[원전 적용을 위한 CFD 스케일 해석 기술 및 실험]
CFD Scale Analysis Techniques and Experiments for Nuclear Applications

원자로계통 고정밀 열수력 실험 및 모델 검증 연구

High-precision TH Experiments and Model Validation for Nuclear Reactor System

2023. 5. 17.

김석

KAERI Korea Atomic Energy Research Institute

OUTLINE

Introduction

Thermal-Hydraulics R&D

Requirements for CFD-grade experiments for TH

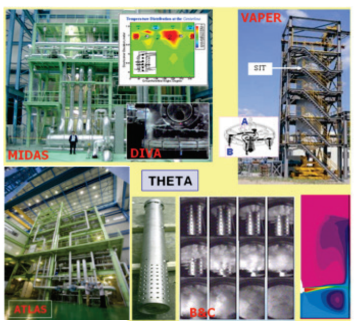
01 Introduction (1)

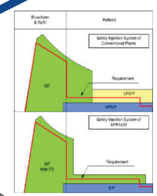
❖ Thermal-Hydraulics R&D of RSSRD

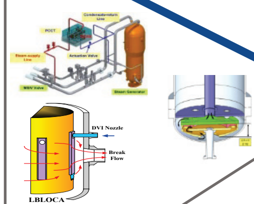
APR1400 NRC-DC Support
RAI (Response to Audit Issues)
- VAPER, MIDAS & ATLAS
- Electrical 4-train Tests

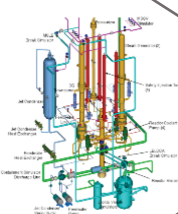
APR+, iPOWER, APR1000 Development
Improved Design Features
- DVI+, FD+, PAFS, PCCS, PECCS
- HSIT, Mixed cooling

APR1400/OPR1000 Safety
Comprehensive R&D
- IET: ATLAS, RCP
- SET: THETA, PURIUS, ICARUS

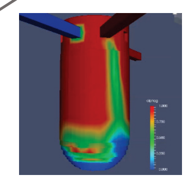


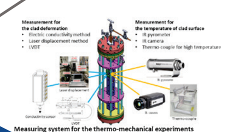






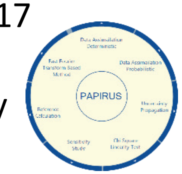
R&D Scope

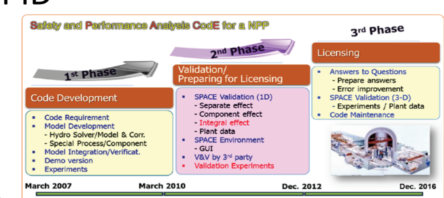




Code Development (V&V)
TH Sys. Codes + BEPU Tool
- MARS-KS transferred to KINS
- SPACE licensed in 2017
- PAPIRUS developed
- Simulator technology

Multi-Scale Code
- CUPID



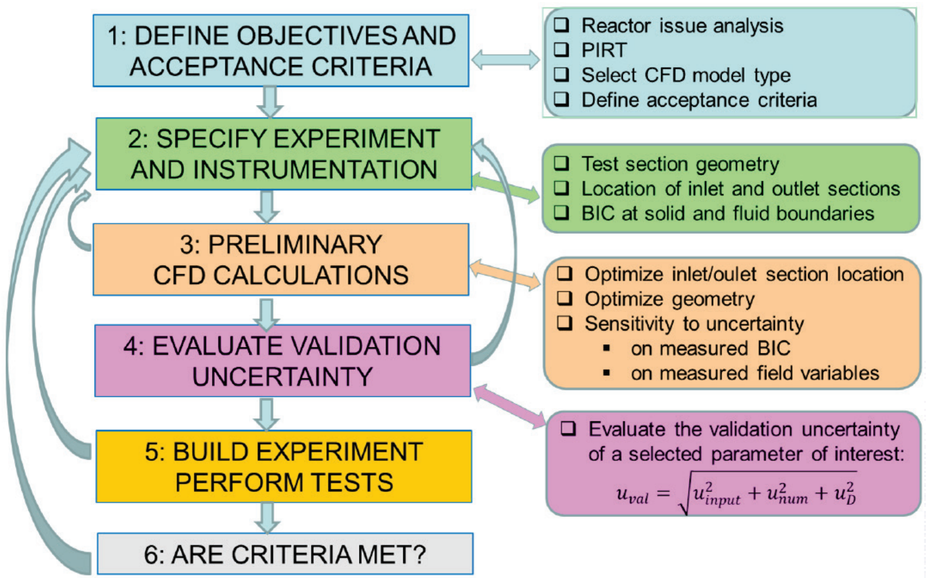


Basic TH Exps. & Modeling
Multi-physics (Fuel + TH + CTMT)
- Phenomena understanding and modeling
- Measurement technique

SMR & Gen.IV Safety
SMART Passive Concepts
SFR Validation and SCO_2 System
i-SMR Safety Validation
- IET & SET

❖ Requirements for CFD-grade experiments for TH

- What is a CFD-grade experiment?
  - Validate of CFD: give an information on the quality of physical models
  - Determine CFD model uncertainty
  - Allow BEPU
- Scope
  - BIC and physical properties of fluid and solid
  - Flow parameter measurement
  - Measurement uncertainty



Requirements for CFD-grade experiments for nuclear reactor thermalhydraulics, D. Bestion et al., NEA/CSNI, 2020

Roadmap for designing and performing a CFD-grade experiment

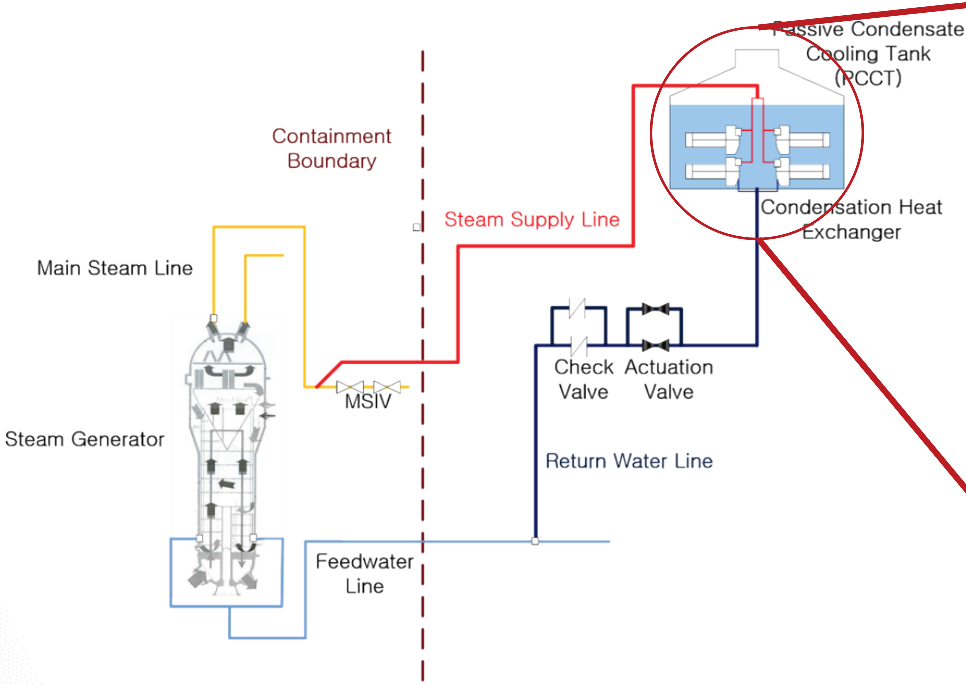
Natural Convection in a Pool

Local Thermal Mixing Characteristics inside a PCCT

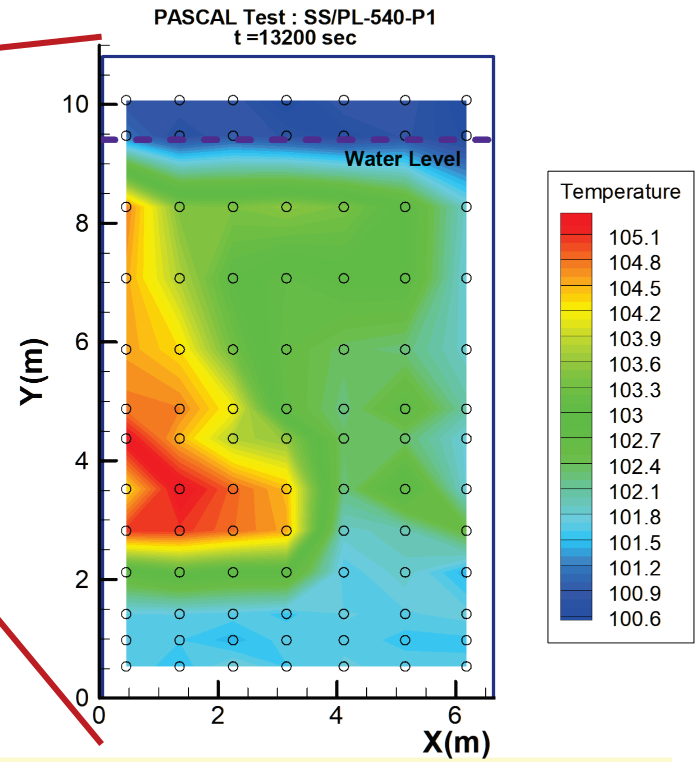
CUPID Code Analysis

Small-sized Pool Experiment

❖ Local Thermal Mixing Characteristics inside a PCCT

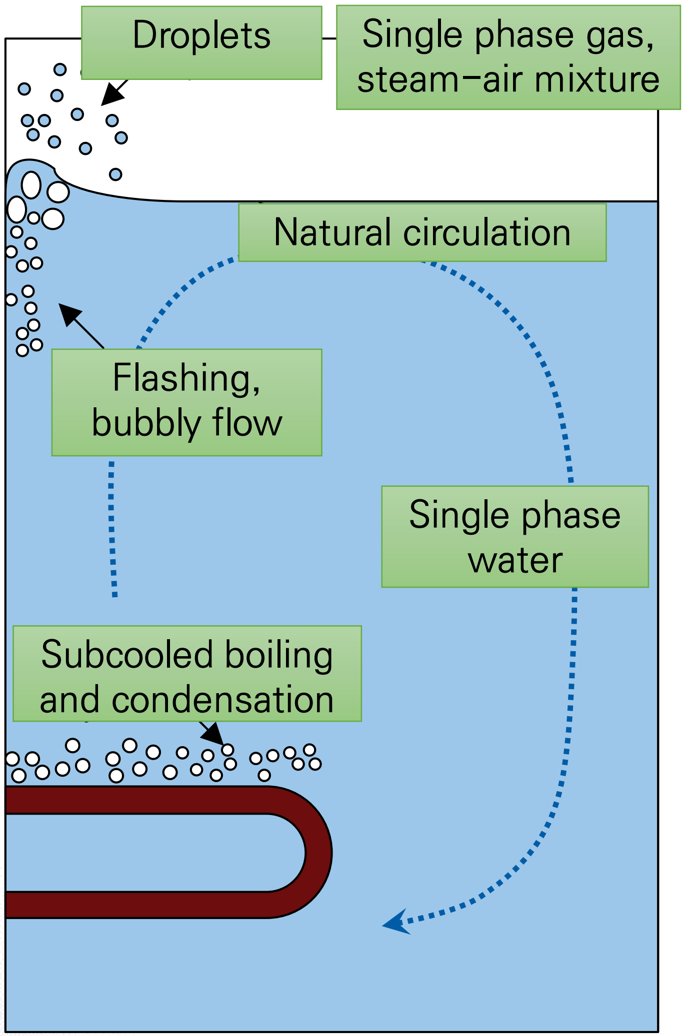


Schematics of PAFS



Fluid temperature distribution inside a PCCT (PASCAL)

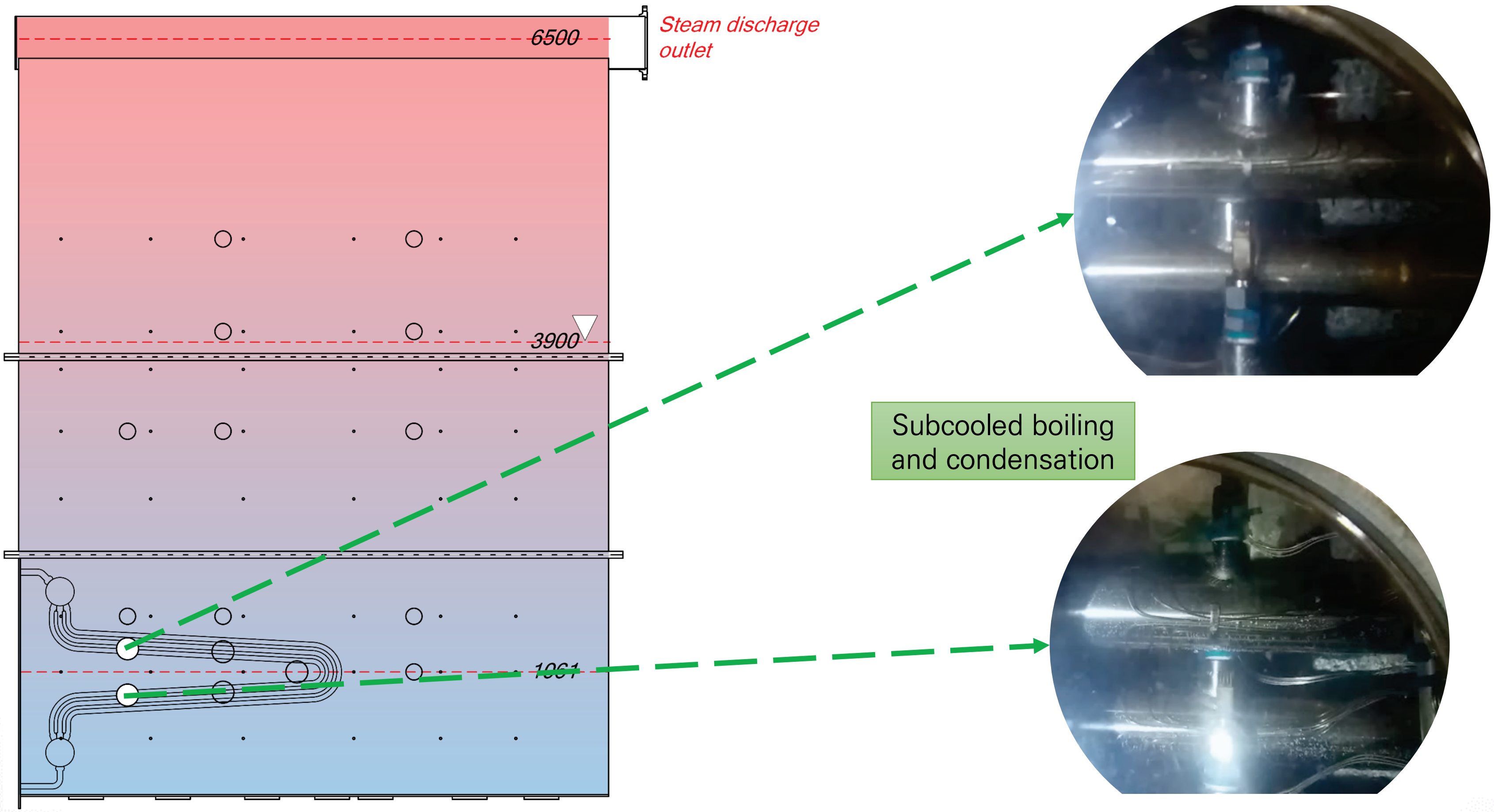
❖ Local Thermal Mixing Characteristics inside a PCCT



- Complexity in physical phenomena
  - Single– and two–phase natural circulation
  - Subcooled boiling and condensation
  - Flashing
  - Evaporation on the free surface
- Difficulty in numerical analysis
  - Various flow patterns
  - Phase change under low pressure state
  - Long transient time over 30,000 sec.
  - Complicated geometry of the heat exchanger and its supporting structure

Numerical Analysis of the Passive Condensation Cooling Tank (PCCT) using the CUPID Code, S.J. Lee et al., CFD4NRS-4, 2012

❖ Local Thermal Mixing Characteristics inside a PCCT

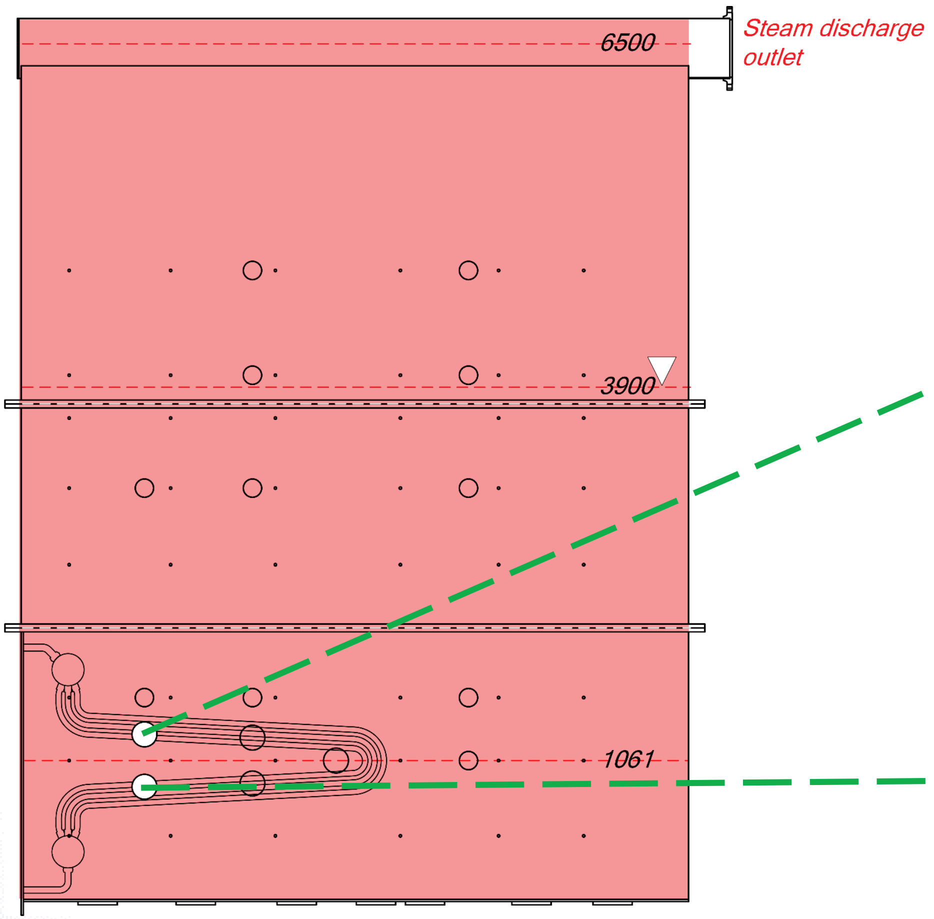


Schematics of ATLAS-PAFS PCCT

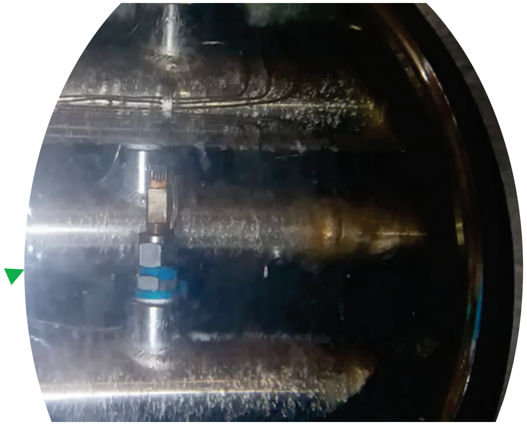
Fluid temperature around the PCHX : ~ 82 ˚C

02 Natural Convection in a Pool (2)

❖ Local Thermal Mixing Characteristics inside a PCCT



Schematics of ATLAS-PAFS PCCT

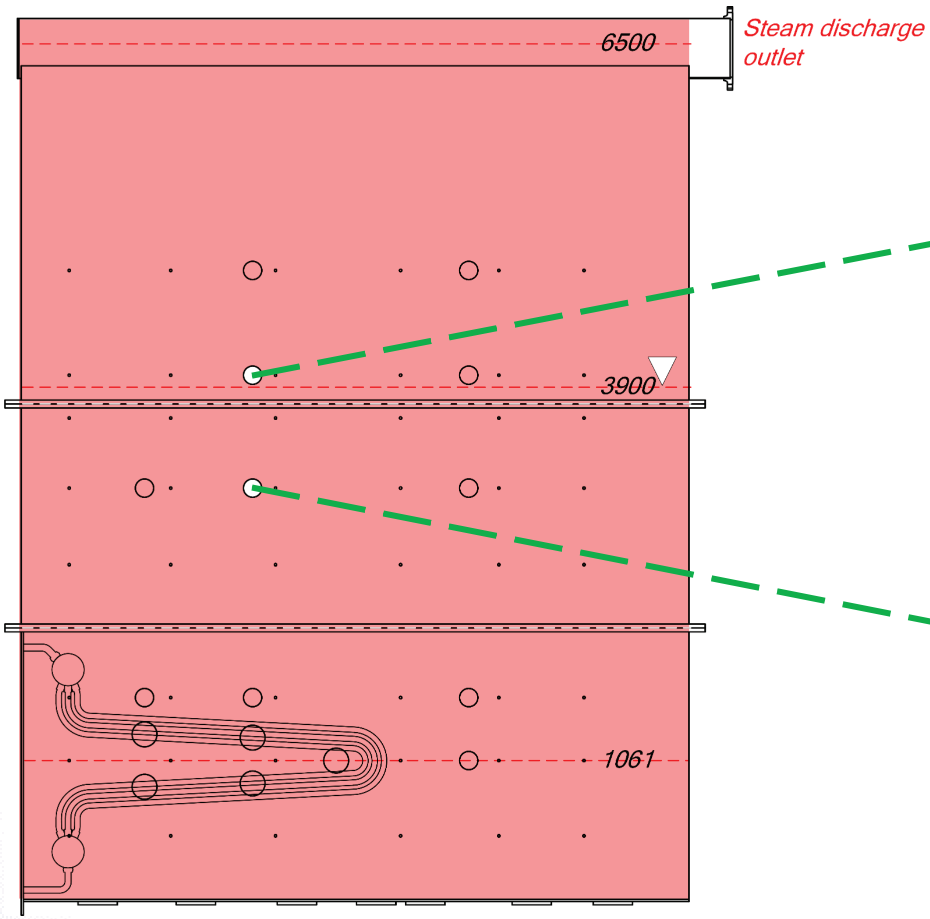


Subcooled boiling and condensation

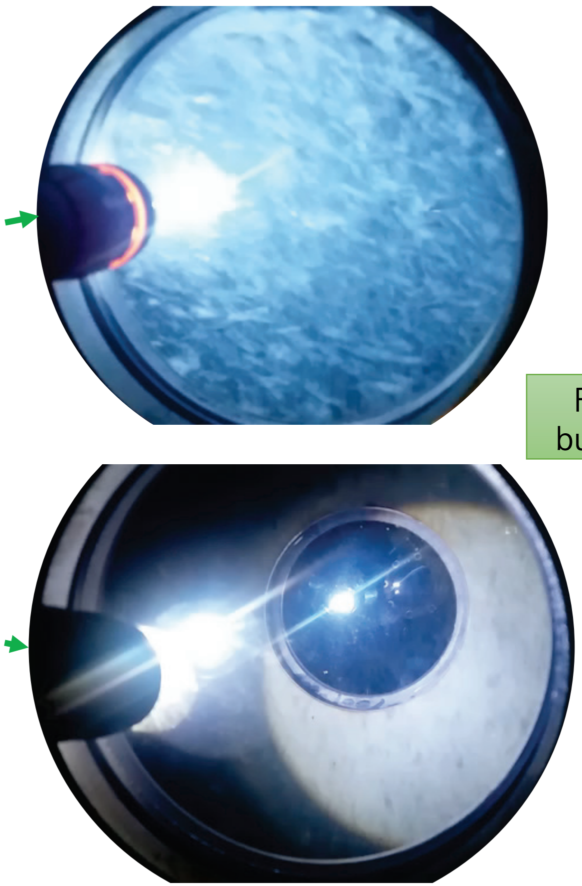
Fluid temperature around the PCHX : ~ 100 ˚C

02 Natural Convection in a Pool (2)

❖ Local Thermal Mixing Characteristics inside a PCCT



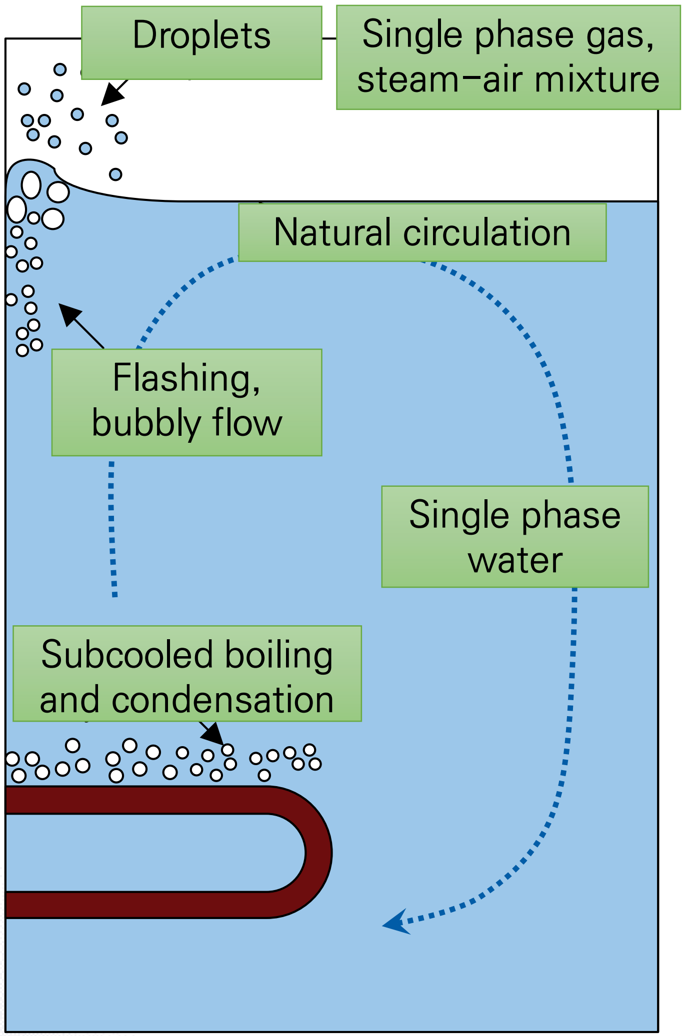
Schematics of ATLAS-PAFS PCCT



Flashing, bubbly flow

Fluid temperature around the PCHX : ~ 100 ˚C

❖ Local Thermal Mixing Characteristics inside a PCCT



- Complexity in physical phenomena
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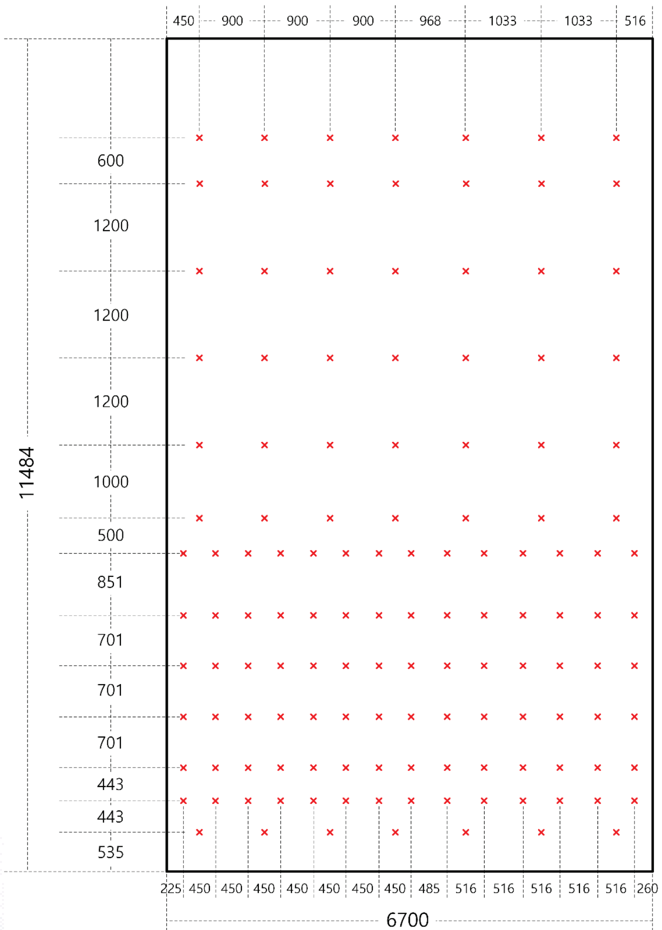
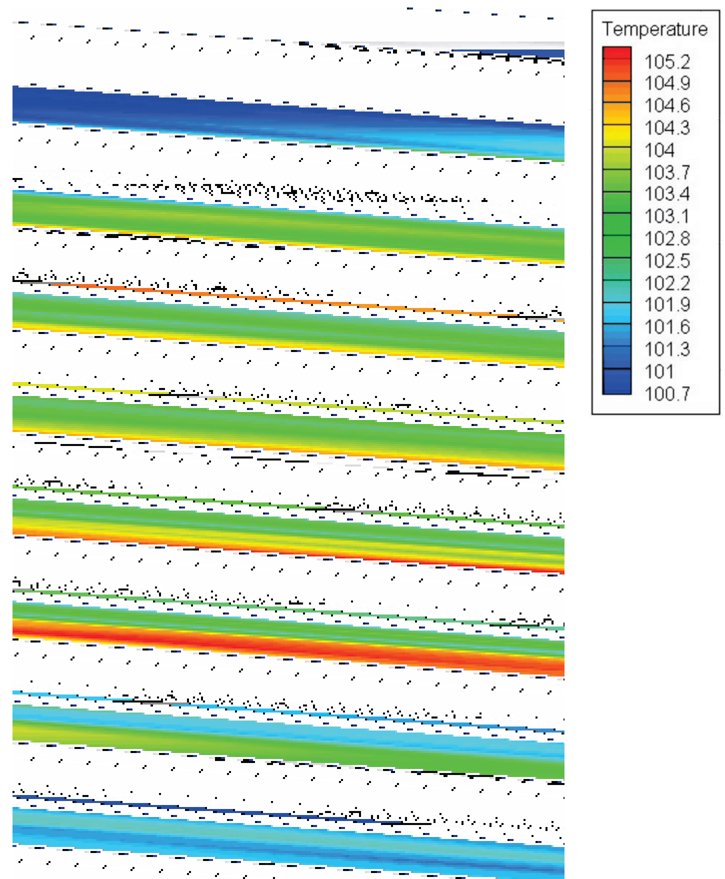
Numerical Analysis of the Passive Condensation Cooling Tank (PCCT) using the CUPID Code, S.J. Lee et al., CFD4NRS-4, 2012

02 Natural Convection in a Pool (3)

❖ Local Thermal Mixing Characteristics inside a PCCT



Schematics of PASCAL PCCT
(133 TC installed)



Fluid temperature for 540 kW test condition

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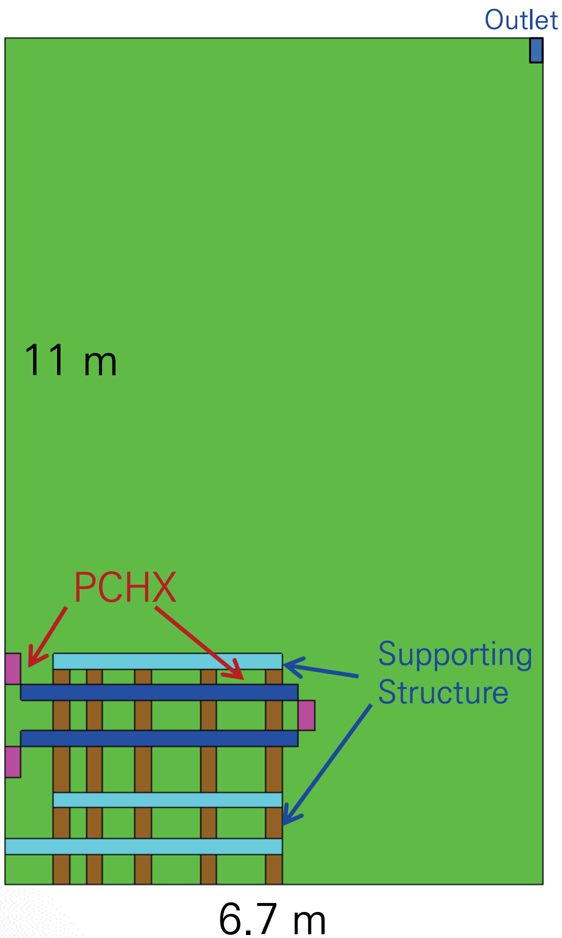
❖ CUPID Code Analysis

- PASCAL test for SS/PL-540-P1 case



- Geometry: 6.70 m x 11.0 m x 0.112 m
- Approximated in two dimensions
- Grid = 33x55
- Porous media: heat exchanger tube
- Open media: pool-side
- Supporting structure: porous media, no heat
- Heat structure: whole area
- Transient: 30,000 sec
- Heat source boundary condition: 540 kW

Numerical Analysis of the Passive Condensation Cooling Tank (PCCT) using the CUPID Code, S.J. Lee et al., CFD4NRS-4, 2012

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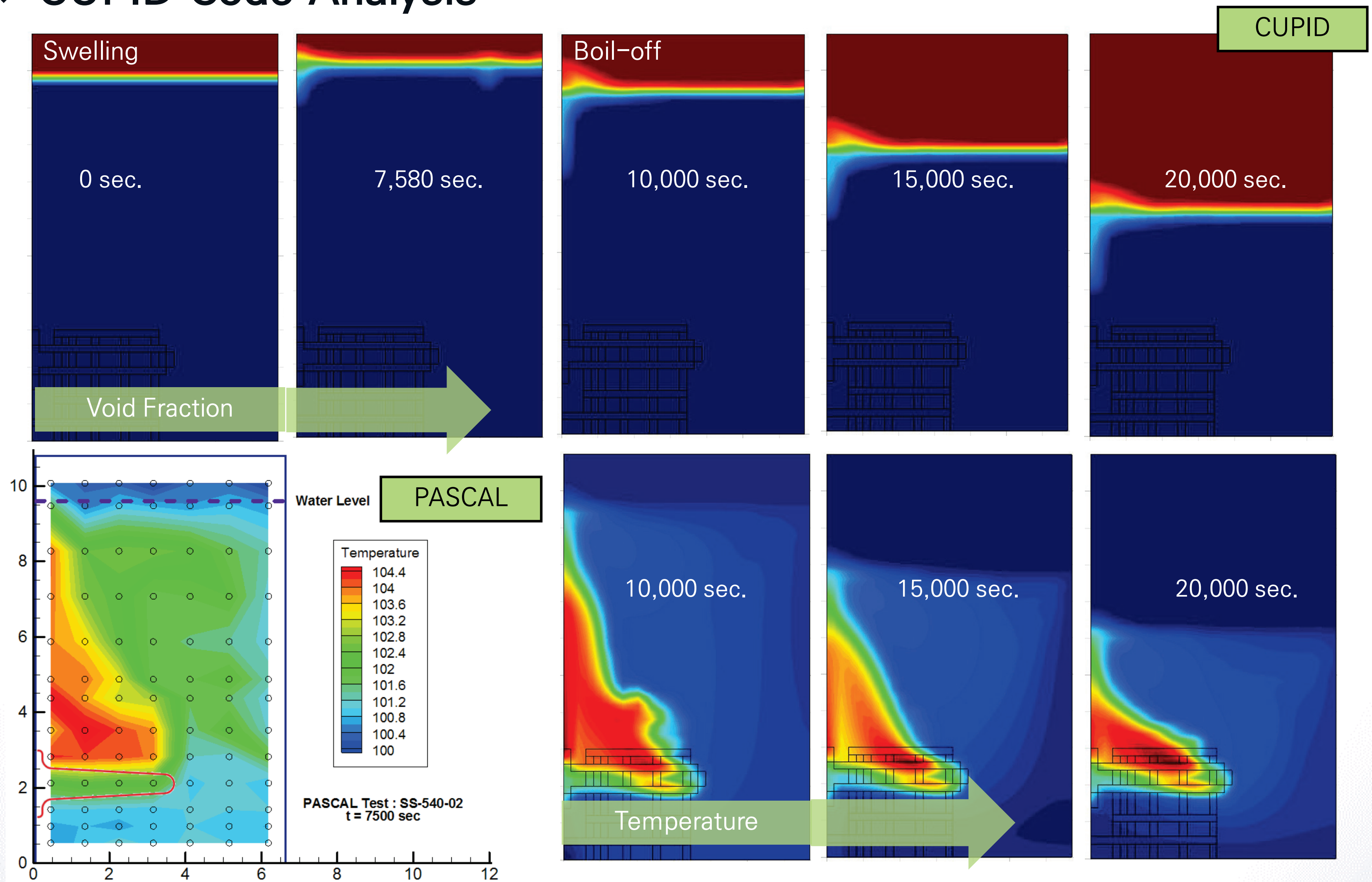
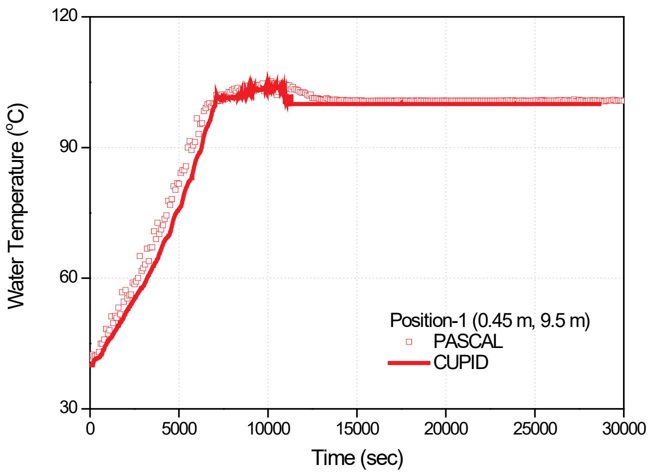
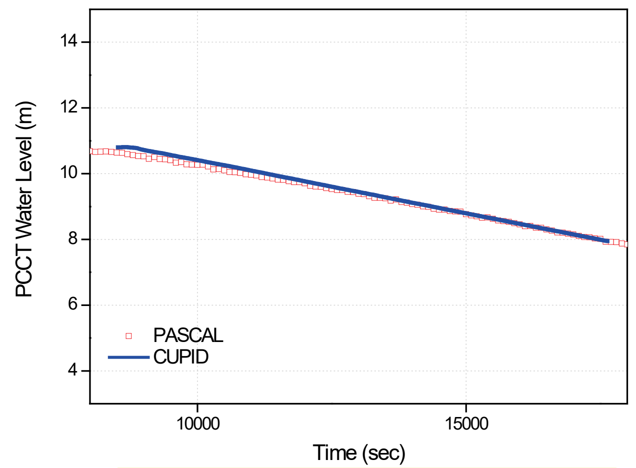
❖ CUPID Code Analysis

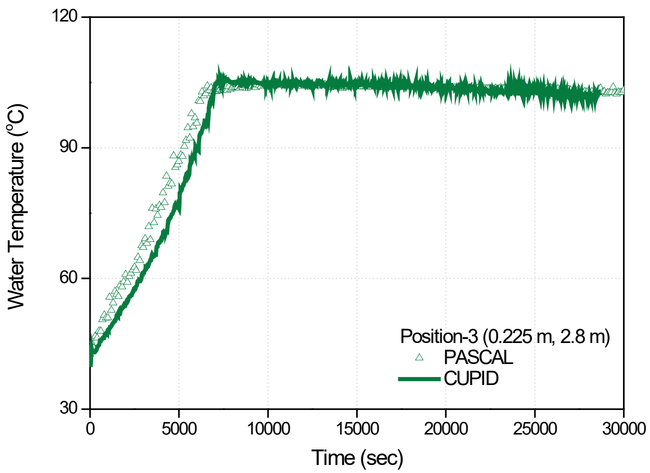


❖ CUPID Code analysis

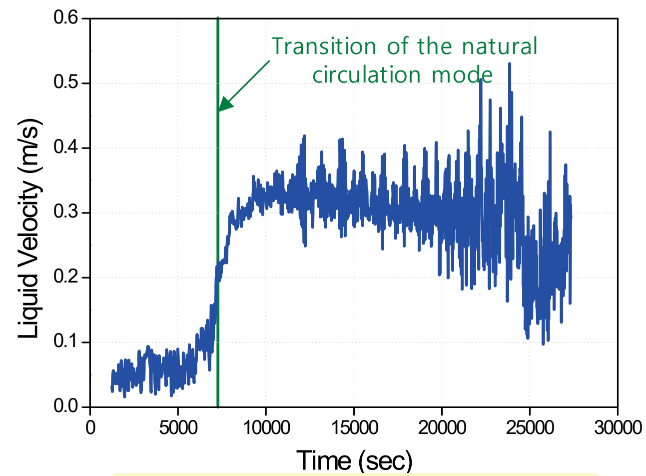




Collapsed water level



Fluid temperature inside a PCCT



Liquid velocity

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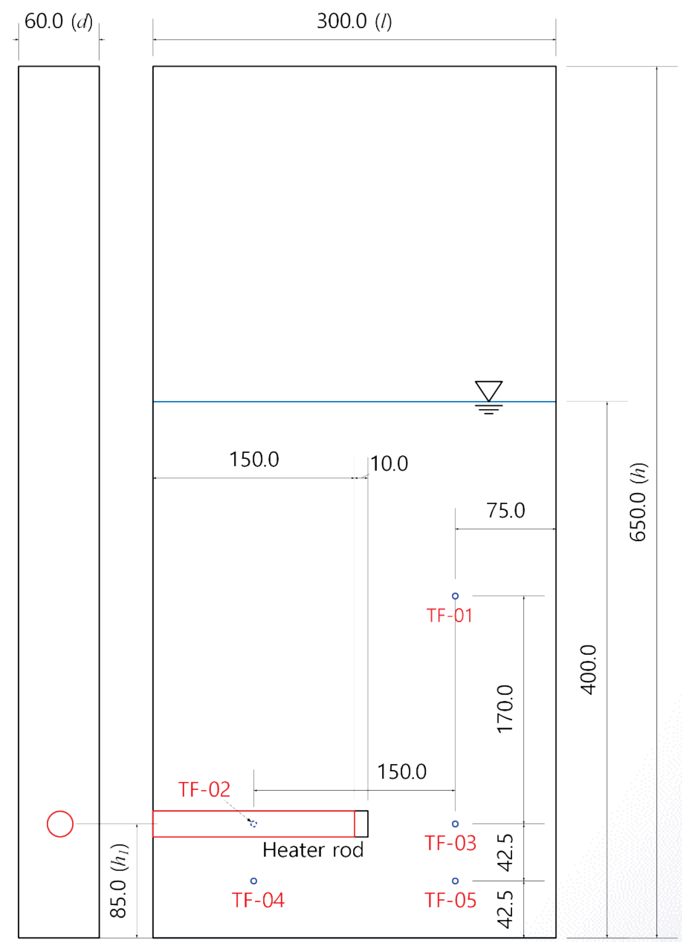
❖ Small-sized Pool Experiment

- To obtain the flow velocity information of liquid phase

Size of test rig		300 × 650 × 60 mm^3
Water inventory		300 × 400 × 60 mm^3
Material of test rig	Front	Pyrex (3 mm thickness)
	Back	Polycarbonate (15 mm thickness)
	Left	Stainless steel (20 mm thickness)
	Right	Pyrex (3 mm thickness)
	Bottom	Stainless steel (20 mm thickness)
Heater rod		3/4” diameter, L: 150 mm, 600 W



02 Natural Convection in a Pool (6)

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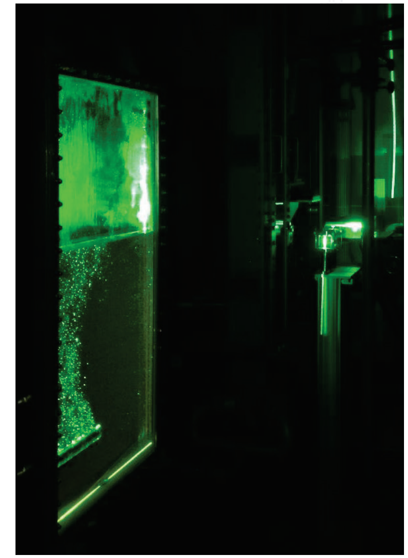
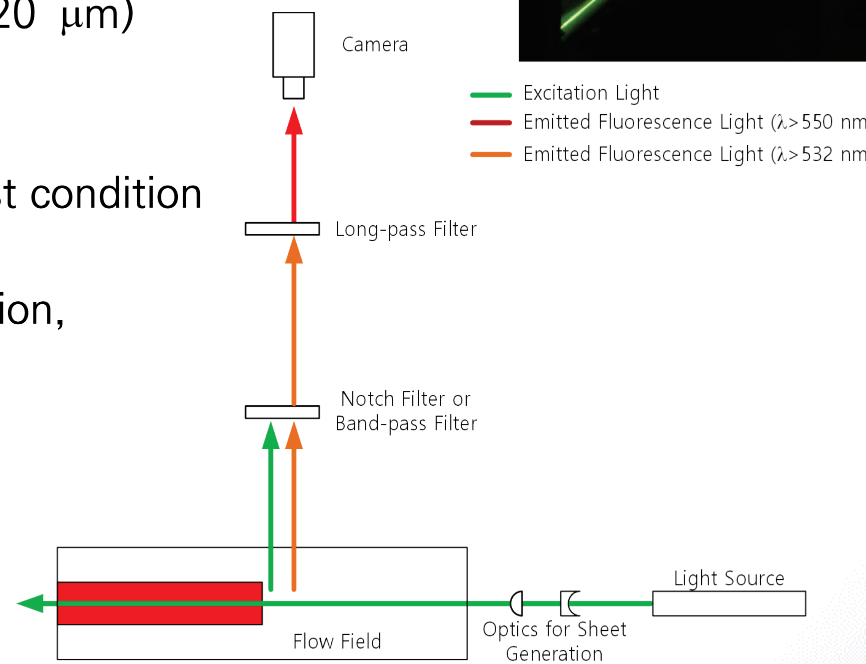
❖ Small-sized Pool Experiment

- PIV system configuration
  - 4M pixels CCD Camera
  - 65 mJ two-head Nd:YAG laser
  - Pulse generator, 8 frames per second
  - Notch filter (λ=532 nm)
  - Long-pass filter (λ 〉550 nm)
  - Fluorescent polymer particle (ϕ ~ 20 μm) (SG=1.02)
  - Spatial resolution (Δx): 3 mm
  - 1,000 velocity vector fields per test condition are acquired
  - Ensemble average: mean, fluctuation, turbulence intensity





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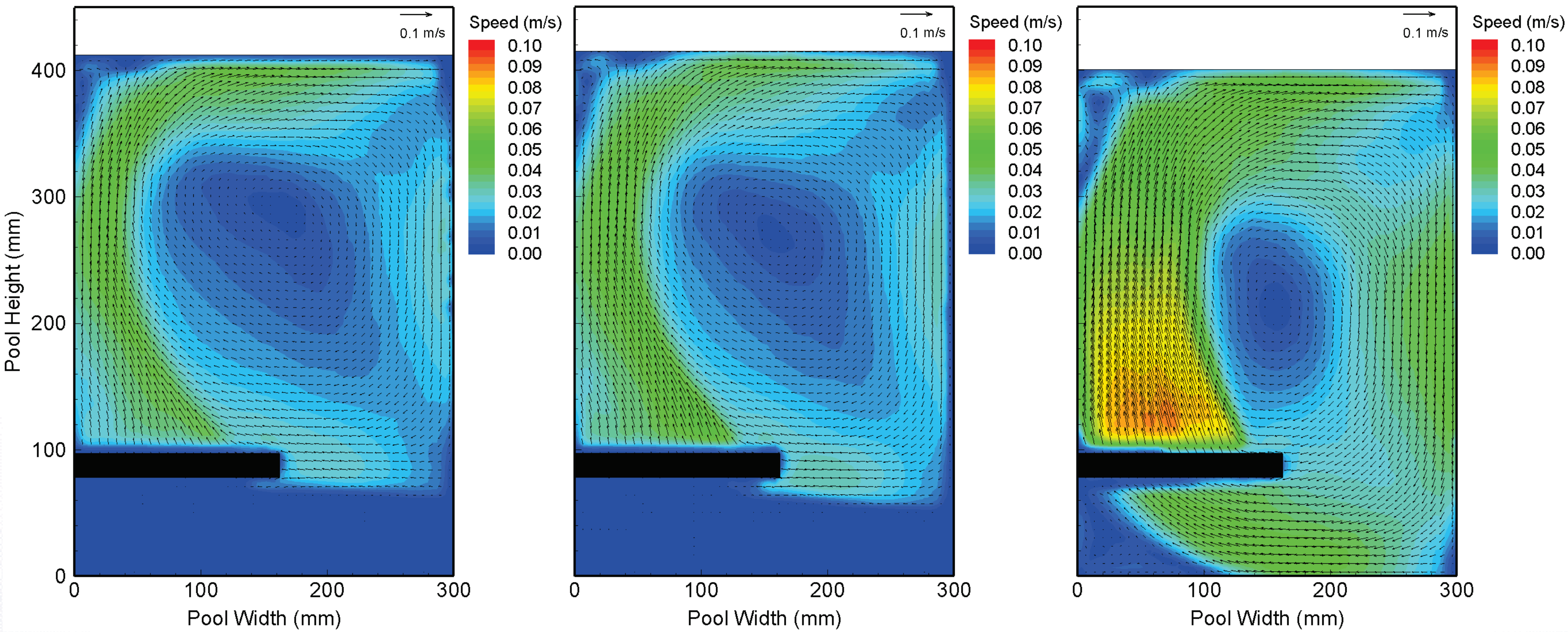
❖ Small-sized Pool Experiment

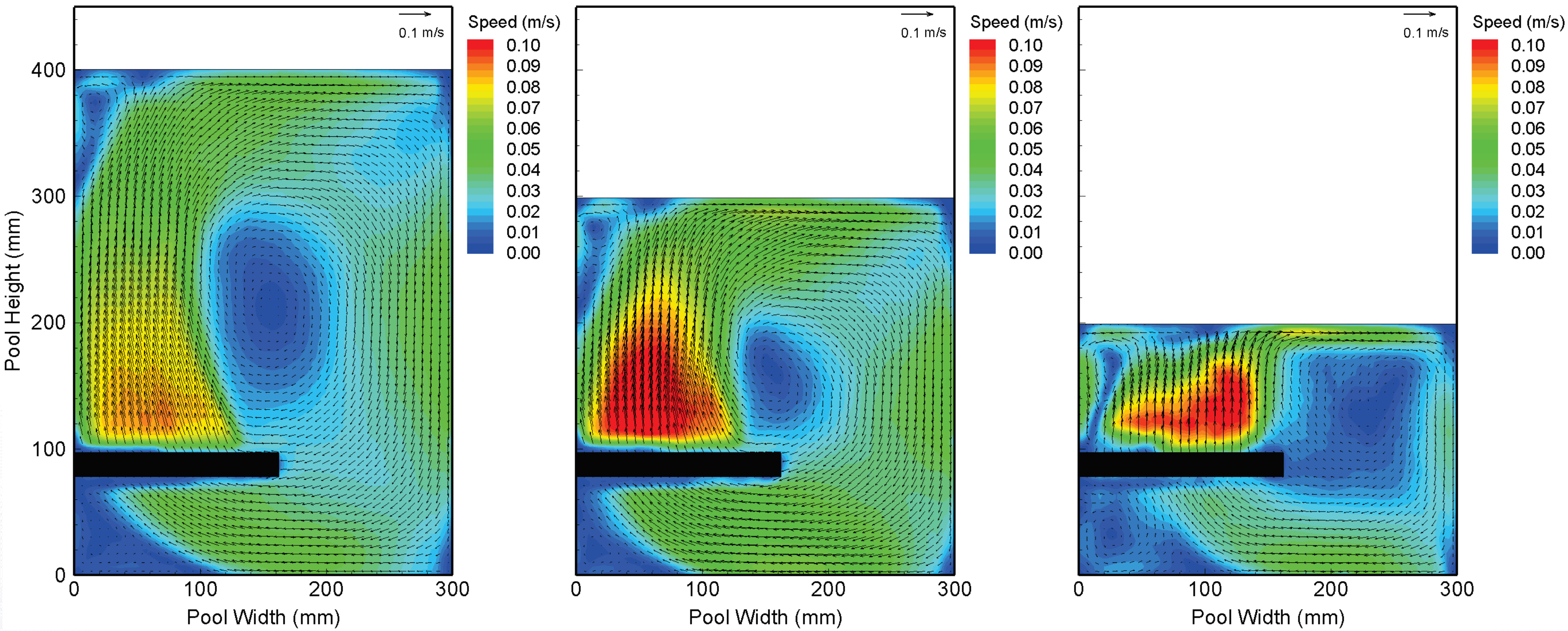
- Featured mean velocity vector field (with varying pool temperatures)



T070H400 T090H400 T100H400

❖ Small-sized Pool Experiment

- Featured mean velocity vector field (with varying pool temperatures)



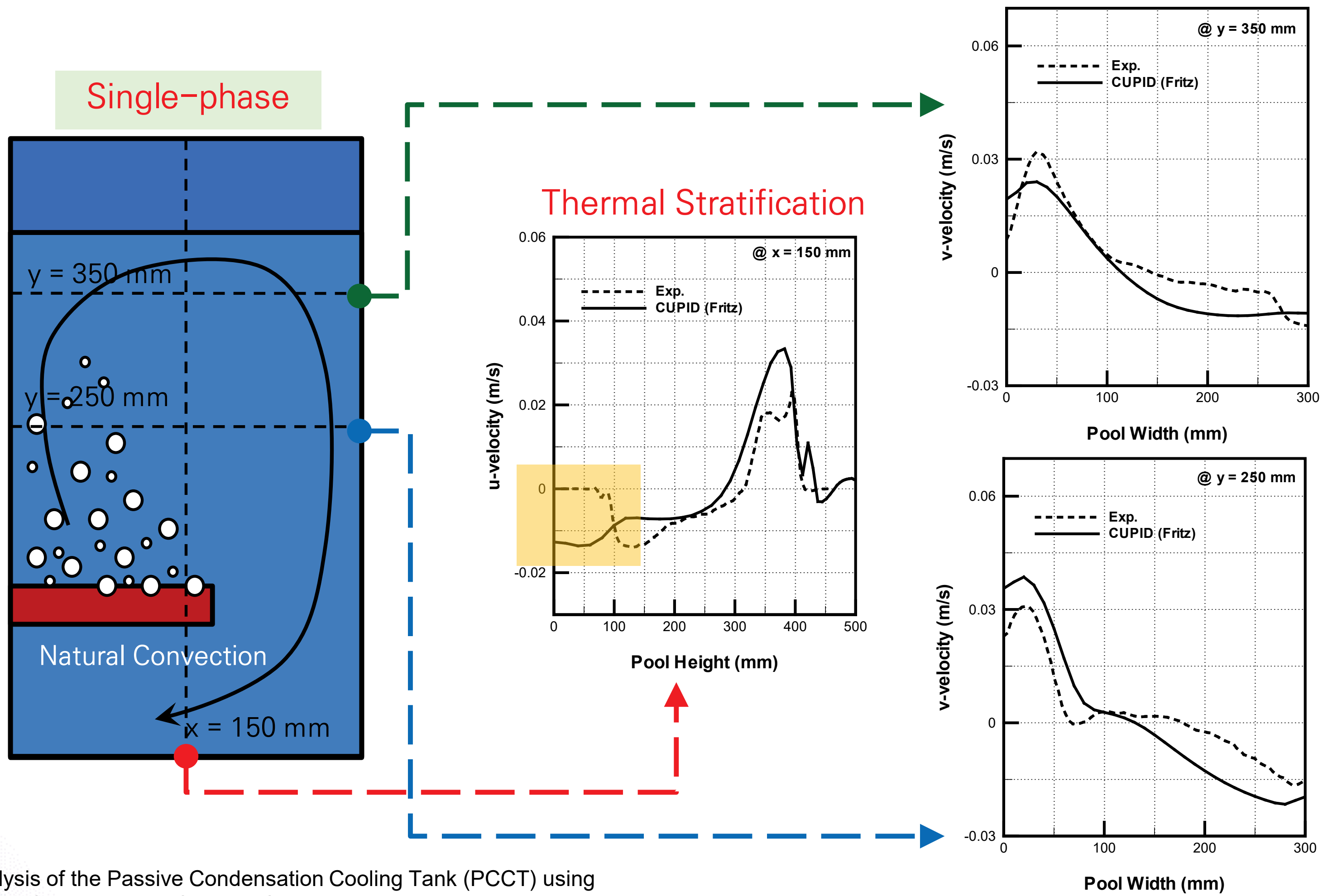
T100H400

T100H300

T100H200

❖ Small-sized Pool Experiment

- CUPID code analysis to verify the performance of turbulence model



Numerical Analysis of the Passive Condensation Cooling Tank (PCCT) using the CUPID Code, S.J. Lee et al., CFD4NRS-4, 2012

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❖ Small-sized Pool Experiment

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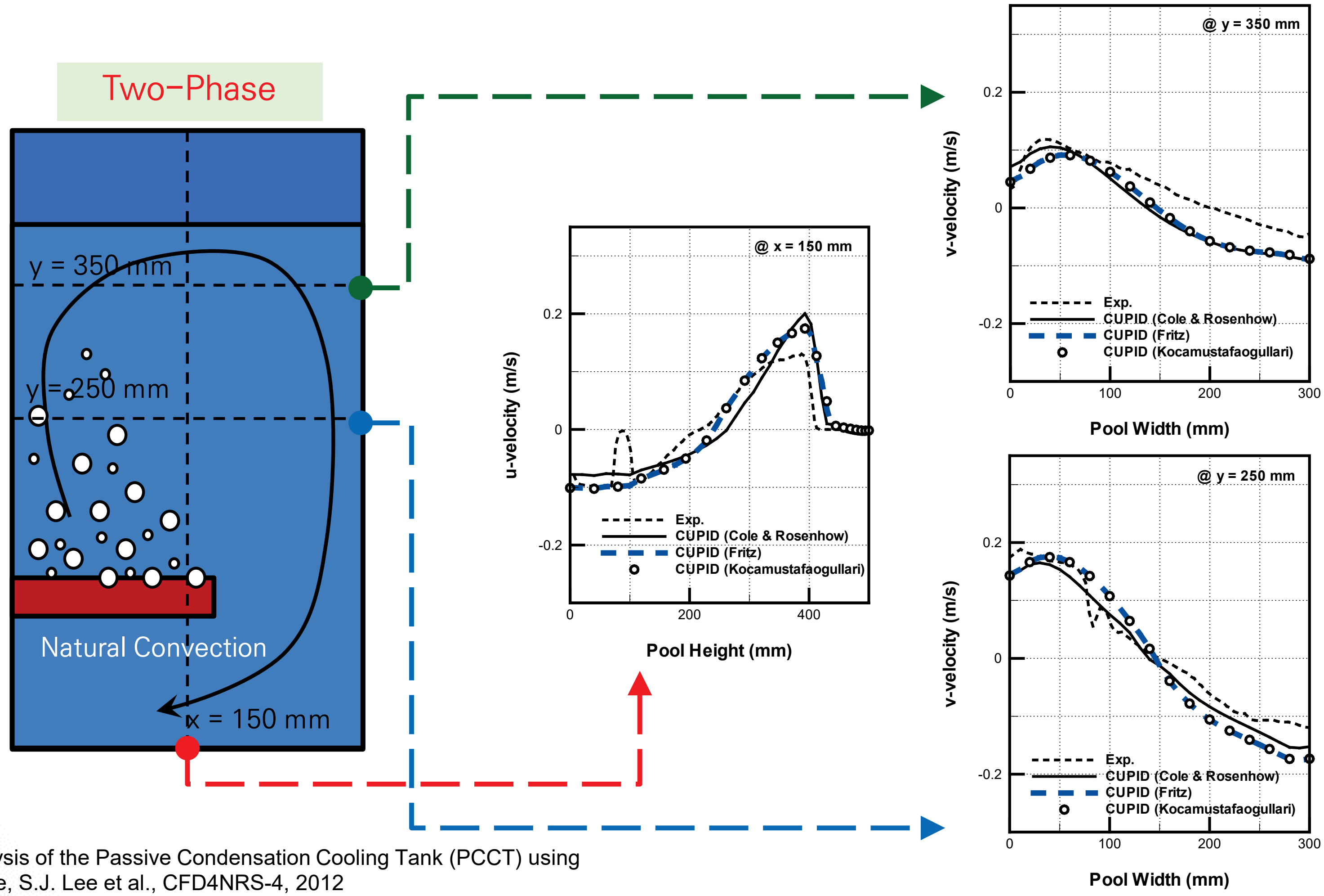
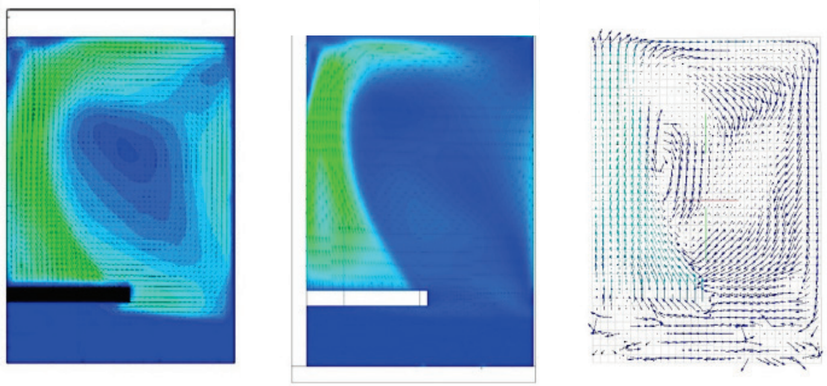


Numerical Analysis of the Passive Condensation Cooling Tank (PCCT) using the CUPID Code, S.J. Lee et al., CFD4NRS-4, 2012

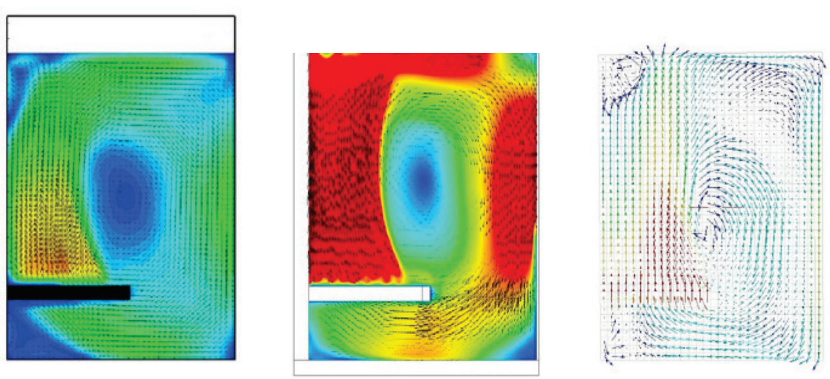
❖ Small-sized Pool Experiment

- Assessment using CFD and 3D thermal-hydraulic system code



Experiment Fluent CATHARE

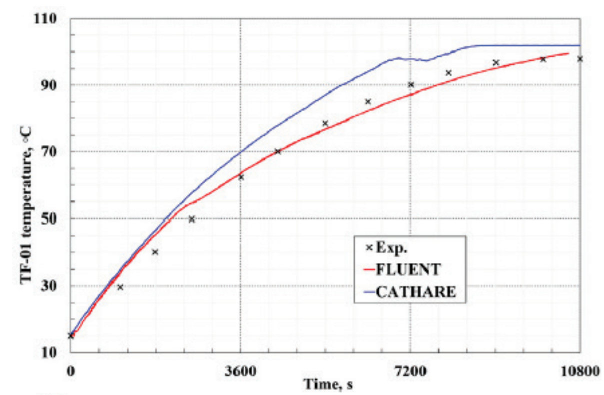
Velocity contour at water temperature 91.3 °C

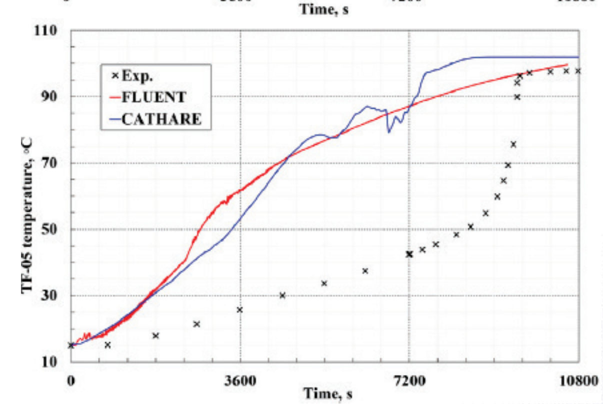


Experiment Fluent CATHARE

Velocity contour at water temperature 98.1 °C

Parameter	Experiment	FLUENT	CATHARE-2
Presence of bottom stratification	Yes	Yes	Yes
Recirculation zone(s)	Yes	Yes	Yes
Stratification break-up	9600 s	4400 s	5600 s
Number of nodes	–	313964	3600
Turbulence model	–	Yes	No
Calculation time CPU	–	504 h	52 h





Comparative study of CFD and 3D thermal-hydraulic system codes in predicting natural convection and thermal stratification phenomena in an experimental facility, Audrius Grazevicius et al., NET, 2023

Rod Bundle Flow Behavior

Chimney Effect

PRIUS Test Program

Macroscopic Turbulence Model

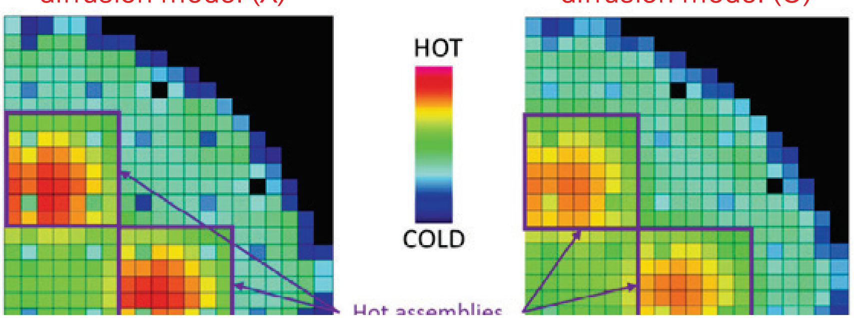
CFD code Analysis

❖ Chimney Effect

- IBLOCA encounter significant 3D effects in core due to the radial power profile, with cross flows and diffusion–dispersion.
  - There are many complicated phenomena during a transient accidents such as chimney effect.

Turbulence dispersion–diffusion model (X)

Turbulence dispersion–diffusion model (O)

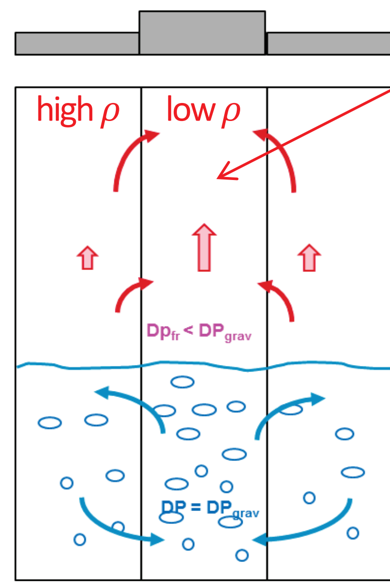


Max. steam flow temperature
(CEA, CATHARE–3D Analysis)

Important radial transfers may have a significant impact on PCT in SB/IBLOCA

No measurements available of radial transfers!

Energy Dispersion–Diffusion



Low G, High P
SB/IBLOCA
Core Uncovery

Dry zone
Crossflows from cold to hot

Swell level
Homogenized by gravity

2–phase zone
Void mixing
Homogenization of steam flow at swell level

〈CEA–KAERI, Core Mixing, WGAMA mtg., 2019〉

❖ PRIUS Test Program

in-PWR Rod-bundle, Investigation of Undeveloped mixing flow between Sub-channels.

- PRIUS experimental campaign has launched to construct a database and improve the turbulence model for crossflow between subchannels.
- Int'l cooperative research work with CEA (METERO)

PRIUS-I ('15-'17)	PRIUS-II ('18-'21)	PRIUS-III ('22-'29)
• 4×6 Rod Array (Acryl) • Single-phase flow (Atmospheric P.)	• 6×12 Rod Array (Acryl) (Bare/Spacer grid w mixing vane) • Single-phase flow (Atmospheric P.)	• 4×6 Heater Rod Array (SG wo mixing vane) • Two-phase flow / ~ 5 MPa
• Non-uniform/uniform inlet velocity • Velocity field database	• Non-uniform/uniform inlet velocity • Velocity field database • Pressure drop	• Inhomogeneous inlet T, Q / asymmetric Power • Void size and fraction (WMS) • Pressure drop / heat transfer
• Verification of MIR-PIV method	• Improvement of macroscopic turbulence model	• Development of 3D k-e turbulence model, turbulence mixing model

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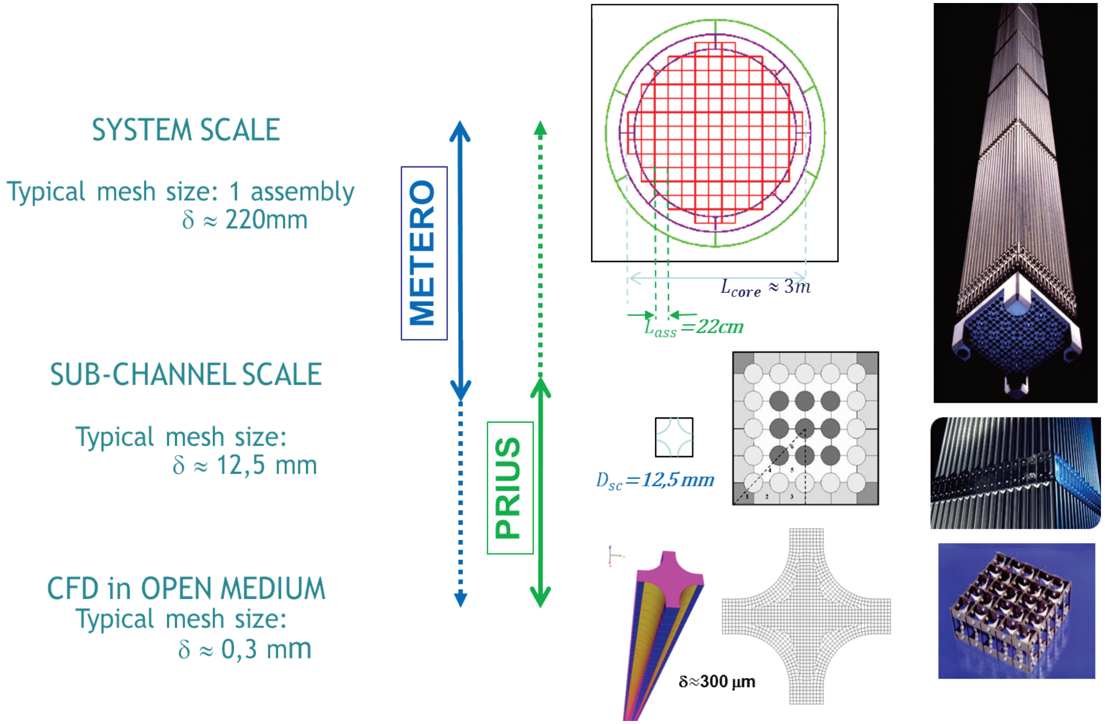
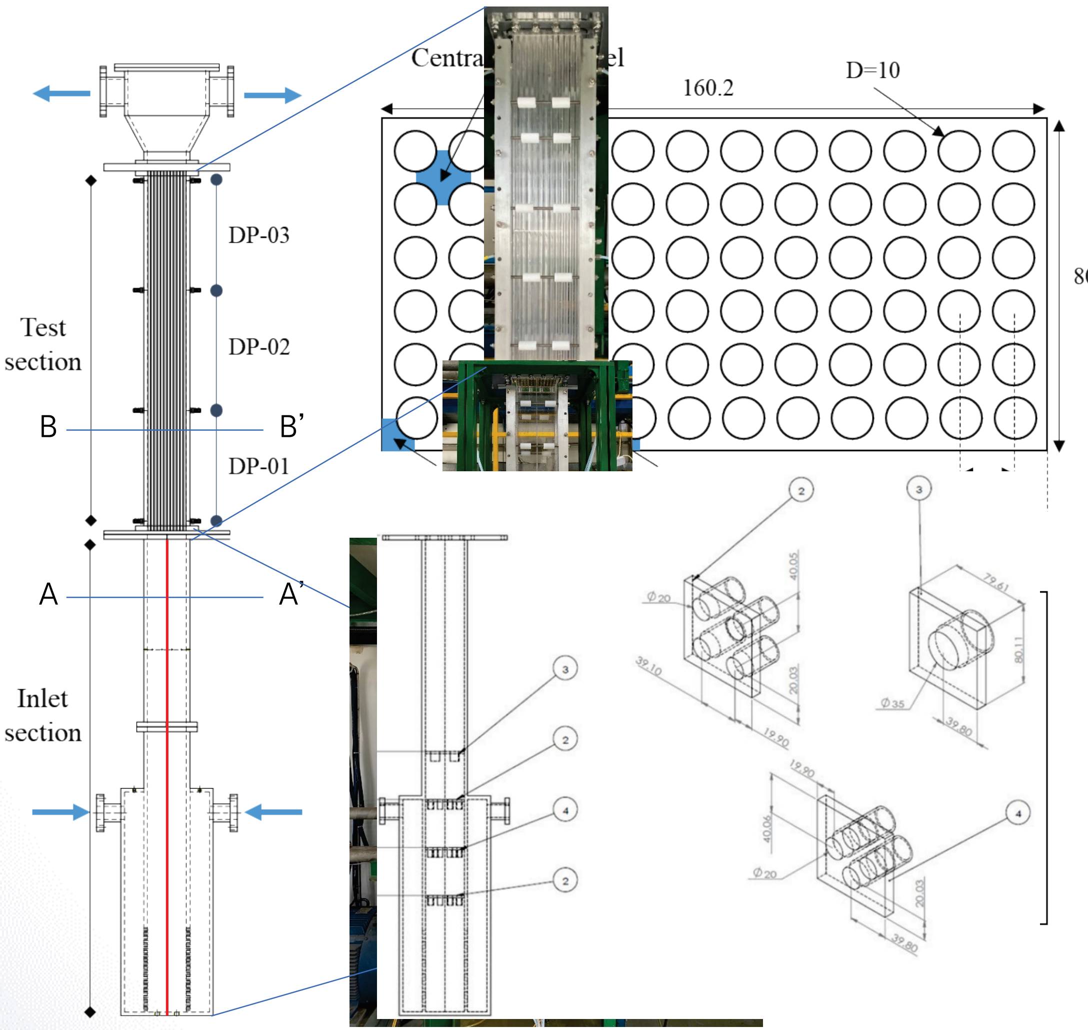
❖ PRIUS Test Program

- To construct high-resolution experimental database to verify the multi-scale safety analysis code on various analysis platforms.
- To validate and improve the turbulence model using the CFD and TH analysis codes.

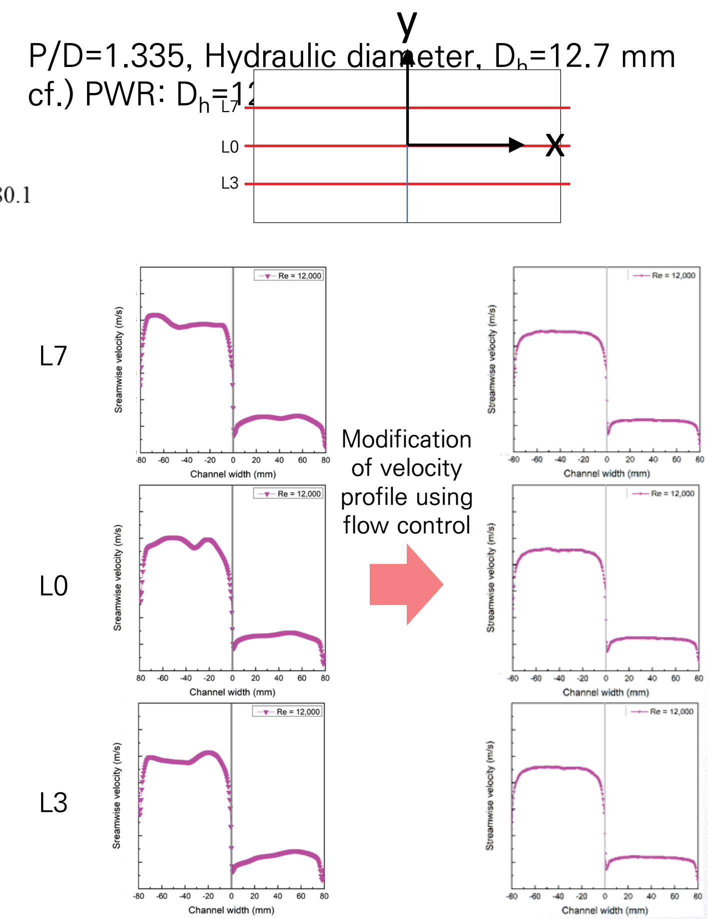


〈CEA-KAERI, Core Mixing, WGAMA mtg., 2019〉

❖ PRIUS-II Test Section Geometry

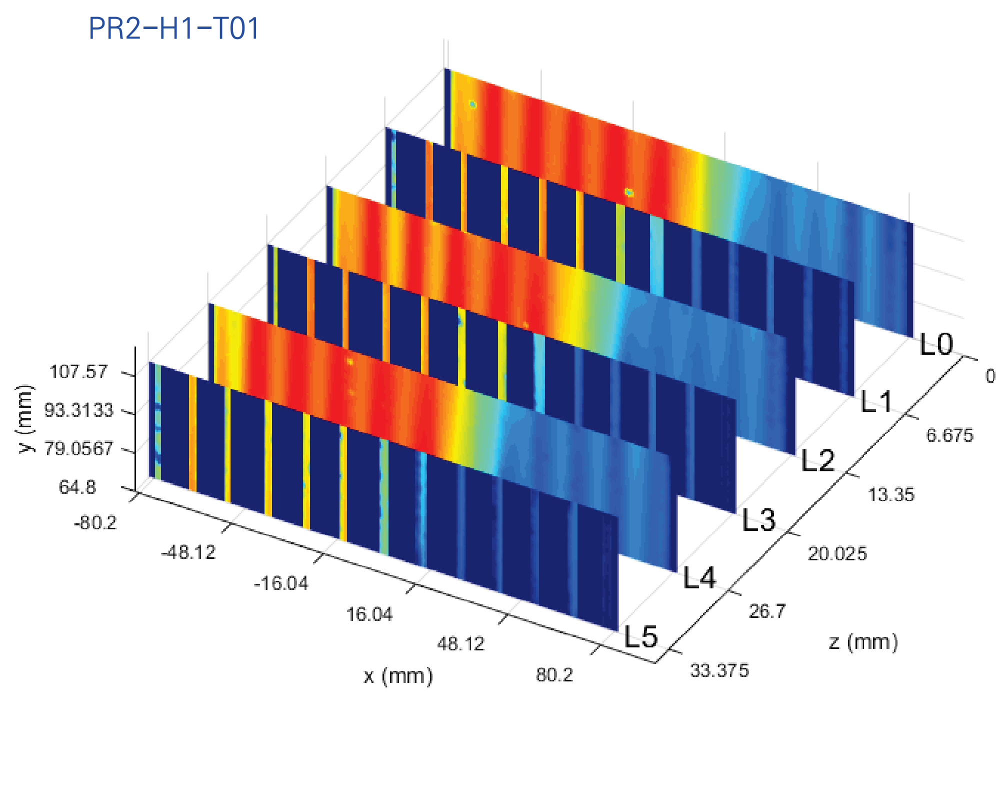


P/D=1.335, Hydraulic diameter, D_h=12.7 mm
cf.) PWR: D_h=12

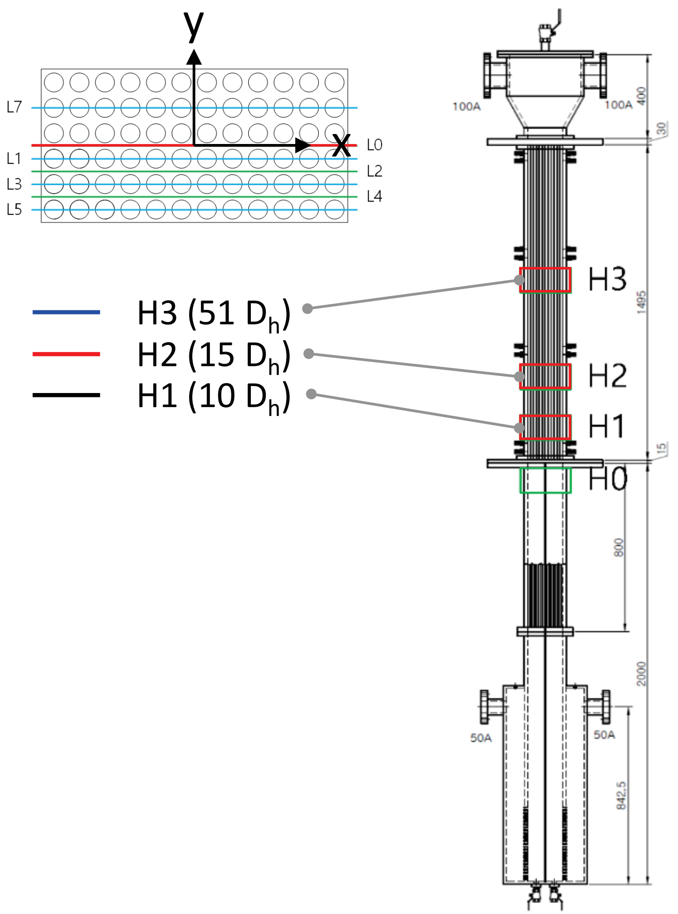


❖ Featured streamwise flow behavior

- Re_{D_h}=9,000, 8:2 / 6.5:3.5



⟨Mean streamwise velocity⟩ ⟨Streamwise turbulence intensity⟩

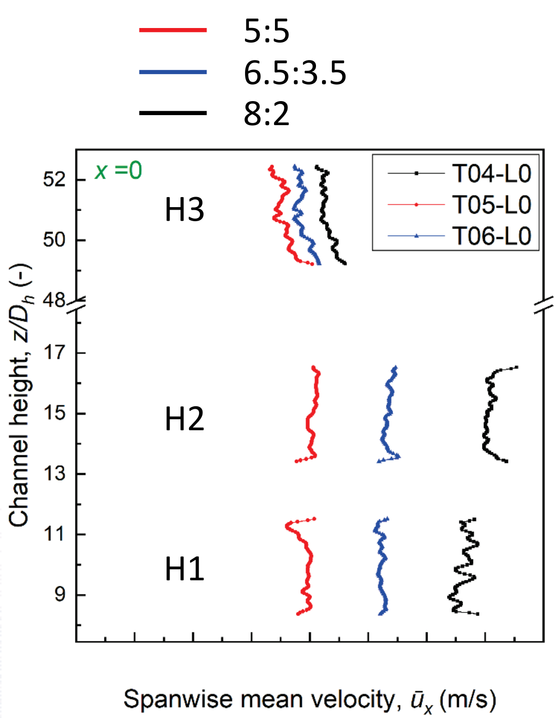


⟨Measurement plane⟩

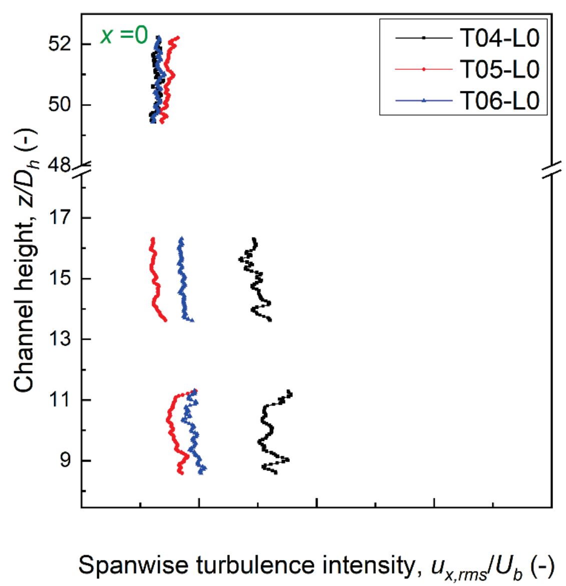
03 Rod Bundle Flow Behavior (4)

❖ Featured spanwise flow behavior

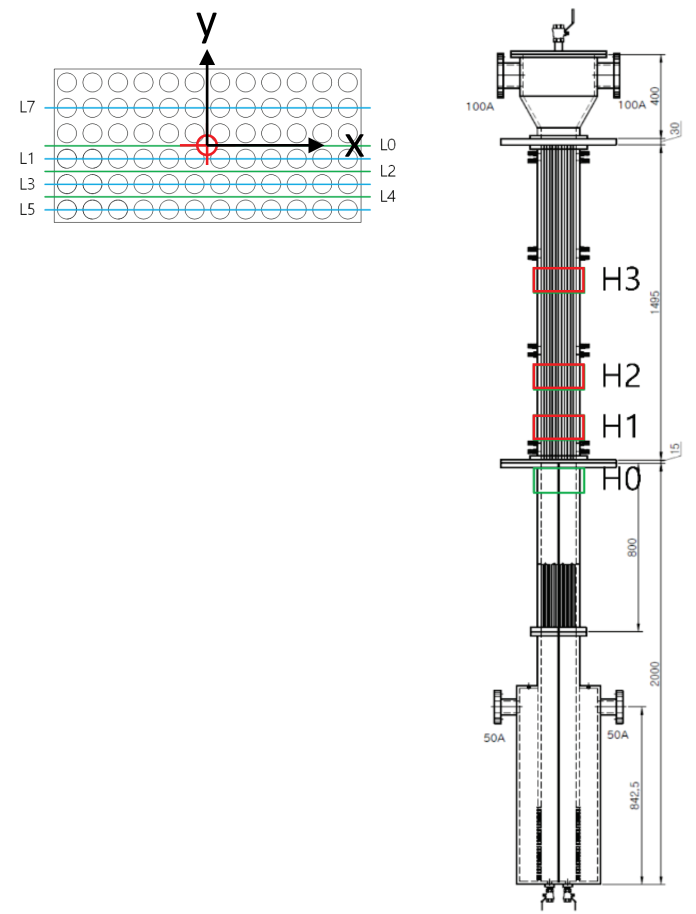
- Re_{D_h}=9,000, 8:2 / 6.5:3.5 / 5:5



〈Mean spanwise velocity〉



〈Spanwise turbulence intensity〉



〈Measurement plane〉

❖ Macroscopic Two-equation Turbulence Model

- Several source term models have been developed for various geometry conditions.
- Chandesris et al. (2001) and Nakayama and Kuwahara (2008) developed source term models for rod-bundle geometry condition.

$$\phi\frac{\partial\langle k\rangle_f}{\partial t}+\frac{\partial}{\partial x_j}\left(\phi\langle\bar{u}_j\rangle_f\langle k\rangle_f\right)=2\phi\nu_t\langle s_{ij}\rangle_f\langle s_{ij}\rangle_f+\frac{\partial}{\partial x_j}\left(\left(\nu+\frac{\nu_t}{\sigma_k}\right)\frac{\partial\phi\langle k\rangle_f}{\partial x_j}\right)-\phi\langle\varepsilon\rangle_f+\boxed{\phi S_k}$$

$$\phi\frac{\partial\langle\varepsilon\rangle_f}{\partial t}+\frac{\partial}{\partial x_j}\left(\phi\langle\bar{u}_j\rangle_f\langle\varepsilon\rangle_f\right)=\frac{\partial}{\partial x_j}\left(\left(\nu+\frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial\phi\langle\varepsilon\rangle_f}{\partial x_j}\right)+\phi\left(2c_1\nu_t\langle s_{ij}\rangle_f\langle s_{ij}\rangle_f-c_2\langle\varepsilon\rangle_f\right)\frac{\langle\varepsilon\rangle_f}{\langle k\rangle_f}+\boxed{\phi S_\varepsilon}$$

	S_k	S_ε
Nakayama and Kuwahara (2008)	$S_k=\phi^2 b\left\|\langle\bar{u}\rangle_f\right\|^3,$ $b=\dfrac{0.3164}{2D_h\,\mathrm{Re}_{D_h}^{0.25}\phi^2}$	$S_\varepsilon=c_{2\varepsilon}\phi^2 b\sqrt{\dfrac{c_D\phi}{2K}}\left\|\langle\bar{u}\rangle_f\right\|^4,$ $K=\dfrac{\phi}{32}D_h^2$
Chandesris (2006)	$S_k=\varepsilon_\infty,$ $\varepsilon_\infty=2C_f\dfrac{\langle\bar{u}\rangle_f^3}{D_h}\left(1-y_{\lim}^+\sqrt{\dfrac{C_f}{2}}\right)$	$S_\varepsilon=c_2\dfrac{\varepsilon_\infty^2}{k_\infty},$ $k_\infty=c_p\langle\bar{u}\rangle_f^2\,\mathrm{Re}_{D_h}^{-1/6}$

〈Source term models for the longitudinal flow condition〉

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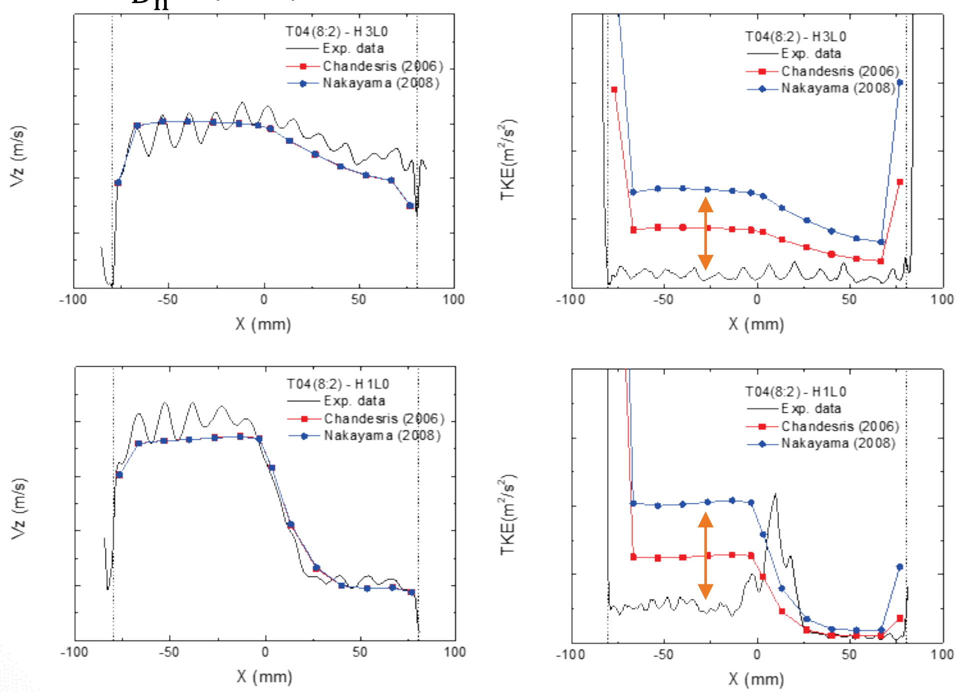
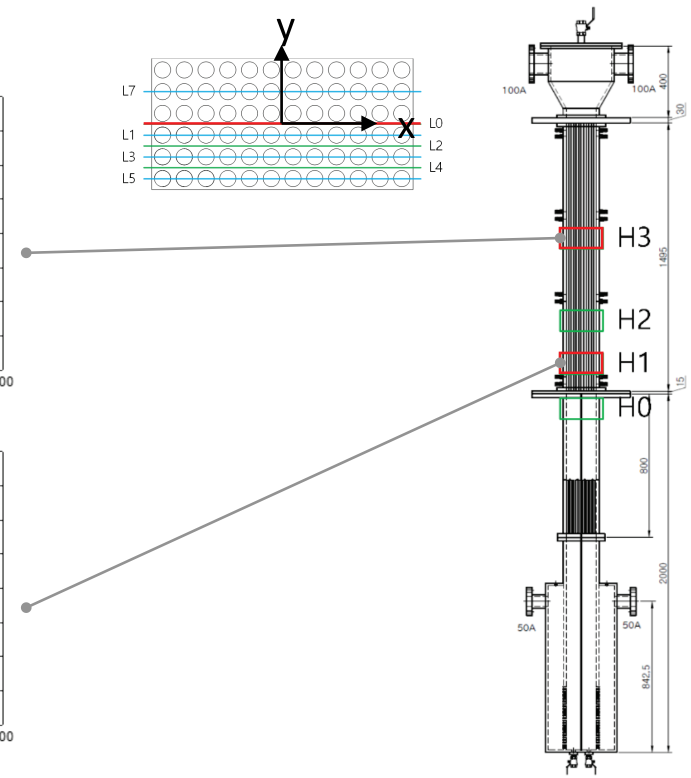
❖ Prediction Performance of Existing Models

- Chandesris (2006) model and Nakayama and Kuwahara (2008) model predicted the mean velocity distribution well.
- Both models gave the TKE to be greater than the experimental values.

Re_{D_h}=9,000, 8:2



⟨Mean streamwise velocity⟩ ⟨TKE distribution⟩



⟨Measurement plane⟩

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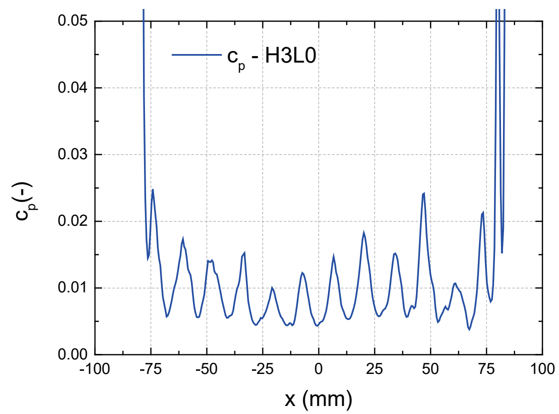
❖ Modification of the Experimental Constant c_p

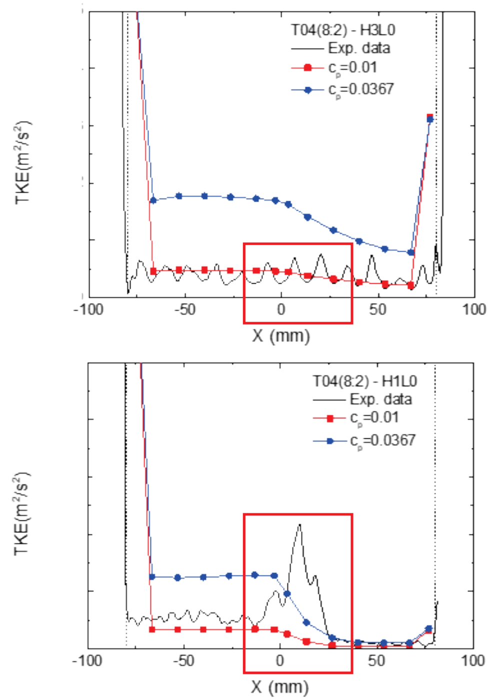
- The experimental constant of Chandesris (2006) model was obtained using the data measured in the fully developed region.

$$c_p = \frac{k_\infty}{\langle \overline{u} \rangle_f^2 \, \mathrm{Re}_{D_h}^{-1/6}}$$

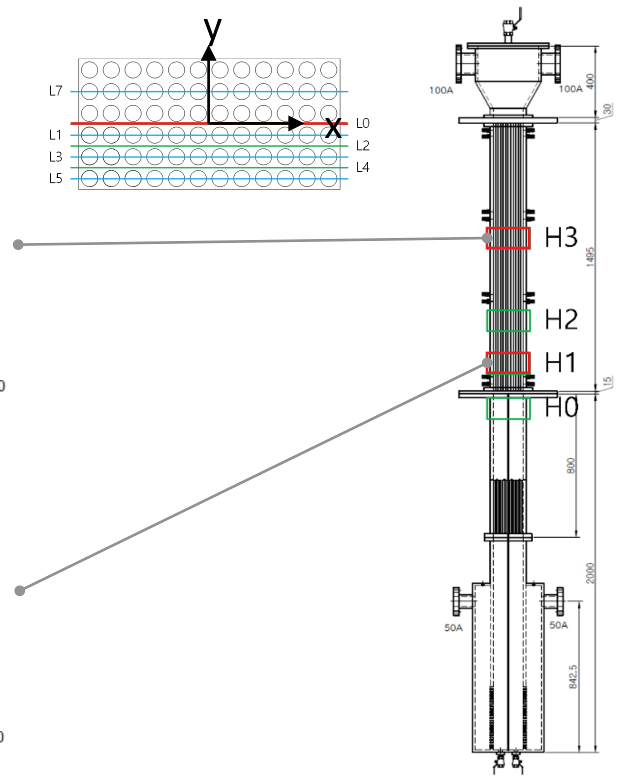


Chandesris (2006): 0.0367 for the pipe
PRIUS-II (2021): 0.01

$Re_{\mathrm{D_h}}$=9,000, 8:2



〈TKE distribution〉



〈Measurement plane〉

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❖ Experimental constant c_p modeling

- Based on the assumption that the velocity gradient affects the turbulence dissipation, a new type of c_p was proposed.

$$c_p = 0.01 + c_1 \mathrm{Re}_l^{c_2} \boxed{\left(\frac{\partial u_z}{\partial x}\right)^2}$$

❖ S_k modeling

- Term including the velocity gradient was added to the source term of the TKE transport equation.

$$S_k = \varepsilon_\infty + \boxed{S_a} \qquad S_a = c_k \frac{\mu}{\rho} \boxed{\left(\frac{\partial u_z}{\partial x}\right)^2} \qquad c_k = 0.225\,\mathrm{Re}_l$$

	S_k	S_ε
Chandesris (2006)	$S_k = \varepsilon_\infty$, $\varepsilon_\infty = 2C_f \frac{\langle \bar{u} \rangle_f^3}{D_h}\left(1 - y_{\lim}^+ \sqrt{\frac{C_f}{2}}\right)$	$S_\varepsilon = c_2 \frac{\varepsilon_\infty^2}{k_\infty}$, $k_\infty = c_p \langle \bar{u} \rangle_f^2 \mathrm{Re}_{D_h}^{-1/6}$

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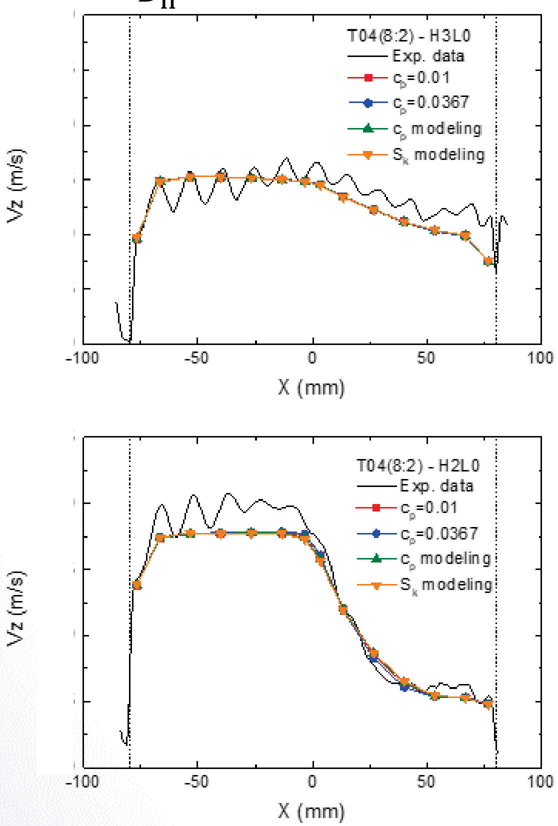
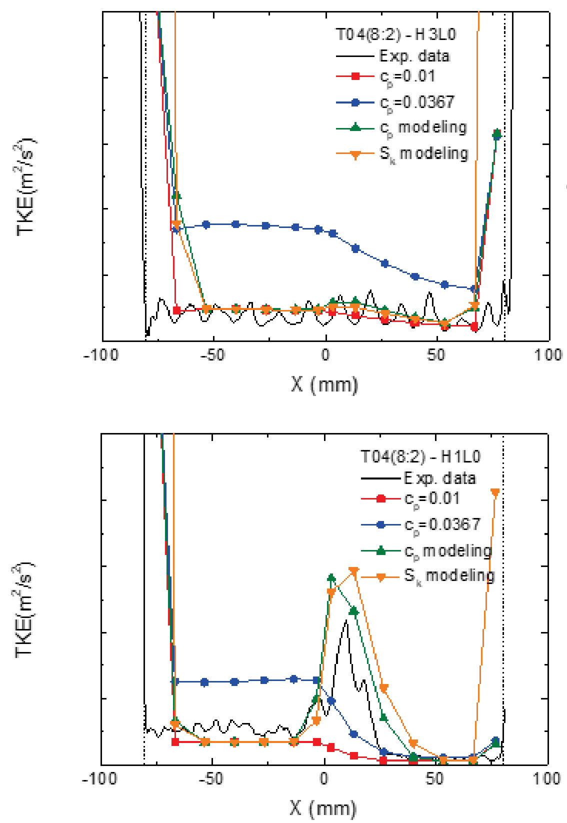
❖ Prediction Performance of the Improved Models

- Improved source term model predicted the TKE under asymmetric flow conditions better than the previous model.

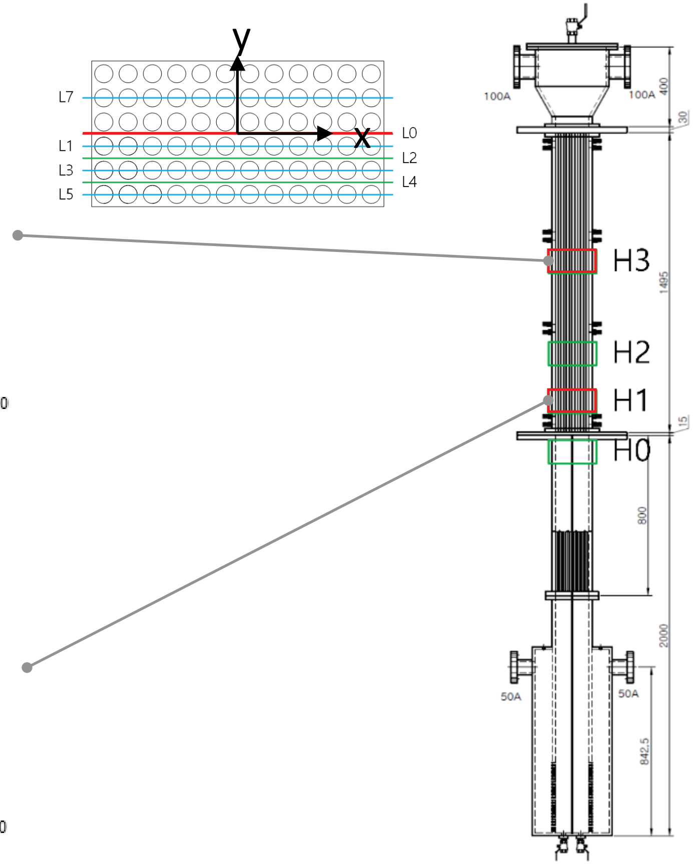
Re_{D_h}=9,000, 8:2



⟨Mean streamwise velocity⟩



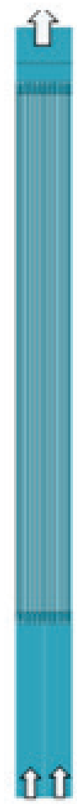
⟨TKE distribution⟩



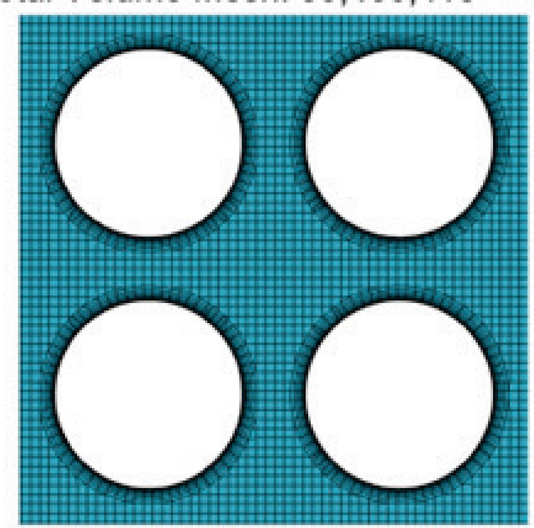
⟨Measurement plane⟩

❖ CFD Code Analysis

- STAR-CCM+ 15.06.008
- Models
  - Steady
  - Turbulence Model (k−ε, k−ω, RST
  - Constant Density

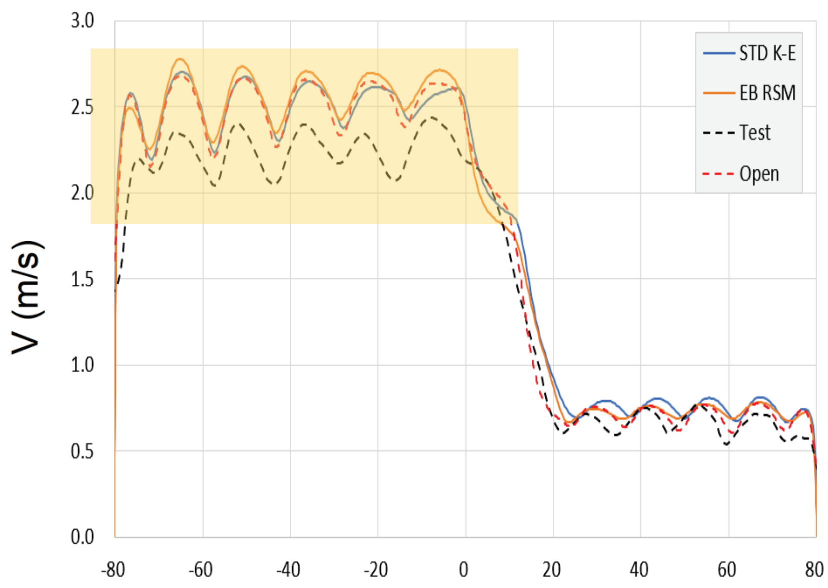


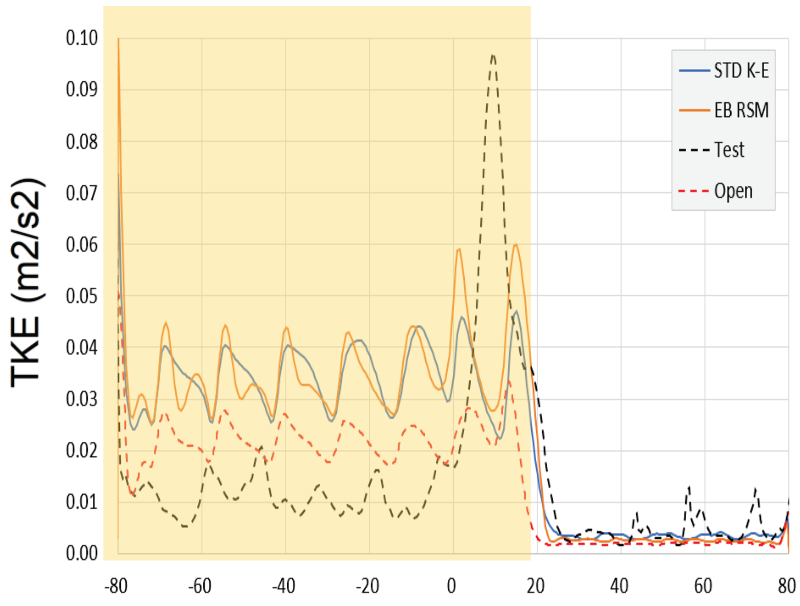
- Trimmed Mesh
  - Base Size: 0.5mm
  - Number of Layer: 12개
  - Layer Thickness: 2mm
  - Total Volume Mesh: 39,460,415



❖ CFD Code Analysis

- k−ε / EB(Elliptic Blending) RSM models showed similar velocity profiles.
- TKE was over-predicted.





Summary

❖ CFD-grade Experiment

- To validate the physical model used in CFD simulations.
  - Experiment provides a relatively low uncertainty of validation and allows a good determination of the model uncertainty.

❖ Application of passive system and core mixing problems

- Identification of lacking data for code validation of some passive systems and core multi-dimensional flow phenomena
  - Collect experimental data with mixing in presence of buoyancy effects
  - Core TH
    - Upscaling of models from CFD to sub-channel and to porous 3D
    - CUPID code for validation of sub-channel model + validation of CFD

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