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The Implementation of Mixing Vane Directed Cross Flow Model in CUPID for Subchannel Scale T/H Analysis

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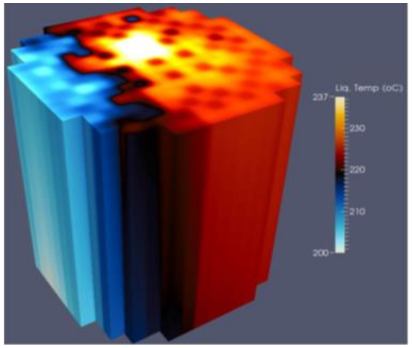
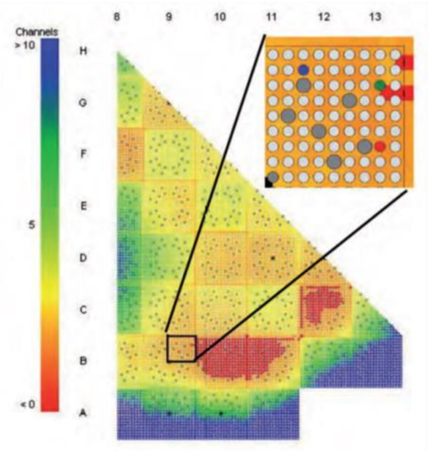
Contents

Background

- Multi-physics reactor core analysis with high fidelity thermal-hydraulic simulation tool
- Maintaining higher safety standards
  - Coupled 3D methods are the most suitable tools for transient analysis with asymmetric power.
- Minimizing economic uncertainty
  - Optimization of fuel design and fuel cycle costs
- Subchannel scale whole core pin-by-pin analysis
  - COBRA-TF (CTF in CASL, NURESAFE)
  - COBRA-FLX (ARCADIA code system in AREVA)
  - SUBCHANFLOW (KIT)
  - MATRA (KAERI)



MSLB analysis at the HZP condition, CASL (Kucukboyaci et al. (2015))*



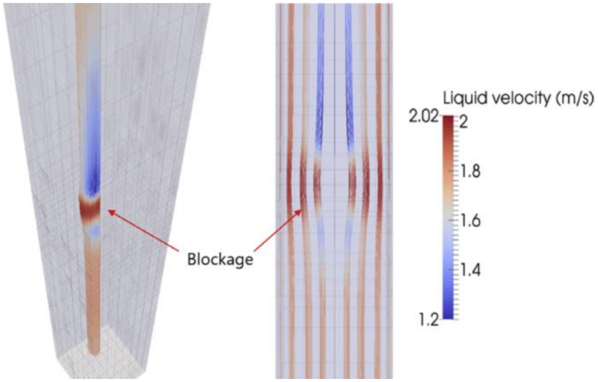
Rod ejection analysis using COBRA-FLX (DNBR and film boiling)
(Gensler et al. (2013))**

*) Kucukboyaci et al., COBRA-TF Parallelization and Application to PWR Reactor Core, CASL-U-2015-0167-000, 2015.
**) Gensler et al., LWR Core Safety Analysis with Areva's 3-dimensional Methods, International Journal for Nuclear Power, 2013.

Background

- MATRA
  - Developed by KAERI (based on COBRA)
  - Very effective for reactor core design and evaluation of DNBR margin
    - Achievement of required accuracy within reasonable time
  - Systematically validated against large experimental database
  - Features not optimized for accident analyses
    - Homogeneous Equilibrium Model (HEM) ⇒ **Velocity difference** between two phases
    - Spatial marching scheme in the axial direction ⇒ **Reverse flow** or **cross-flow dominant cases**

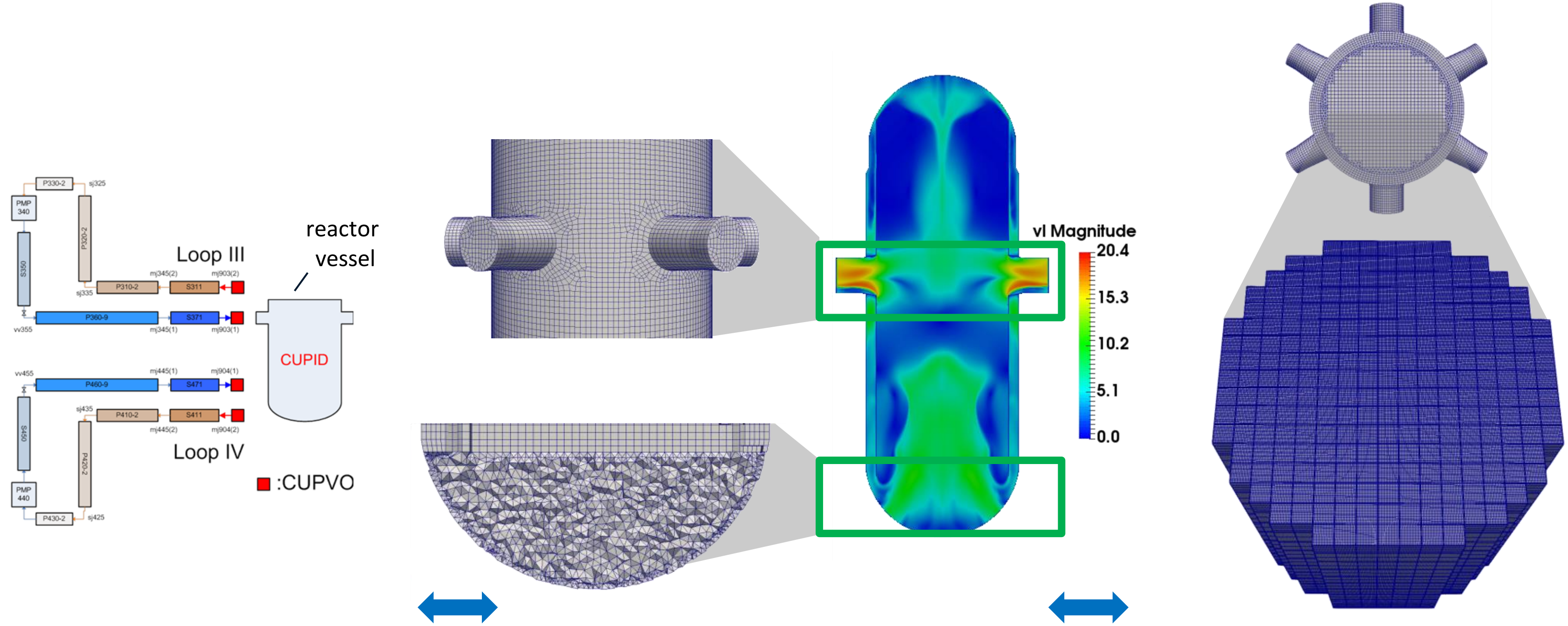
- CUPID (KAERI's inhouse code)
  - Has been developed by KAERI for multi-dimensional two-phase flow simulation
  - Physical models
    - Two-fluid model for two-phase flow
      ⇒ **Velocity difference** between two phases
  - Numerical solver
    - Highly parallelized, pressure correction equation for whole computational domain.
      ⇒ **Reverse flow** or **cross-flow dominant cases**



Validation of PNL 7x7 flow blockage test
(S.J. Yoon et al (2018))*

*) YOON, Seok Jong, et al. APPLICATION OF CUPID FOR SUBCHANNEL-SCALE THERMAL–HYDRAULIC ANALYSIS OF PRESSURIZED WATER REACTOR CORE UNDER SINGLE-PHASE CONDITIONS. Nuclear Engineering and Technology, 2018.

Plan for multi-scale analysis using CUPID



1D system scale (MARS) 3D CFD scale (CUPID) 3D subchannel scale (CUPID)

- Open medium approach with turbulence model and non-drag force models
  - Similar with commercial CFD codes
- Porous medium approach with flow regime map and corresponding constitutive models
  - Steam generator(pipes), reactor core(fuel rods)
- Unstructured grid
  - Collocated grid (Cell-centered)

Previous work

- The implementation of fundamental subchannel models on CUPID
  - Crossflow model
    - Friction factor model : axial direction

$$\Delta P = -\frac{1}{2}\left(\frac{f}{d_{hy}} + K'\right)\left(\frac{G_k^2}{\rho_k}\right)$$

    - Form loss model : lateral direction

$$\Delta P = -\frac{K_G}{2}\left(\frac{W_{IJ,k}|W_{IJ,k}|}{l_{IJ}\rho_k s_{IJ}}\right)$$

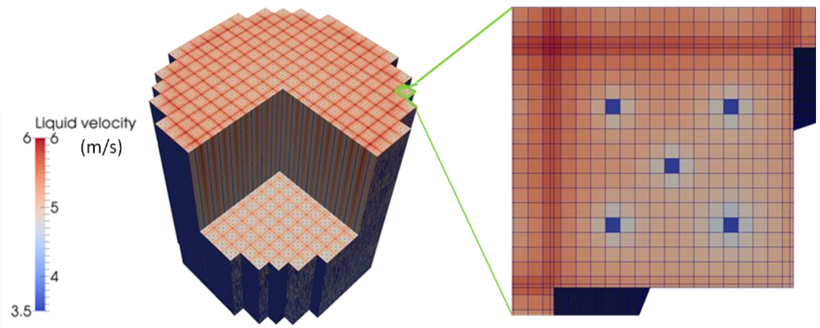
  - Turbulent mixing and void drift model
    - EM (Equal Mass exchange)
    - EVVD (Equal Volume exchange and Void Drift)

- The validation of subchannel models implemented on CUPID against various experiments

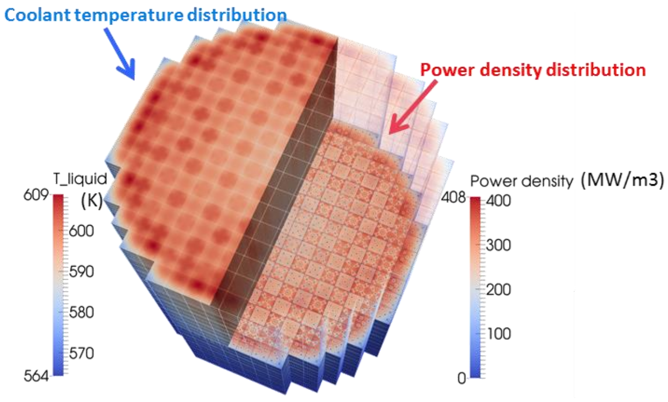
Tests			CUPID
Single-phase	Unheated	CNEN 4×4 mixing test	O
		PNL 7×7 flow blockage test	O
		CE 15×15 inlet jetting test	O
		Weiss' 14×14 inlet blockage test	O
	Heated	PNNL 2×6 buoyancy effect test	O
Two-phase	Unheated	RPI air-water mixing test	O
		Tapucu two-channel test	O
		Van der Ros two-channel test	O

Previous work and objectives of the present study

- Preliminary APR1400 whole core simulation
  - MPI domain decomposition
  - Wall-clock time: 38 minutes with 100 cores
  - Volumetric heat source in the **coolant**



Velocity distribution



Coolant temperature and power density distribution

- In the present study,
  - To extend the capability of CUPID to subchannel scale T/H analysis using more realistic models
    - ✓ Implementation of grid-directed cross flow model
    - ✓ Improvement of fuel rod heat conduction model
  - Demonstration of the whole core analysis using implemented models

Contents

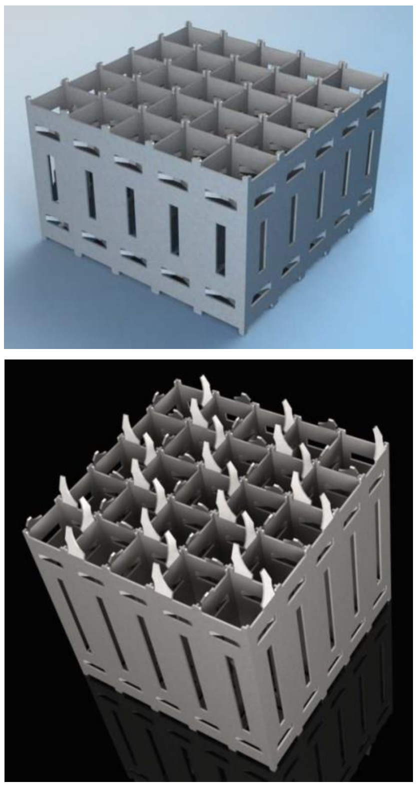
Grid-directed cross flow model

- Spacer grid and mixing vane
  - Prevention of rod bundle vibration
  - Enhancement of wall heat transfer

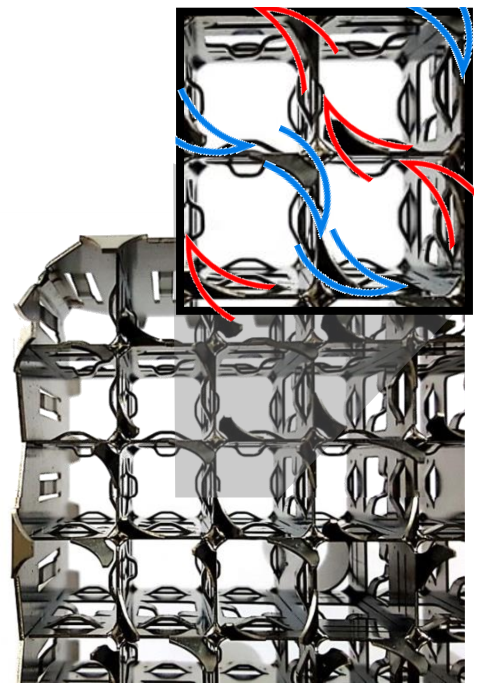
- Momentum equation (CTF) $M_k = f^2 u_l \rho_l A \times u_l$

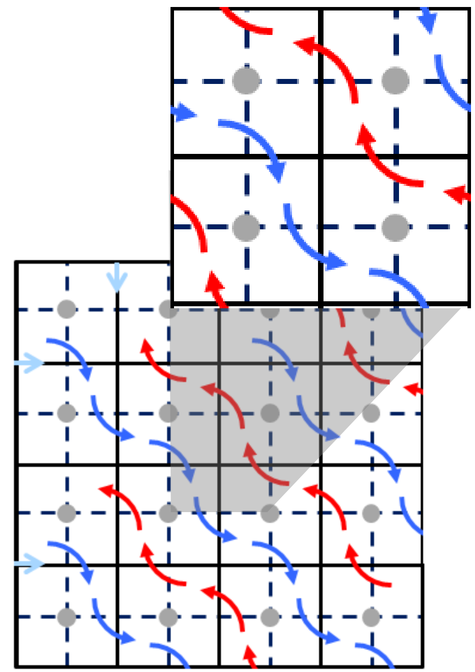
  f : Lateral convection factor (lateral velocity/axial velocity)

  M_k : Lateral momentum transfer due to grid-directed cross flow model



Non-mixing vane spacer grid(up) and mixing vane spacer grid(down) of PSBT 5x5 experiment



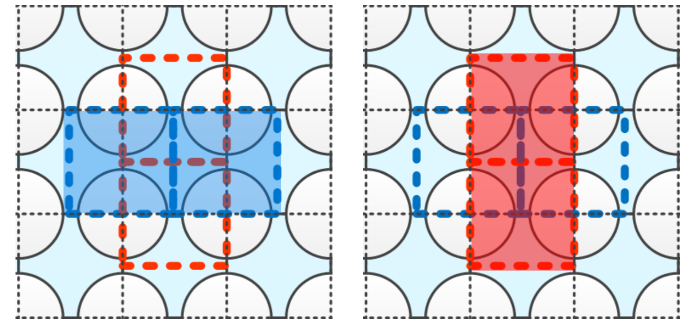


*) A. RUBIN et al., OECD/NRC Benchmark based on NUPEC PWR subchannel and bundle tests (PSBT), Volume I: Experimental Database and Final Problem Specifications. US NRC OECD Nuclear Energy Agency (2010).

Grid-directed cross flow model

- Direction of coolant transfer was simplified.
  - Perpendicular with subchannel face
- Staggered grid : CTF
- Collocated grid : CUPID

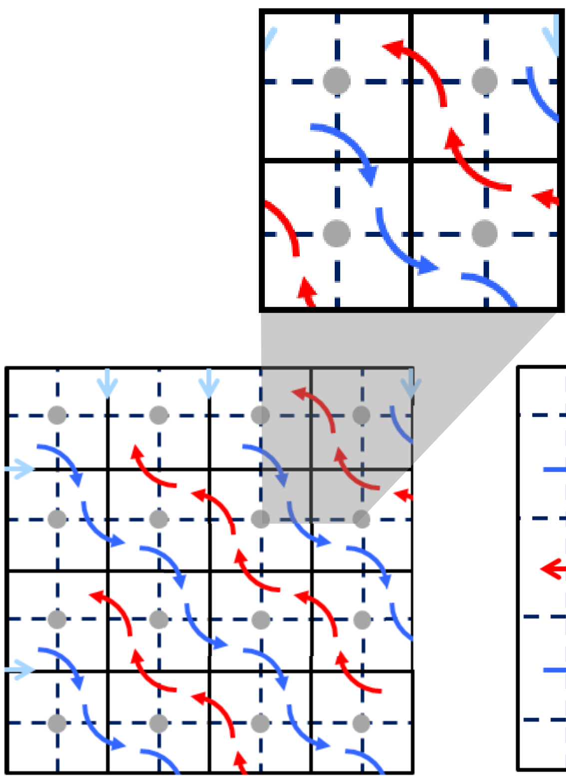
CTF(staggered grid)

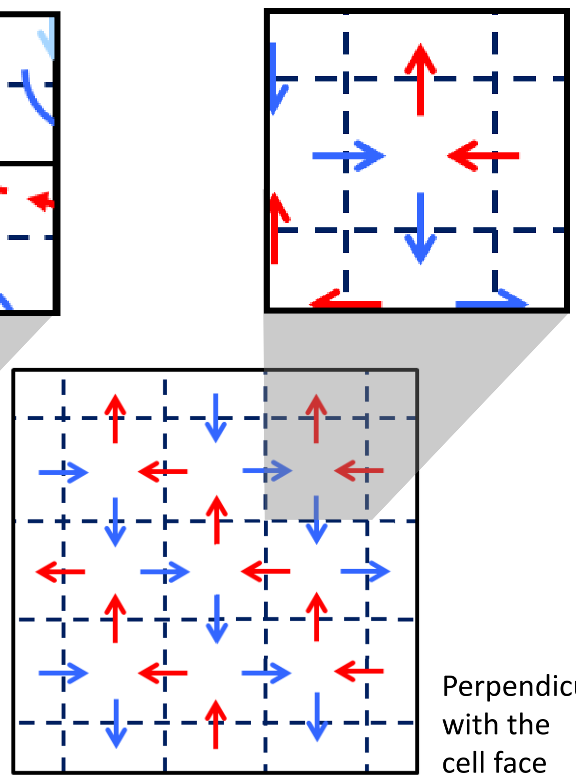


⋯⋯ : Scalar mesh cell

⋯⋯ : x-direction momentum mesh cell

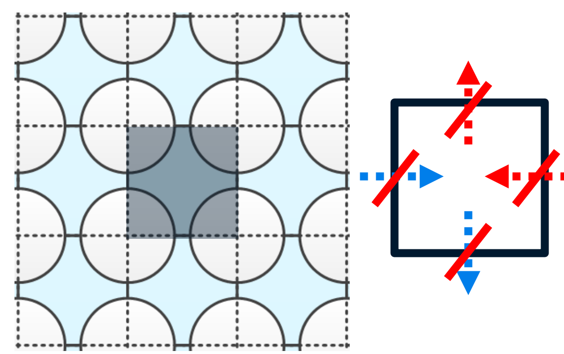
⋯⋯ : y-direction momentum mesh cell





Perpendicular with the cell face

CUPID (collocated grid)



⋯⋯ : Mesh cell

Grid-directed cross flow model for collocated grid

1. Grid-directed cross flow model was additionally implemented into scalar equation.

- Momentum equation $M_k = f^2 u_l \rho_l A \times u_l$

  f : Lateral convection factor (lateral velocity/axial velocity)

  M_k : Lateral momentum transfer due to grid-directed cross flow model

- Mass equation $M_e = f u_l \rho_l A$
- Energy equation $M_h = f u_l \rho_l A \times h_l$

  M_e, M_h : Lateral mass and energy exchange due to grid-directed cross flow model

2. Additional turbulent mixing coefficient (β') was applied.

- Flow scattering (Zimmermann, M. (2015)*)

$$C_\beta{}^{grid} = \Theta_{tm,grid}(z,\gamma,\epsilon) \cdot C_\beta$$

$$C_\beta{}^{sp,vd} = \Theta_{vd,grid}(z,\gamma,\epsilon) \cdot C_\beta{}^{vd}$$

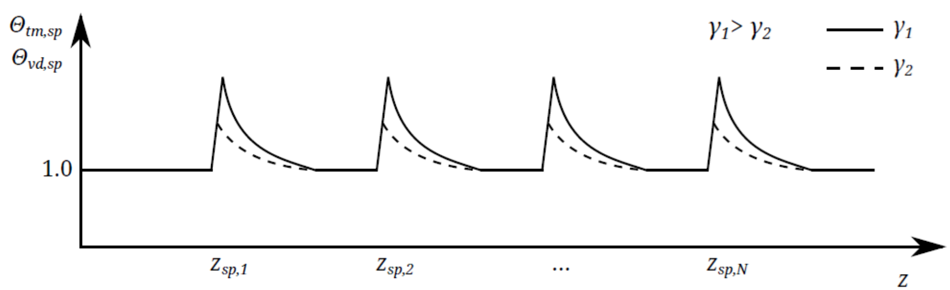
C_β : turbulent mixing coeff.

$C_\beta{}^{vd}$: void drift coeff.

z : axial position

γ : mixing vane angle

ϵ : blockage ratio



(Zimmermann, M. (2015)*

– β' : Determined from code to code comparison between CUPID and CTF

$$V^T = \frac{\beta G_{avg}}{\rho_{avg}} s_{gap} \qquad \beta = \beta_{origin} + \beta'$$

Turbulent mixing model

$$M_k^T = V^T(\rho_f v_f - \rho_g v_g)\theta\left[\alpha_{v,J} - \alpha_{v,I} - (\alpha_{v,J} - \alpha_{v,I})_{equil}\right]$$

$$M_e^T = V^T(\rho_f - \rho_g)\theta\left[\alpha_{v,J} - \alpha_{v,I} - (\alpha_{v,J} - \alpha_{v,I})_{equil}\right]$$

$$M_h^T = V^T(\rho_f h_f - \rho_g h_g)\theta\left[\alpha_{v,J} - \alpha_{v,I} - (\alpha_{v,J} - \alpha_{v,I})_{equil}\right]$$

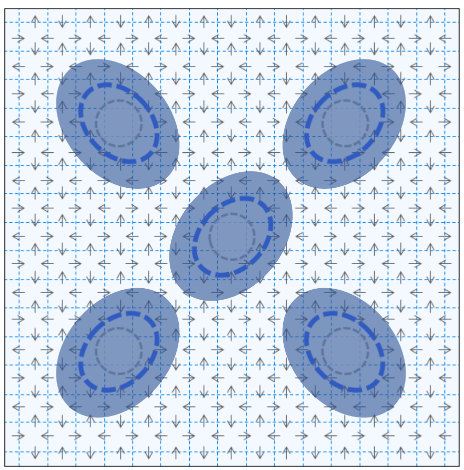
*) Zimmermann, Markus. Development and Application of a Model for the Cross-Flow Induced by Mixing Vane Spacers in Fuel Assemblies. Diss. KIT-Bibliothek, 2015.

Grid-directed cross flow model

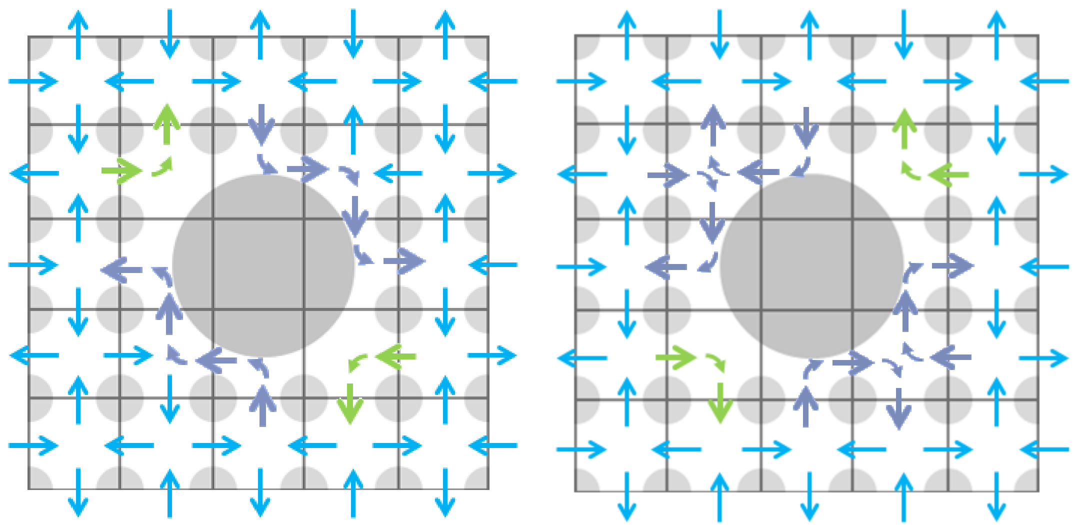
- Guide tube consideration
  - CE type fuel assembly (5 guide tubes)
    - 4 guide tubes
      - Coolant passes through the guide tube
    - 1 guide tube
      - Coolant slightly blocked by the guide tube

Cell number	+x	−x	+y	-y
⋮		⋮		
71	-1	1	1	-1
72	0	-1	0	1
73	0	0	0	0
74	1	0	-1	0
75	-1	1	1	-1
76	1	-1	-1	1
77	-1	1	1	-1
78	1	-1	-1	1
⋮		⋮		

Input of coolant direction for grid-directed cross flow model



Direction of coolant transfer due to mixing vane in the single assembly



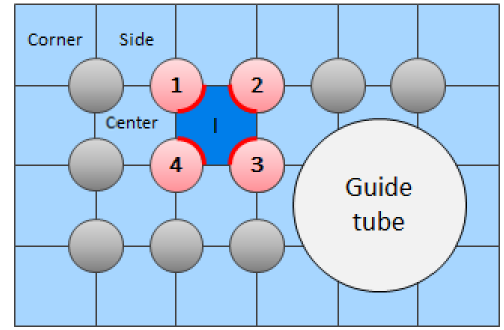
Direction of coolant transfer near the guide tube

Fuel rod heat conduction model

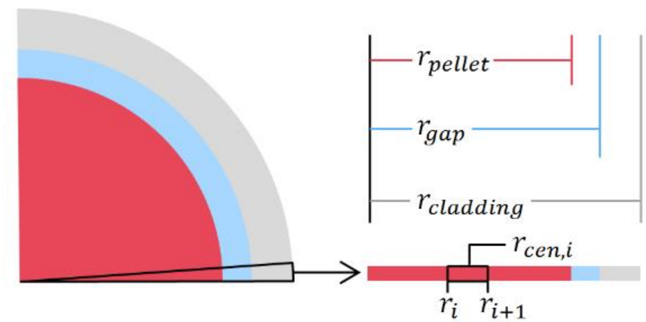
- Fuel rod heat conduction model improvement
  - Subchannel-rod connectivity : 1~4 rods
  - One-dimension heat conduction equation, quarter fuel rod
  - Simple gap heat conduction model
    - HTC of gap between pellet and cladding

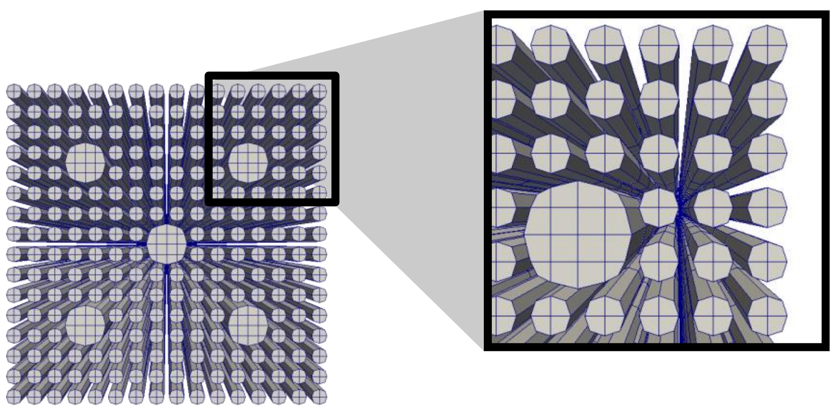
$$h_g = \frac{k_{gas}}{\delta_{eff}} + \frac{\sigma}{(1/\varepsilon_f) + (1/\varepsilon_c)} \frac{T_{fo}^4 - T_{ci}^4}{T_{fo} - T_{ci}}$$

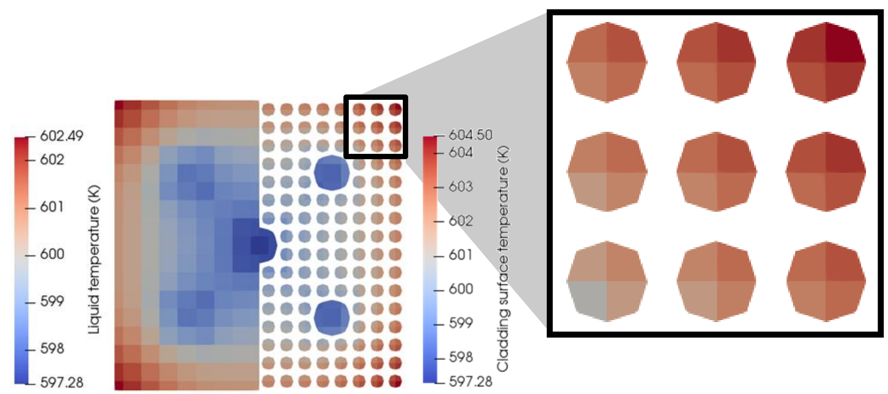
δ_{eff} : effective gap width,
σ : Stefan-Boltzman constant,
ε_f, ε_c : surface emissivity of the fuel and cladding,
T_{fo} : fuel surface temperature,
T_{ci} : cladding inner surface temperature.



Subchannel-rod connectivity
: Depending on the location



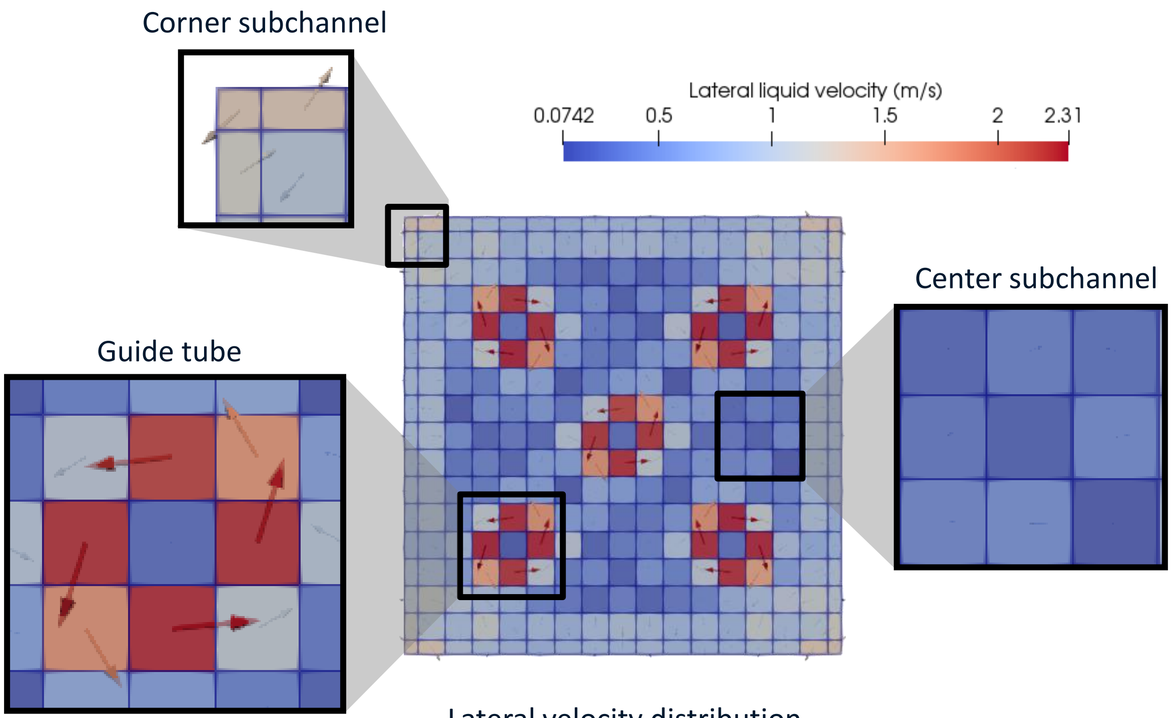




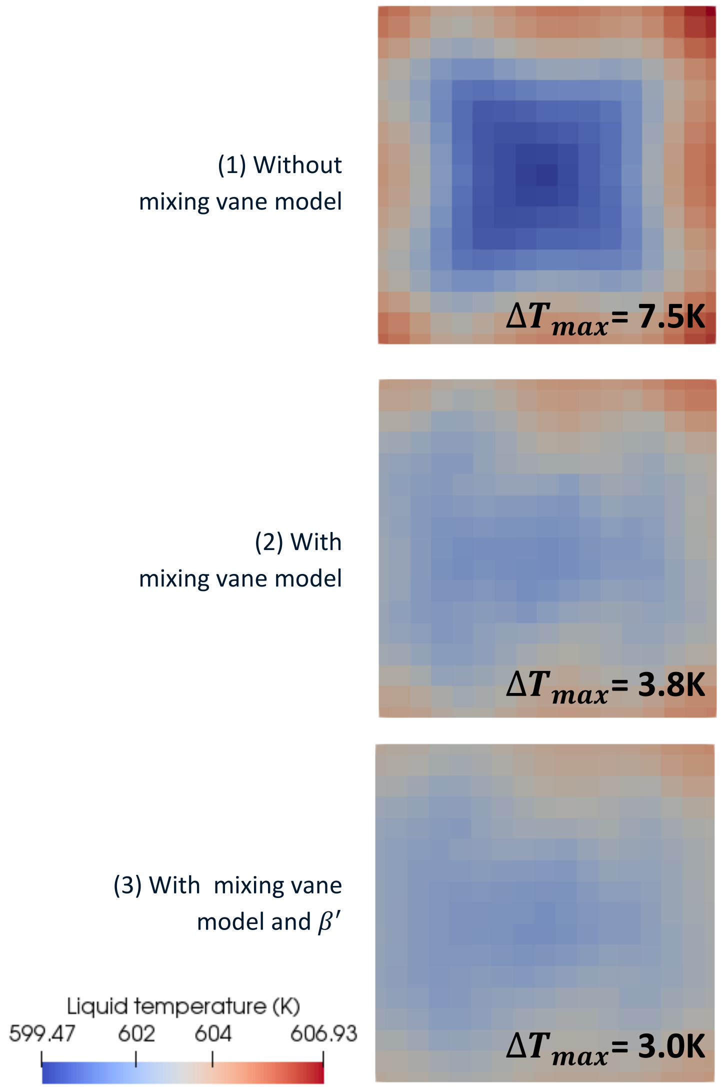
Contents

Verification of grid-directed cross flow model

- Plus7 fuel assembly
- Power distribution
  - From the neutronics code nTRACER*
  - Pin-wise power distribution from maximum power assembly



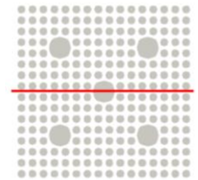
Lateral velocity distribution

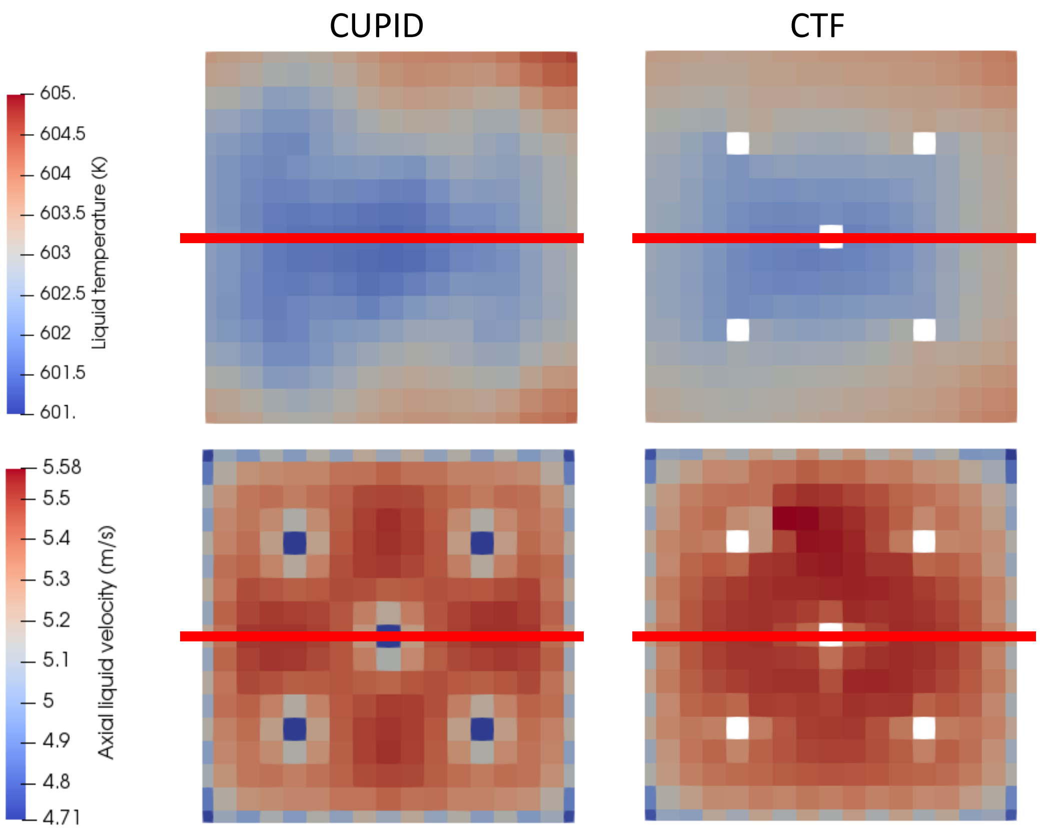


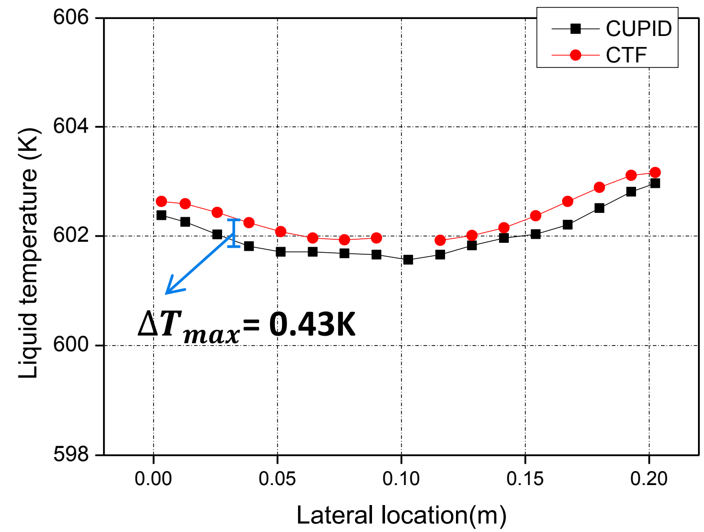
Coolant temperature distribution at he outlet

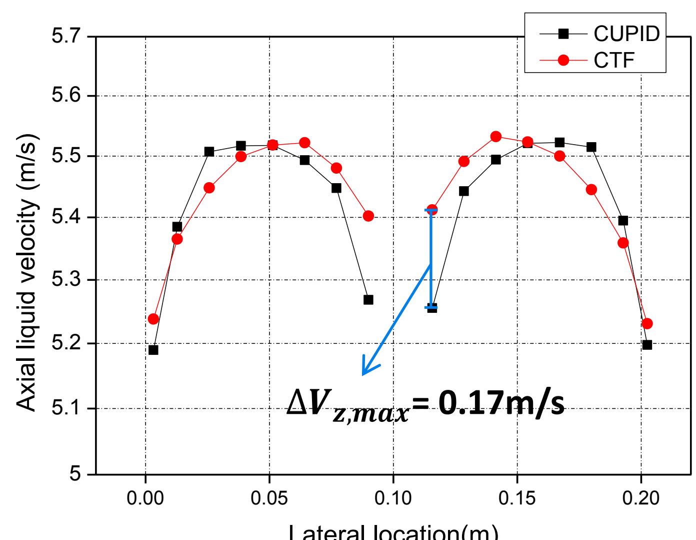
Verification of grid-directed cross flow model

- Comparison with CUPID and CTF
  - Centerline extraction
    - Liquid temperature
    - Axial liquid velocity



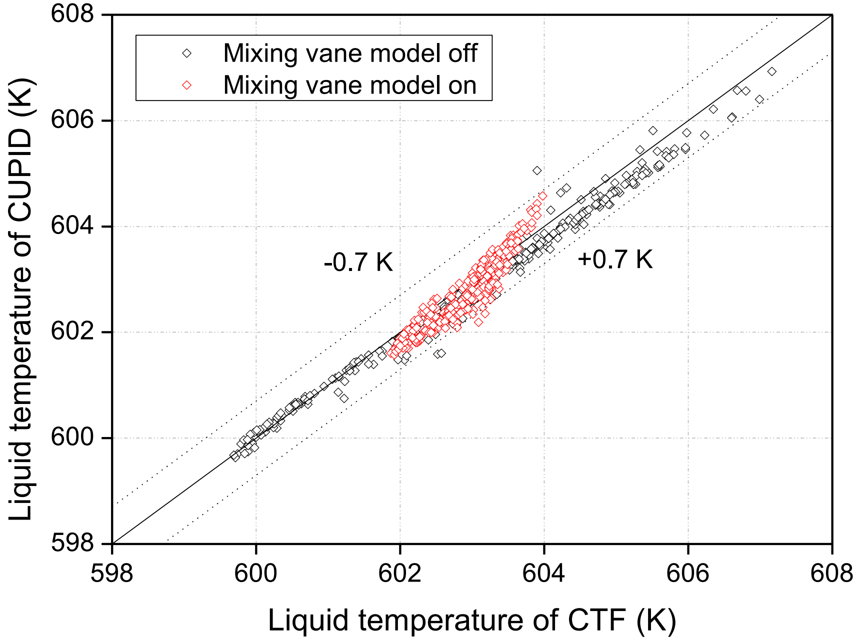


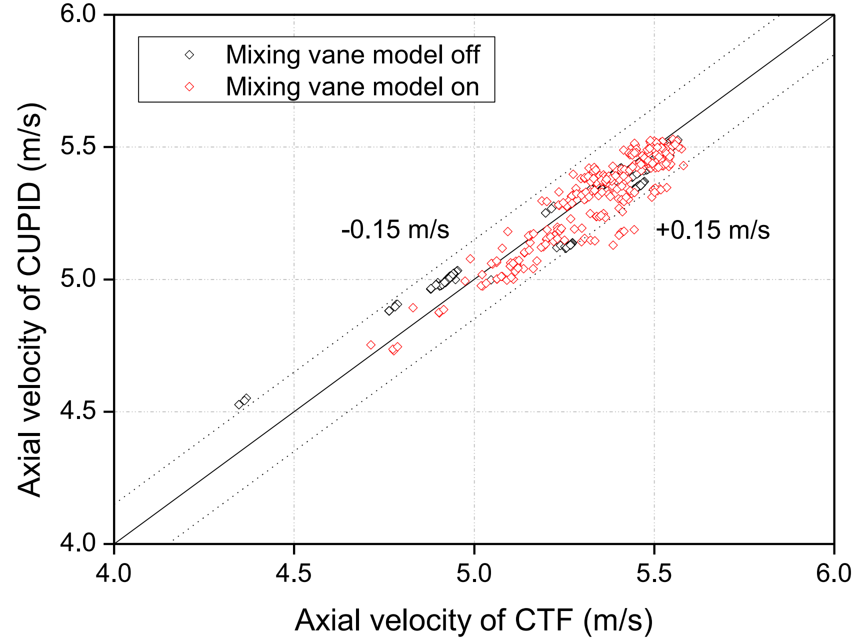




Verification of grid-directed cross flow model

- Comparison with CUPID and CTF : mixing vane model off
  - Temperature comparison between CUPID and CTF
  - Axial velocity comparison between CUPID and CTF

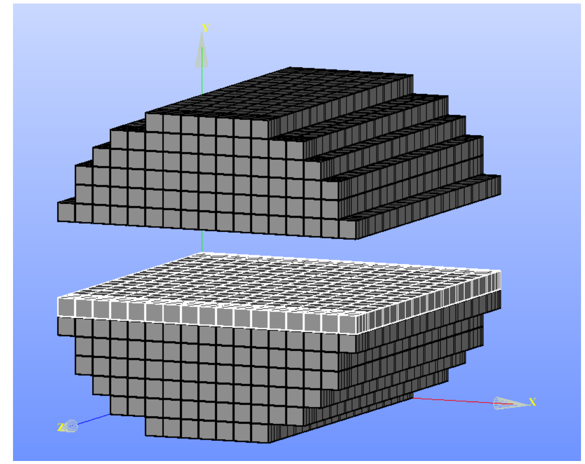


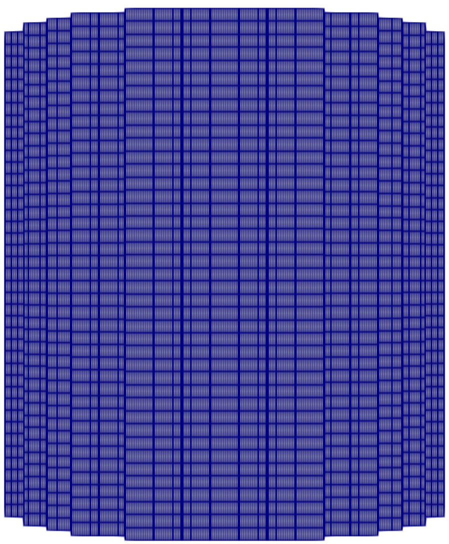


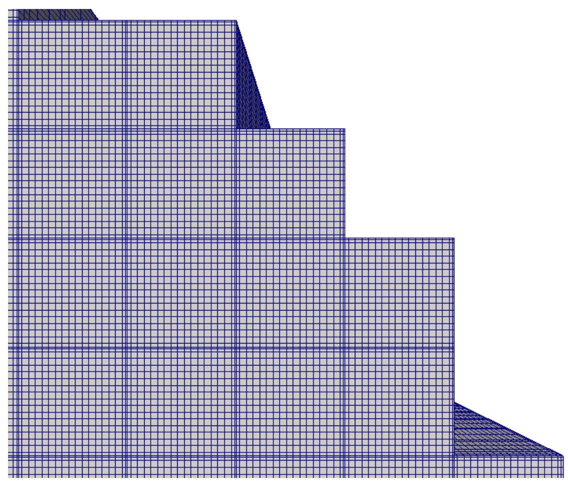
Contents

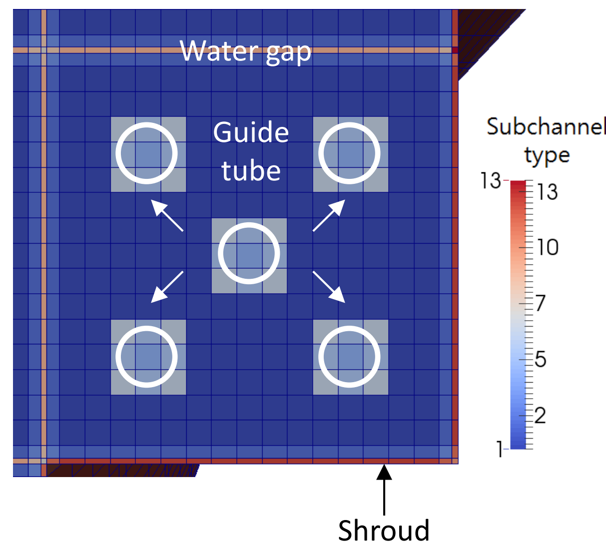
APR1400 whole core preliminary simulation

- Geometry of whole core
  - Normal subchannel
  - Water gap, guide tube, shroud
- Total cells : 3,226,576





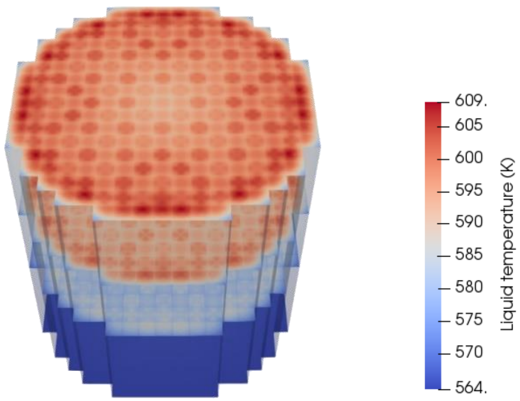


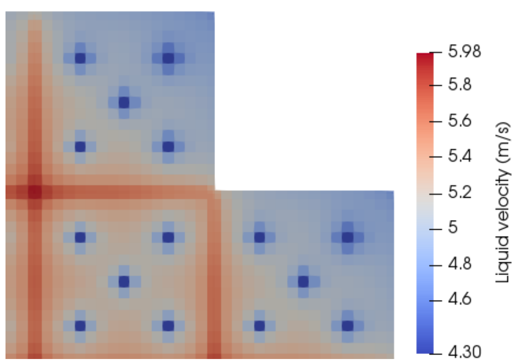


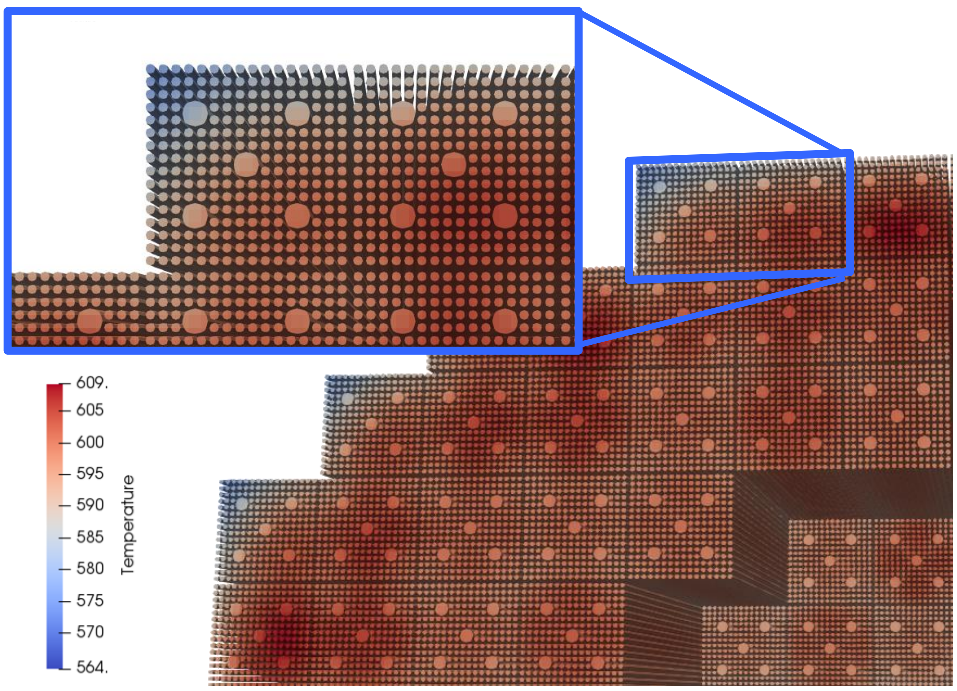
APR1400 whole core preliminary simulation

- Using fuel rod heat conduction model
- Distribution of
  - Liquid temperature
  - Liquid velocity
  - Cladding outer surface temperature

Parameters	
Problem time for steady-state	2.0 sec
Number of cores	136
Total wall-clock time	41 min



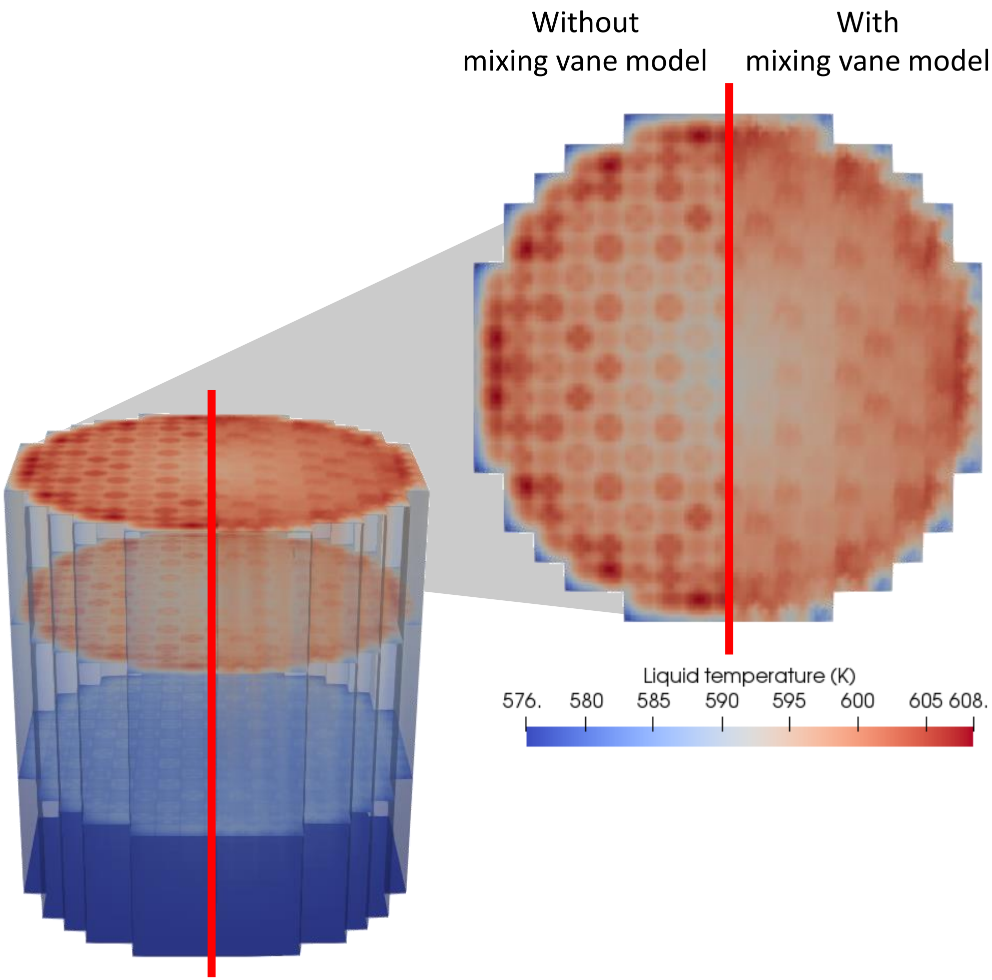


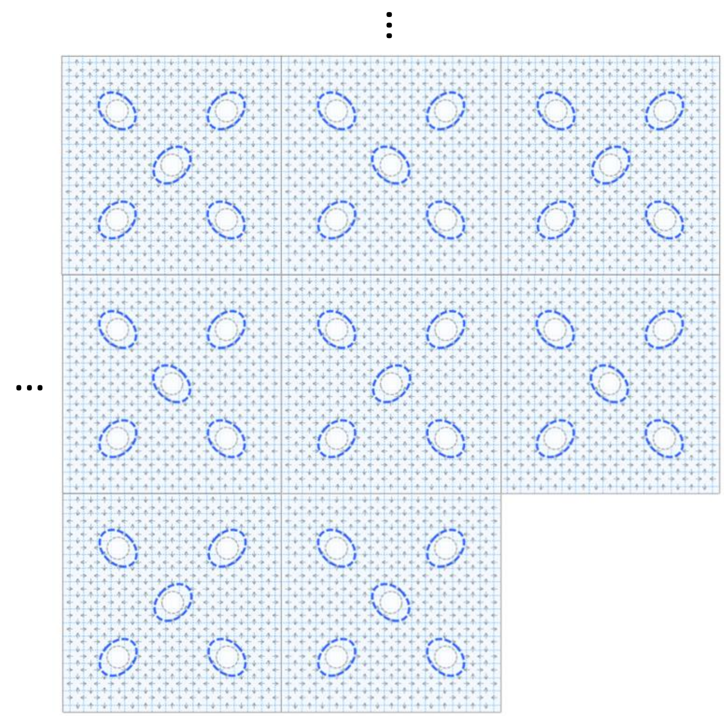


APR1400 whole core preliminary simulation

- Using grid-directed cross flow model
- Distribution of
  - Liquid temperature

Parameters	
Problem time for steady-state	2.0 sec
Number of cores	136
Total wall-clock time	41 min → 98 min





Contents

Conclusion

- The grid-directed cross flow model was implemented for subchannel scale T/H analysis.
  - Grid-directed cross flow model applied in the mass, momentum and energy equation.
  - Additional turbulent mixing coefficient (β') was applied.
    - Modification was made to consider the difference between the collocated and staggered grid systems.

- The verification of grid-directed cross flow model against single assembly of APR1400 was conducted.
  - Liquid and cladding surface temperature, liquid velocity

- In the future,
  - Quantitative analysis for the mixing induced by the grid-directed cross flow model will be conducted for the validation of models.
    - PSBT benchmark, etc.
  - Wall heat transfer enhancement by a spacer grid needs to be considered.

Thank you for your attention!