

2023 춘계 원자력 학회

# CFD 스케일 비등열전달 및 액적인자 실험 연구

-원전 적용을 위한 CFD 스케일 해석 기술 및 실험 워크샵-

2023년 5월 17일

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기계공학부 원자력시스템 전공

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- Subcooled Boiling in a 4 x 4 Rod Bundle Channel
- Boiling in an Inclined Downward Wall-heated Rectangular Channel

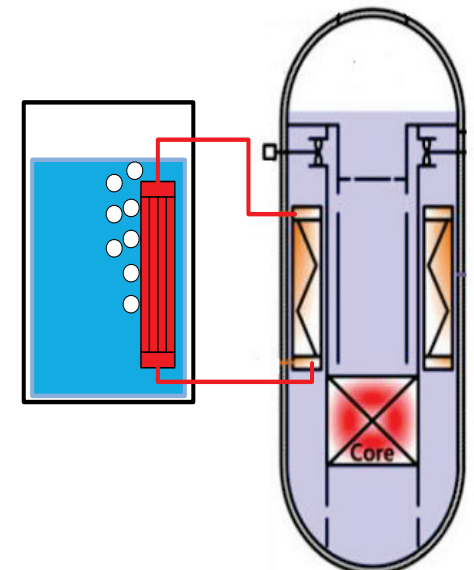
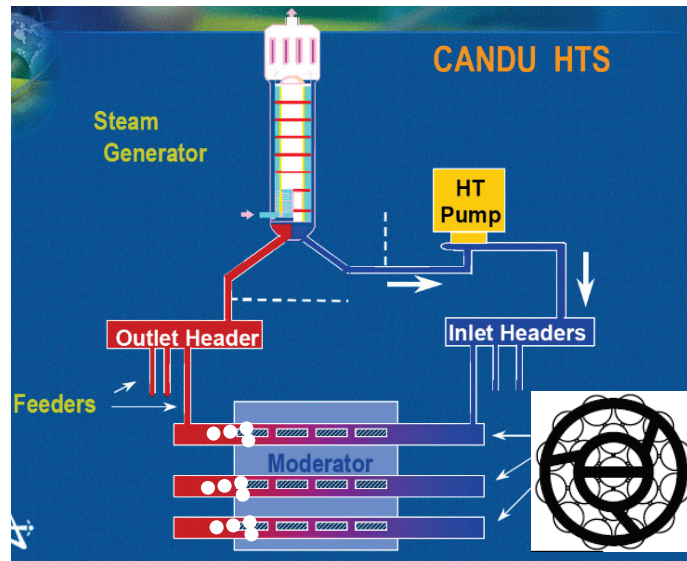
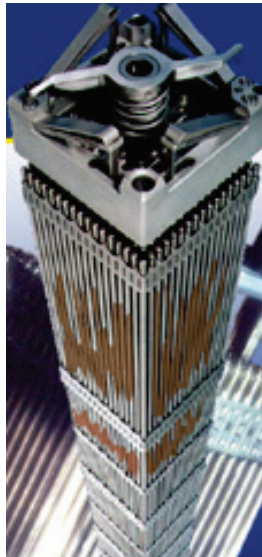
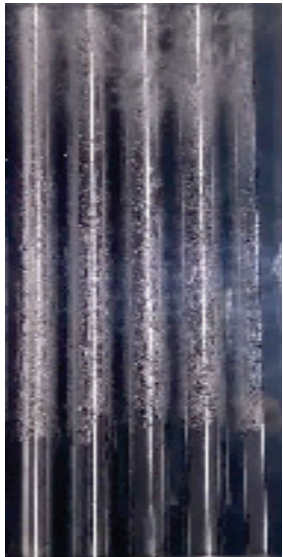
## ■ Air-water Droplet Flow Tests for LBLOCA Reflood Phase

- Droplet Parameters in a Vertical Pipe
- Droplet Parameters in a Rod bundle Channel
- Droplet Parameters in a Horizontal Pipe

# High Pressure Subcooled Boiling Test (1)

## ■ Subcooled boiling expected in the NPP

- 비등은 원전의 정상 운전과 사고 조건에서 발생하는 핵심 열수력 현상
- 핵연료 상부에서는 비등에 의한 보론 침적과 크러드 형성, 축방향 열출력 분포 왜곡
- 중수로의 노심 출구에서 기포율 20%의 과냉 비등이 발생
- 피동안전계통 열교환기에서 발생하는 비등 열전달은 열제거 성능에 영향



# High Pressure Subcooled Boiling Test (2)

## ■ 과냉 비등 다차원 실험 데이터는 저압 조건에 국한

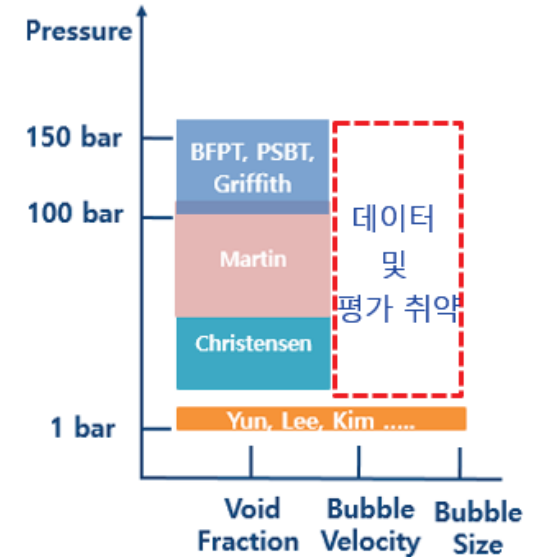


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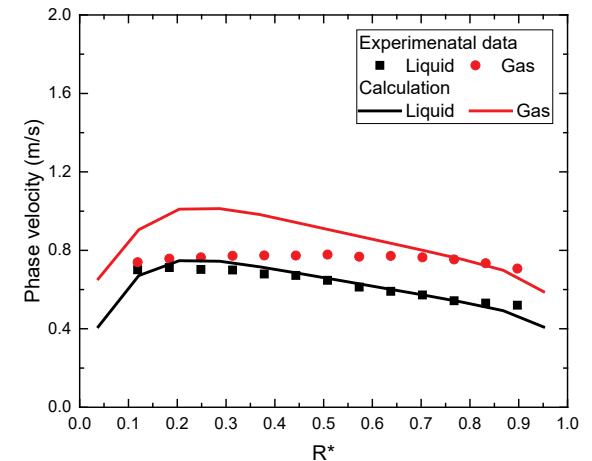
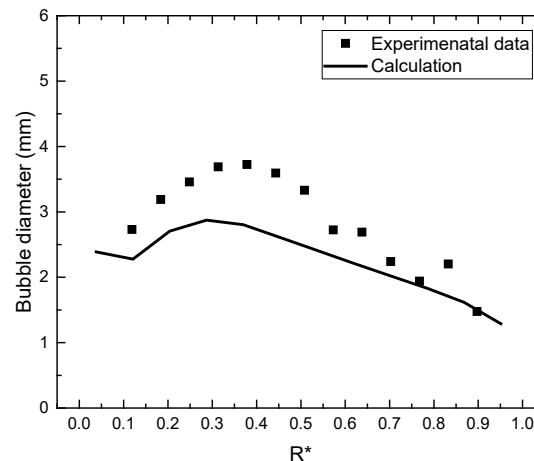
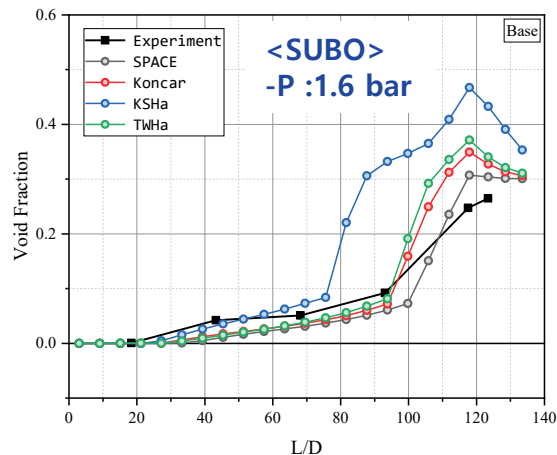
-Fluid : water  
-Pressure : 1.5 bar

<F-SUBO>

-Fluid : R134a  
-Pressure : 27 bar

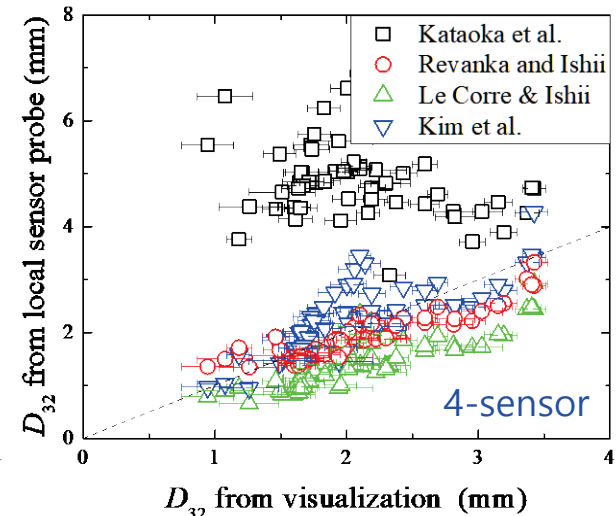
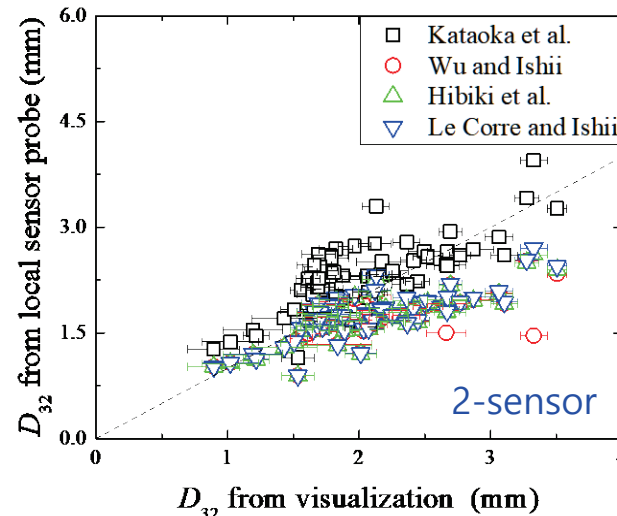
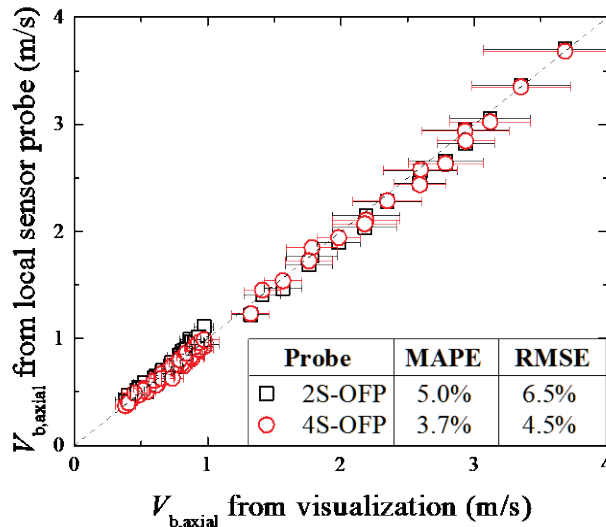
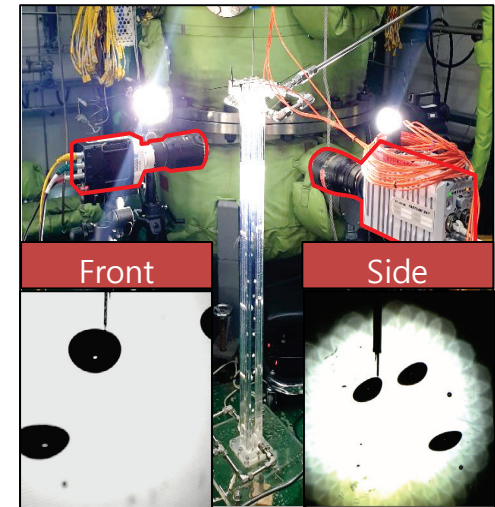
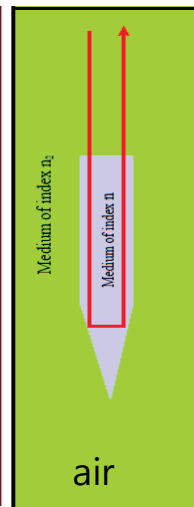
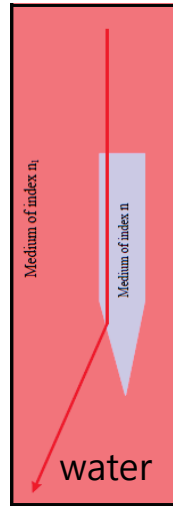


<Experimental range of existing subcooled boiling data>



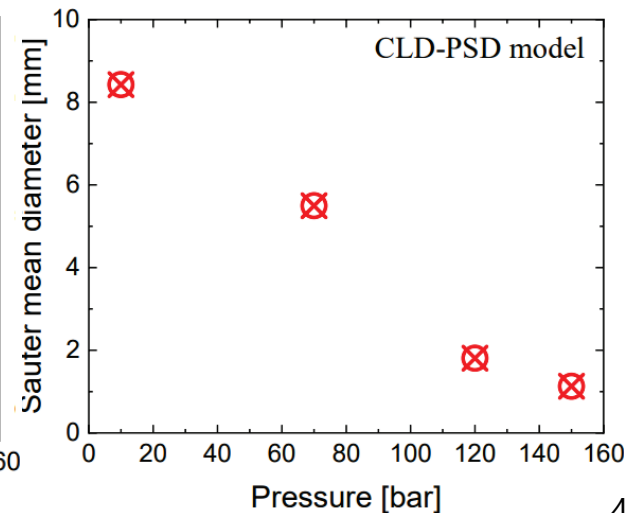
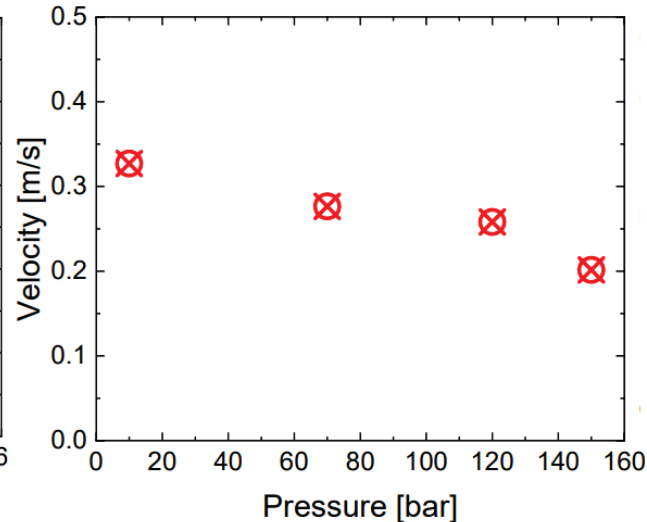
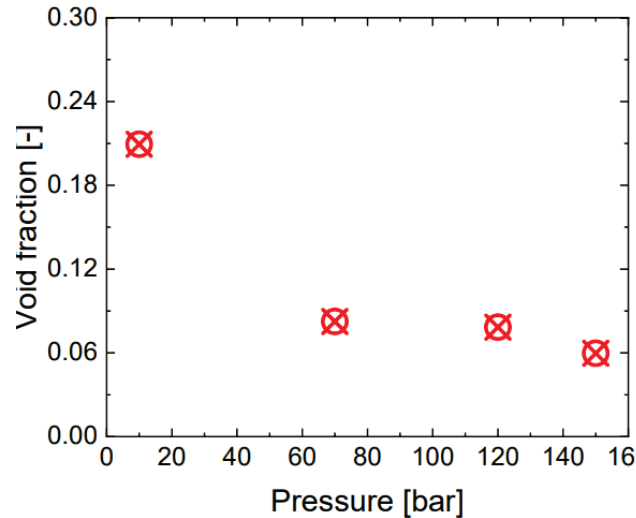
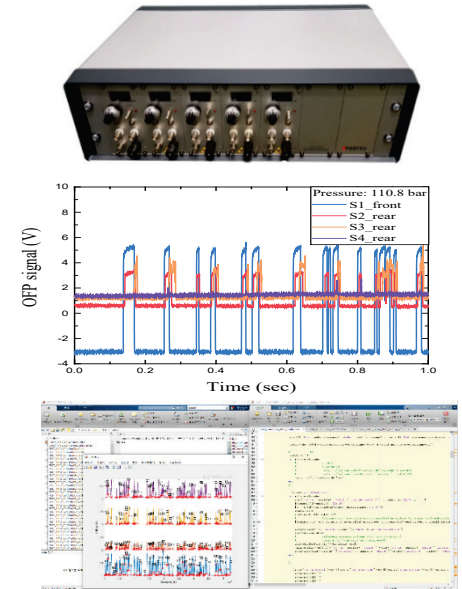
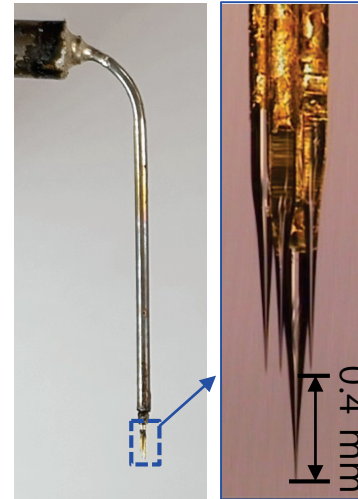
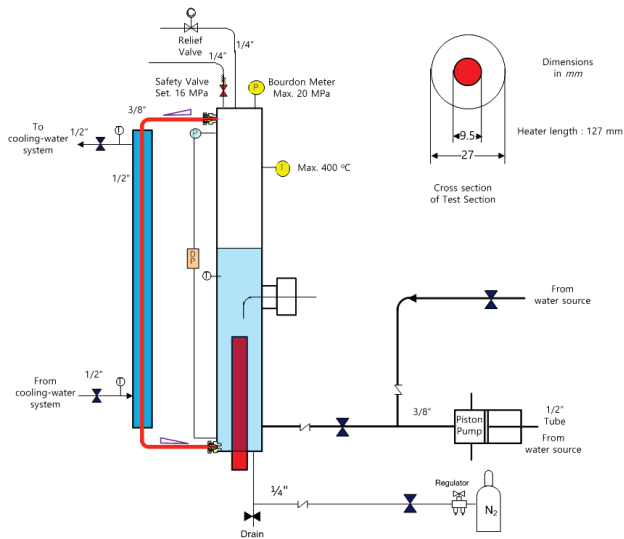
# High Pressure Subcooled Boiling Test (3)

## Development of multi-sensor optical fiber sensor probe



# High Pressure Subcooled Boiling Test (4)

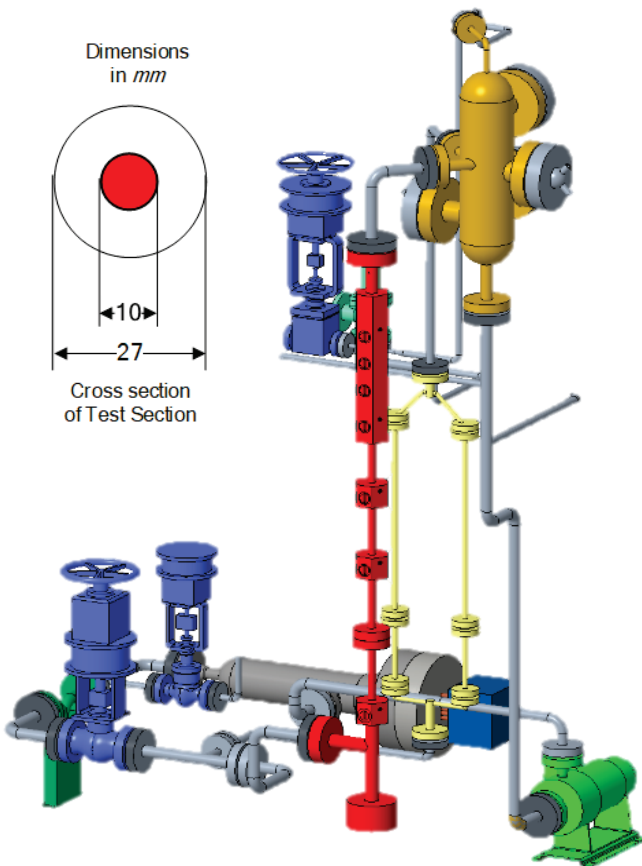
- Sensor test in the 2 phase natural circulation boiling loop



# High Pressure Subcooled Boiling Test (5)

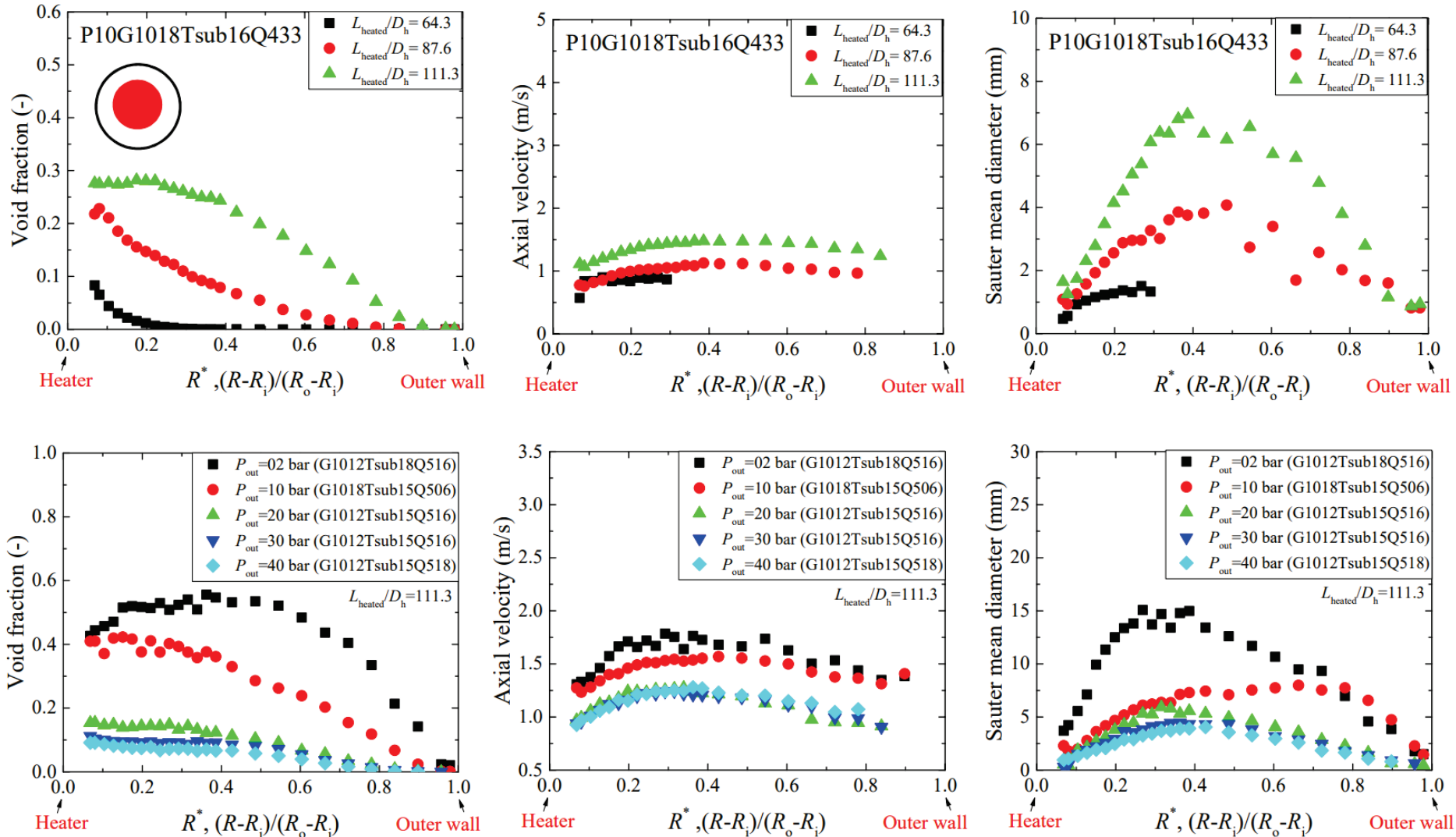
## ■ PHIBO (PNU High Pressure Boiling) test facility

- Max. P & T : 150 bar, 340 °C
- Max G : 5,000 kg/m<sup>2</sup>s



# High Pressure Subcooled Boiling Test (6)

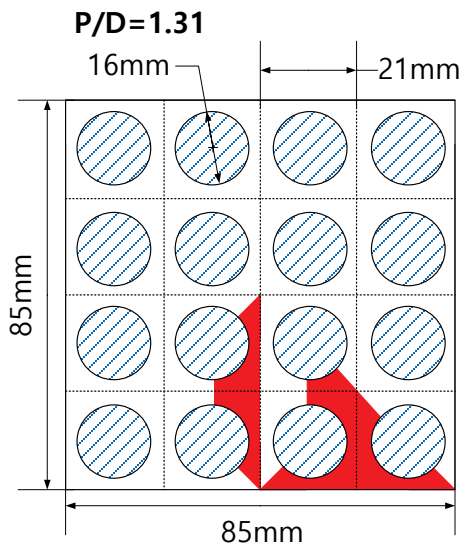
## Bubble parameter distributions



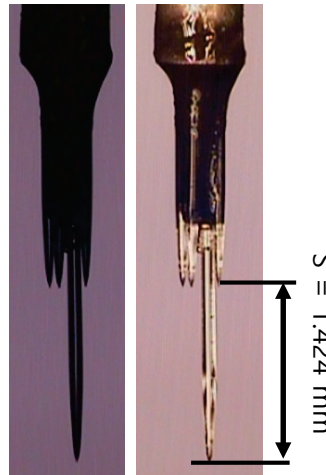
# Subcooled Boiling in a 4 x 4 Rod Bundle Channel (1)

## ■ 4 x 4 Rod bundle subcooled boiling test

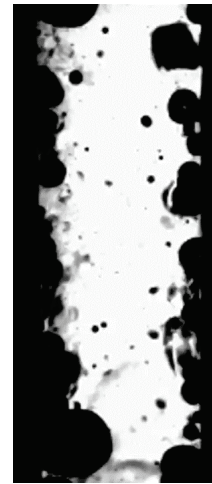
- To investigate the effect of bundle in the low pressure condition
- Experiment apparatus
  - Flow channel : 85 x 85 mm
  - Heater diameter = 16 mm, Pitch = 21 mm
  - Heated length( $Z$ ) = 590 mm ,  $D_h = 14.01$  mm
- Measurement
  - The local data was measured with 4-sensor OFP
  - Measuring location :  $Z/D_h = 41.4$ , number of measurement points : 466



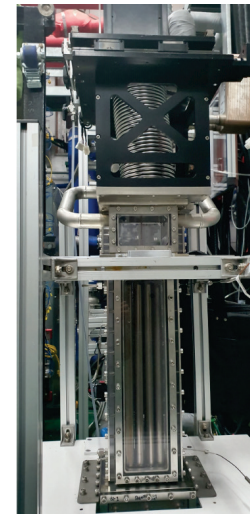
<Cross-section of channel>



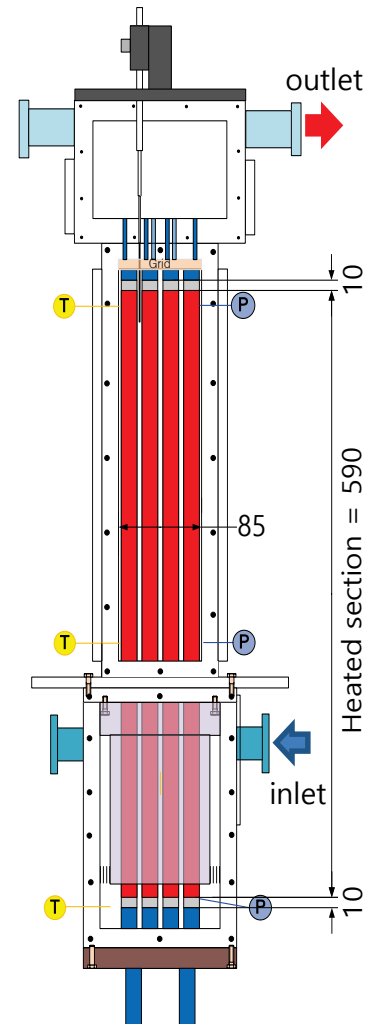
<4-sensor OFP>



$$q'' = 143.4 \text{ kW/m}^2$$
$$G = 249.5 \text{ kg/m}^2\text{s}$$



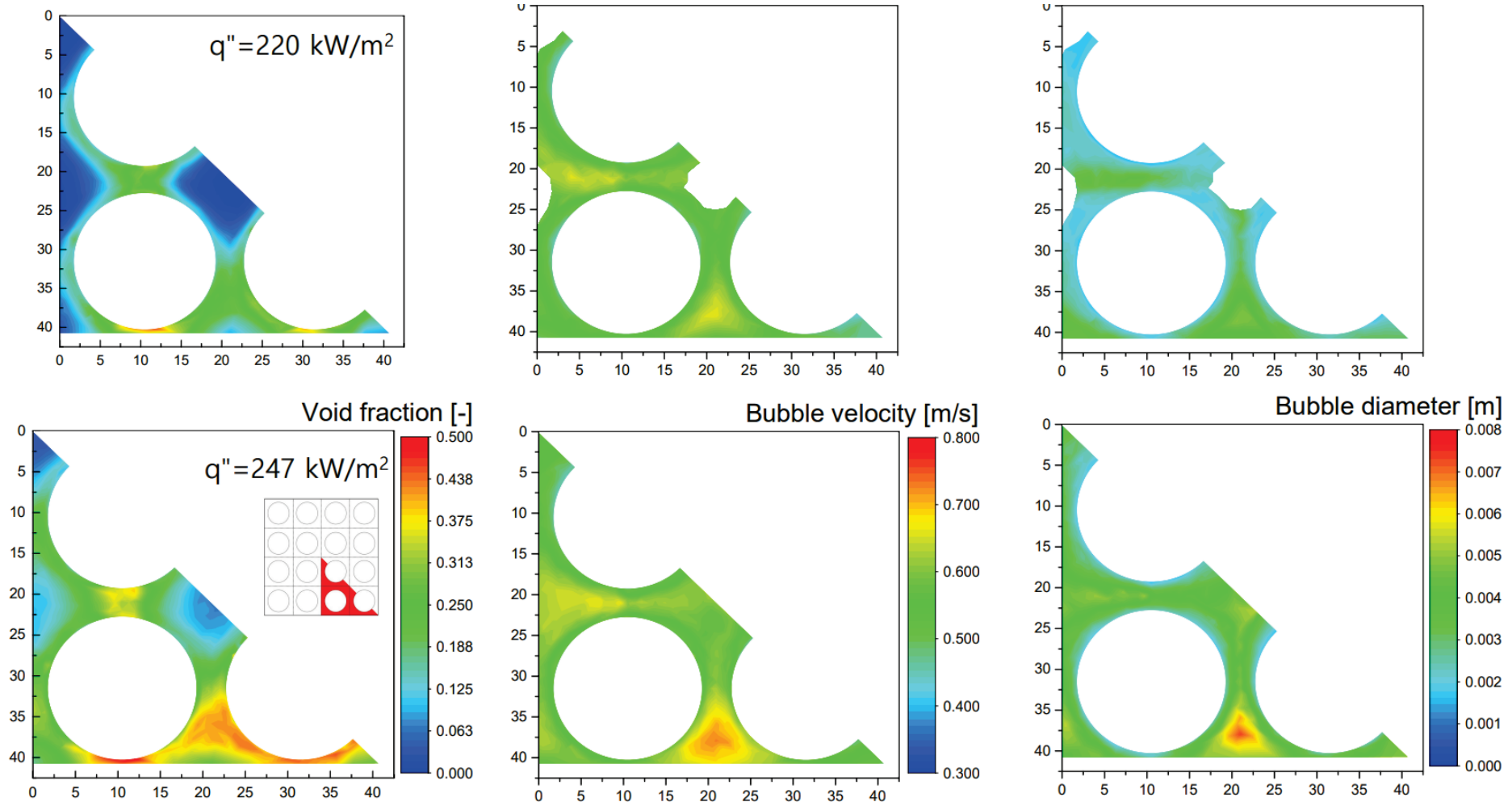
<Test section>



# Subcooled Boiling in a 4 x 4 Rod Bundle Channel (2)

## Bubble parameter distributions

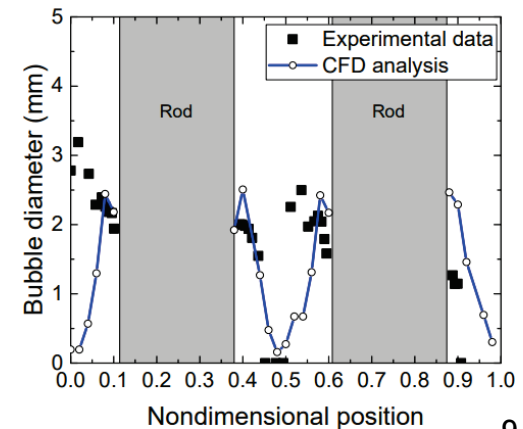
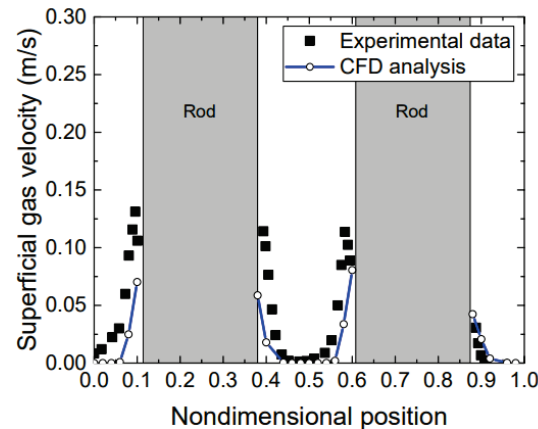
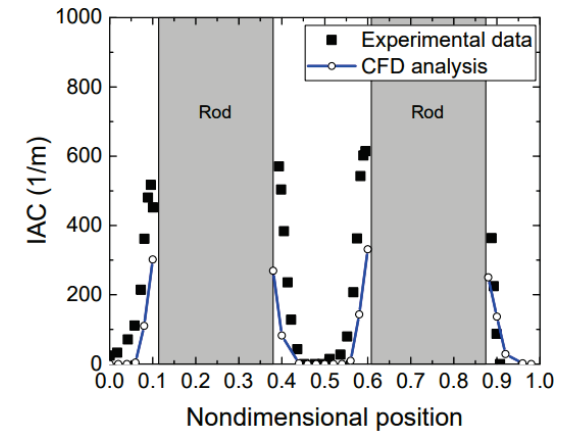
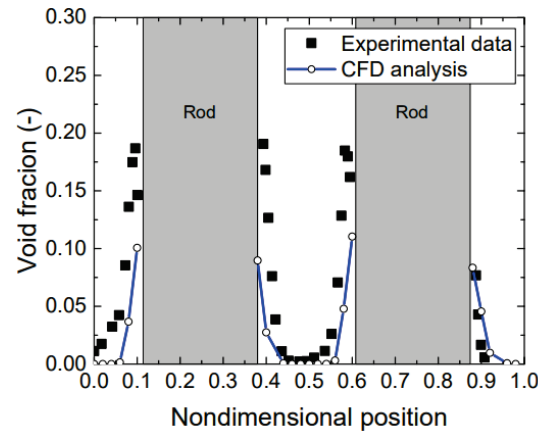
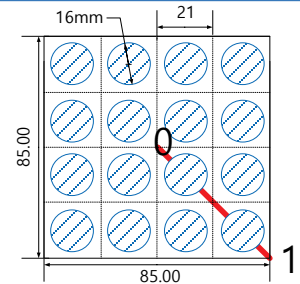
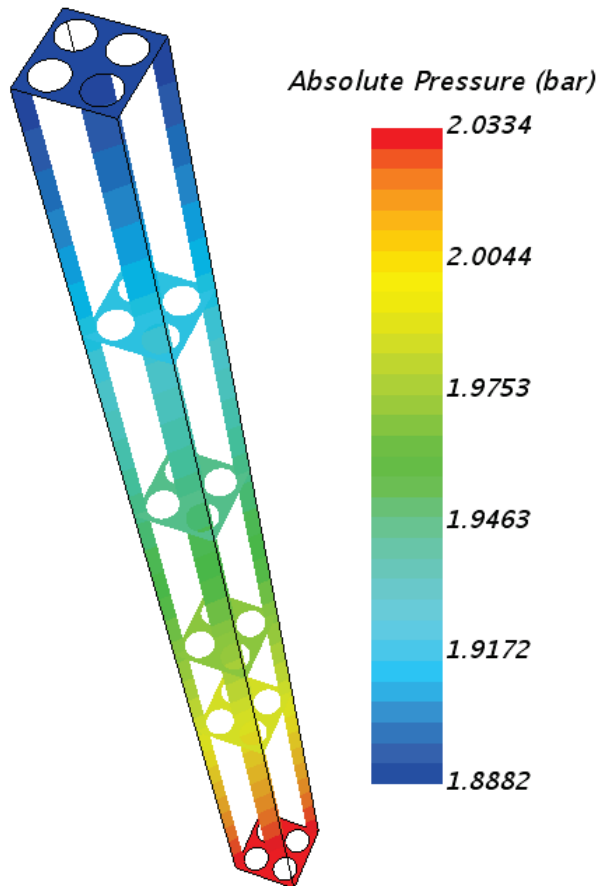
- $P = 2 \text{ bar}$ ,  $G = 350 \text{ kg/m}^2\text{s}$ ,  $\Delta T_{\text{sub,in}} = 22.5^\circ\text{C}$



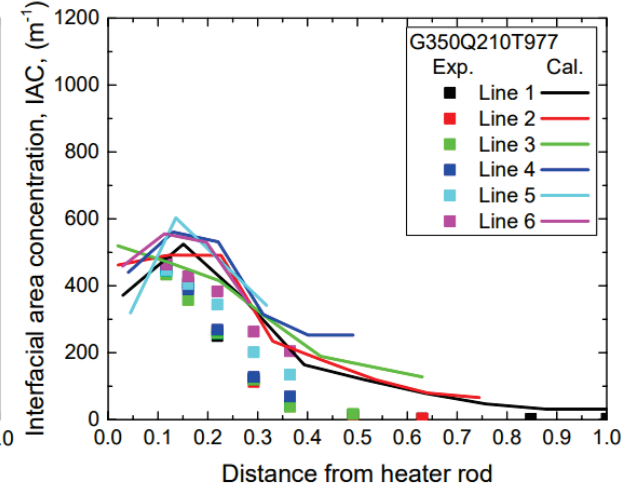
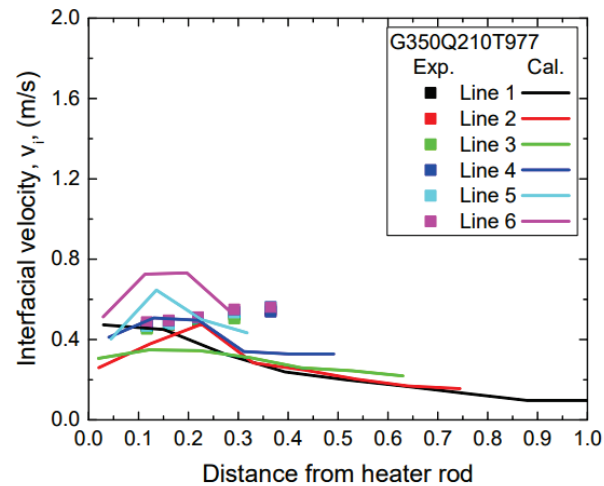
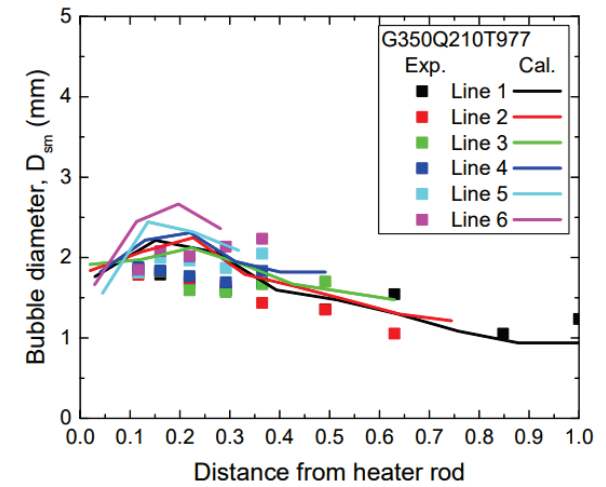
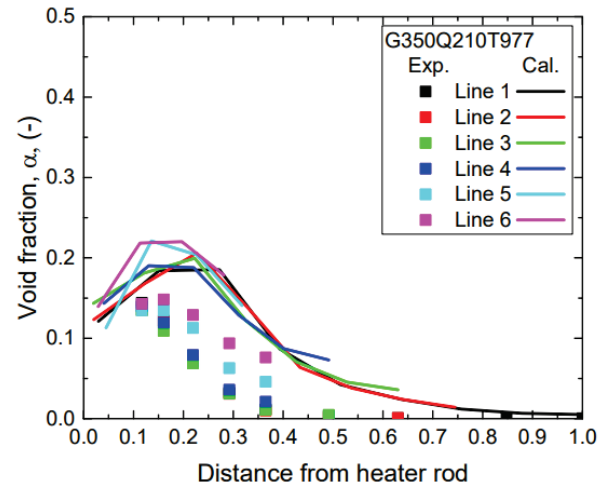
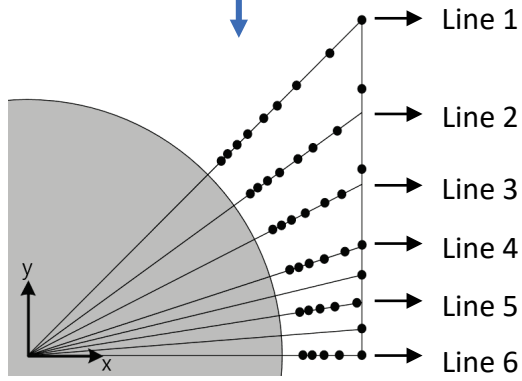
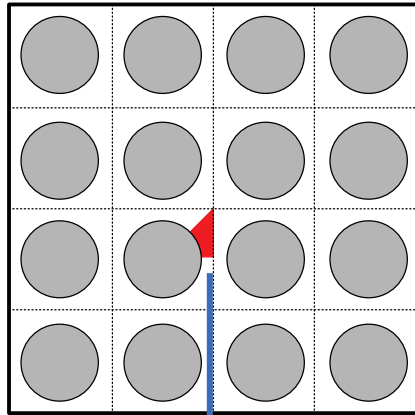
# Subcooled Boiling in a 4 x 4 Rod Bundle Channel (3)

## CFD benchmark calculation

- Development of optimized wall boiling and bubble size models
- Code : STAR-CCM+



# Subcooled Boiling in a 4 x 4 Rod Bundle Channel (4)



# Boiling in an Inclined Downward Wall-heated Rectangular Channel (1)

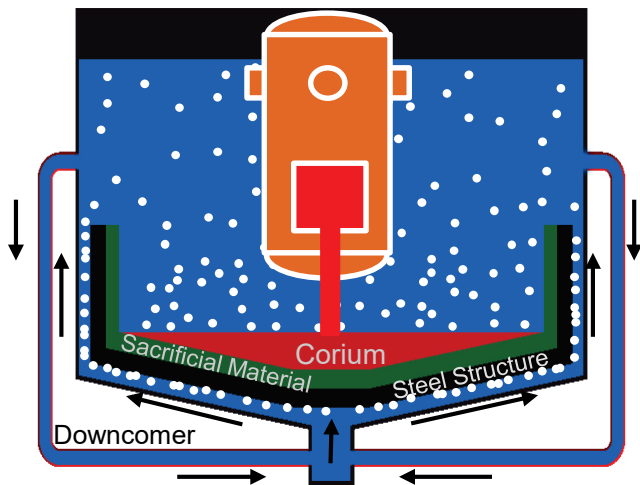
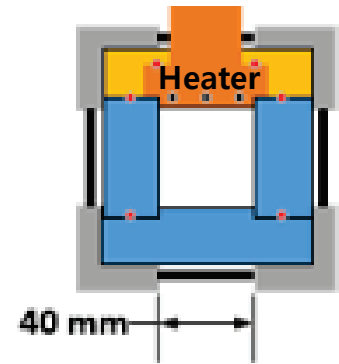
■ **Background** : EU-APR1400 adopts core catcher.

■ **Research Goal**

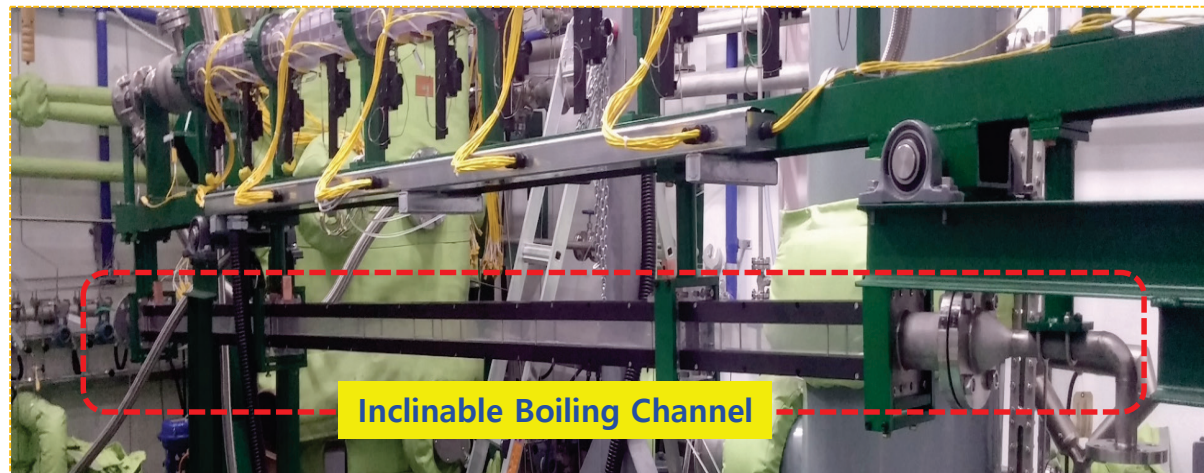
- Experimental study of flow boiling in an inclined rectangular channel with downward wall heating

■ **Test Section**

- 40 mm x 40 mm x 3.6 m rectangular channel with 2.8 m downward facing-heated wall
- 10° inclination from horizontal plane



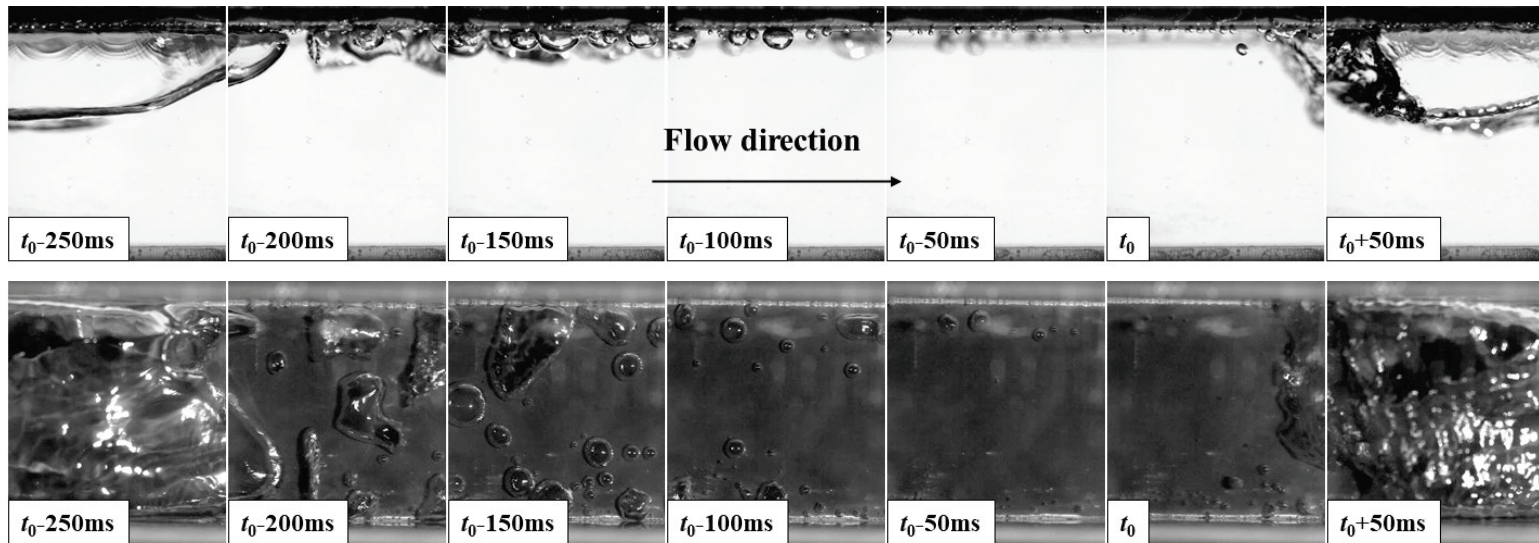
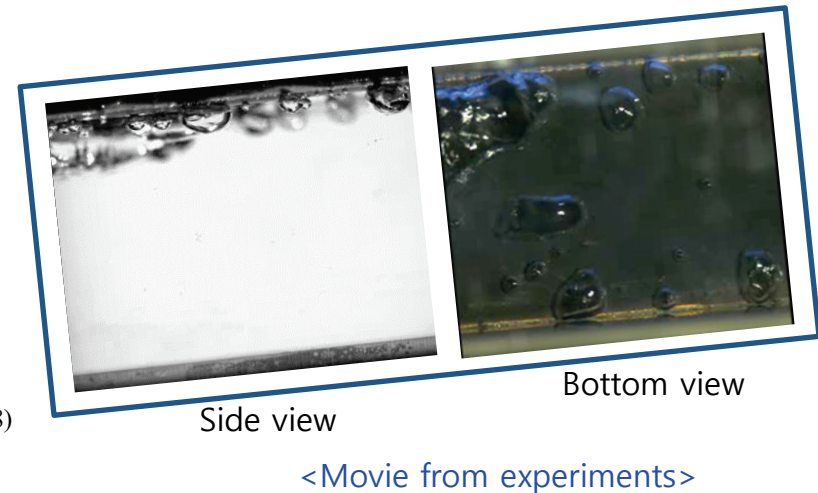
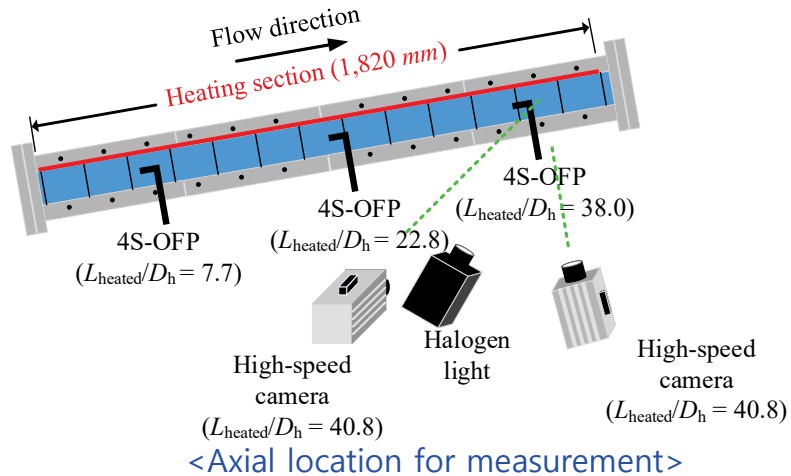
<Concept of core catcher>



<Test facility>

# Boiling in an Inclined Downward Wall-heated Rectangular Channel (2)

## Experimental Results

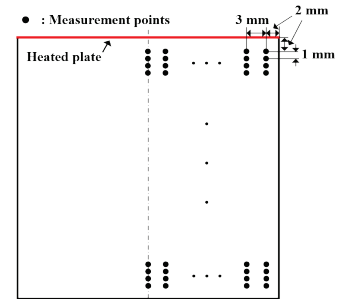
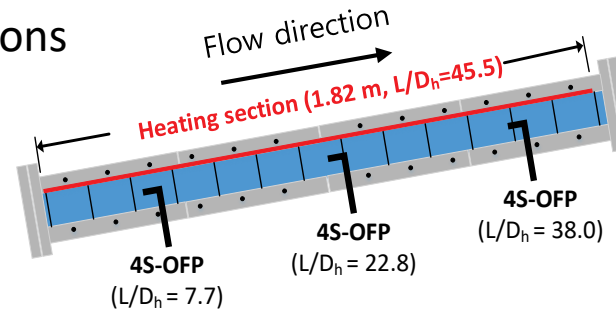


<Mass flux=153 kg/m<sup>2</sup>s,  $T_{\text{inlet}}=90\text{ }^{\circ}\text{C}$ ,  $q''=97\text{ kW/m}^2$ >

# Boiling in an Inclined Downward Wall-heated Rectangular Channel (3)

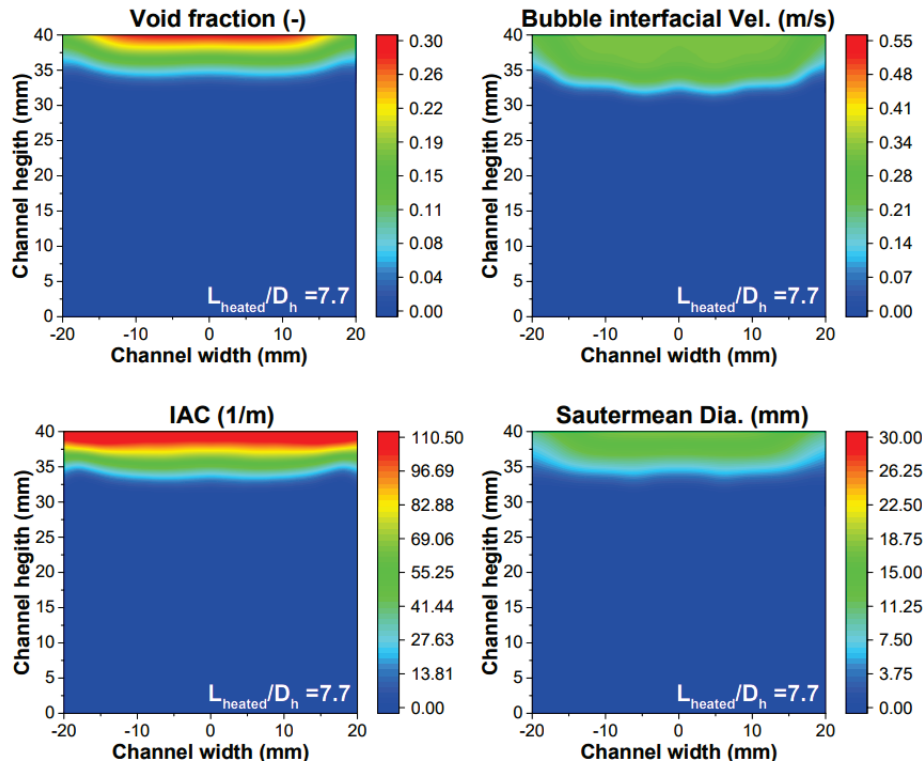
- Local bubble parameter distributions

- $G = 148.57 \text{ kg/m}^2\text{s}$
- $\Delta T_{\text{sub,in}} = 20.8 \text{ K}$
- $q'' = 142.51 \text{ kW/m}^2$

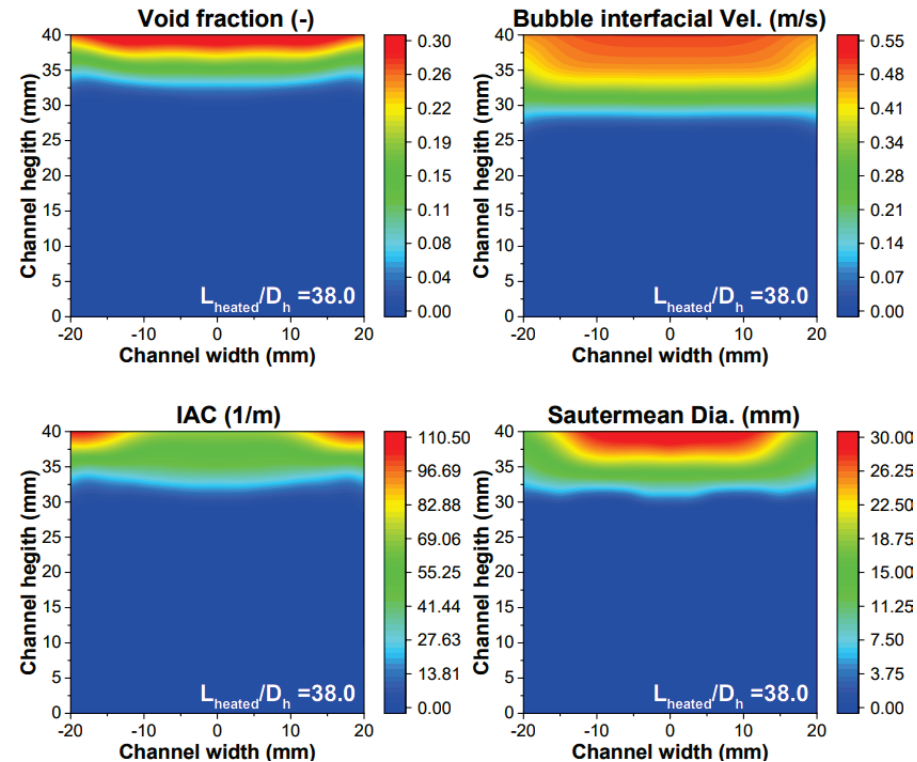


<Measurement planes>

<Measurement points on the plane>



< $L_{\text{heated}}/D_h = 7.7$ >



< $L_{\text{heated}}/D_h = 38.0$ >

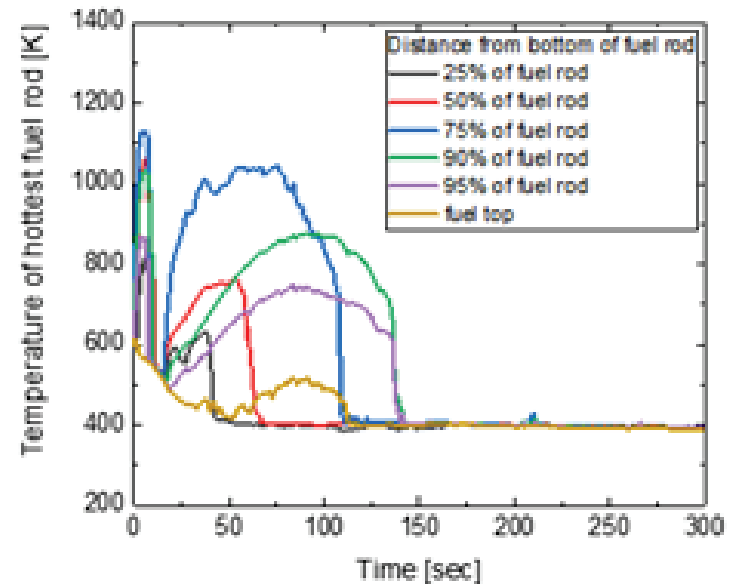
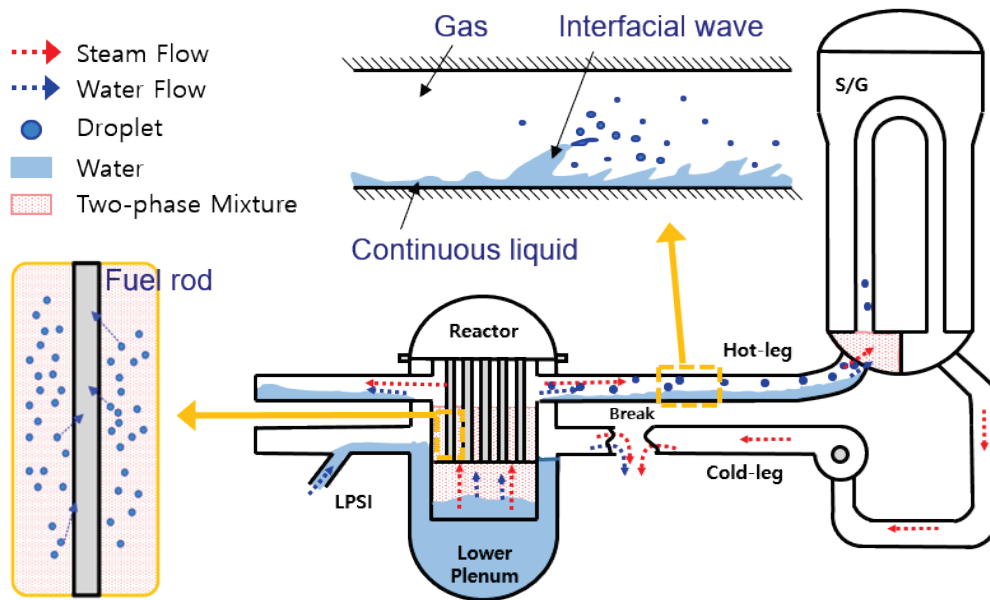
# Droplet Parameters for LBLOCA Reflood Phase (1)

## ■ Background

- Droplet flow affects significantly the cooling of fuel rod and water level in the core under the LBLOCA.

## ■ Research Goal

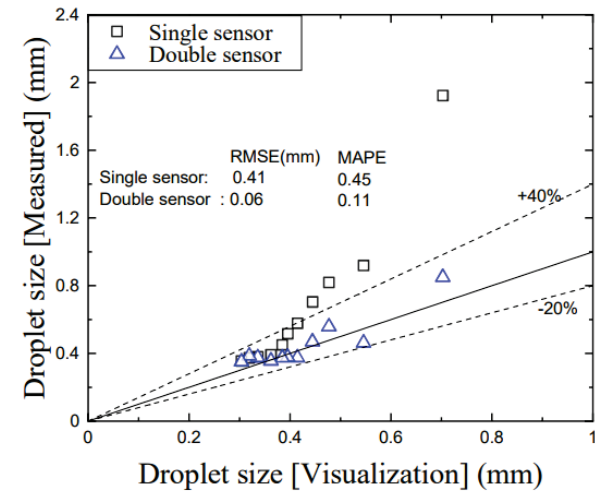
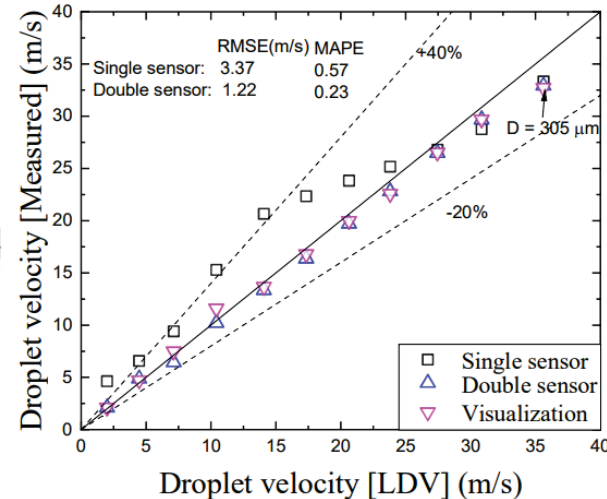
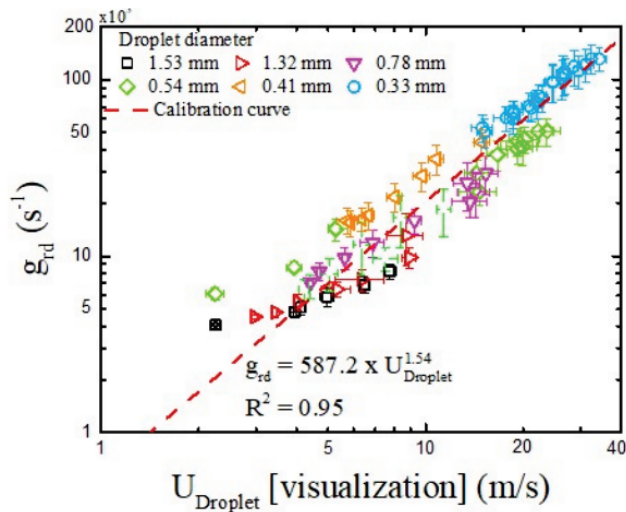
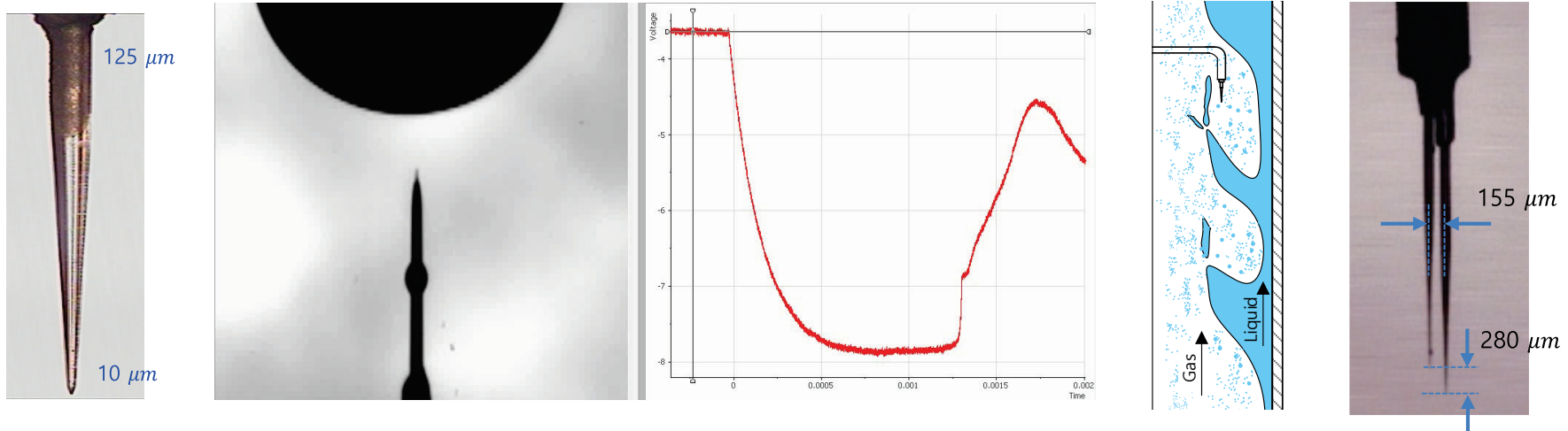
- Establishment of experimental database and modeling of droplet parameters.



< Droplet flow during LBLOCA reflood phase >

# Droplet Parameters for LBLOCA Reflood Phase (2)

## Optical Fiber Sensor for Local Droplet Parameters

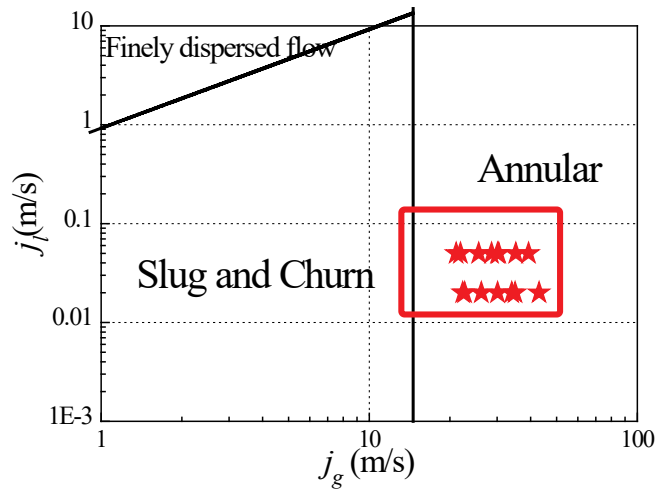


# Droplet Parameters in a Vertical Pipe (1)

## ■ Droplet Flow in Air-water Vertical Pipe

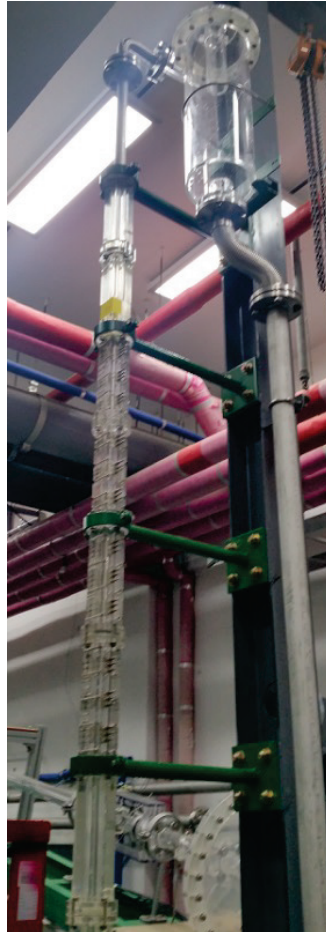
- Test section and experimental conditions

- ✓ Inlet diameter : 19.05 mm
- ✓ Channel length : 3.9 m (204.7D)
- ✓ Flow pattern : annular-mist flow
- ✓ Pressure : 1bar

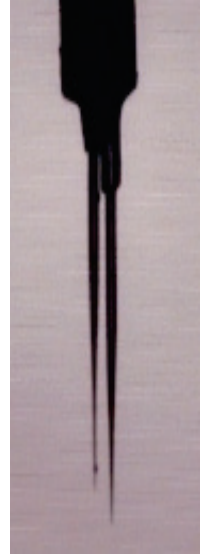
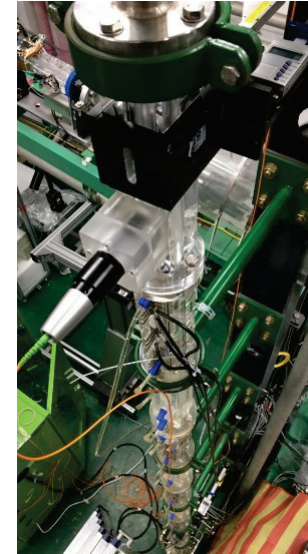


Exp. range	min	max
$j_L$ (m/s)	0.02	0.05
$j_g$ (m/s)	20	40

< Experimental conditions >



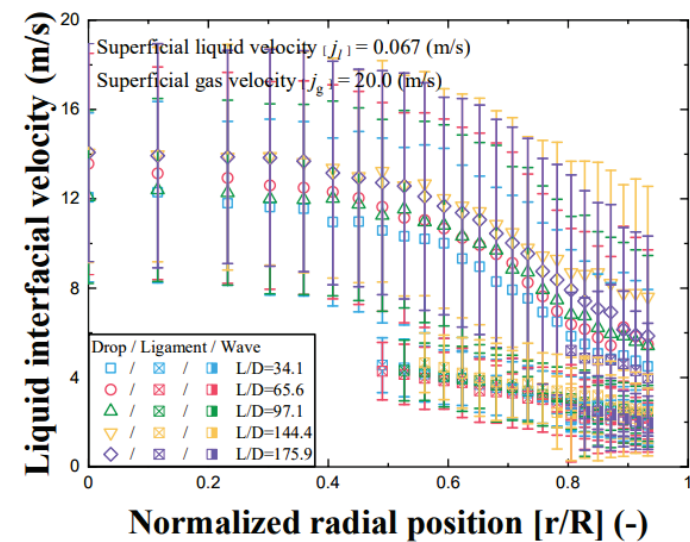
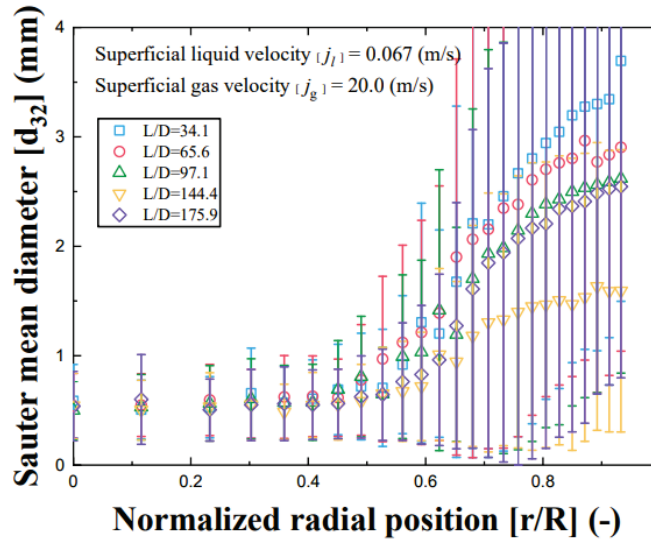
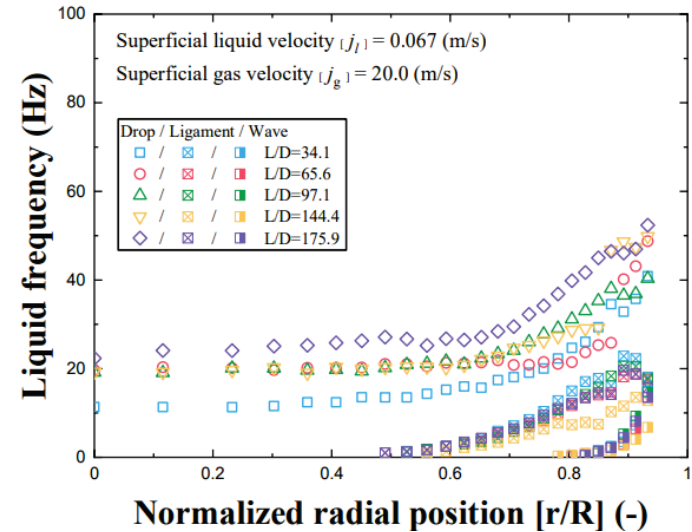
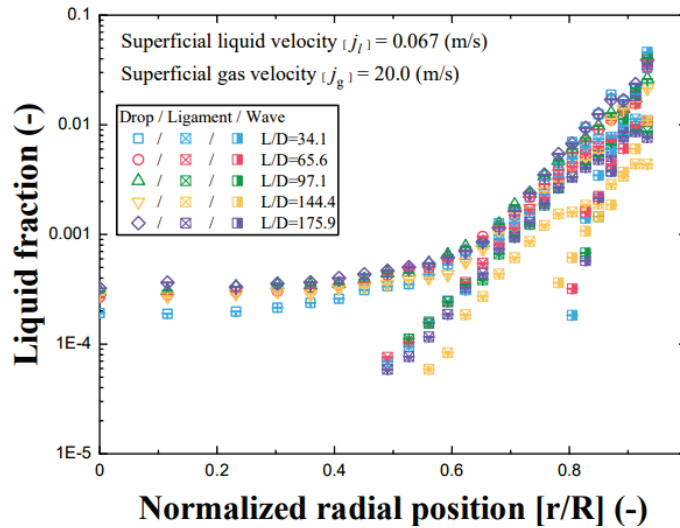
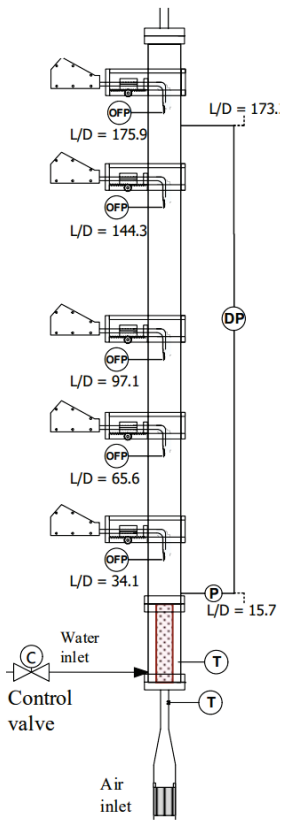
< Experimental apparatus >



< Measurement section >

# Droplet Parameters in a Vertical Pipe (2)

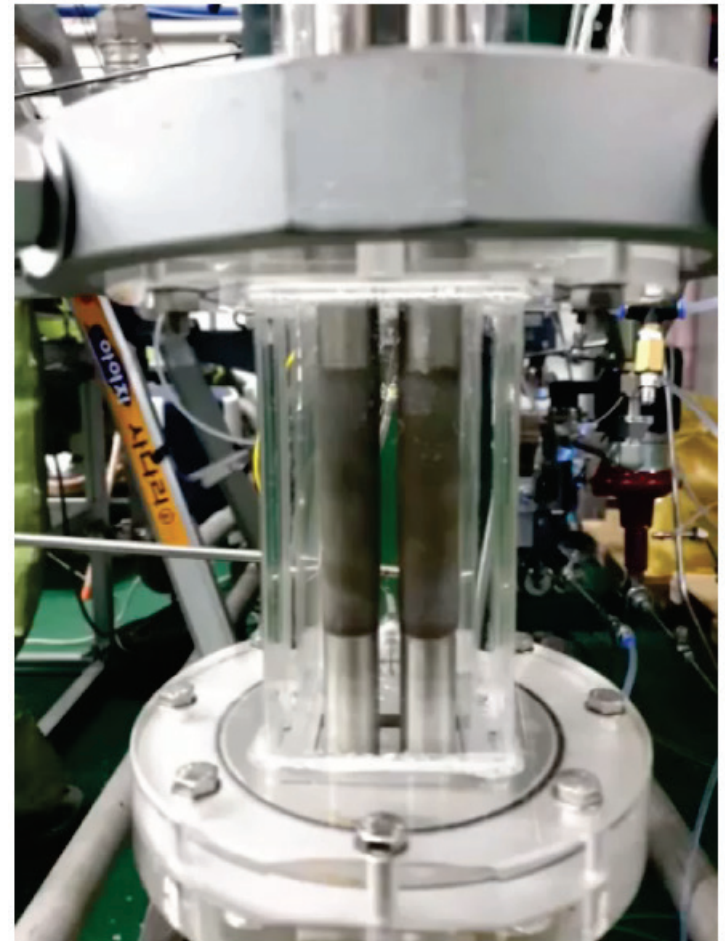
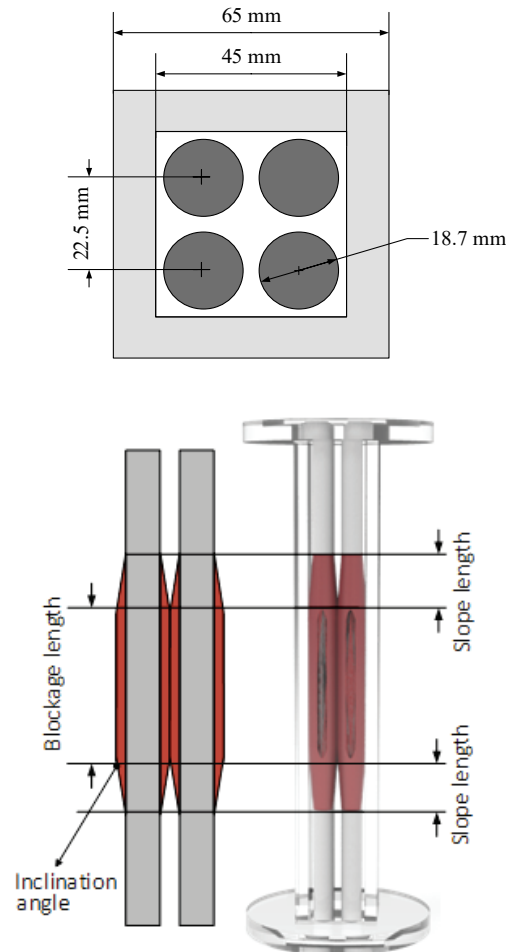
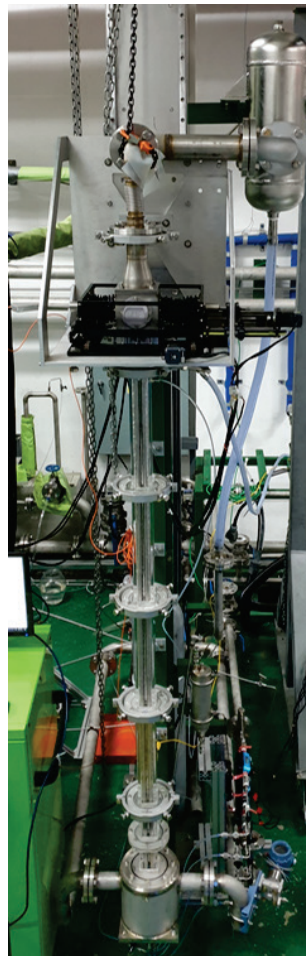
- Experimental results



# Droplet Parameters in a Rod Bundle Channel (1)

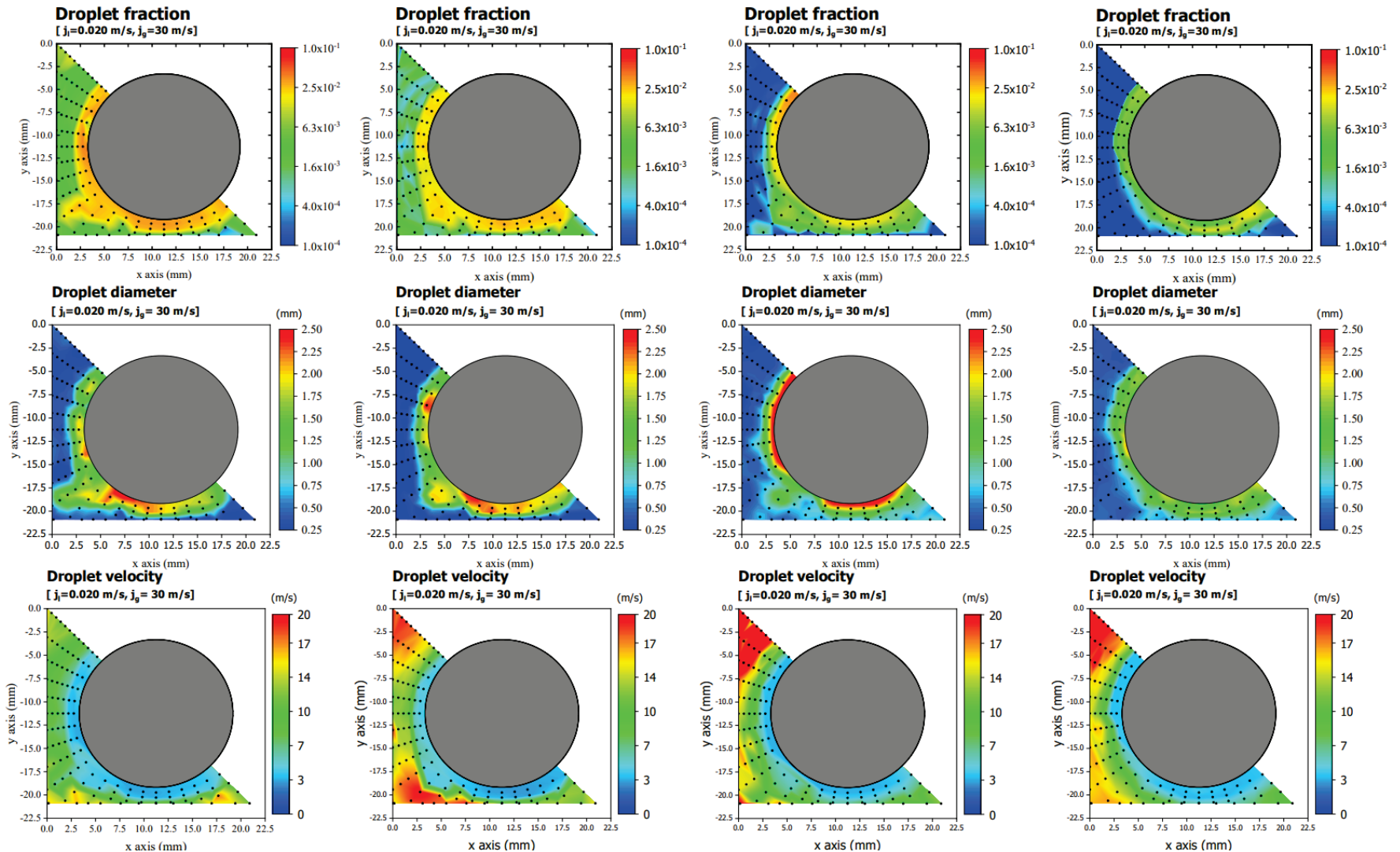
## ■ Droplet parameters in the intact and deformed 2 x 2 rod bundle channel

- Atmospheric air-water annular-mist flow conditions
- Intact and deformed bundles



# Droplet Parameters in a Rod Bundle Channel (2)

- Results for deformed bundle



15 mm

60 mm

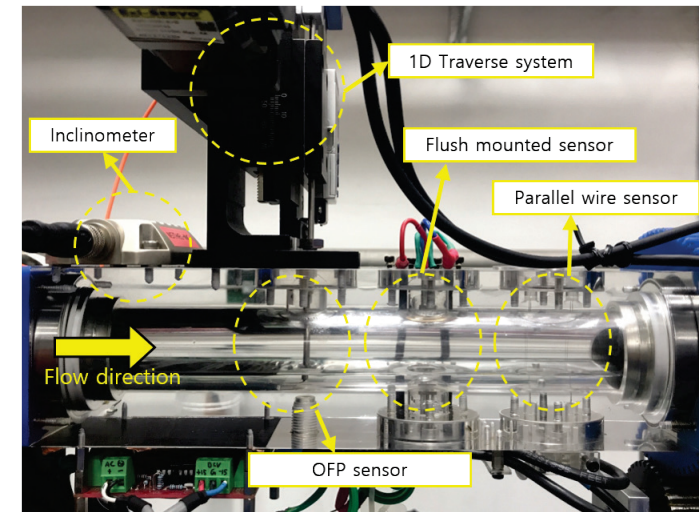
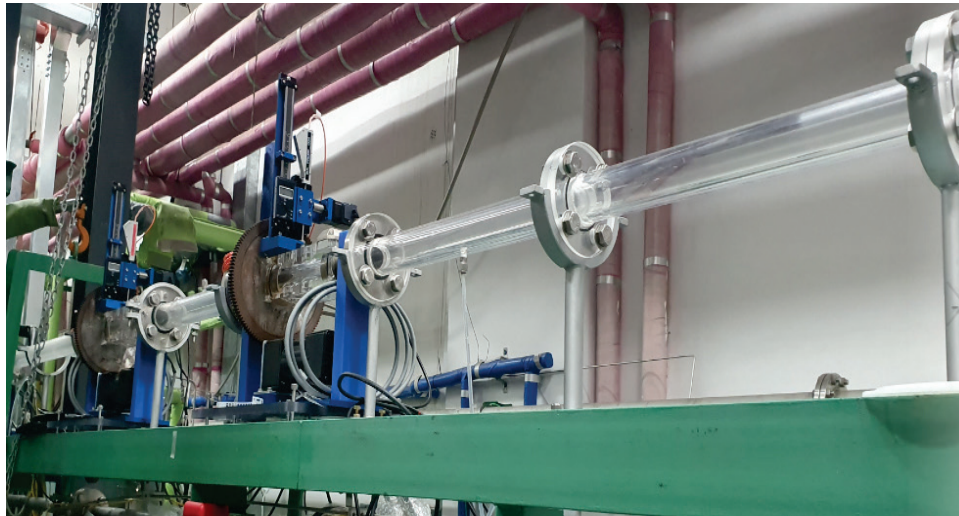
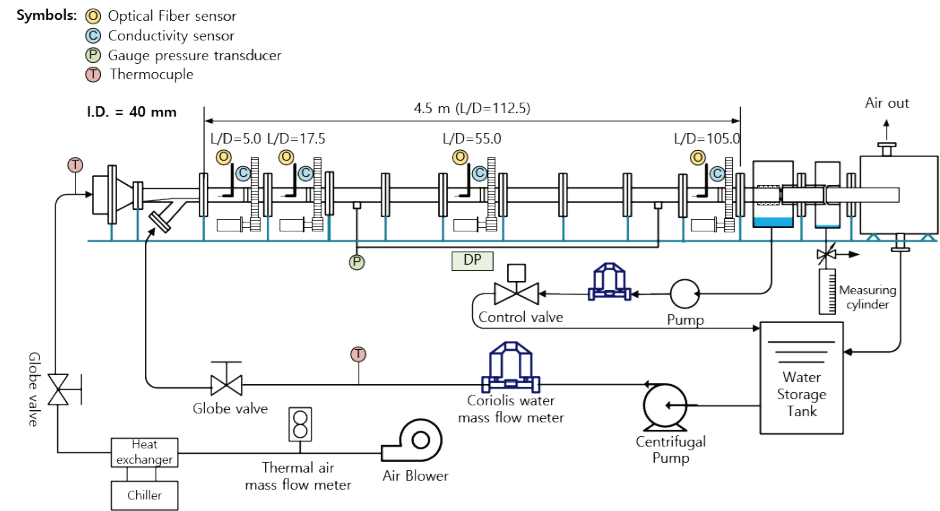
410 mm

Intact

# Droplet Parameters in a Horizontal Pipe (1)

## ■ Experiment for Droplet Parameters in the Horizontal Pipe

- Experimental apparatus
  - ✓ Pipe inner diameter : 40 mm
  - ✓ Length : 5.5 m
- Measurement method
  - ✓ Single optical fiber probe : 4ea
  - ✓ Liquid film extraction method : 1set
  - ✓ Rotatable measurement section



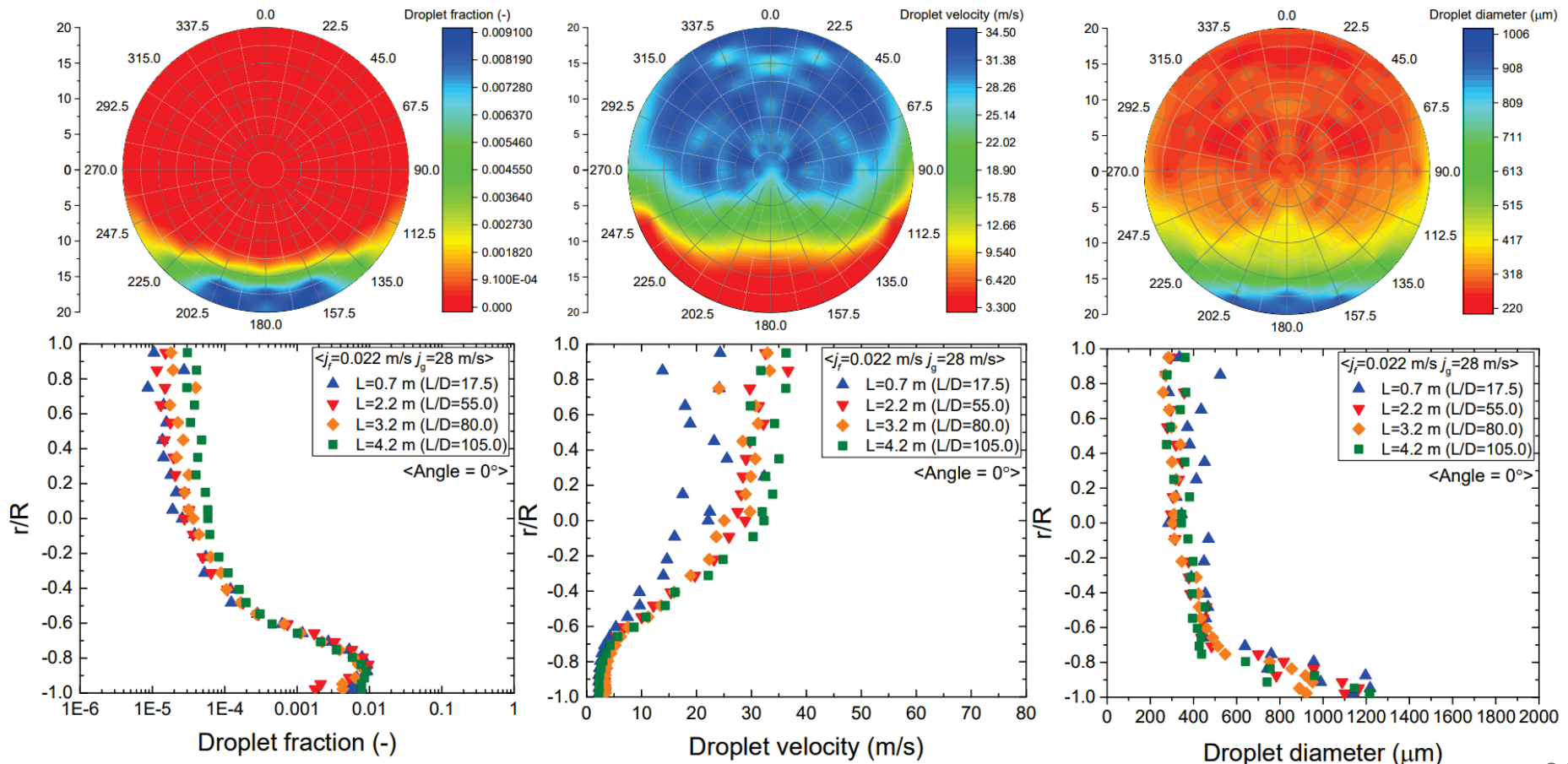
# Droplet Parameters in a Horizontal Pipe (2)

- Experimental results
  - ✓ Flow condition :  $j_f=0.022$  m/s,  $j_g=28.0$  m/s
  - ✓ Contours for droplet parameters at  $L/D=105.0$

<Droplet fraction>

<Droplet velocity>

<Droplet diameter>



# Summary and Conclusions

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- Local optical fiber instrumentations were developed for the measurement of bubble and droplet parameters in the wide range of flow and pressure conditions.
- Local bubble parameters were obtained in the subcooled boiling tests such as the high pressure annulus, 4x4 rod bundle and downward wall heated inclined channels.
- Local droplet parameters were produced from the air-water vertical and horizontal tubes and also 2x2 intact and deformed rectangular channels for the LBLOCA reflood phase.
- The established experimental database can be used for the benchmark of CFD codes and development of models and correlations for them.

감사합니다.