Visualization Experiment for Sliding Bubble Behaviors on a Horizontal Tube Heater

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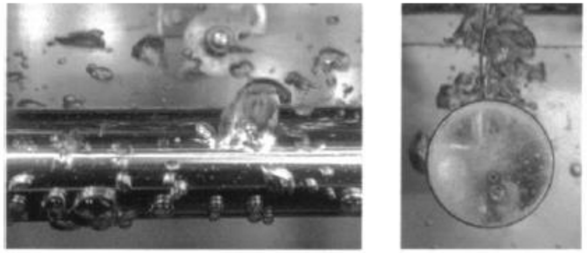
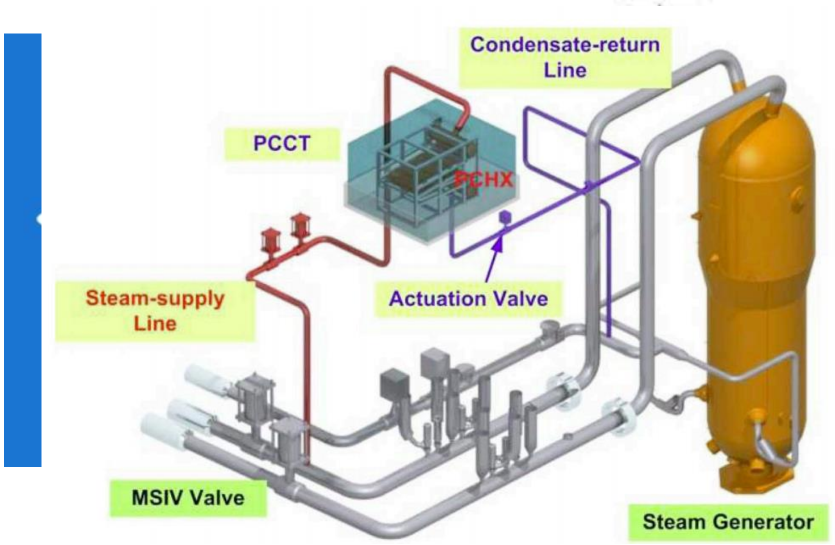
Contents

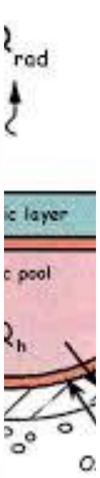
❖ Boiling heat transfer on downward heating surface

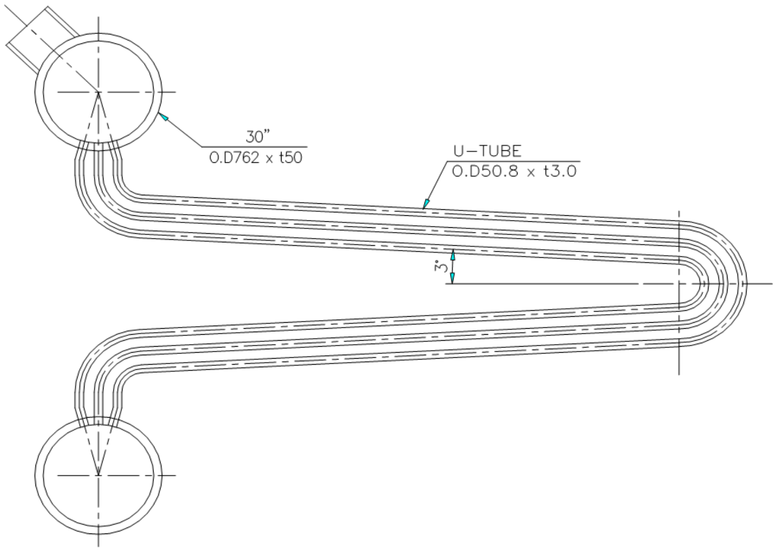
- Horizontal tube, inclined channel and hemisphere
  - Steam generator U-tube
  - External Reactor Vessel Cooling
  - Fuel rod, Calandria tube, Calandria tank of CANDU
  - Core catcher
  - Passive Auxiliary Feed-water System (PAFS)

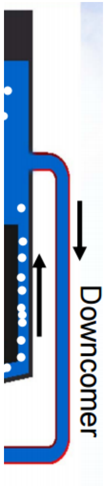


- Kang, 2005









- Calandria tube of CANDU
- IVR-ERVC (Duspiva, 2014)
- Core catcher (Lee, 2013)

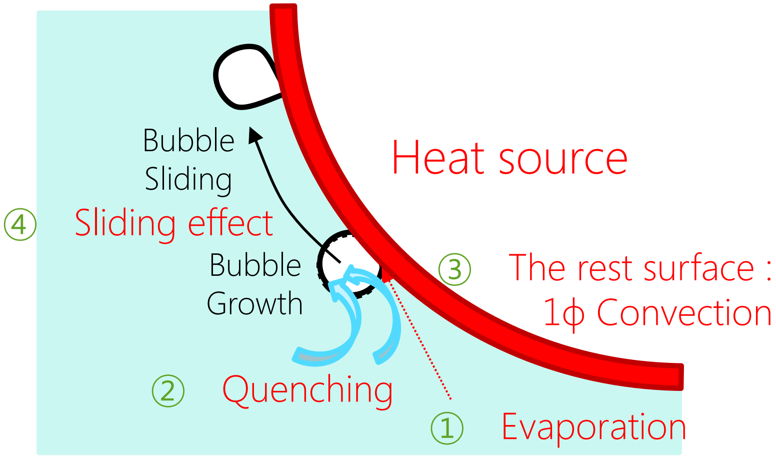
Duspiva, "Comparison of In-Vessel and Ex-Vessel Retention" (2014)
Kang, "Local Pool Boiling Coefficients on the Outside Surface of a Horizontal Tube", Journal of Heat Transfer (2005)

1. Introduction

❖ Heat partitioning model

- Widely accepted boiling heat transfer model in Computational Fluid Dynamics(CFD)
- Decomposition of heat transfer mechanism
  - ① Evaporation
  - ② Quenching
  - ③ Single-phase convection

\+ ④ Sliding bubble effect(vertical surface, tube)



- Schematic of boiling heat transfer on tube outside

$$q_{tot} = (\overset{①}{q_{me}} + \overset{②}{q_{tc}})x_{st} + \overset{④}{\boxed{(q_{mes} + q_{tcs})}}x_s + \overset{③}{q_{sp}}$$

$$q_{mes} = \frac{1}{6}\pi\left(\boxed{d_l{}^3} - \boxed{d_d{}^3}\right)\boxed{\rho_v h_{fg}}\boxed{n_b f}$$

$$q_{tcs} = 2\sqrt{\frac{\boxed{k_f \rho_f c_{pf}}}{\pi \boxed{t_w}}}\boxed{\Delta T}\boxed{n_b t_w f}\int_{\boxed{t_d}}^{\boxed{t_l}} K\boxed{d(t)U_b(t)}dt$$

🟥 : Bubble parameters

🟦 : Fluid properties

Kurul, "Multidimensional effects in forced convection subcooled boiling", Heat Transfer Conference (1990)
G. Sateesh, "Analysis of pool boiling heat transfer: effect of bubbles sliding on the heating surface", International Journal of Heat and Mass Transfer(2005)

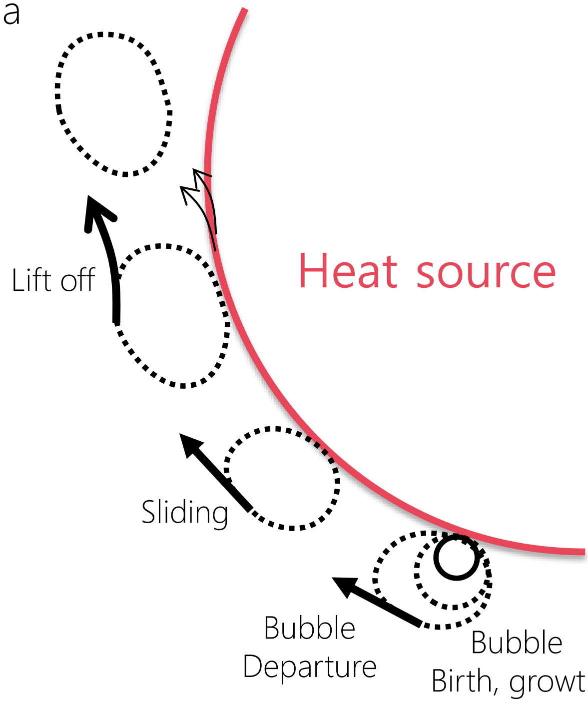
1. Introduction

Sliding bubble behaviors

- Bubble parameters
  - Lift-off diameter, departure diameter, bubble frequency, waiting time, bubble diameter, bubble velocity etc.
- Distinctive characteristics of a sliding bubble on a curved surface
  - Location of the nucleation site
  - Continuously varying force direction of the forces exerted on a bubble

⇨ Needs of experimental results on horizontal tube

- Life-cycle of bubble

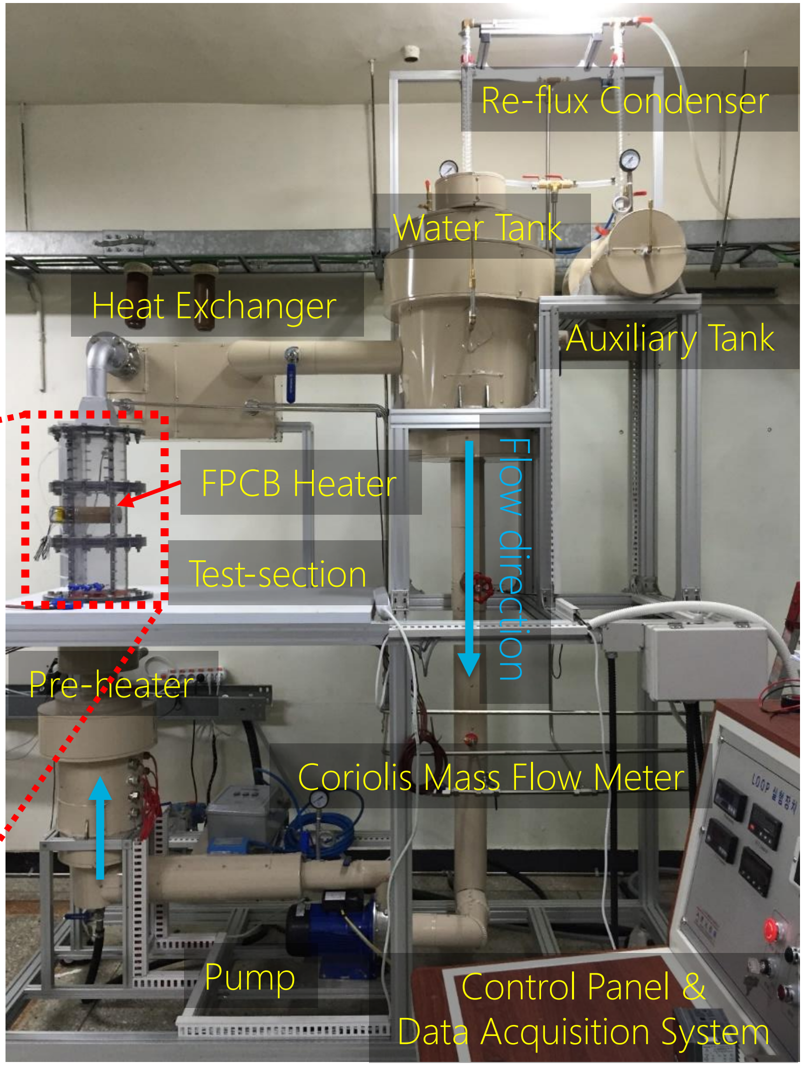


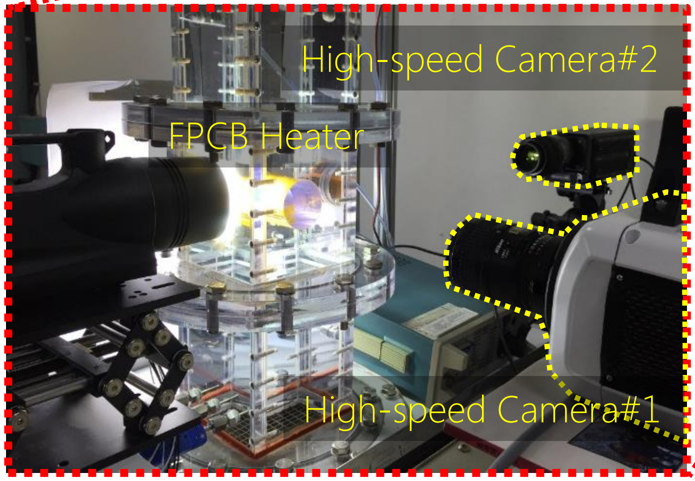
Objective of this study

- To visualize the boiling bubble on horizontal heater
- To measure key parameters of boiling heat transfer model

2. Visualization Experiment (1/6)

- Measurement method
  - 2 Synchronized high-speed cameras
  - Shadowgraphy for bubble motion
- Experimental condition
  - Atmospheric pressure
  - Nearly saturation temperature
  - 15~30mm/s flow velocity





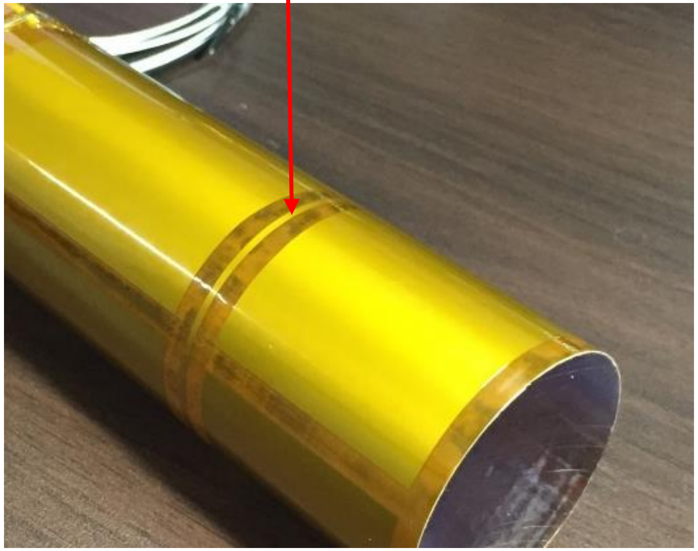
2. Visualization Experiment (2/6)

❖ Flexible Printed Circuit Board(FPCB) heater

- To overcome the visual interference by overlapping bubbles
- Narrow heating width (0.5mm, 1.0mm, 1.5mm)

- Boiling on conventional cartridge heater

- Boiling on FPCB heater



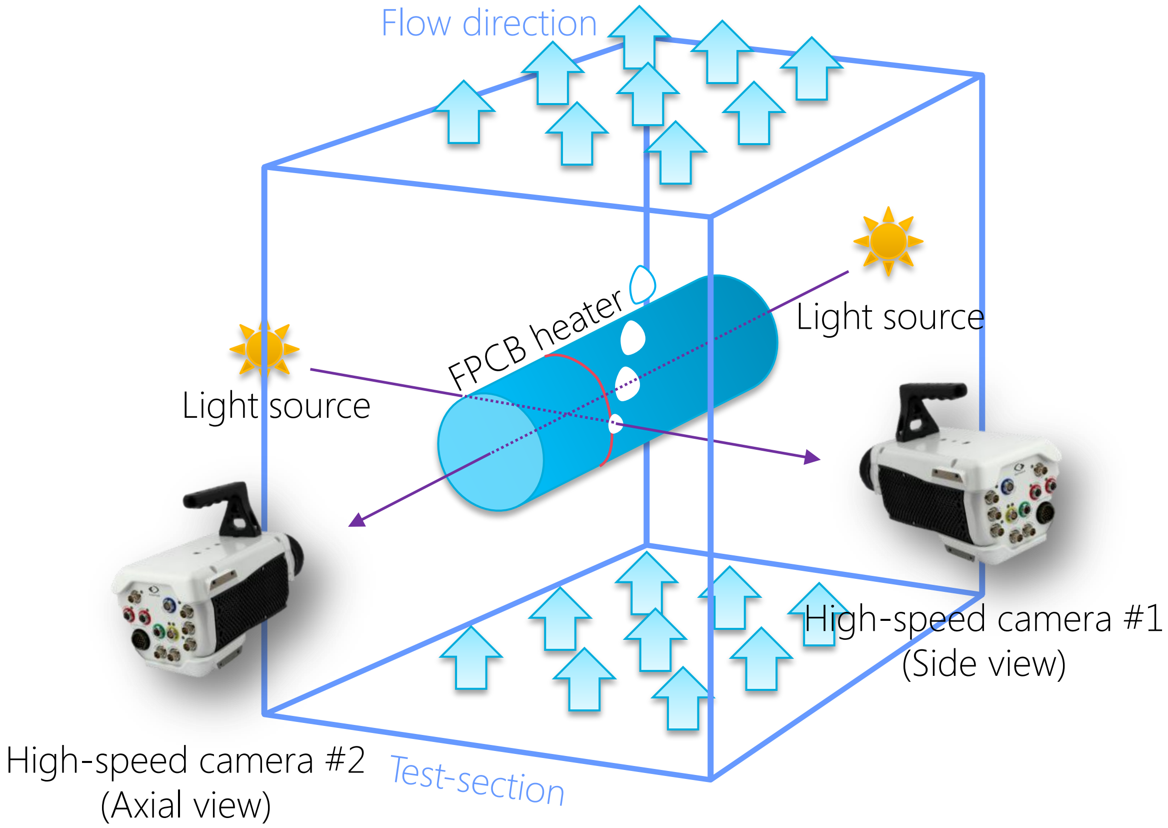
Heating area

- FPCB heater

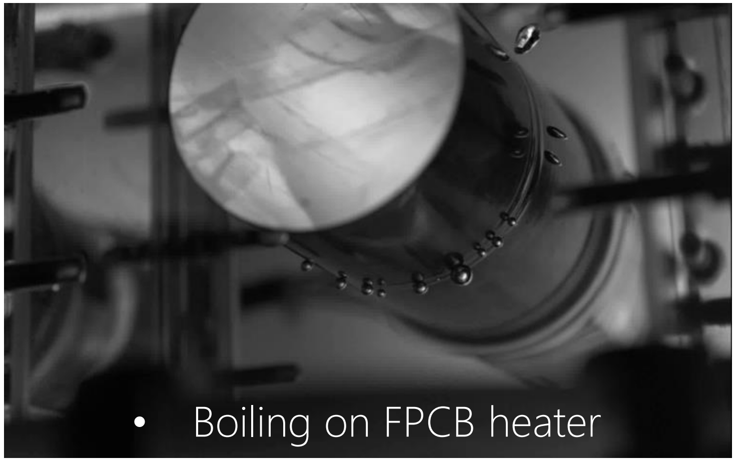
2. Visualization Experiment (3/6)

❖ Visualization and phase separation

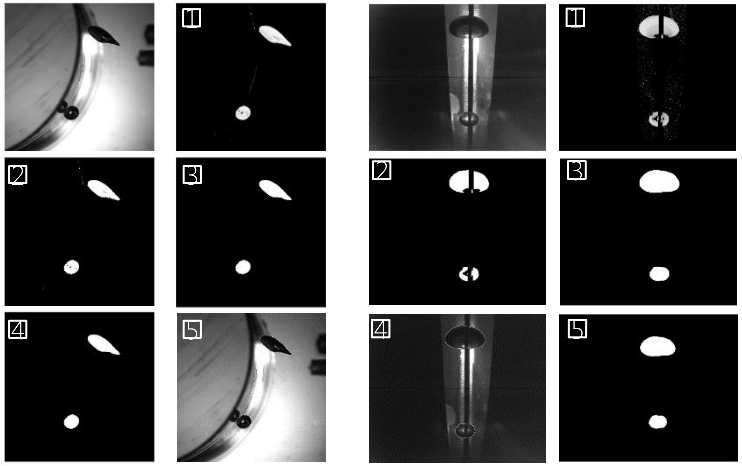
- Stereoscopic observation
- Shadowgraphy



- Schematic of visualization systems setup



- Boiling on FPCB heater



- Phase discrimination process

1. Image complement & background removal
2. Binarization
3. Filling holes + convex hull
4. Verification

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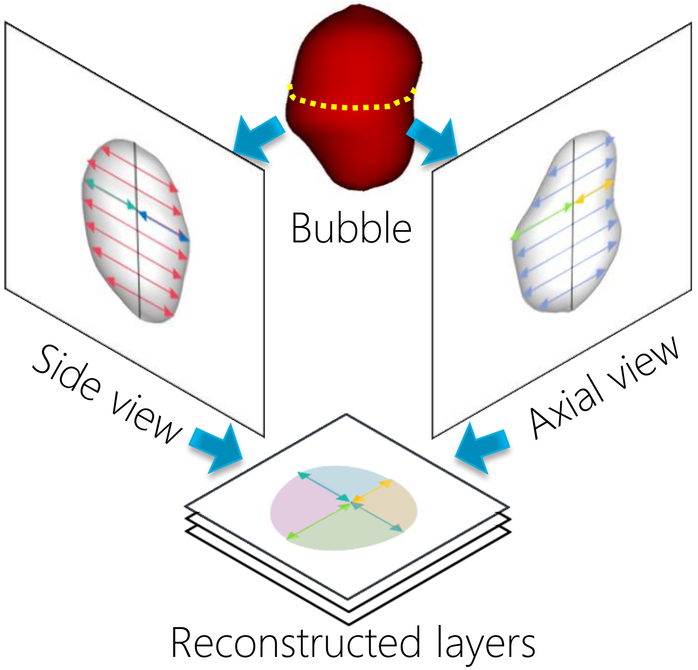
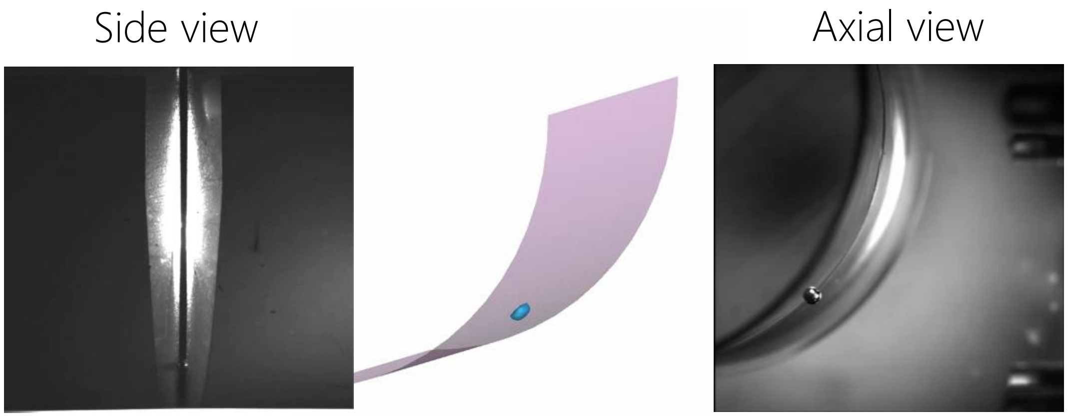
2. Visualization Experiment (4/6)

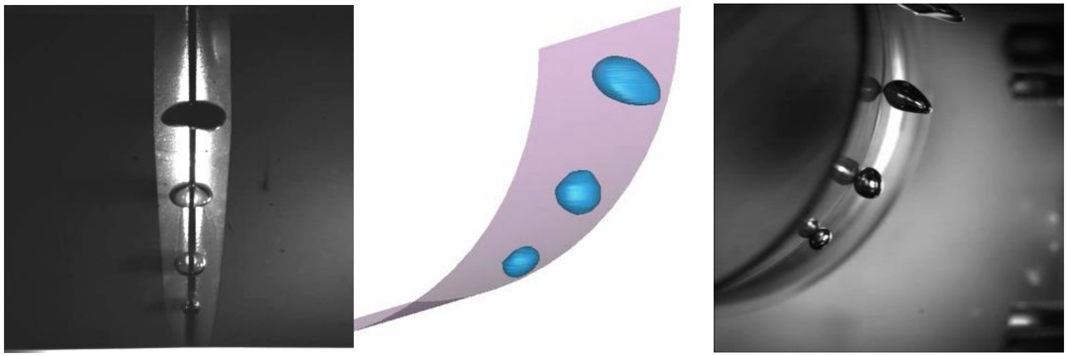
❖ 3-Dimensional bubble reconstruction



- Reconstruction process



- 95kW/m^2, 27.6mm/s, 45°



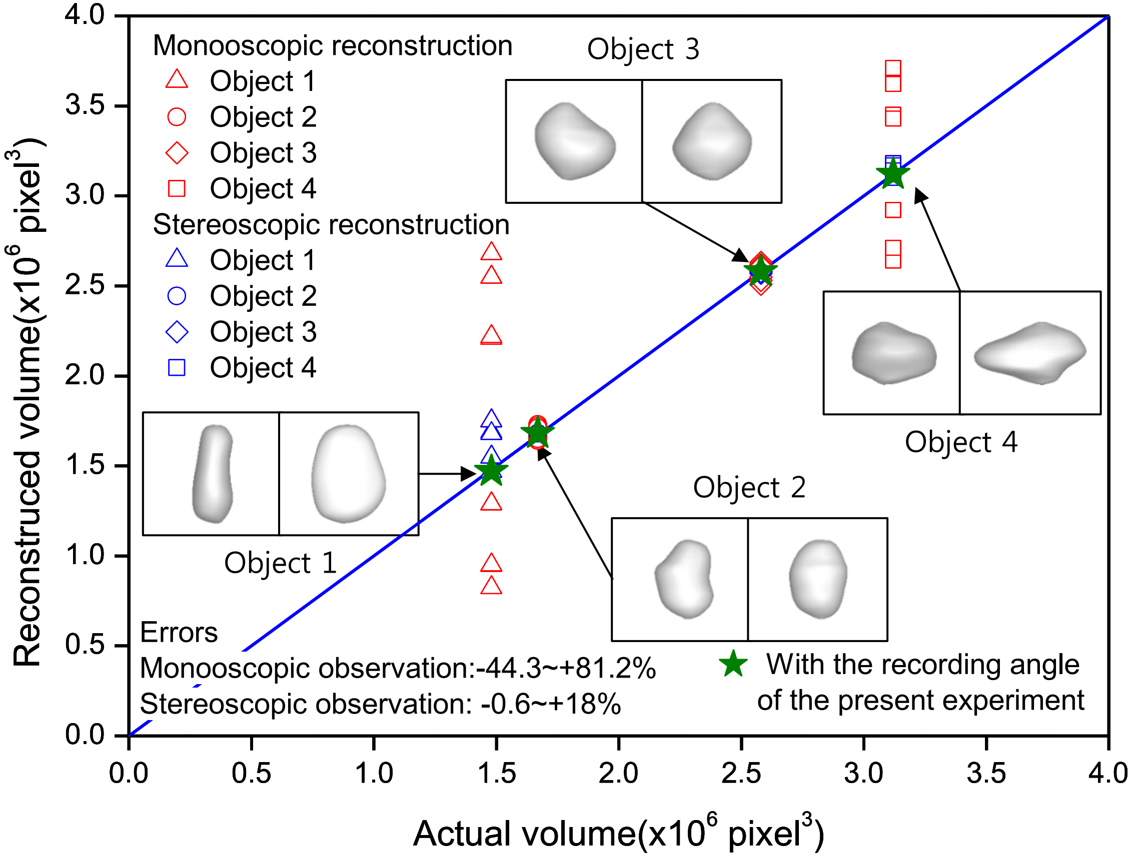
- 129kW/m^2, 27.6mm/s, 45°

- Reconstruction results

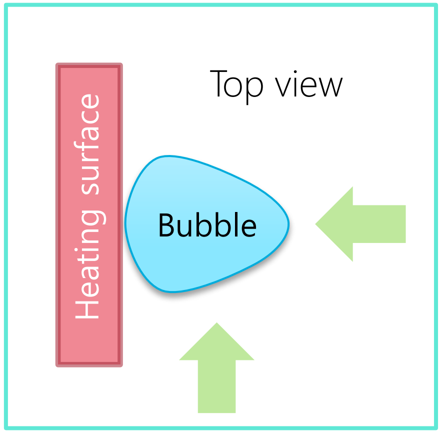
2. Visualization Experiment (5/6)

Validation of 3D reconstruction

- Using various phantoms created with CAD
  - Visualization on major & minor axis of objects shows under 1% volumetric error.
  - It was conclude that the stereoscopic measurement can give reliable results.



- Recording angle



S.J. Kim, "Interfacial heat transfer of condensing bubble in subcooled boiling flow at low pressure", International Journal of Heat Mass (2011)

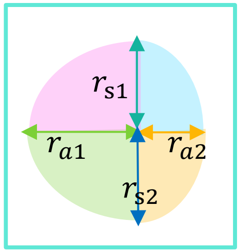
2. Visualization Experiment (6/6)

❖ Measurement of bubble parameters

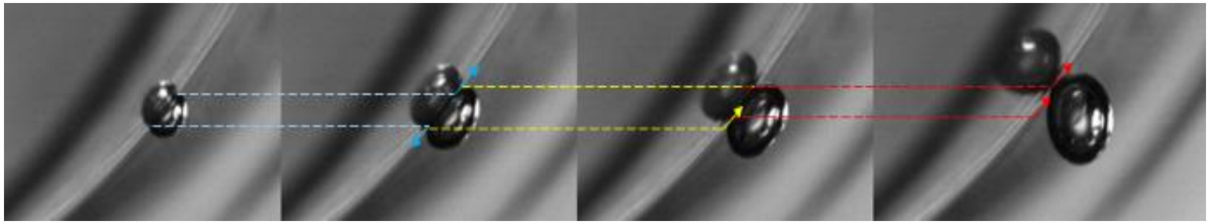
- Bubble volume & equivalent diameter
  - Sum of cross section area which consists of four different pieces of ellipses in each quadrant

$$V_{bubble} = \sum_{bottom}^{top} \frac{1}{4}(r_{a1} \times r_{s1} + r_{s1} \times r_{a2} + r_{a2} \times r_{s2} + r_{s2} \times r_{a1})dh$$

$$d_{equi} = \sqrt[3]{\frac{6}{\pi} V_{bubble}}$$



- Departure
  - Moment when both contact points move to same direction

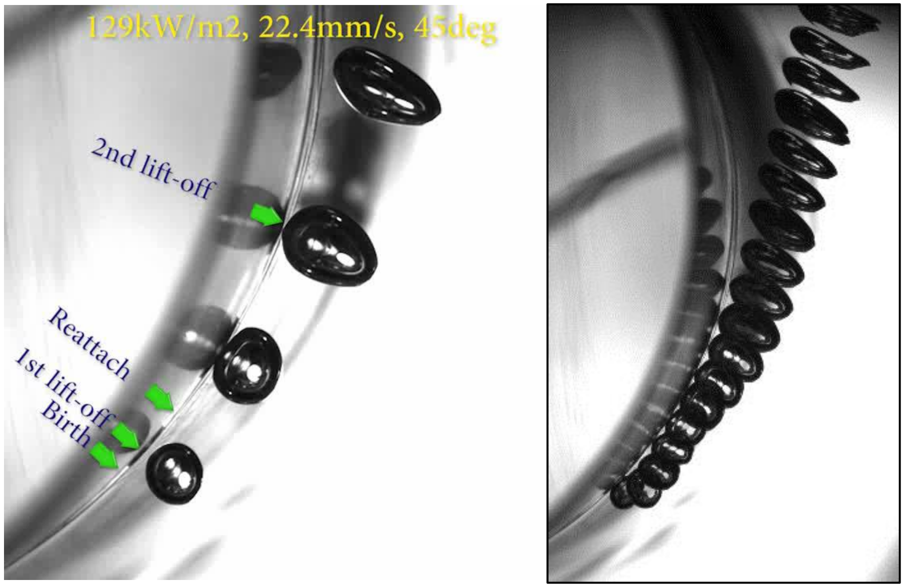


- lift-off
  - Moment when contact diameter becomes zero
- Velocity
  - Movement of center per unit time

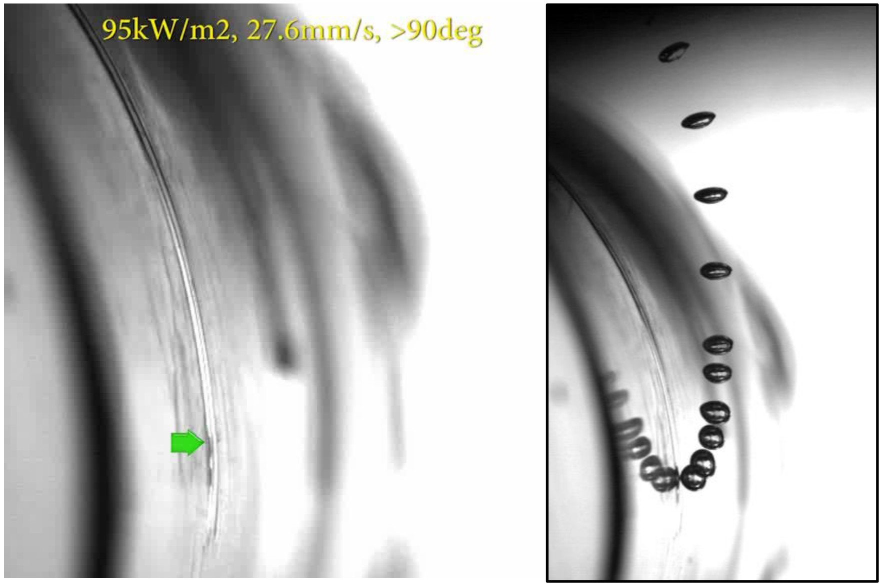
3. Experimental Results (1/6)

Phenomena description

- Sliding occurs if the nucleation site is located at lower half of the heater.
- Bubble life cycle
  - Birth – departure – 1st lift-off – reattach – sliding – 2nd lift-off



- Sliding (under 90°)

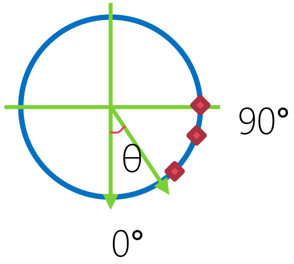


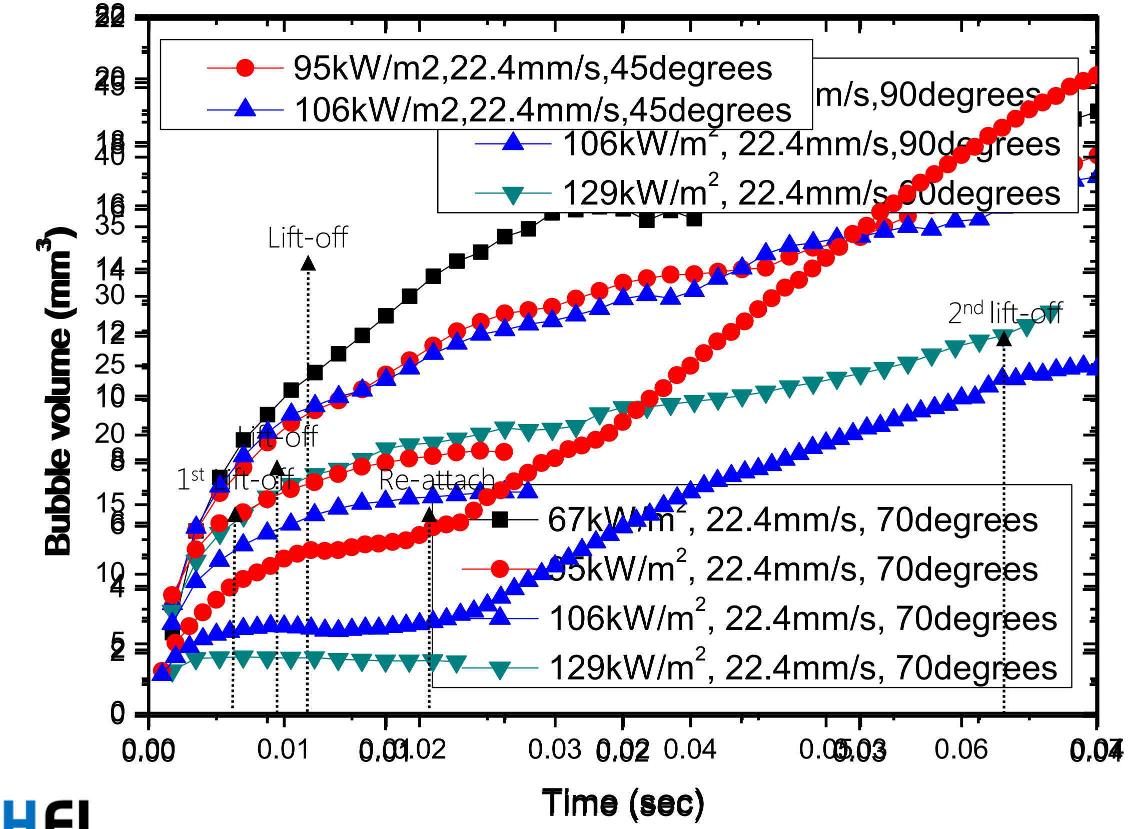
- No sliding (over 90°)

3. Experimental Results (2/6)

❖ Measured bubble parameters

- Bubble volume transient (bubble growth history)
  - The transient is closely related with the bubble life cycle.
  - Lower heat flux→ lower bubble frequency → longer waiting time → formation of superheated layer→ larger bubble volume





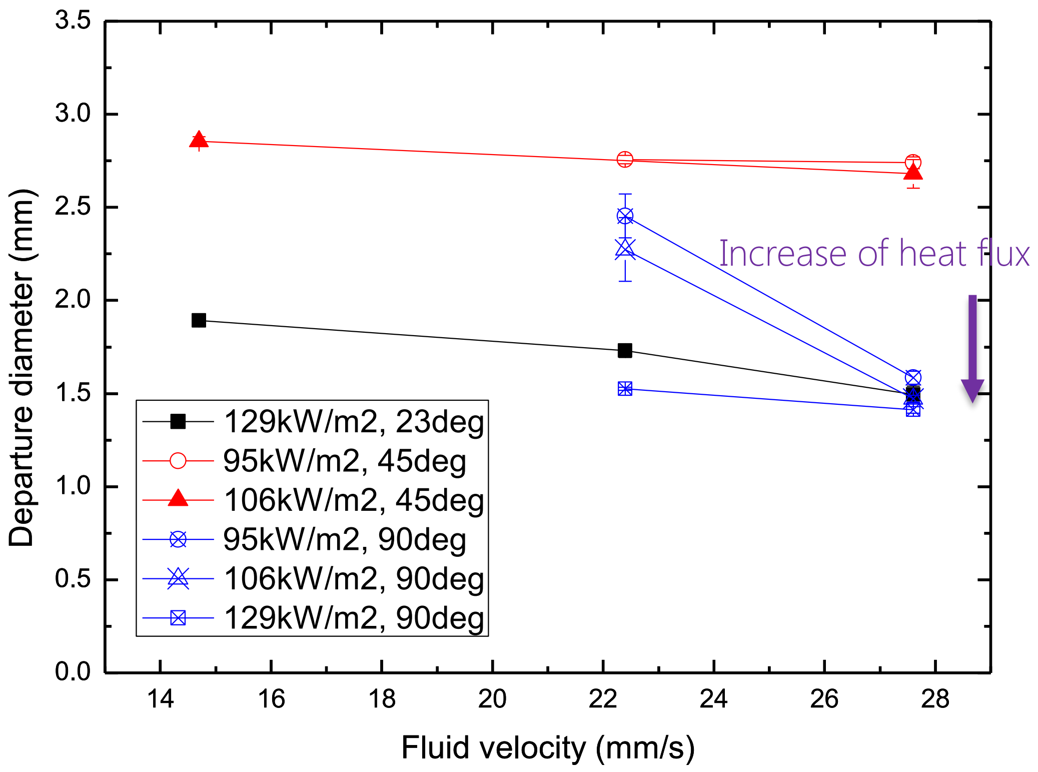
106kW/m², 22.4mm/s, 45 degrees

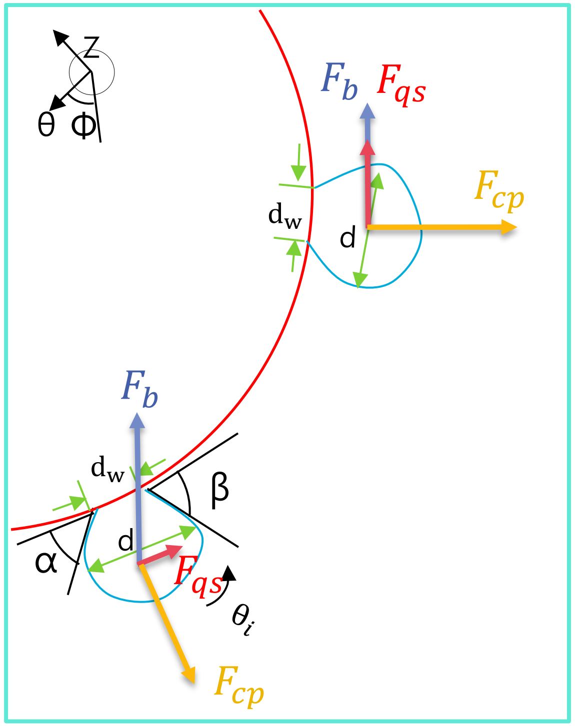
106kW/m², 22.4mm/s, 70 degrees

3. Experimental Results (3/6)

Measured bubble parameters

- Departure diameter(or 1st lift-off diameter): 1.0~3.0mm
  - Competition of forces determines the departure diameter.
    - Buoyancy force, contact pressure force, drag force
  - When the angle of nucleation site is small,
    - The normal directional forces to the surface : dominant effect on departure.





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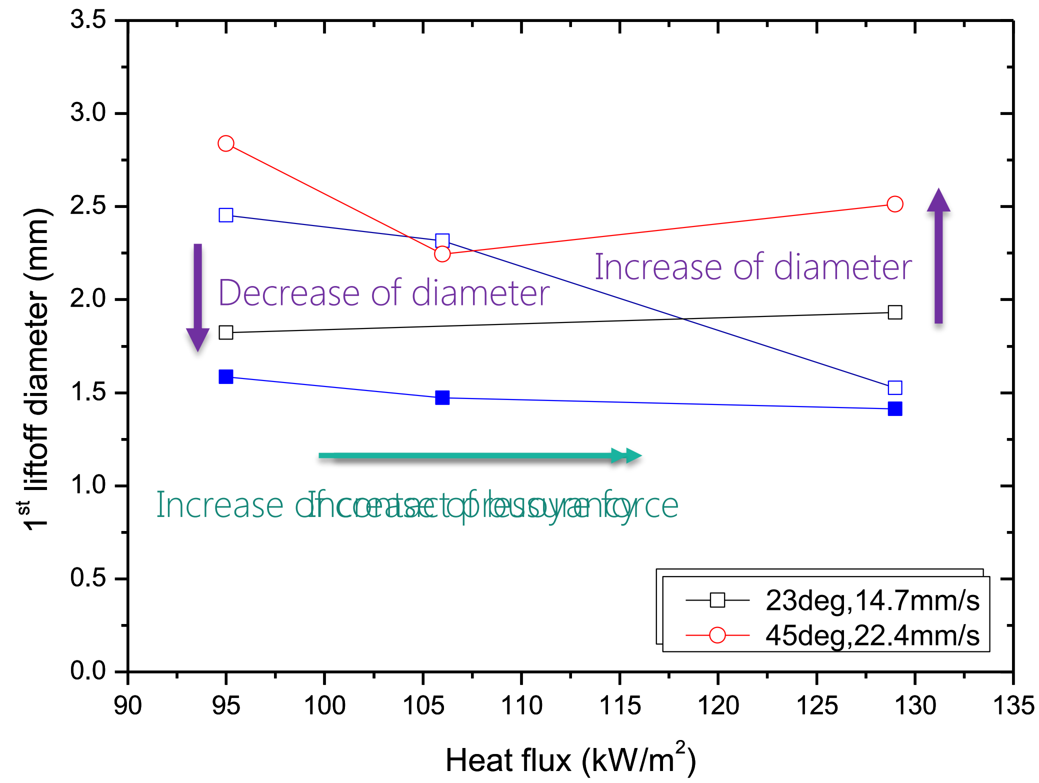
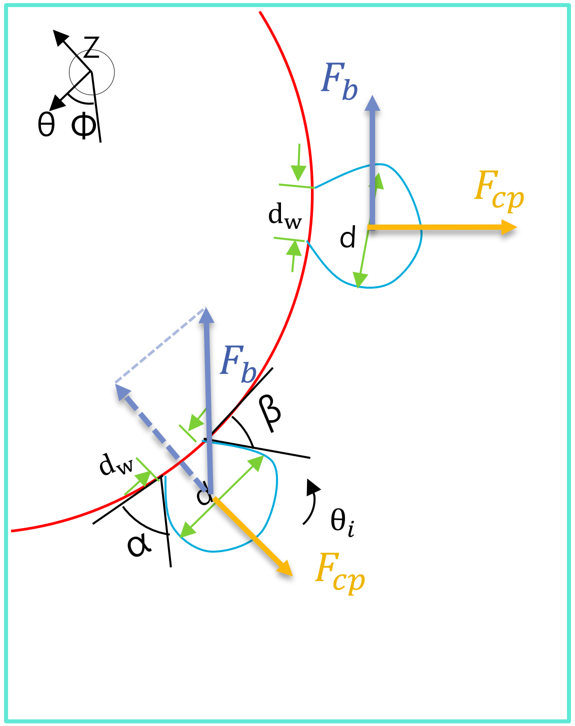
J.F.Klausner, "Vapor bubble departure in forced convection boiling", International Journal of Heat Mass Transfer (1993)
B. J. Yun, "Prediction of a subcooled boiling flow with advanced two-phase flow models", Nuclear Engineering and Design (2012)

3. Experimental Results (4/6)

- Measured bubble parameters
  - 1st lift-off diameter: 1.0~3.0mm
    - Higher heat flux → larger contact pressure force → smaller lift-off diameter
    - At 45°, 106kW/m2 → 129kW/m2 (22.4mm/s)
      : even if contact pressure force increases, 1st lift-off diameter increases due to large buoyancy.





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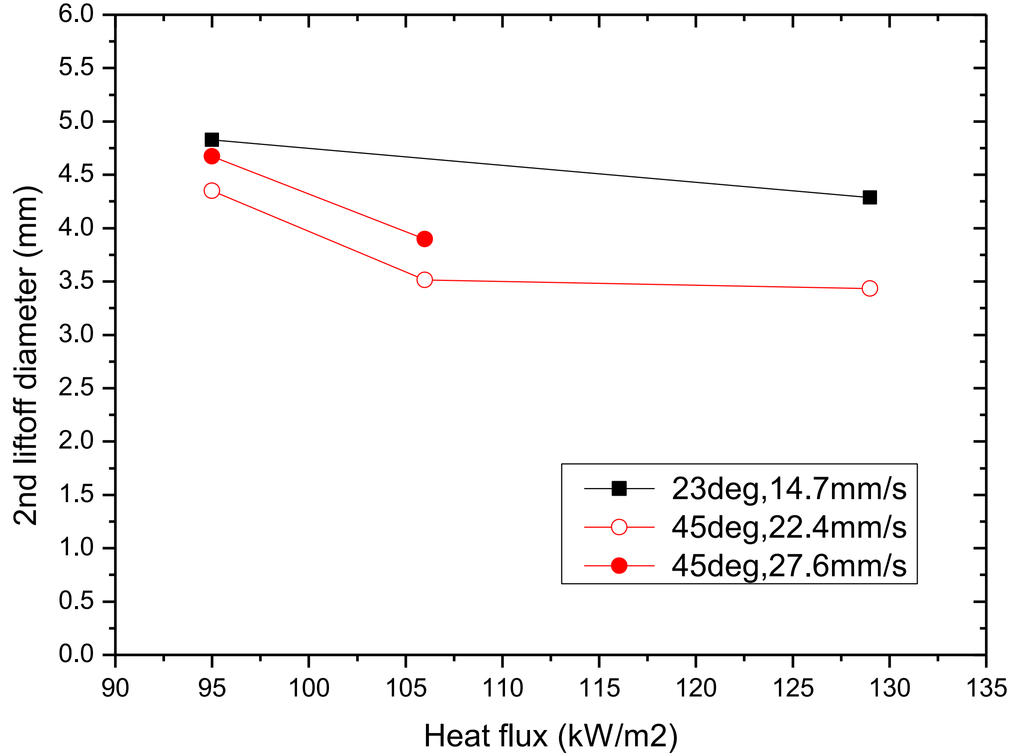
3. Experimental Results (5/6)

❖ Measured bubble parameters

- 2nd lift-off diameter: 3.0~5.0mm
  - Smaller angle of nucleation site→ longer sliding length → larger 2nd lift-off diameter
  - Lower heat flux → lower bubble frequency → larger bubble volume → larger buoyancy → moving near heating surface → larger lift-off diameter

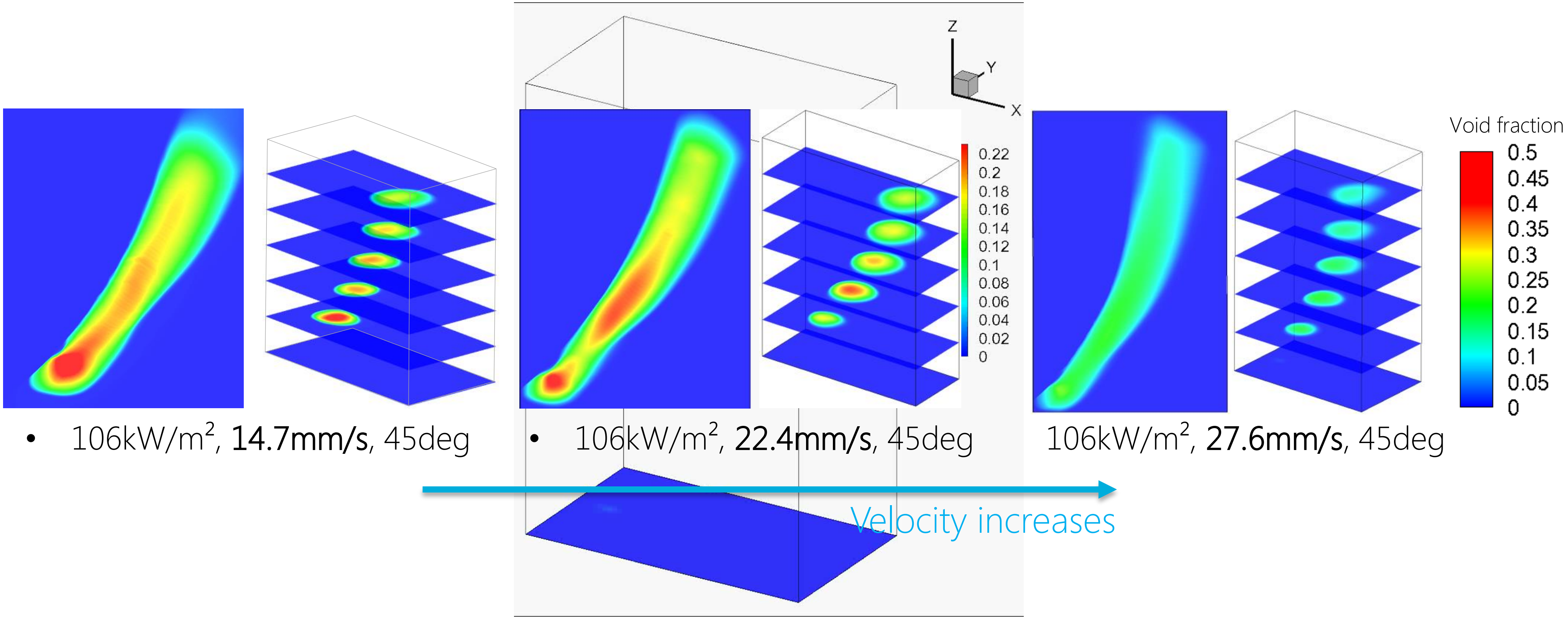


- lift-off diameter (d_l)

- Path of sliding bubble

3. Experimental Results (6/6)

- Measured bubble parameters
  - Time averaged void fraction: volume fraction of bubble
    - One of the most important parameters for CFD two-phase analysis
    - Will be used for the boiling heat transfer model validation.



- 106kW/m^2, **14.7mm/s**, 45deg
- 106kW/m^2, **22.4mm/s**, 45deg

106kW/m^2, **27.6mm/s**, 45deg

Velocity increases

4. SUMMARY

4. Summary

❖ Improvement on experimental method

- Developed FPCB heater for visualization without interference
- 3D bubble reconstruction was conducted and its error was under 1%

❖ Measuring boiling parameters

- Observed boiling phenomena on horizontal tube outside
- Measured important bubble parameters for modeling

❖ Future works

- Development of the force balance model exerted on a boiling bubble
    - To predict the bubble departure diameter and lift-off diameter
- Validation of the existing boiling heat transfer models
    - Using the time averaged void fraction data
- Improve the wall boiling heat transfer model
    - Using the force balance model + validation result

Thank you!

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