고해상도 가시화 실험을 이용한 과냉 유동 조건 비등 기포 시뮬레이션 비교 검증 연구

A comparative study between high-resolution imaging experiment and numerical simulation of a boiling bubble under subcooled convective flow

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0. Contents

1. Introduction

Background : Subcooled Flow Boiling and Departure from Nucleate Boiling

- **Subcooled flow nucleate boiling** is directly related to the safety of reactor operation.
- If **DNB (Departure from Nucleate Boiling)** occurs, **nuclear fuel temperature rises rapidly and serious damage can occur.**

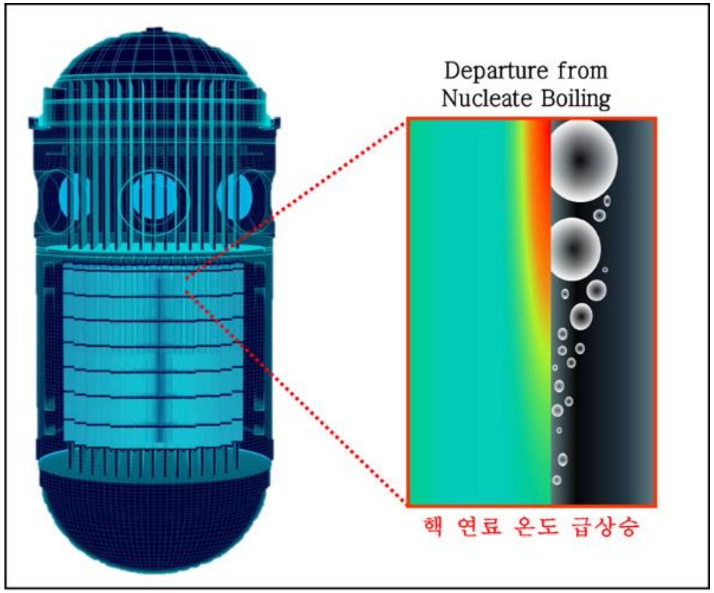


Figure 1. Flow Boiling in Nuclear Power Plants*

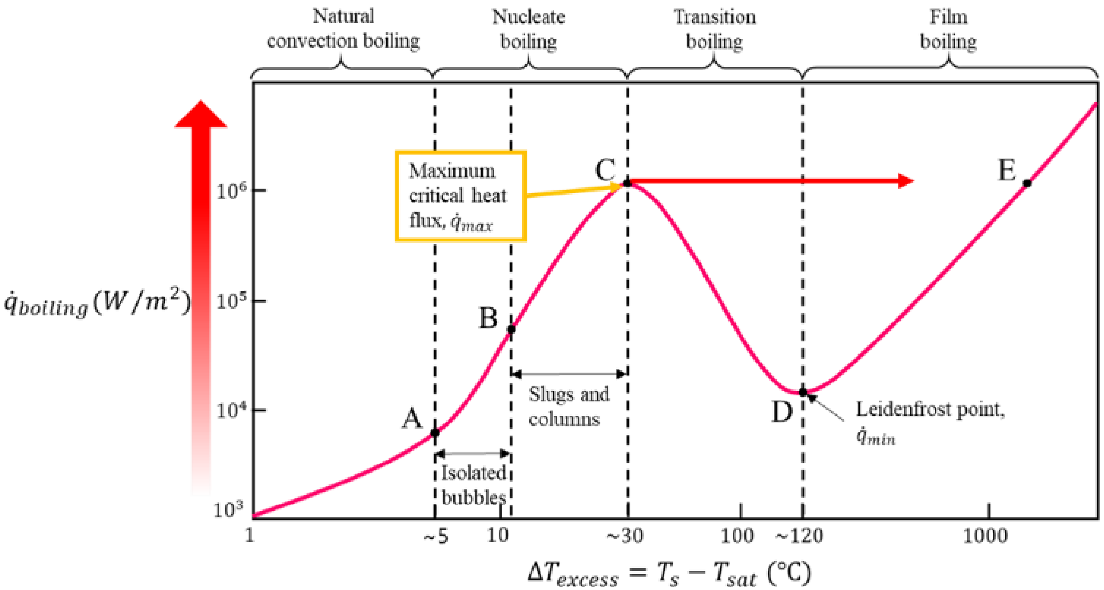


Figure 2. Heat flux curve and critical heat flux point

*Oak Ridge National Laboratory, CASLs legacy: Nuclear industry benefits from groundbreaking mod-sim tools, 2020, https://www.youtube.com/watch?v=Epelitvg49w

Background : Nuclear Safety Design with Experiment and CFD Simulation

- Various visualization experiments and computer simulation are being conducted.

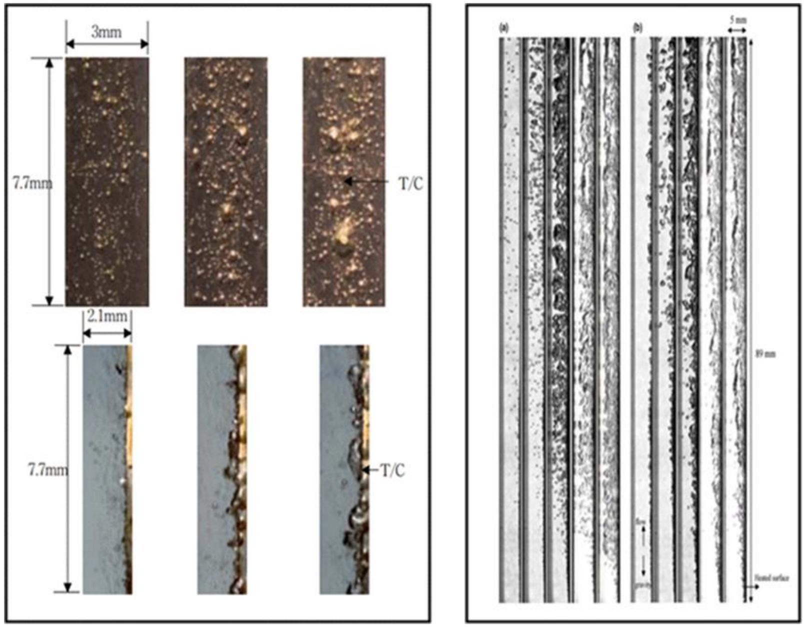


Figure 3. Typical Flow Boiling Visualization Results*

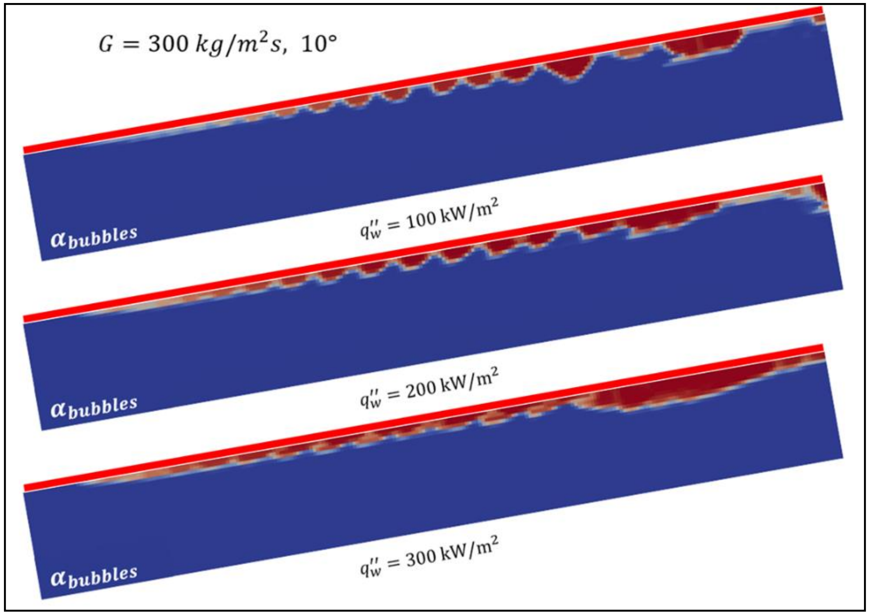


Figure 4. Example of Computational Fluid Dynamics Analysis in this Study Group

*Paek, K B, Cheon, S Y, Moon, S K, Yoon, Y J, and Park, J K. "Visualization study of the subcooled flow boiling under various pressure condition."
*In Cheol Bang, Soon Heung Chang, Won-Pil Baek, "Visualization of the subcooled flow boiling of R-134a in a vertical rectangular channel with an electrically heated wall"

Background : Multi-phase CFD with Interface Tracking (M-CFD with IT) simulation

- **Multi-phase CFD with Interface Tracking (M-CFD with IT) simulation can be enabled** with advances in computer technologies.

- M-CFD with IT **sensitively reflected with artificially set interface tracking algorithm.**

- It is desirable **to validate accuracy using experimental data**.

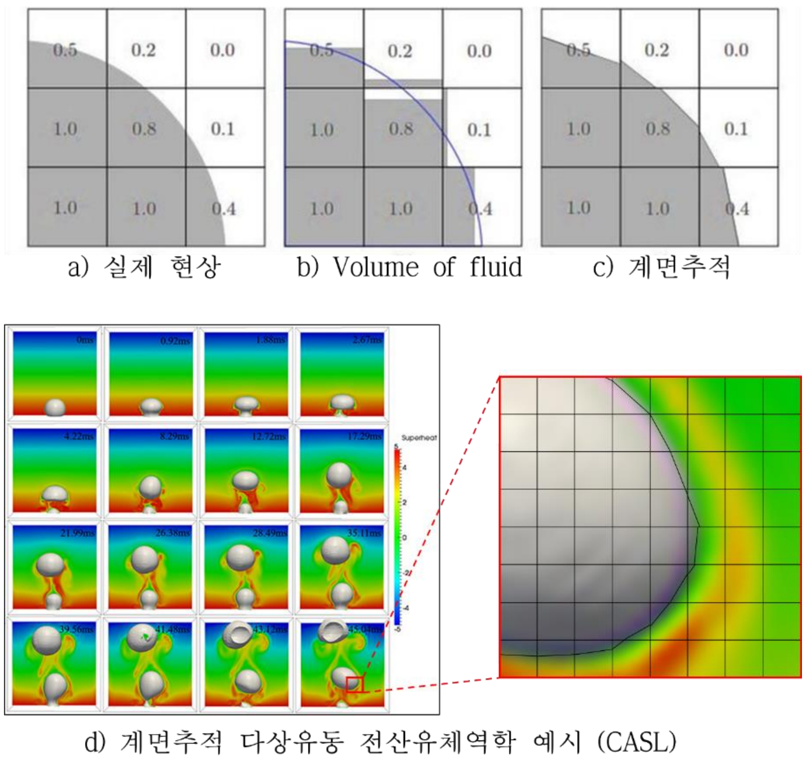


Figure 5. Multi-phase CFD with Interface Tracking*

*M.Li, I.A.Bolotonov, "Nucleate Boiling Simulation using Interface Tracking Method"
*V.Patel, "Numerical and Experimental Study of Droplet Generation and Coalescence using Microcapillaries in an Emulsification Process"

1. Introduction

Motivation : Limitations of Existing Visible Light Boiling Experiment Results

Figure 6. Visualization of Flow Boiling Using Visible Light in this Study Group

- However, **using visible light** can cause **serious distortion of light at the interface.**
- **Visualization with X-ray can solve the problem of visible light** due to parallel rays and small diffraction by wavelength.

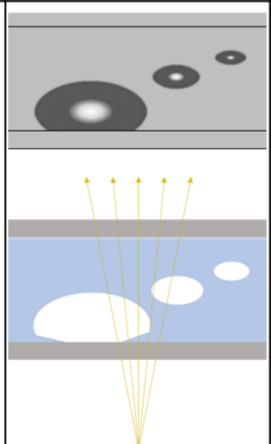
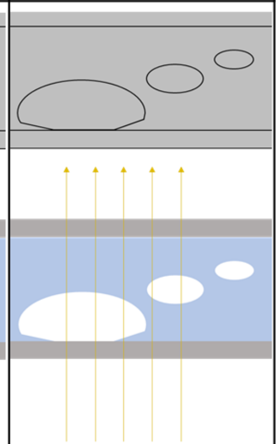
	Visible light	Synchrotron X-ray
Resolution	~10 μm	~2 μm
Distortion	O	X
Visualization		
Beam type	Scattered	Parallel

Figure 7. Comparison with Visible Light and X-ray

PLS - II

Motivation & Goal : X-ray Experiment and Validation of M-CFD with IT

- As a result, until April of this year, we can obtained **visualization data from a subcooled flow single bubble nucleate boiling** using X-ray.

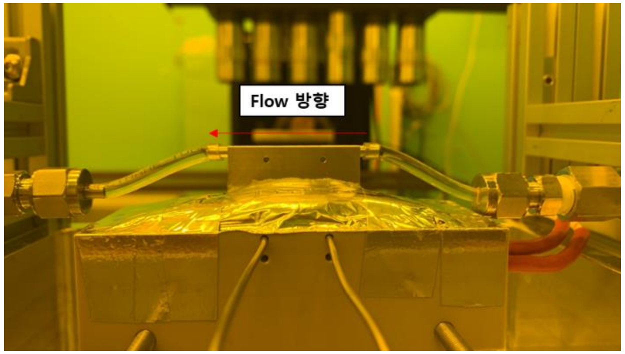


Figure 8. Test section


Figure 9. Beam line set up of PAL II experiment

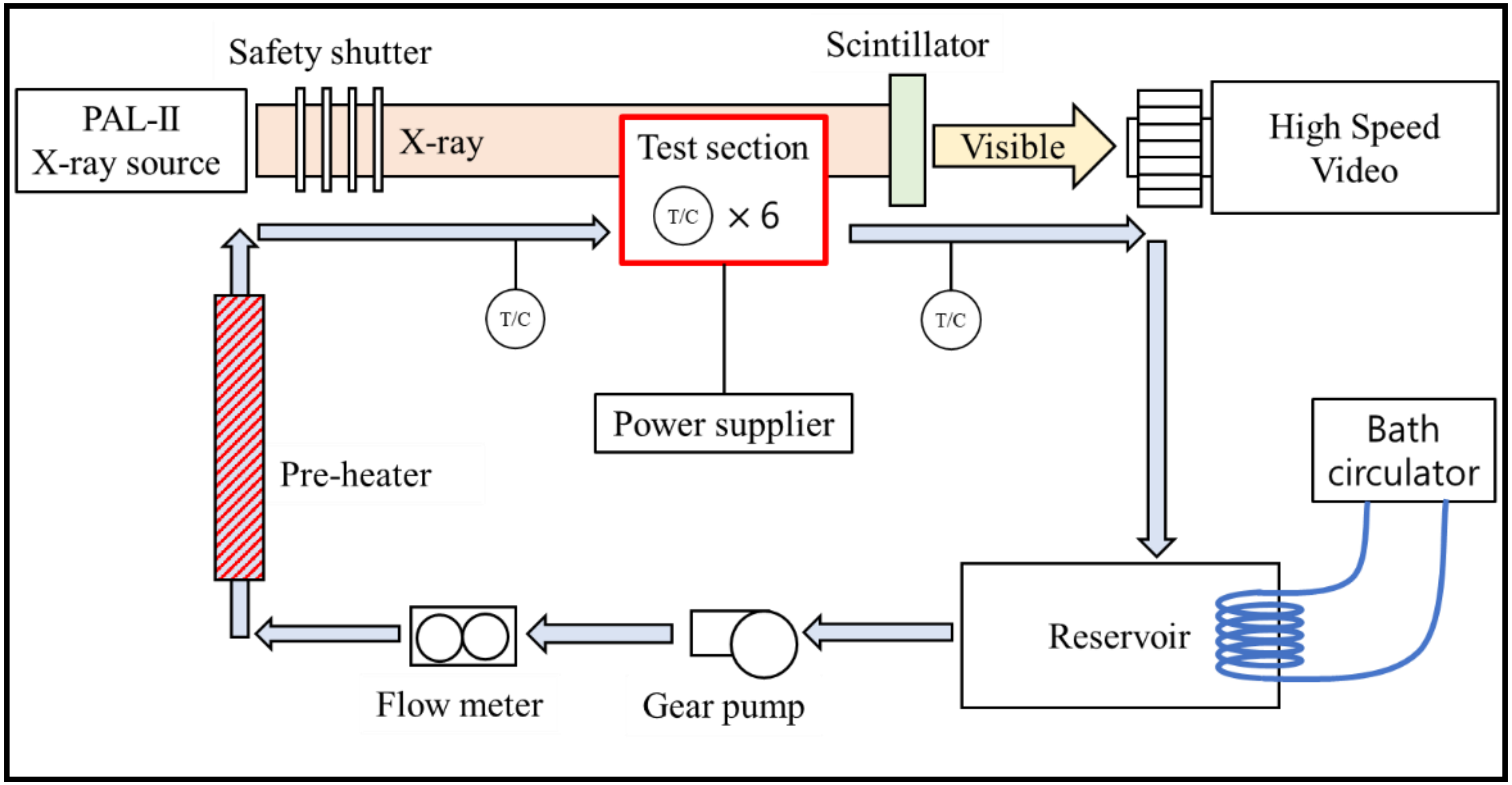
- With the X-ray visualization data, **M-CFD with IT simulation was validated**.

- **OpenFOAM, a CFD tool**, was run to simulate the bubble growth results obtained through the experiment.

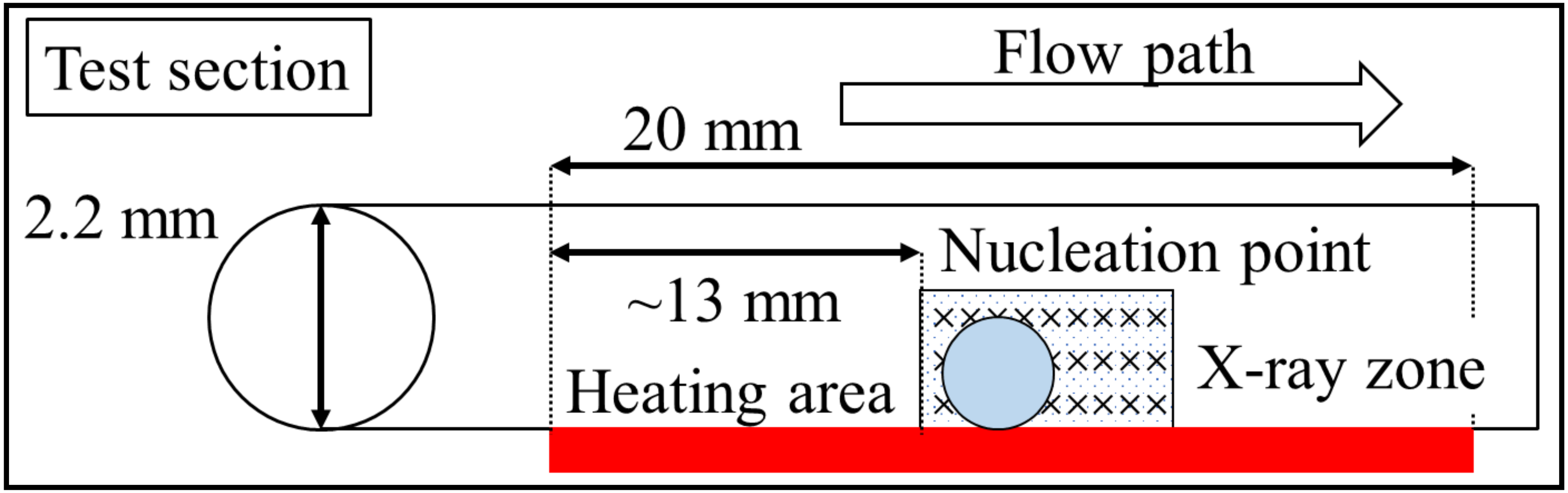
Project Goal → Simulation of the Subcooled Flow Nucleate Boiling Situation & Optimization for Related Simulation Environment.

2. Experiment

Schematic of Experimental Apparatus : Flow Loop



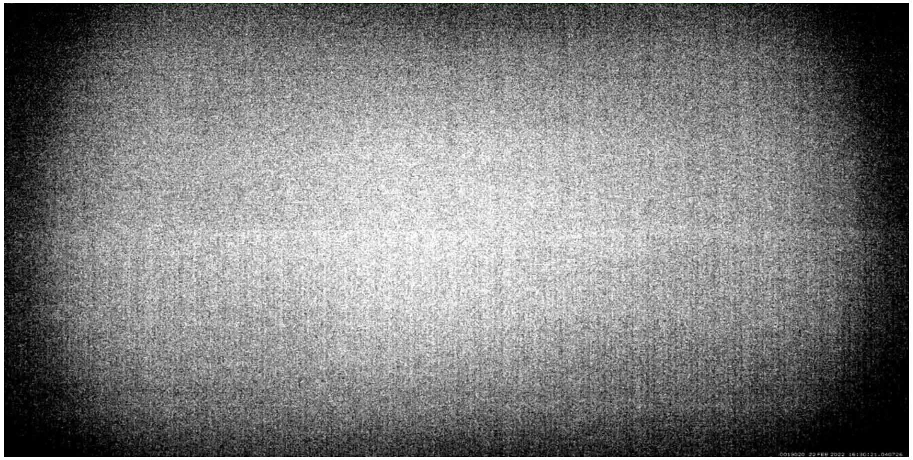
Schematic of Experimental Apparatus : Test Section



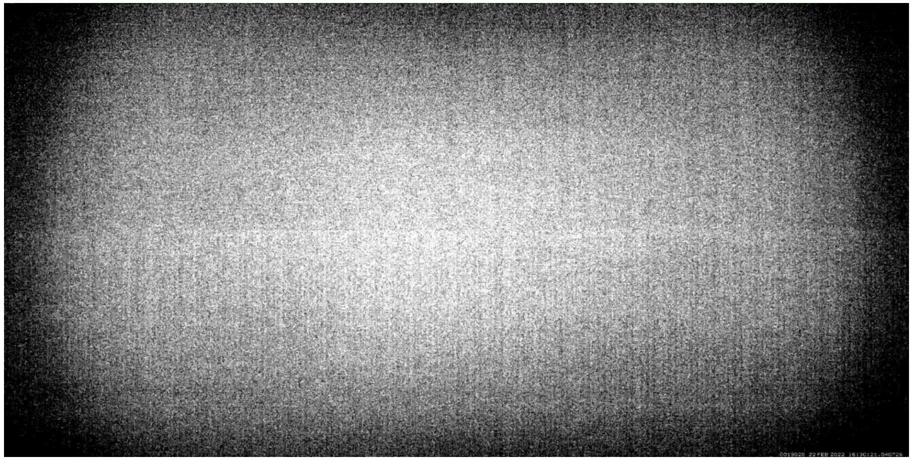
2. Experiment

Condition of Experiment & Visualization Results

Subcooling	Heat Flux	Distance from heating start	Mass Flux
9.7 K	$190\ \mathrm{kW/m^2}$	13 mm	$90\ \mathrm{kg/m^2}s$



Exposure time : 30 us, Frame rate : 4000 Hz,



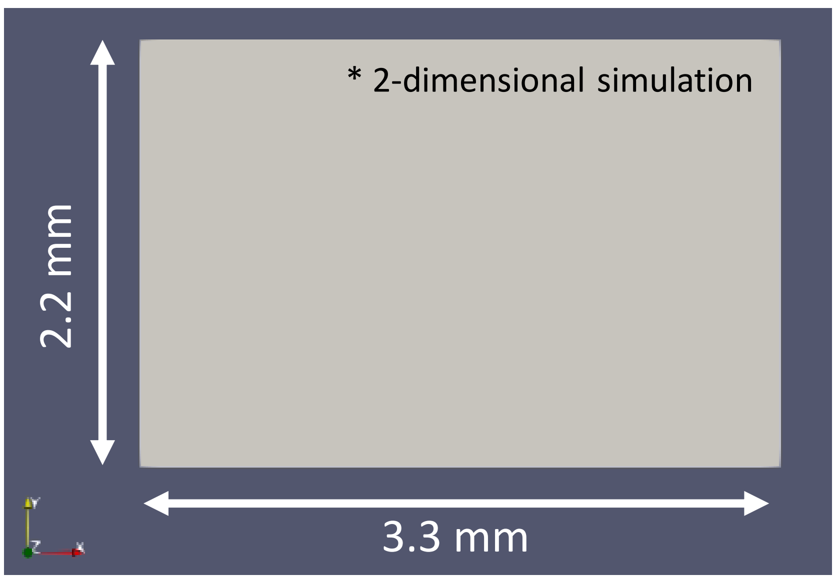
Red highlight at interface

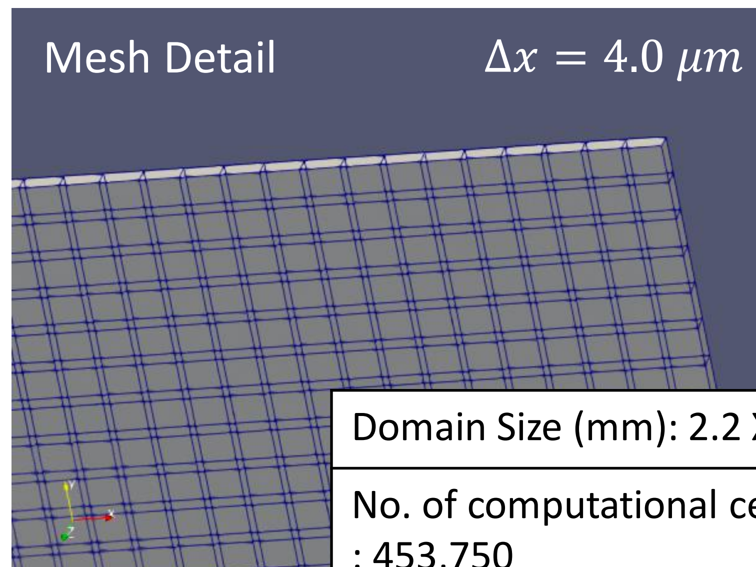
3. Simulation

Solver

- InterMassTransFoam is an interFOAM-based solver capable of M-CFD with IT.
- It implements **heat and mass transfer** and is designed **to incorporate the latest heat transfer variables** such **as interface thickness according to mesh size, thermal resistance at the interface, and thermal diffusion constant.**

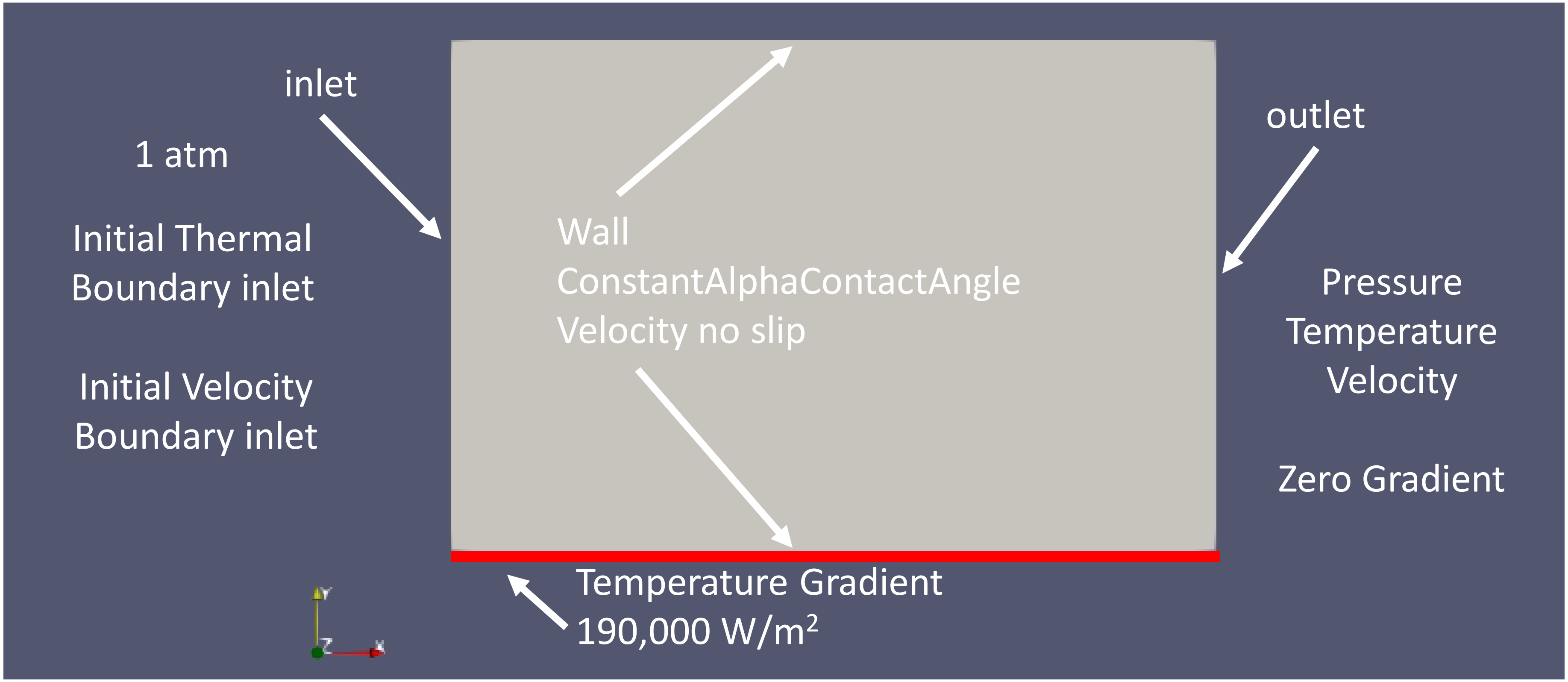
Geometry of Simulation





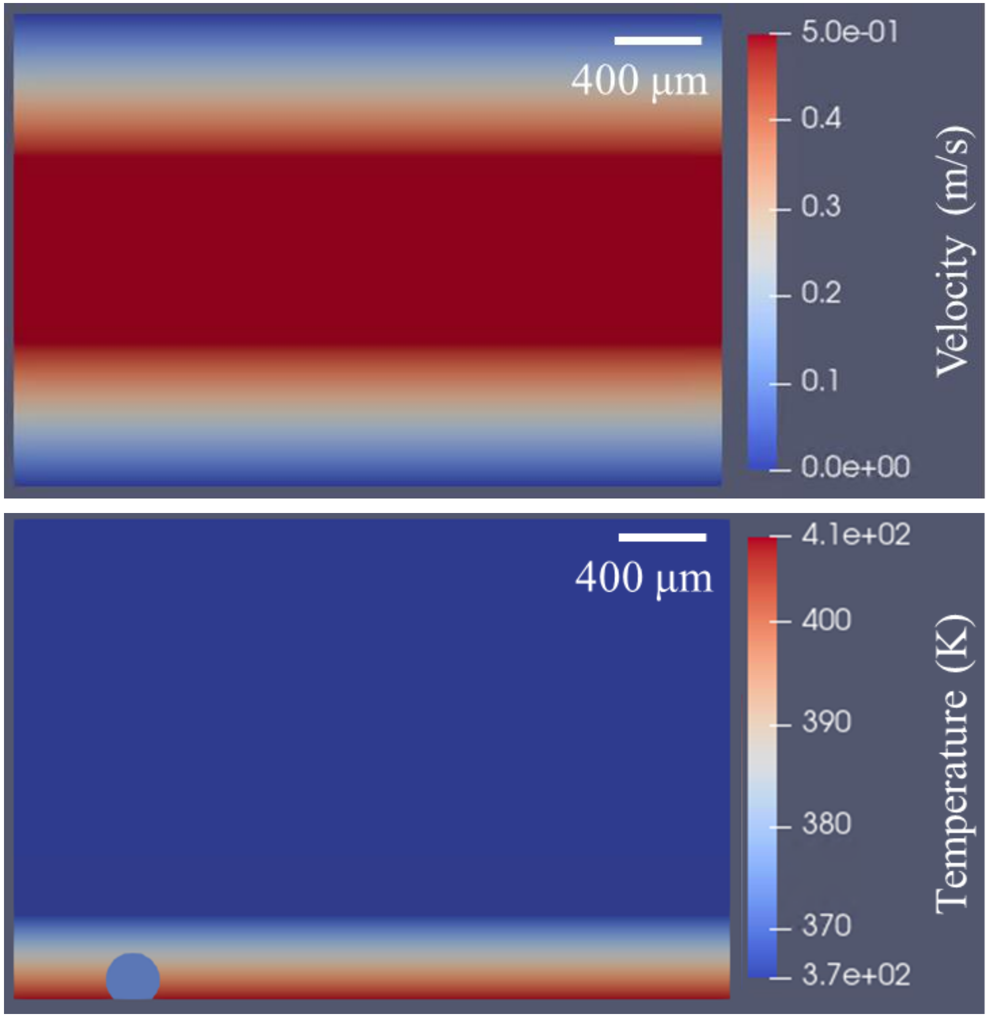
Domain Size (mm): 2.2 X 3.3
No. of computational cells : 453,750

Boundary


inlet
1 atm
Initial Thermal Boundary inlet
Initial Velocity Boundary inlet
Wall
ConstantAlphaContactAngle
Velocity no slip
outlet
Pressure
Temperature
Velocity
Zero Gradient
Temperature Gradient
190,000 W/m²

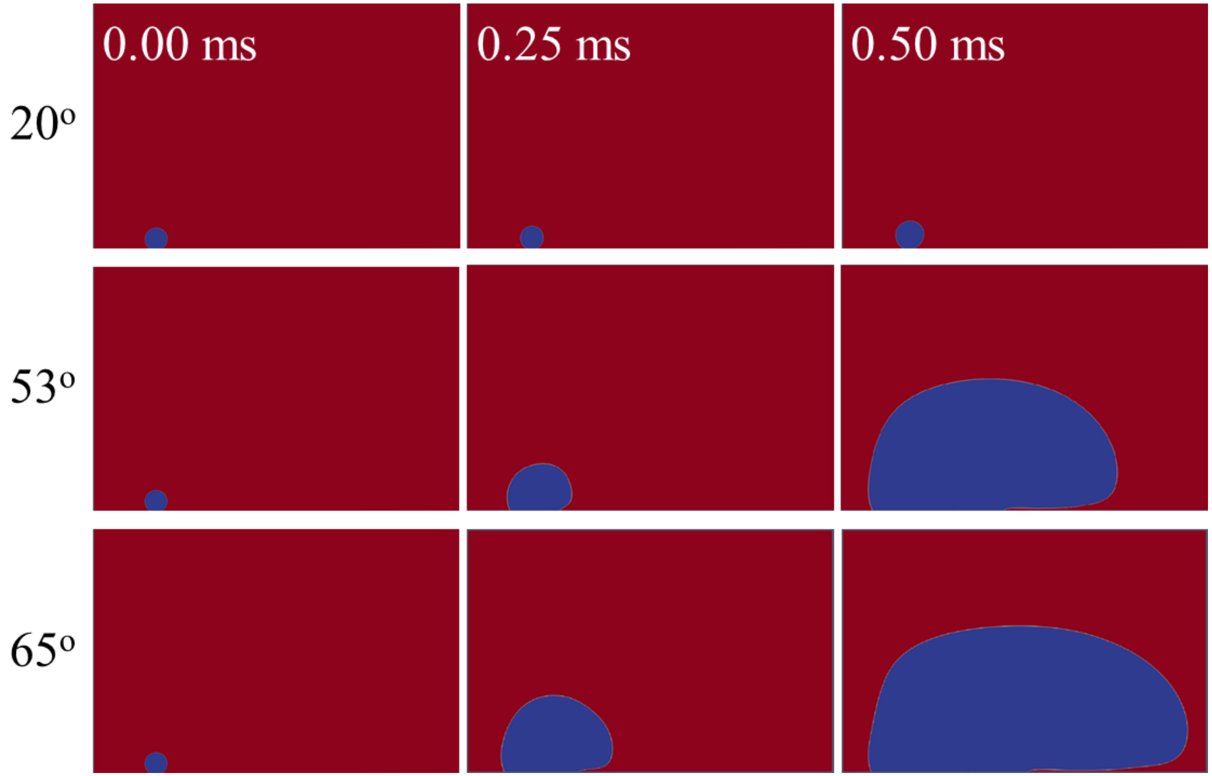
Initial Condition

- **A circle with a radius of 100 μm** was assumed to be an arbitrary bubble nucleation seed for initial condition.
- **The channel flow without mass transfer** was simulated.
- **The initial velocity boundary layer and the initial thermal boundary layer** is assumed.



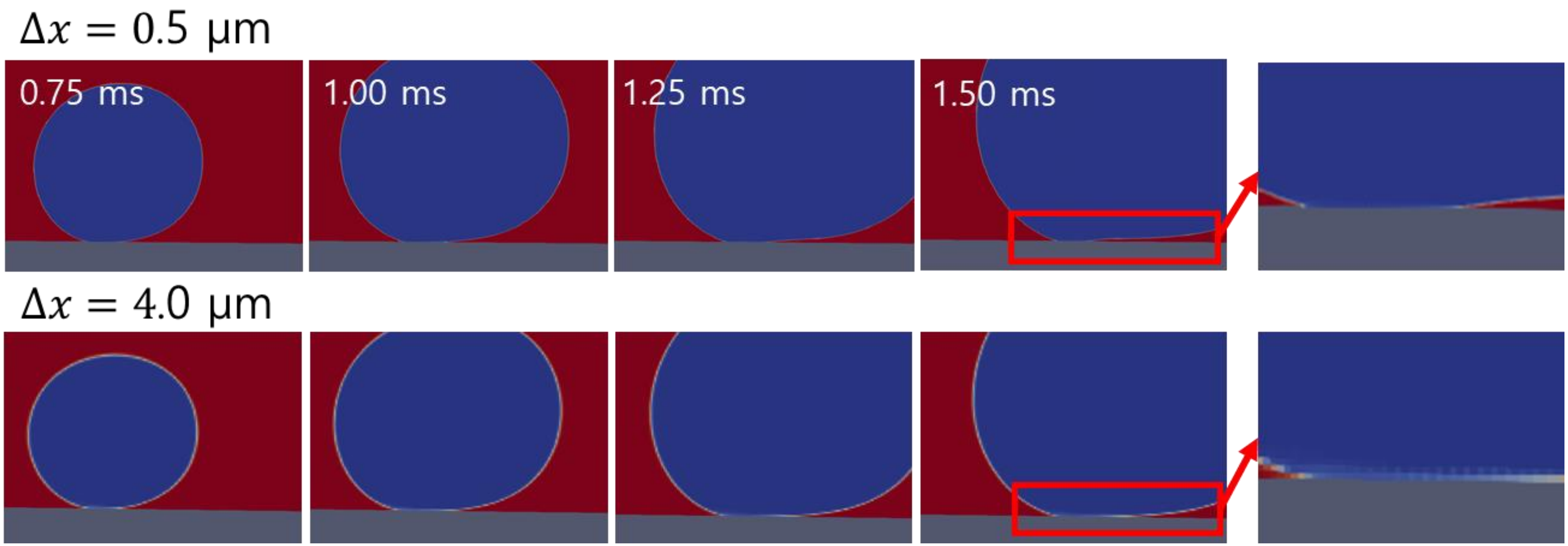
Contact angle sensitivity test

- **Sensitivity test with contact angle was conducted.**
- Three values were used: **20º**, experimentally observed value, **53º**, and **70º**.
- **The growth tendency changes** according to the contact angle.
- For the validation of this simulation, **20º was selected** that showed similar results to the experimental results.



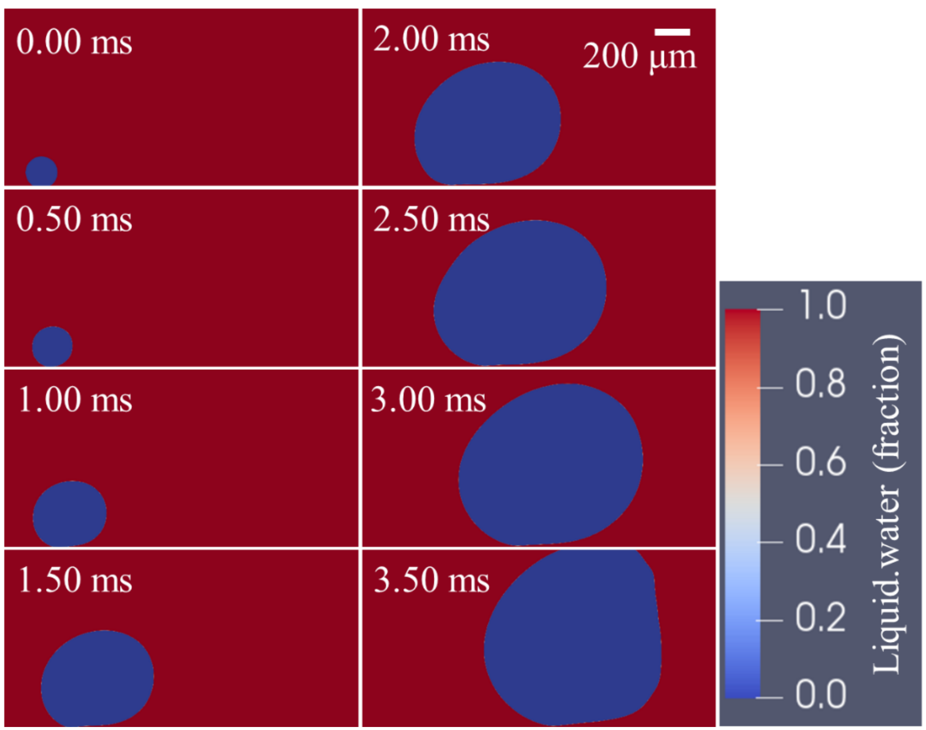
Mesh size sensitivity test

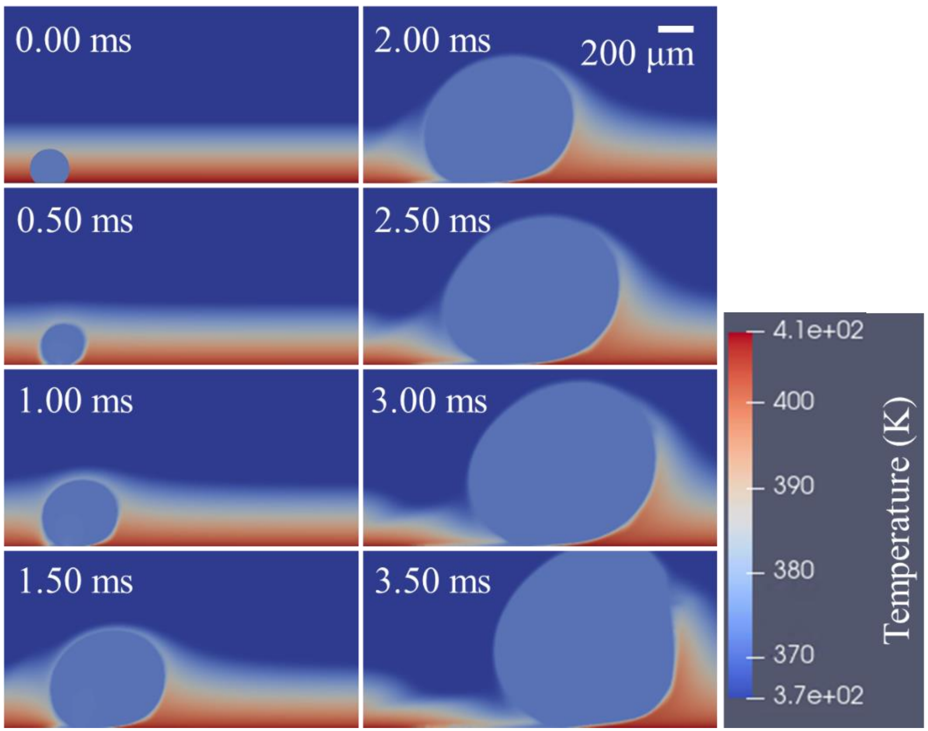
- **Changes by mesh size were tested.** We compared the results for $\Delta x = 4.0$ µm and $\Delta x = 0.5$ µm.
- The growth of bubbles in the overall range did not changed significantly.
- However, **changes of microlayer** is noteworthy.



Bubble Growth and Temperature Profile

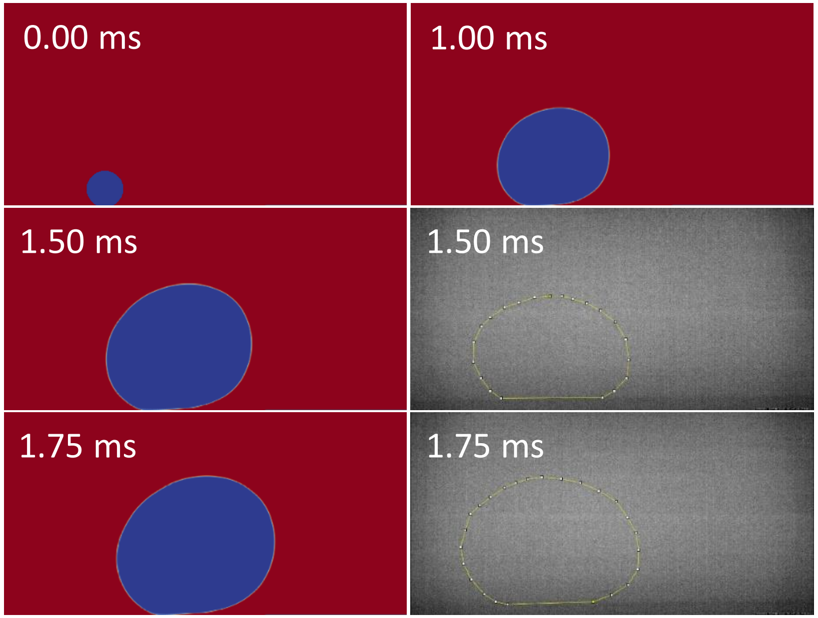
- $\Delta x = $ **0.5 µm** and **20° of contact angle was selected for comparison with experiments.**
- These are a general bubble growth tendency and the temperature profile.



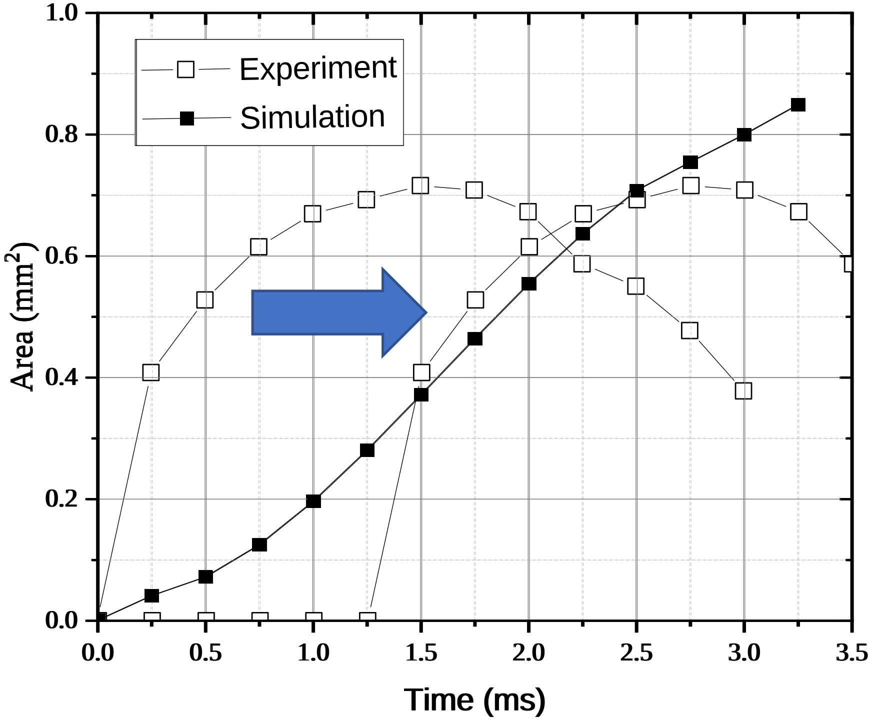


Comparison with simulation and experiment

- **The bubble size changes** in experiments and simulations were compared.
- **Rapid growth in the early stages of bubble nucleation** has not yet been simulated.
- The growth trend was similarly followed, but **bubble departure** was not confirmed.



Simulation vs Experiment



4. Conclusion

Conclusion

- 2D single bubble simulation under subcooled flow condition was conducted.
- Sensitivity tests of contact angle and mesh size were tested.
- Comparisons with experiments were made.

Future works

- **Rapid growth** in the early stages of bubbles by i**nertia growth** should be confirmed.
- It shall be confirmed in later stages, such as the **departure and condensation**.
- **heat transfer variables** such as interface thickness according to mesh size, thermal resistance at the interface, and thermal diffusion constant should be tested.
- Due to **the limits of the experiment**, it is **difficult to identify the temperature and velocity profile**, so the sensitivity test shall be added.

End of Presentation

Q & A