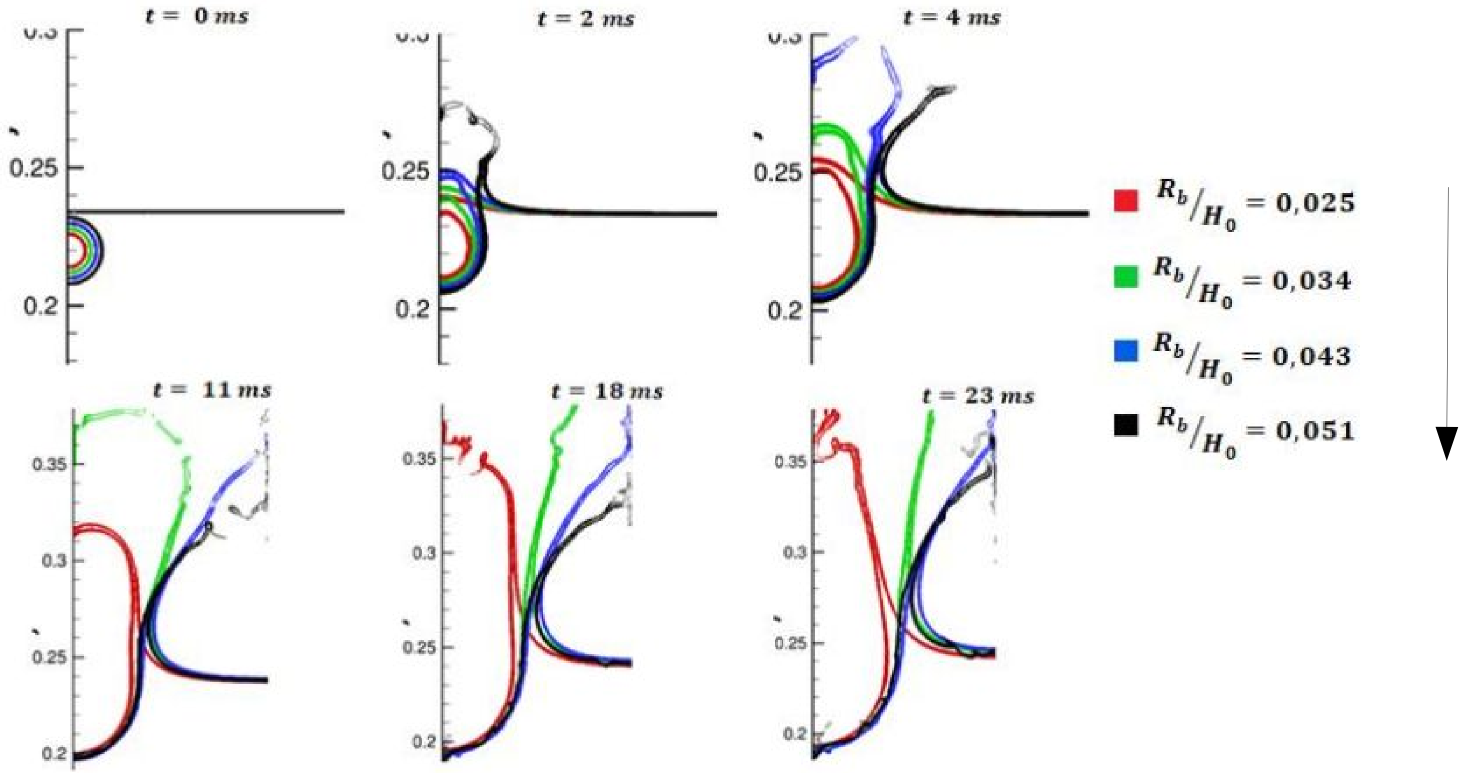


- Final bubble area is higher
- Interface rupture is faster

Small initial density → possible reconnection

Impact of initial conditions on bubble dynamics

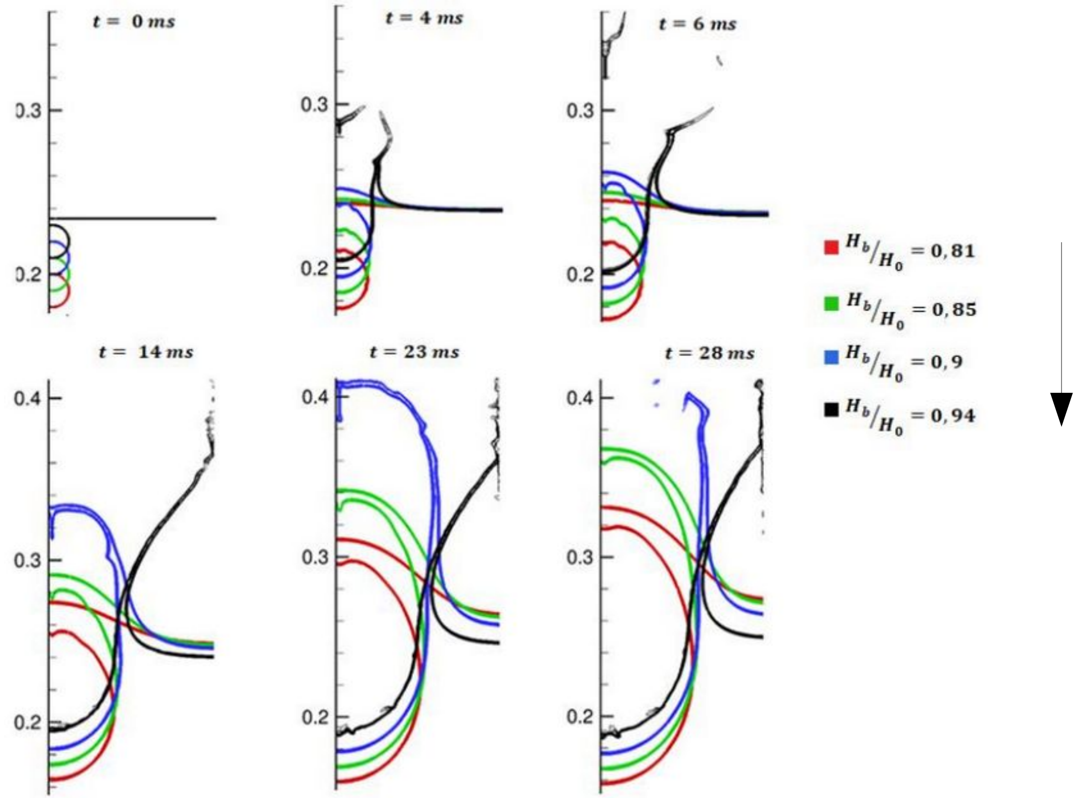
- Initial bubble radius (same location under free-surface)



- Interface rupture is faster
  - at constant depth
  - less liquid above bubble

Impact of initial conditions on bubble dynamics

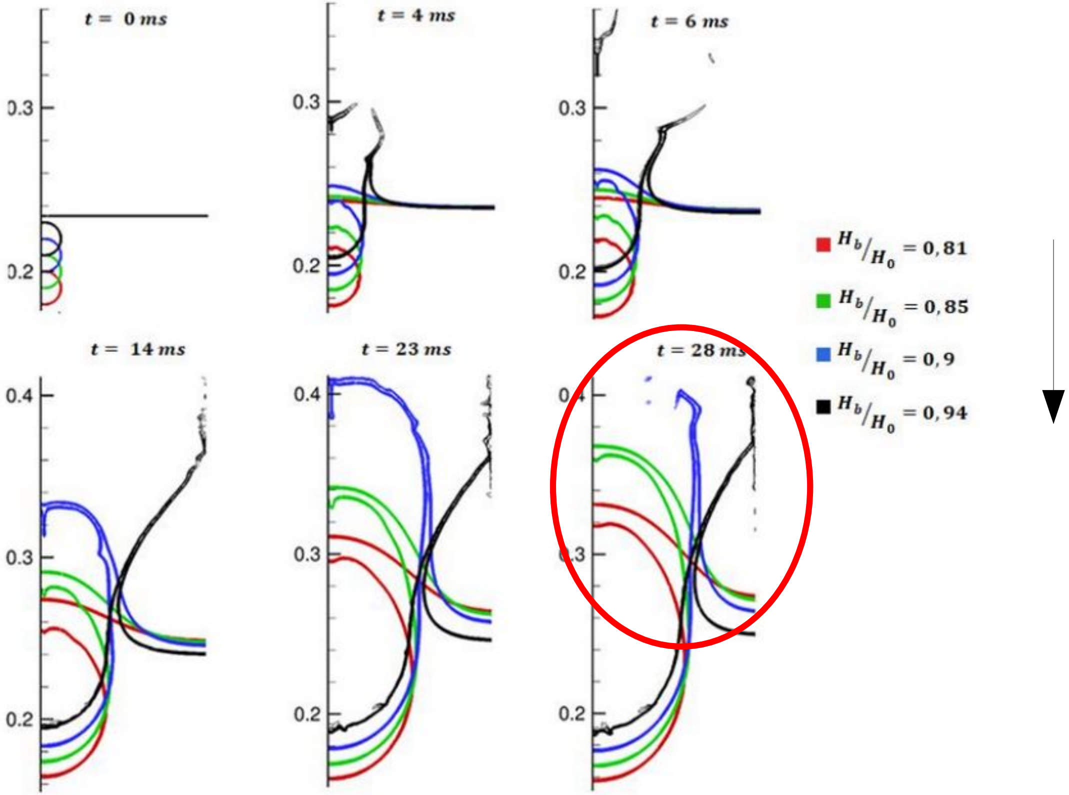
- Initial bubble height (same radius)



- Bubble growth is faster
- Interface break-up is faster
- Direct connection with jet thickness at break-up

Impact of initial conditions on bubble dynamics

- Initial bubble height (same radius)



- Bubble growth is faster
- Interface break-up is faster
- Direct connection with jet thickness at break-up

Best fitting with experimental data

- Experimental conditions

$P_s = 0.98\,kPa \qquad \rho_v = 0.0076 kg/m^{-3} \qquad H_0 = 0.25\,m$

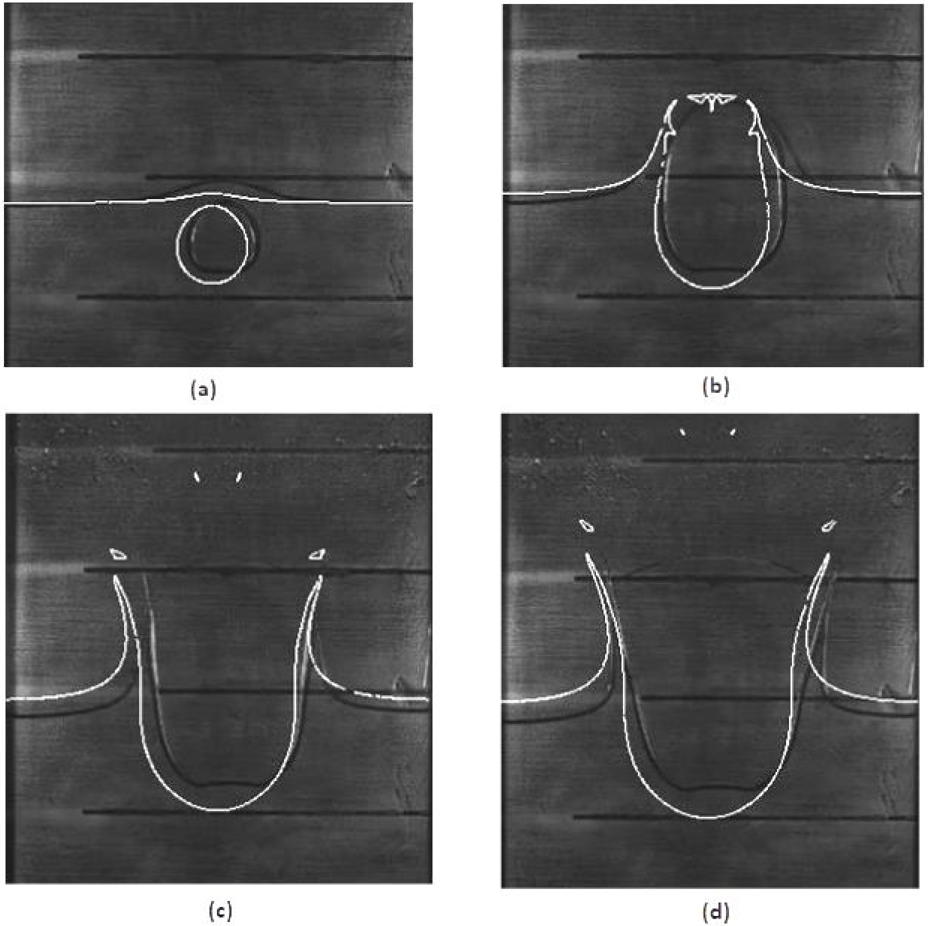
- CFD initial conditions

$\frac{H_b}{H_0} = 0.906 \qquad \frac{R_b}{H_0} = 0.064 \qquad \frac{\rho_b}{\rho_v} = 15$

☑ Interface break-up

☑ Bubble dynamics

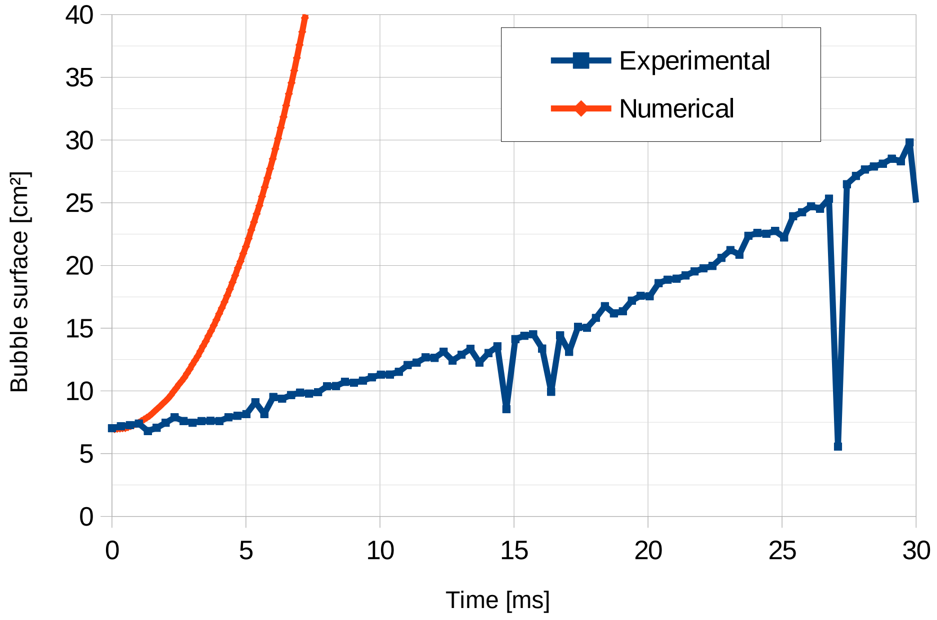
☒ Bubble area VS time



Best fitting with experimental data

- Bubble area VS time

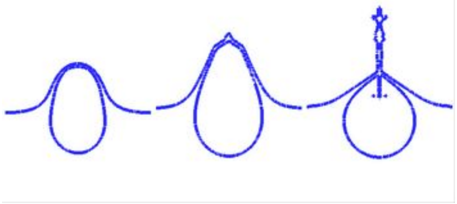
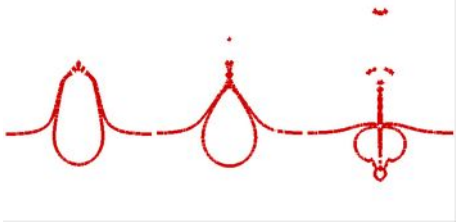
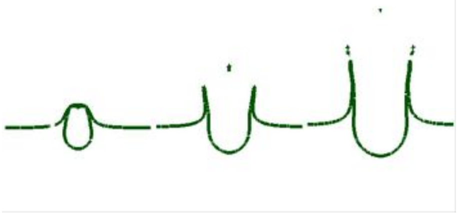
  → CFD much faster than EFD



- Relevant physical effects are missing in CFD

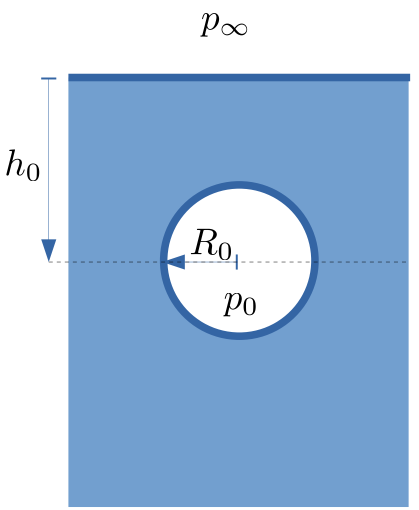
Scenarios

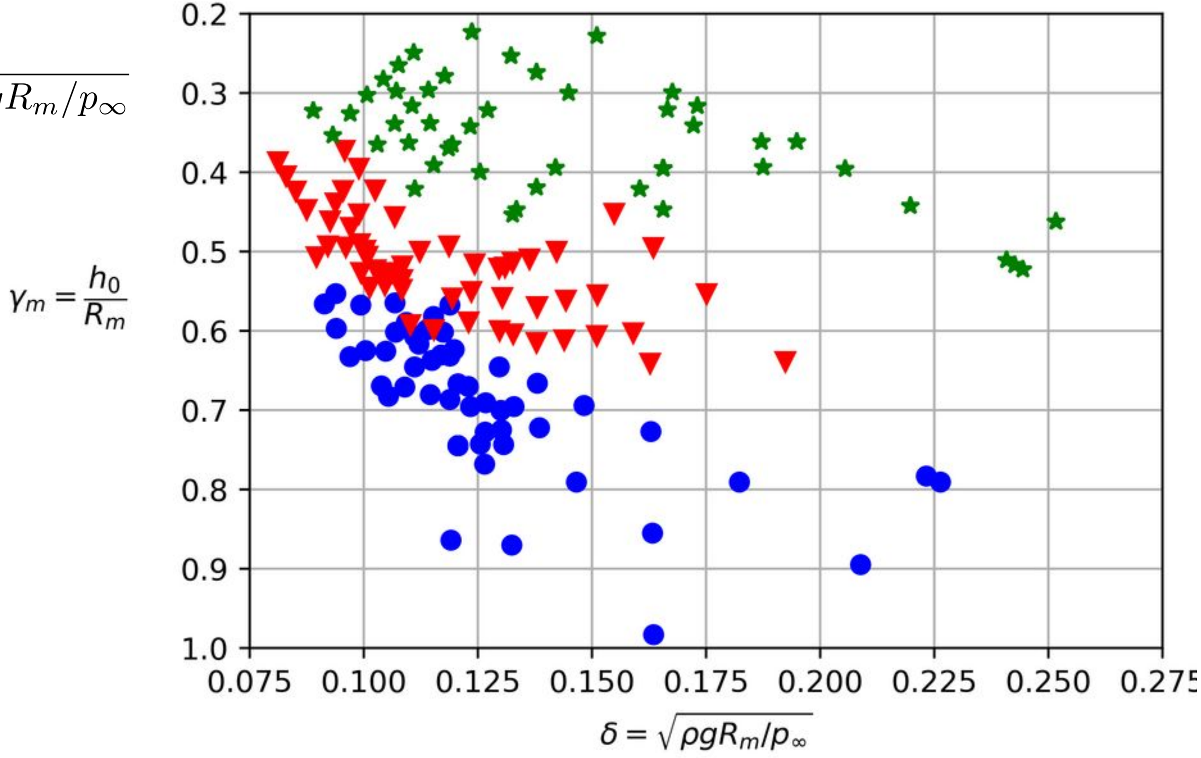
	Pattern I	Pattern II	Pattern III
Cavity opening		☑	☑
Central jet	☑	☑	
Lateral Jet		☑	☑

Scenarios map

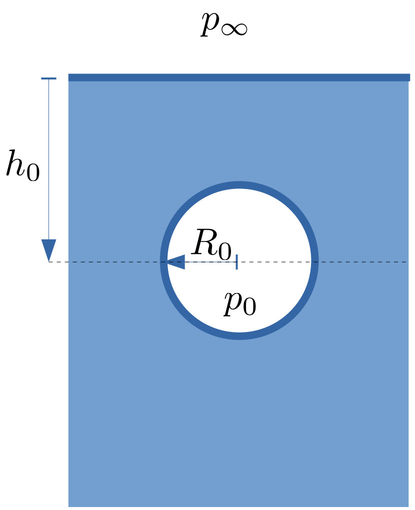
- Non-dimensional analysis [Blake JFM 1987, Zhang JFM 2015]
  - Standoff parameter $\gamma_m = \frac{h_0}{R_m}$
  - Buoyancy parameter $\delta = \sqrt{\rho_l g R_m / p_\infty}$

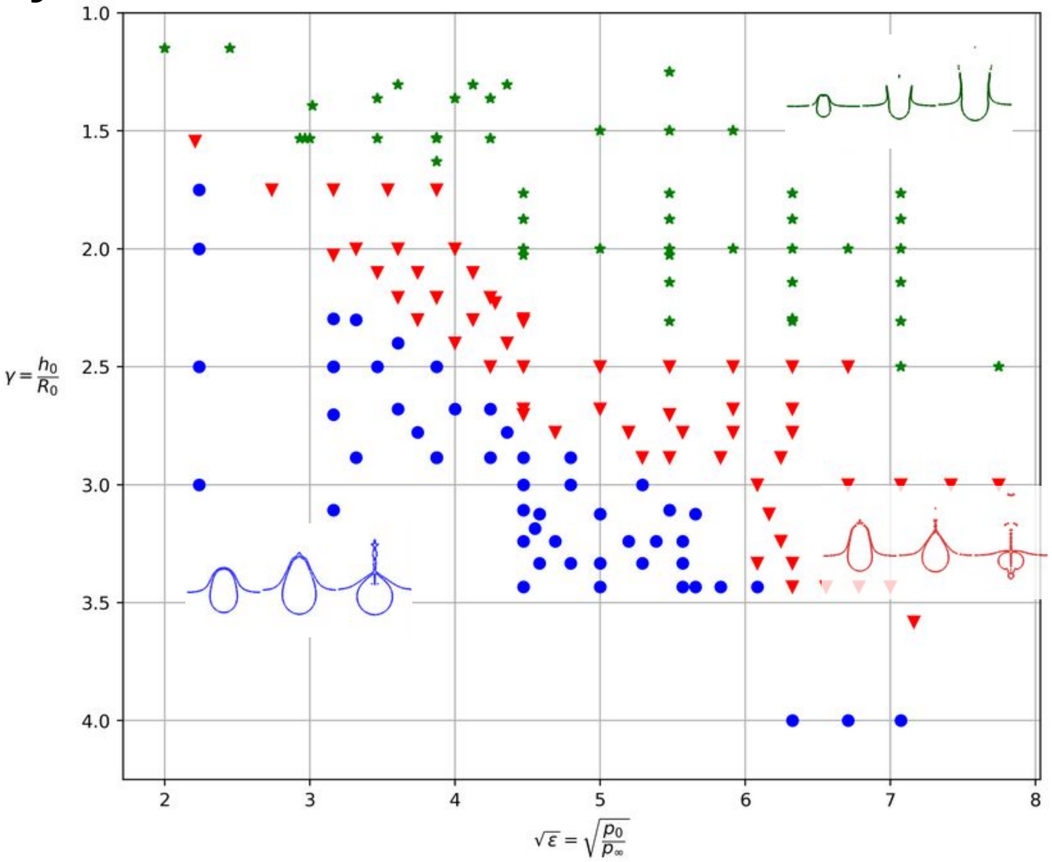




Scenarios map

- Other non-dimensional analysis
  - Standoff parameter $\gamma = \frac{h_0}{R_0}$
  - Strength parameter $\epsilon = \frac{p_0}{p_\infty}$





Prediction?

- Gravity, surface tension, liquid viscosity

  → negligible influence on map

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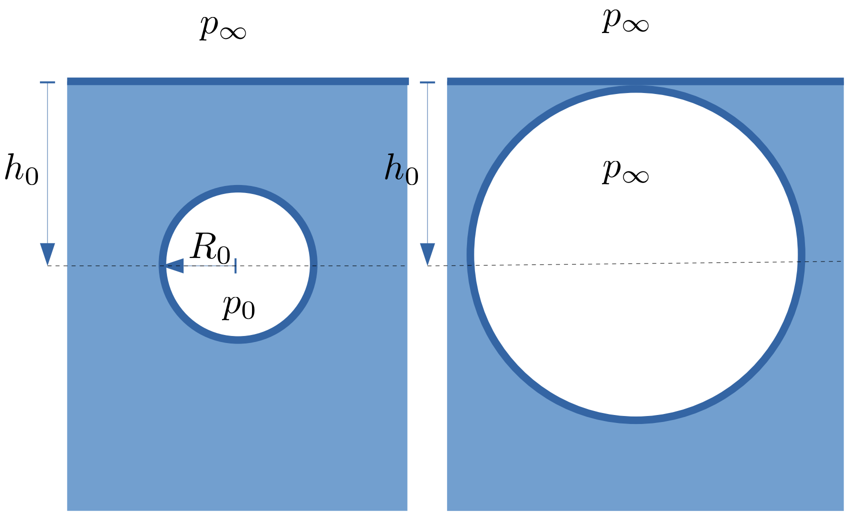
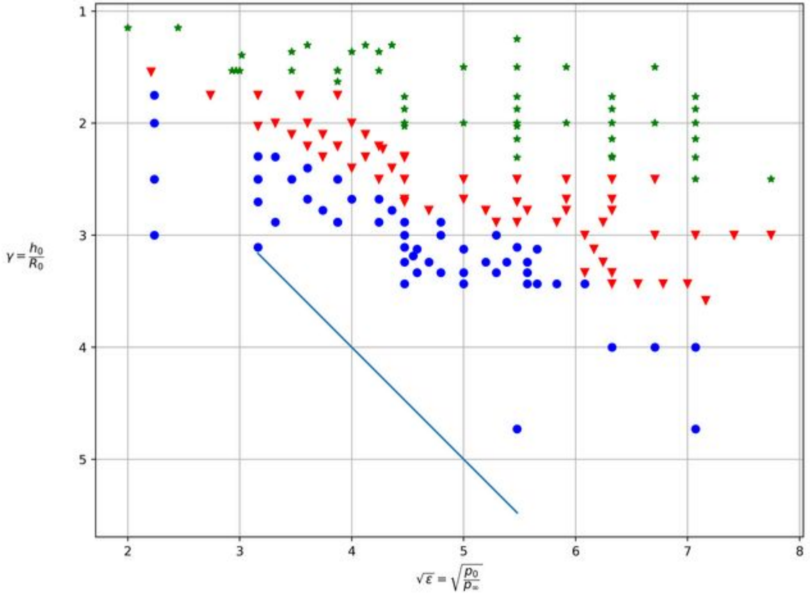
- Static dilatation model



$$\gamma = \sqrt{\epsilon}$$

Inadequate!



Conclusion

- Study of bubble growth under low pressure
- Complex physics
  - Short time-scales
  - Dilatation of a vapour inclusion inside incompressible liquid
- Numerical code robust to handle two fluids with **large density ratio** ($\mathcal{O}(10^5)$)
- Qualitative agreement with experimental observations (bubble growth, free-surface deformation and jet break-up)

- But quantitative agreement needs to improve the model
  - 3D to catch film on front/rear sides of domain
  - Fine discretisation of double interface (surface tension effects)
  - Heat and mass transfer
- Simpler model to predict scenarios