Comparison of MARS-KS and SPACE Code for Modeling a Helical Steam Generator

Nuclear Power & Propulsion Lab

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Contents

01 Introduction

Motivation

- System Thermal Hydraulic (TH) Analysis Codes
  - Concept of computer simulation and V&V
    - In the licensing process for new NPPs, it is necessary to demonstrate the plant's performance and safety using these system codes.
    - For example, the performance & safety analysis of **i-SMR** will be mainly conducted by **SPACE**.

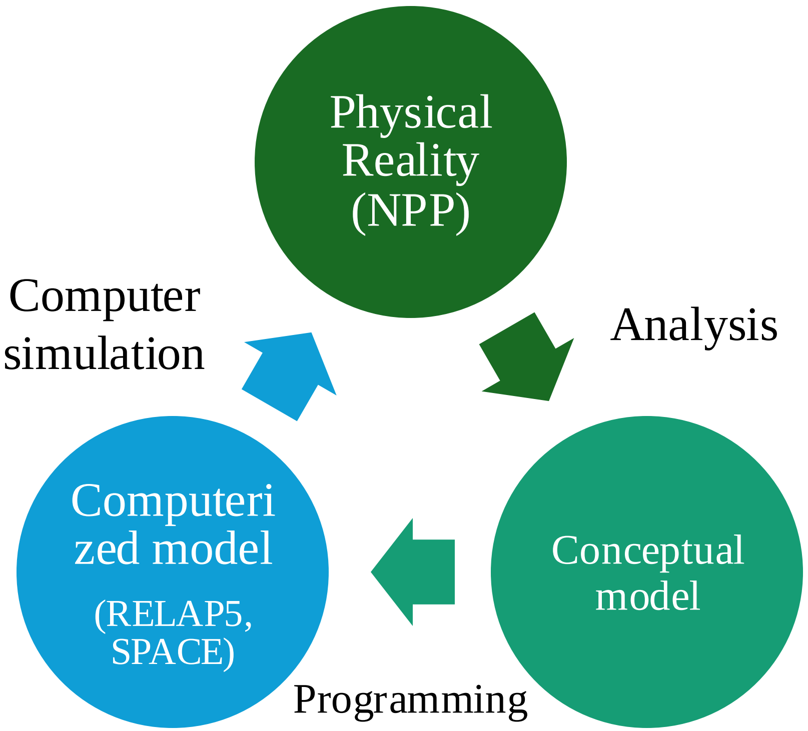


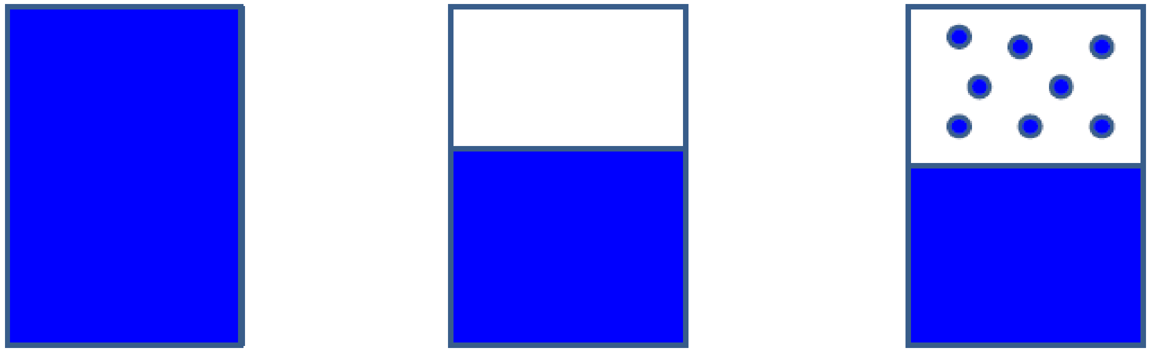
Table. Comparison of various system TH codes

	RELAP5 (US)	**CATHARE2 (France)**	**SPACE (S. Korea)**
Range	Transient, LOCA analysis		
Accuracy	Two-phase, two-field, 1D	Two-phase, two-field, 1D	Two-phase, three-field, 1D or 3D
Language	FORTRAN 90	FORTRAN 90	C++

Motivation

- 6-Equation TH Codes (liquid, gas) vs 9-Equation TH Codes (liquid, droplet, gas)
  - 9-equation TH codes may be accurate for analyzing regions where droplet formation is evident.
  - In PWR-type SMRs, there are not many regions where droplet formation is prominent (except accident scenarios)
    - If SPACE is used, the calculations will include droplets → computational speed ↓
    - Using a 6-equation-based code instead, it is possible to quickly find the system's optimal design point and implement various safety analysis scenarios.

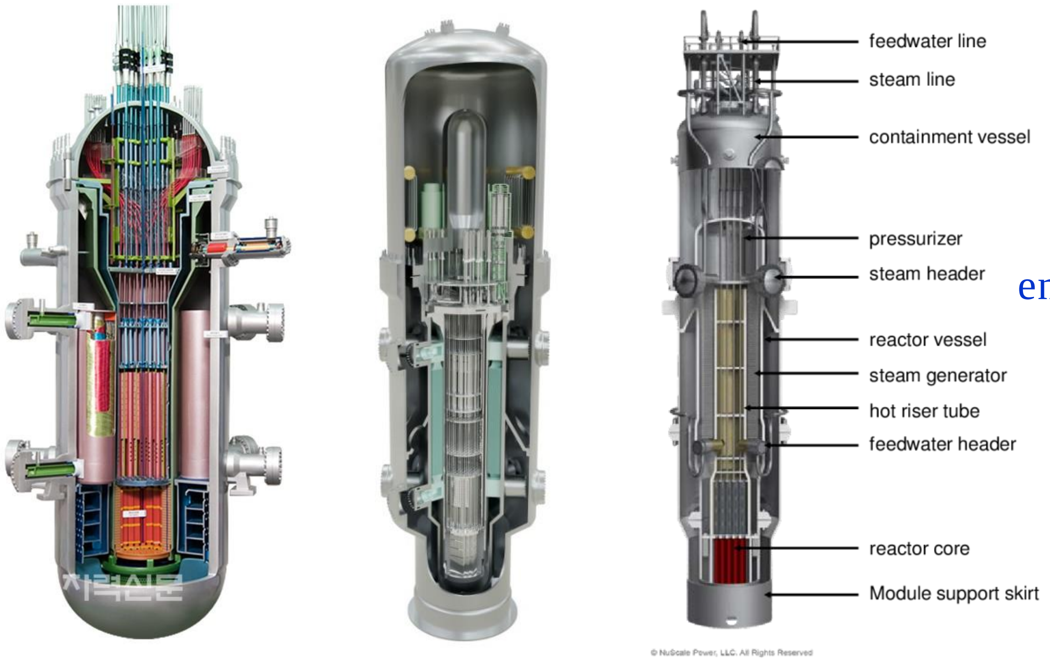
Q *Then, in regions within the PWR where droplet formation is prominent, what would be the difference in the results of the two codes?*



Single phase	Two-phase, two-field	Two-phase, three-field
3 equations	6 equations	9 equations
	Ex) MARS-KS, RELAP5	Ex) SPACE

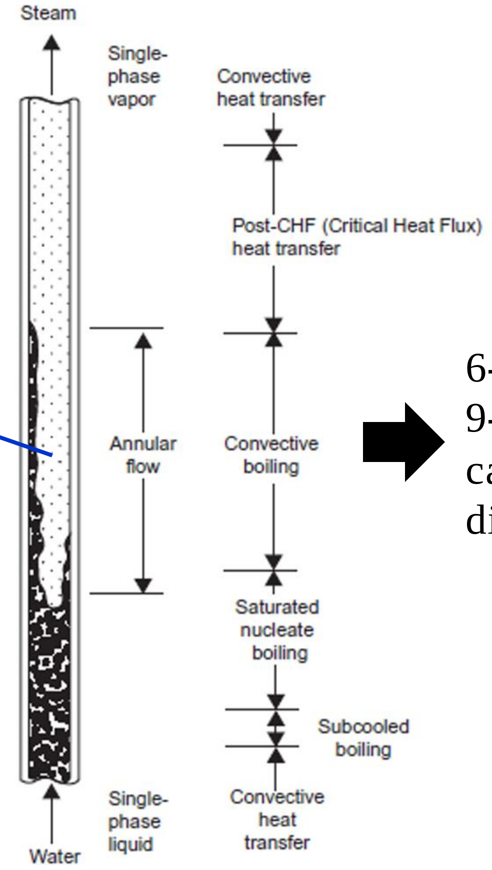
Motivation

- Region where two-phase flow and droplet formation is prominent = **Steam Generator**
  - Many PWR-type SMRs are adopting 'Once Through Helical SG'.
    - Compact design & high heat transfer efficiency
    - Low thermal stress
    - Generates superheated steam (about $\Delta T_{super} = 30$ K)



Examples of SMRs with helical SGs
(SMART, iSMR, NuScale)

Droplet entrainment



Flow pattern inside a once-through tube

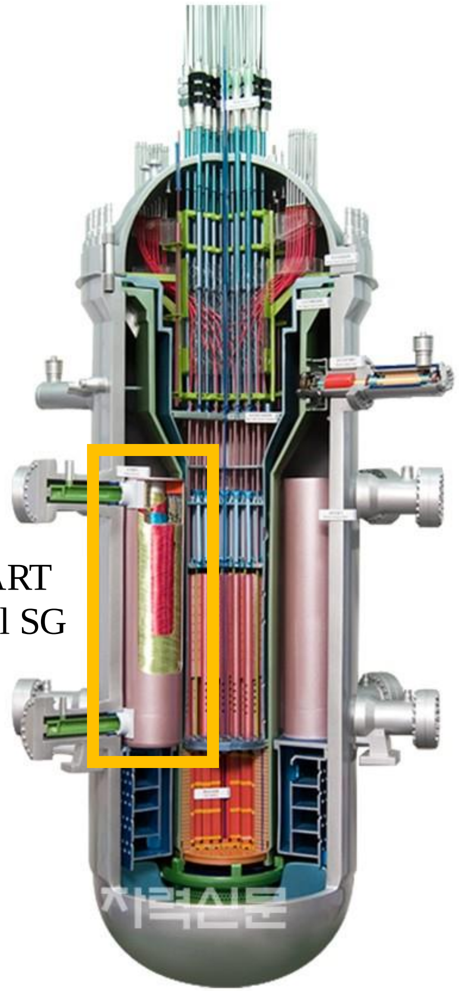
6-equation code and 9-equations code can calculate this region differently.

Research Objectives

❑ Objective: Compare the steady-state calculation results for once-through helical SG.
  - Reference SG type: SMART helical SG cassette
  - TH code: MARS-KS (6-equation) vs SPACE (9-equation)
  - Comparison target
    - Temperature profile
    - Heat transfer mode
    - Flow regime
    - Velocity of each field

※ Pressure drop will not be considered here, as the pressure drop correlations for helical tubes are not integrated into the system codes.

MARS-KS V2.0 vs SPACE V3.3



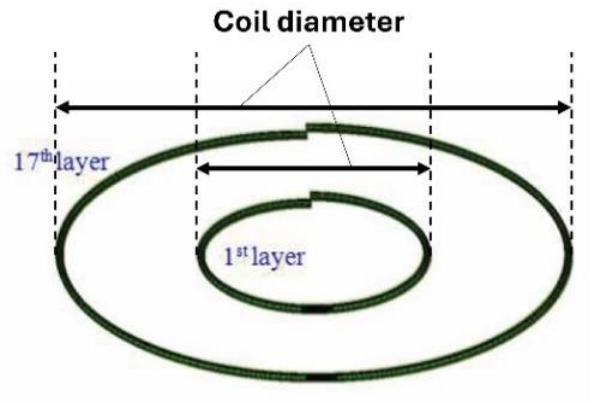
SMART helical SG

02

SMART Steam Generator Modeling

SMART Steam Generator

- SMART SG Design
  - There are 8 SG cassettes per one reactor pressure vessel.
    - Only one cassette will be analyzed in this study.
  - A single SG cassette is composed of 17 layers of helical coils.
    - Each layer has different coil diameter and helical angle.
    - The 17 layers will be modeled separately.

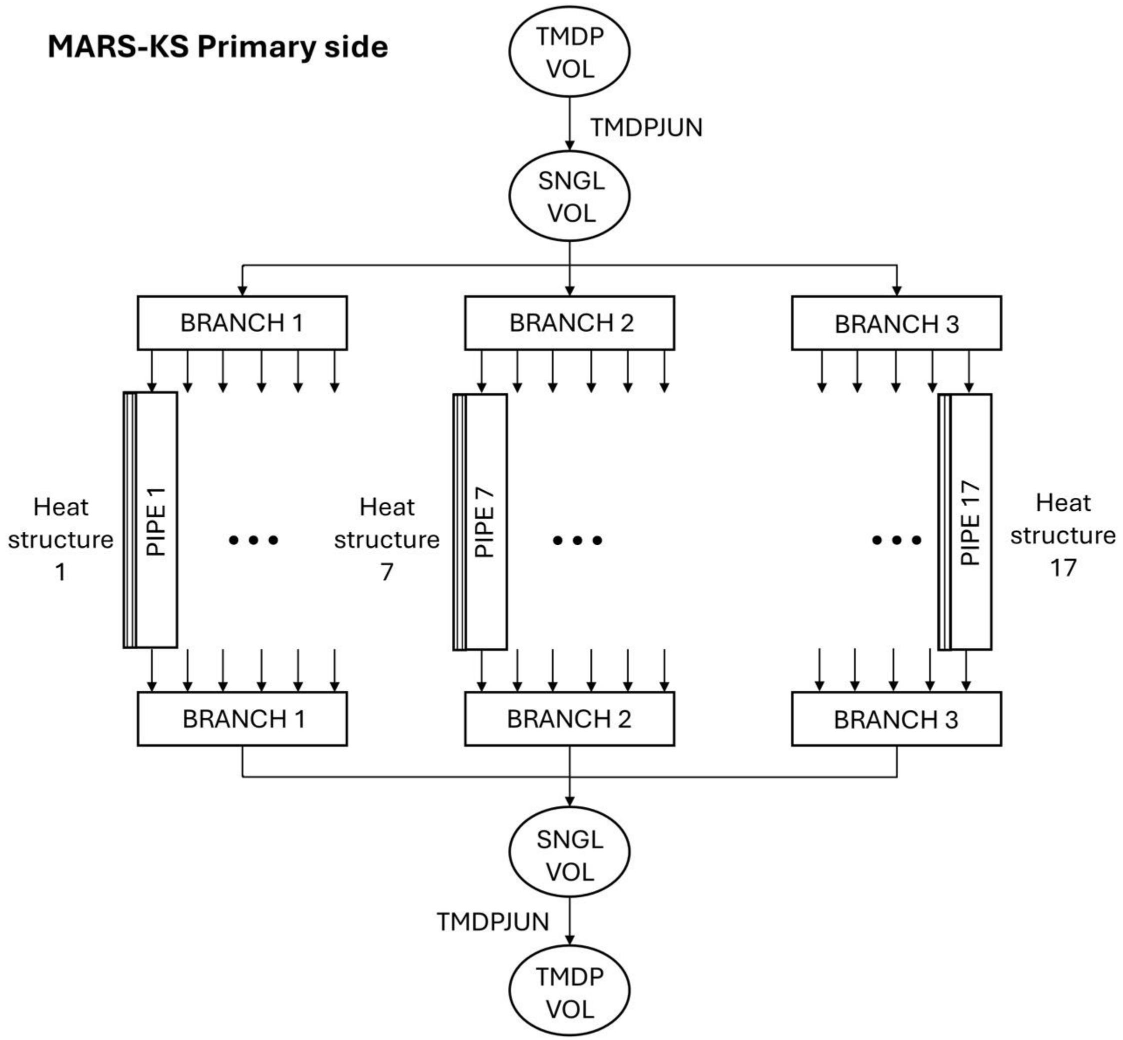


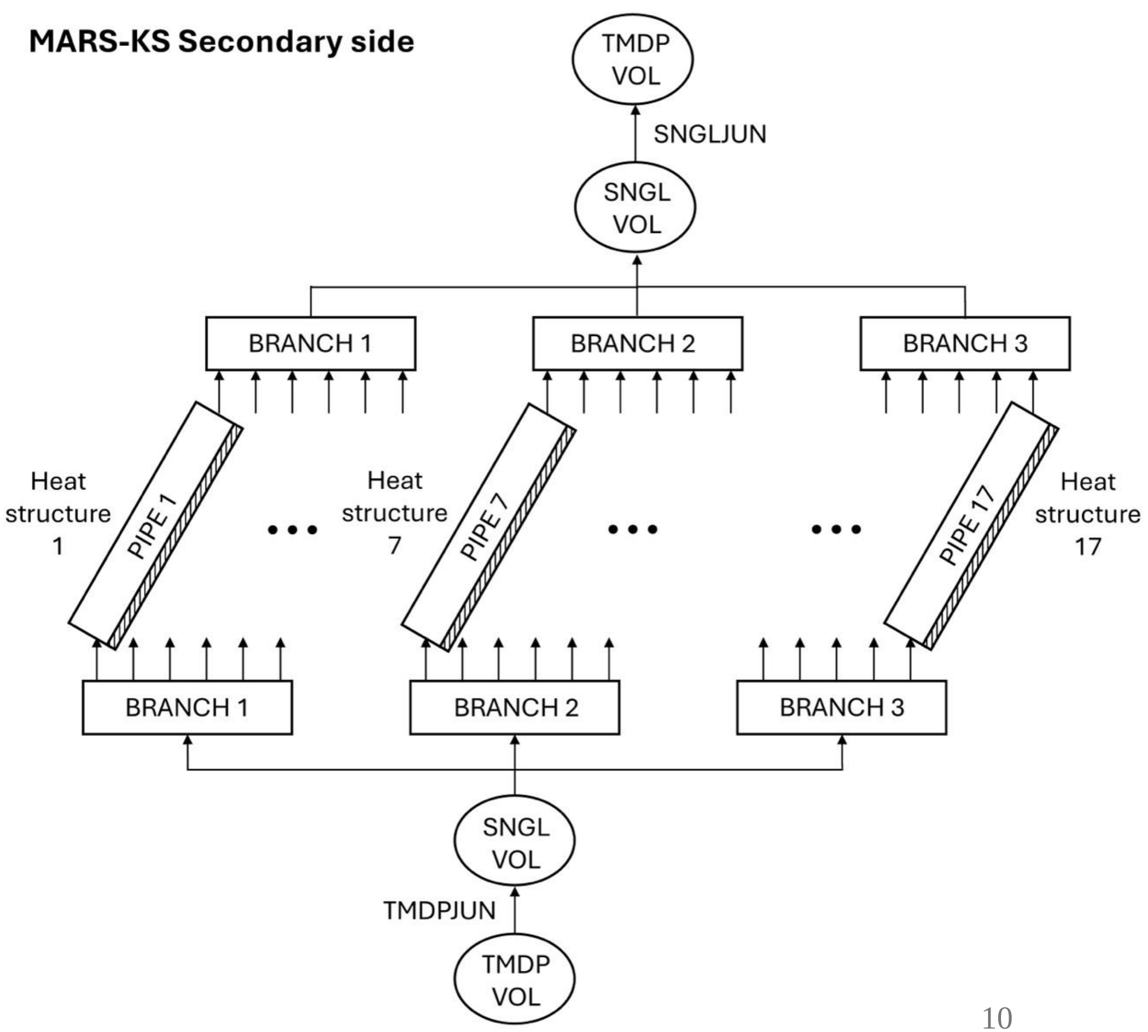
Number of tubes per SG	375	
Tube specifications	Material	Inconel 690
	Inner diameter [mm]	12
	Outer diameter [mm]	17
	Effective height [m]	3.8
	Helical angle [°]	8.5~8.8
Primary side	Pressure [MPa]	15.0
	Inlet temperature [K]	596.15
	Outlet temperature [K]	568.85
	Mass flow rate per SG [kg/s]	261.25
Secondary side	Pressure [MPa]	5.2
	Inlet temperature [K]	473.15
	Outlet temperature [K]	>569.15
	Mass flow rate per SG [kg/s]	20.1

Layer	Coil diameter [m]	Helical angle [°]	Tube length [m]	Number of tubes
1	0.577	8.5	25.4264	13
2	0.622	8.52	25.3696	14
3	0.667	8.54	25.3131	16
4	0.712	8.56	25.2568	17
5	0.757	8.58	25.2007	18
6	0.802	8.59	25.1449	19
7	0.847	8.61	25.0893	20
8	0.892	8.63	25.034	21
9	0.937	8.65	24.9789	22
10	0.982	8.67	24.924	23
11	1.027	8.69	24.8694	24
12	1.072	8.71	24.815	25
13	1.117	8.73	24.7608	26
14	1.162	8.74	24.7069	27
15	1.207	8.76	24.6532	29
16	1.252	8.78	24.5998	30
17	1.297	8.80	24.5465	31

SMART Steam Generator

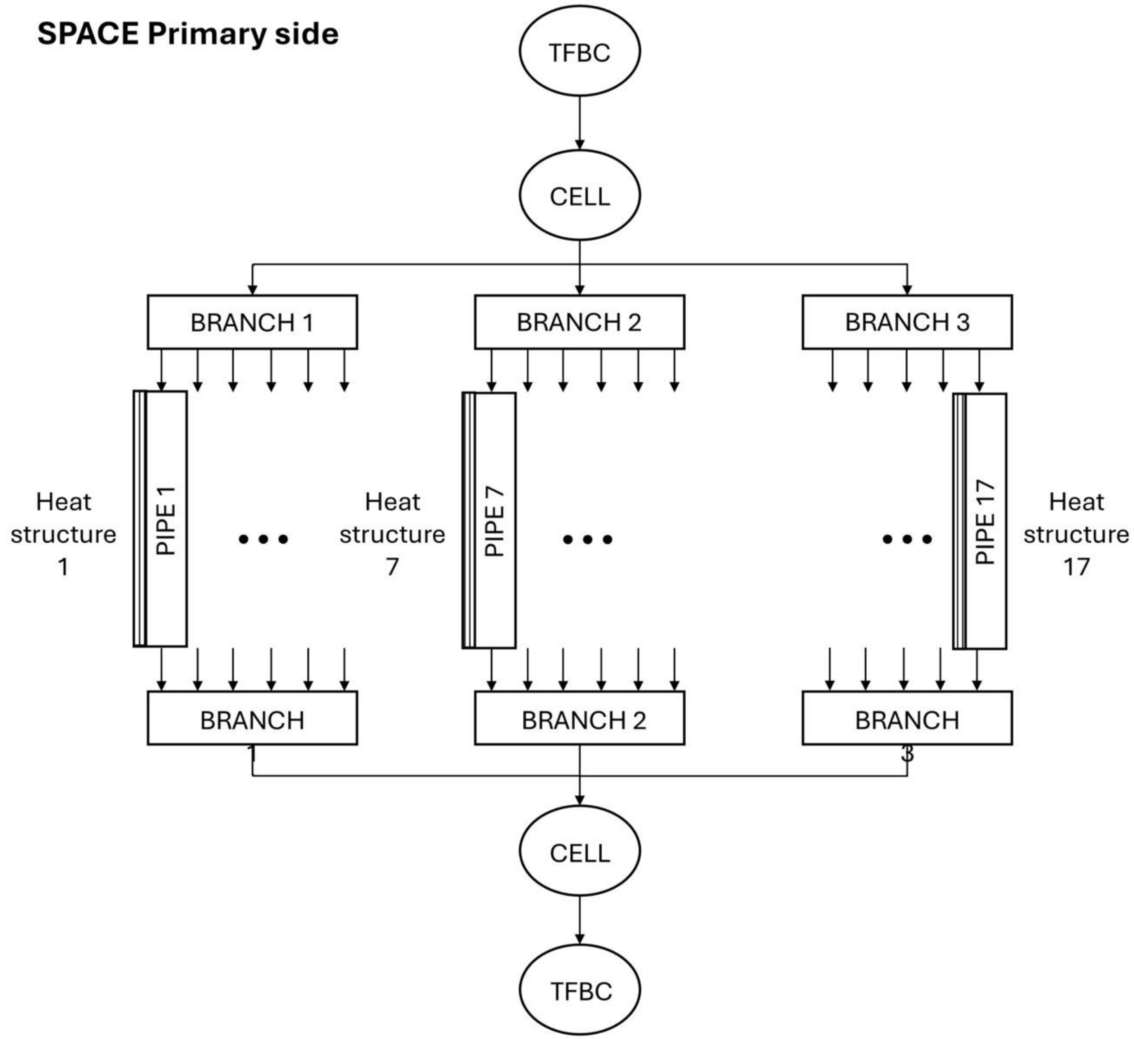
- MARS-KS Nodalization ※Number of volumes in each pipe = 25

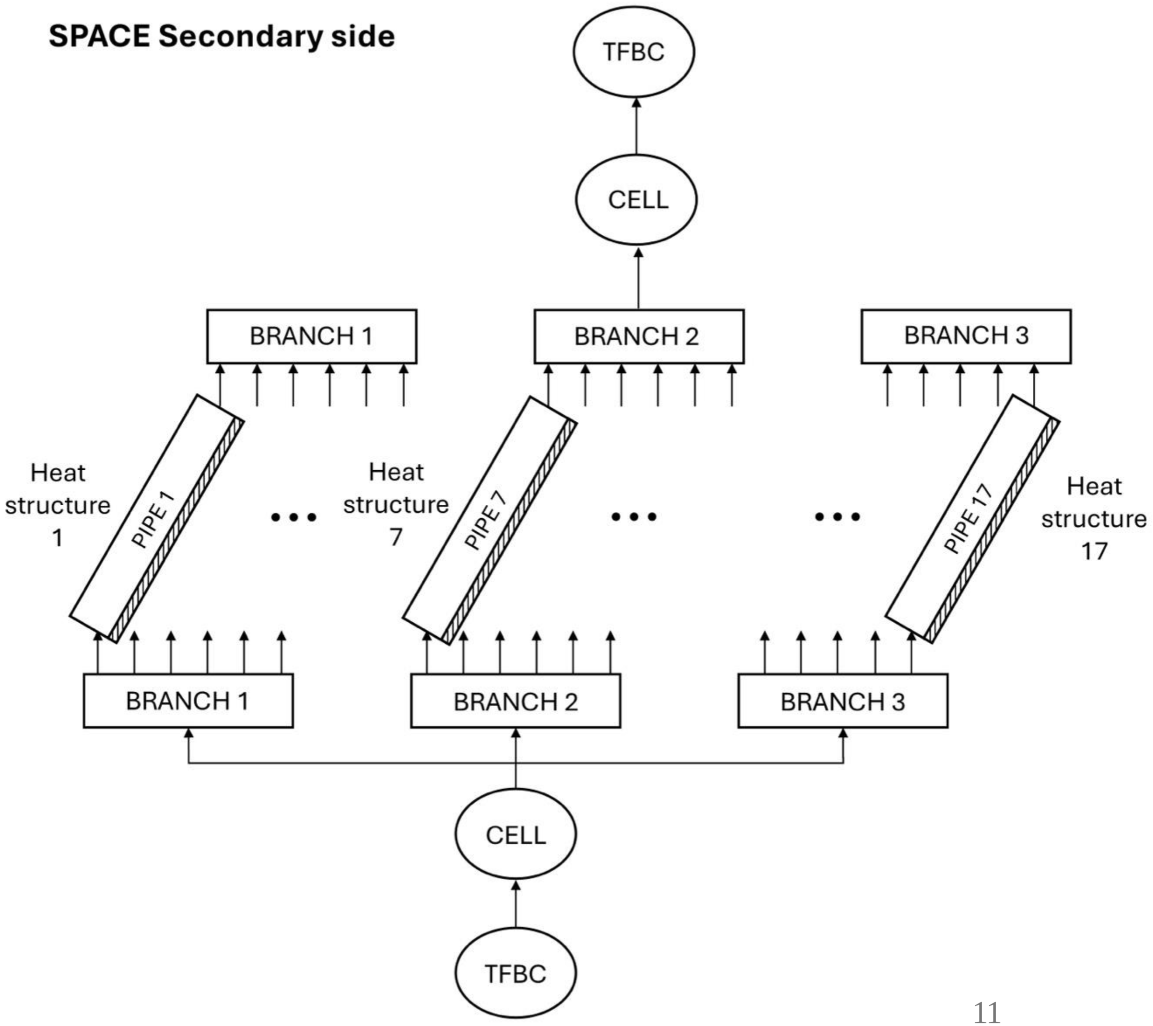




SMART Steam Generator

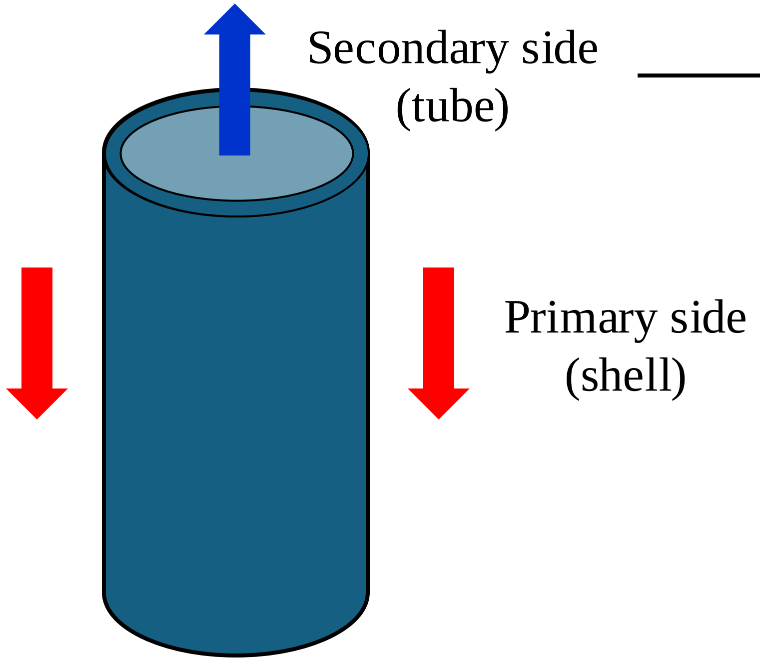
❑ SPACE Nodalization ※Number of volumes in each pipe = 25





Calculation Condition

❑ Heat structure – Boundary condition type



MARS-KS: Helical S/G tube side (#114)
SPACE: Helical S/G tube side (Hxxx-xx-0040 card)

MARS-KS: Zukauskas heat transfer correlation for in-lined bundle cross flow shell side (#162)
SPACE: Helical S/G shell side (Hxxx-xx-0040 card)

※Other conditions (heat transfer area, length, etc.) are the same.

❑ Run Condition

Min. time step [sec]	Max. time step [sec]	End time [sec]
1.0E-6	1.0E-3	1000.0

03

Results and Discussion

SG Temperature Profile

- Comparison of SG temperature profile calculated by MARS-KS and SPACE
  - **Primary side**: good agreement between MARS-KS and SPACE
  - **Secondary side**: disagreement at the superheated region (blue-boxed region)
    - SPACE code calculated the temperature slightly higher
    - Background: disagreement in the flow regime and heat transfer mode

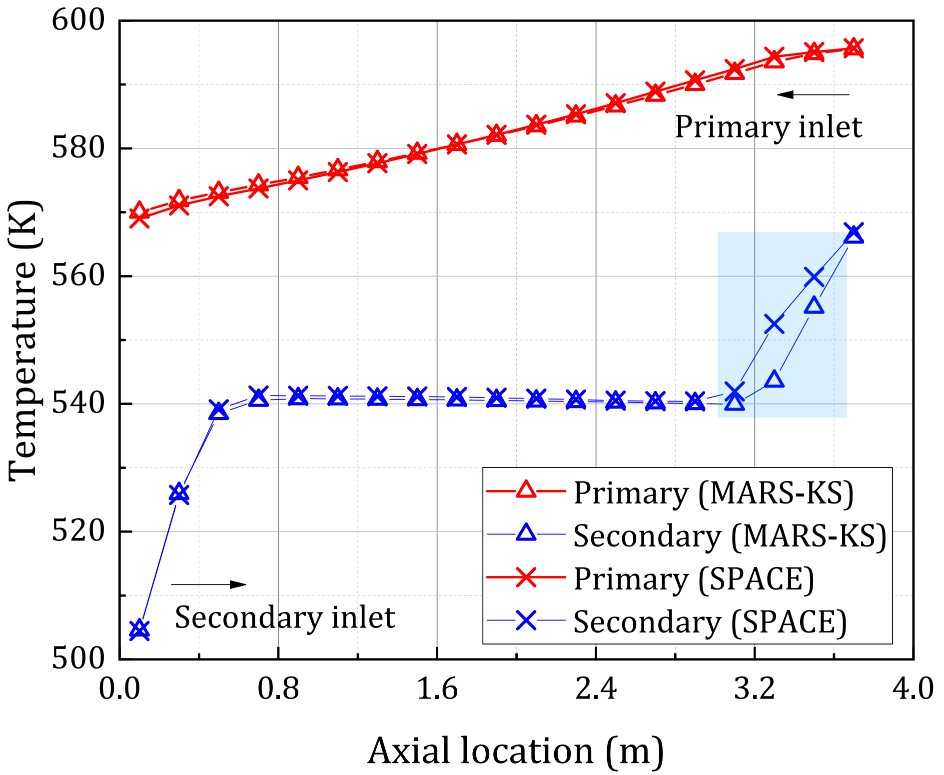


Fig. Primary and secondary side temperature profile

Flow Regime and Wall Heat Transfer Mode

❑ Comparison of flow regime and heat transfer mode (secondary side)

	z [m]	MARS-KS		SPACE	
		Flow regime	Heat transfer mode	Flow regime	Heat transfer mode
Subcooled	~0.4	Bubbly	1Φ Liquid	Liquid	1Φ Liquid
Saturated	0.4~0.6	Bubbly	Subcooled NB	Bubbly	Subcooled NB
Saturated	0.6~1.0	Slug	Subcooled NB	Cap-bubble/ slug	Subcooled NB
Saturated	1.0~1.4	Slug	Saturated NB	Cap-bubble/ slug	Saturated NB
Saturated	1.4~1.6	Slug	Saturated NB	Annular mist	Saturated NB
Saturated	1.6~3.0	Annular mist	Saturated NB	Annular mist	Saturated NB
Superheated	3.0~3.2	Annular mist	Saturated NB	Annular mist	Saturated FB
Superheated	3.2~3.4	Annular mist	Saturated TB	Annular mist	Saturated FB
Superheated	3.4~3.6	Annular mist	1Φ Gas	Annular mist	Saturated FB
Superheated	3.6~3.8	HST	1Φ Gas	Annular mist	Saturated FB

(NB=nucleate boiling, TB=transition boiling, FB=film boiling, HST=horizontally stratified)

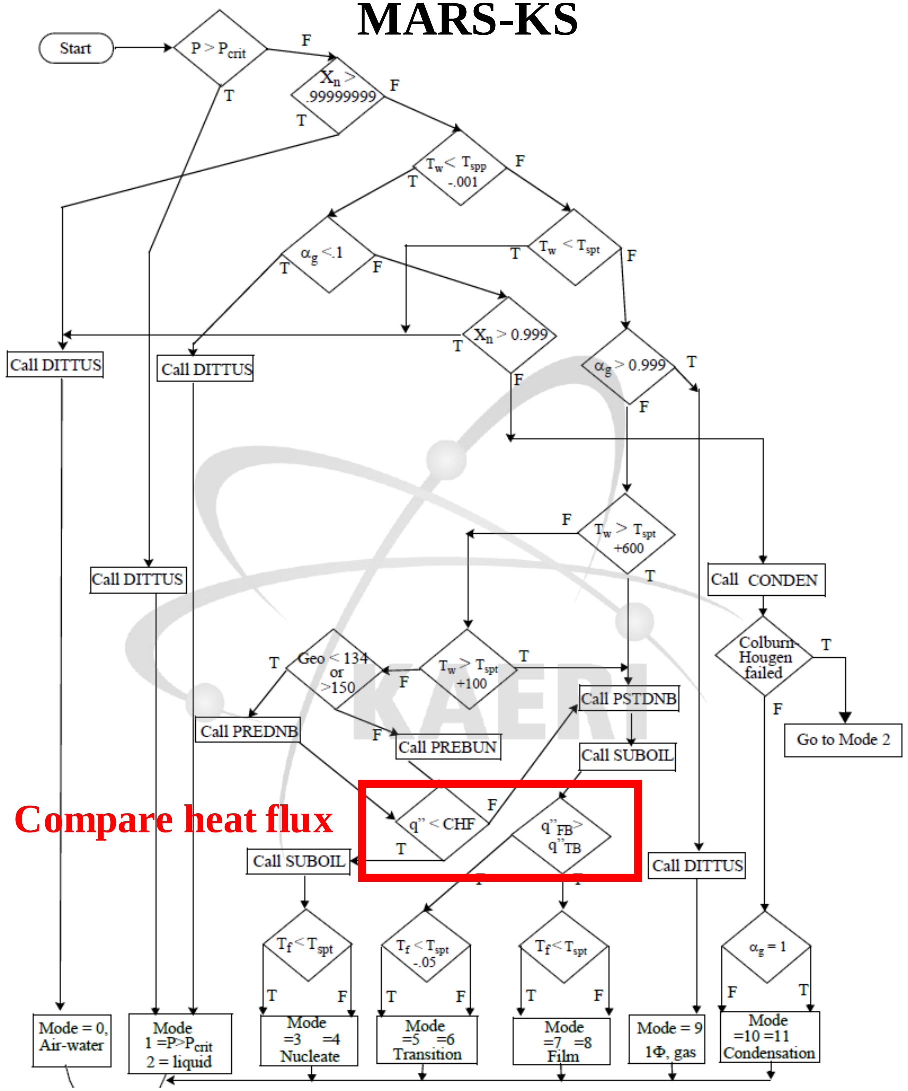
Bubbly flow criteria	
MARS-KS	Void fraction > 0
SPACE	Void fraction > 1E-09

Heat transfer mode determination	
MARS-KS	Compare q''
SPACE	Compare T_{wall} with T_{CHF}, $T_{\min,FB}$

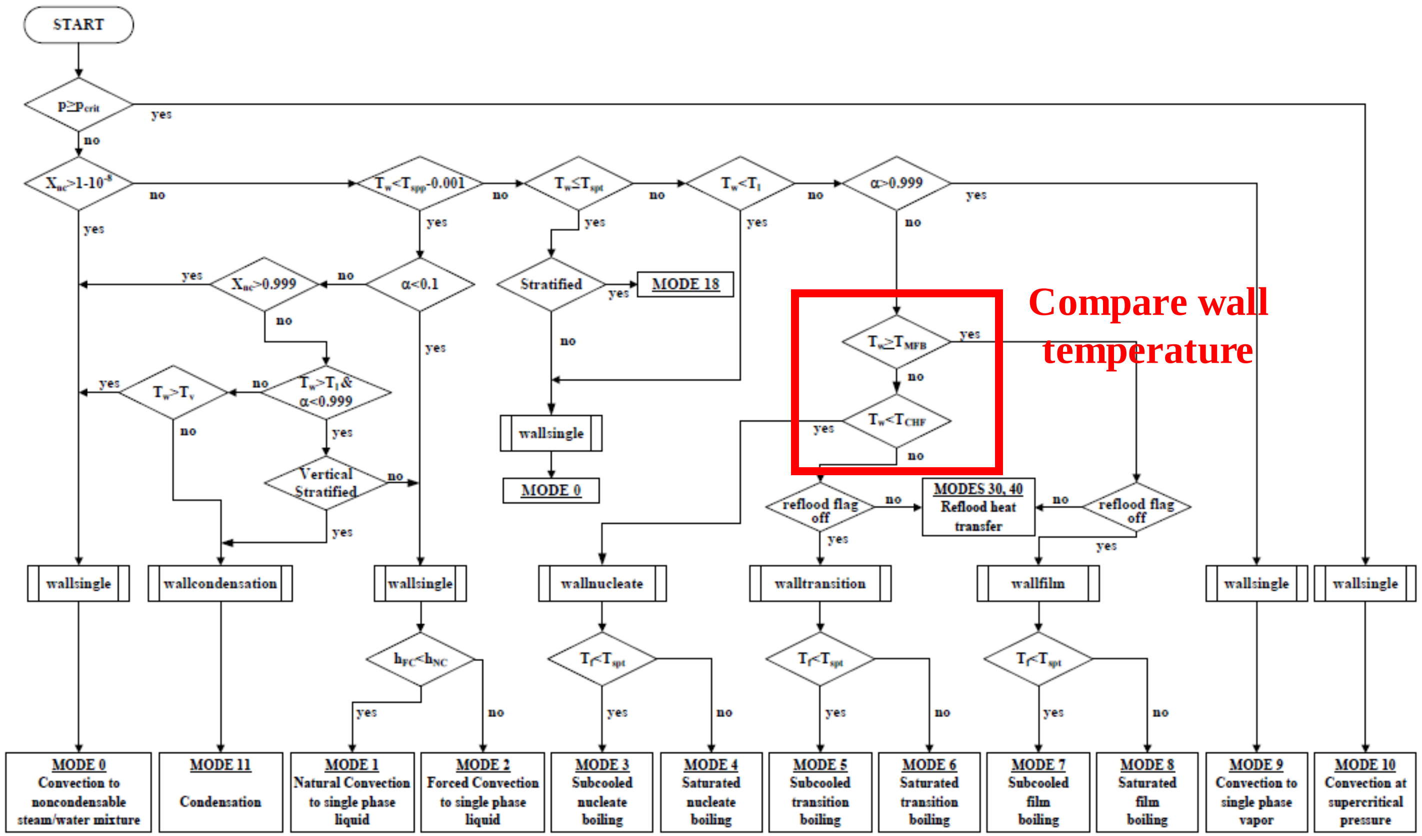
Flow Regime and Wall Heat Transfer Mode

- Comparison of wall heat transfer flow chart

MARS-KS



SPACE



Heat Transfer Coefficient (HTC)

- ❑ Comparison of HTC profile (secondary side)
  - ① z < 1.8 m: HTCs are almost identical.
  - ② z > 1.8 m: Liquid HTC of SPACE drops near the end of the saturated nucleate boiling region.
  - ③ z = 3.0 m: Liquid HTC of SPACE sharply increases. (transition to saturated film boiling)

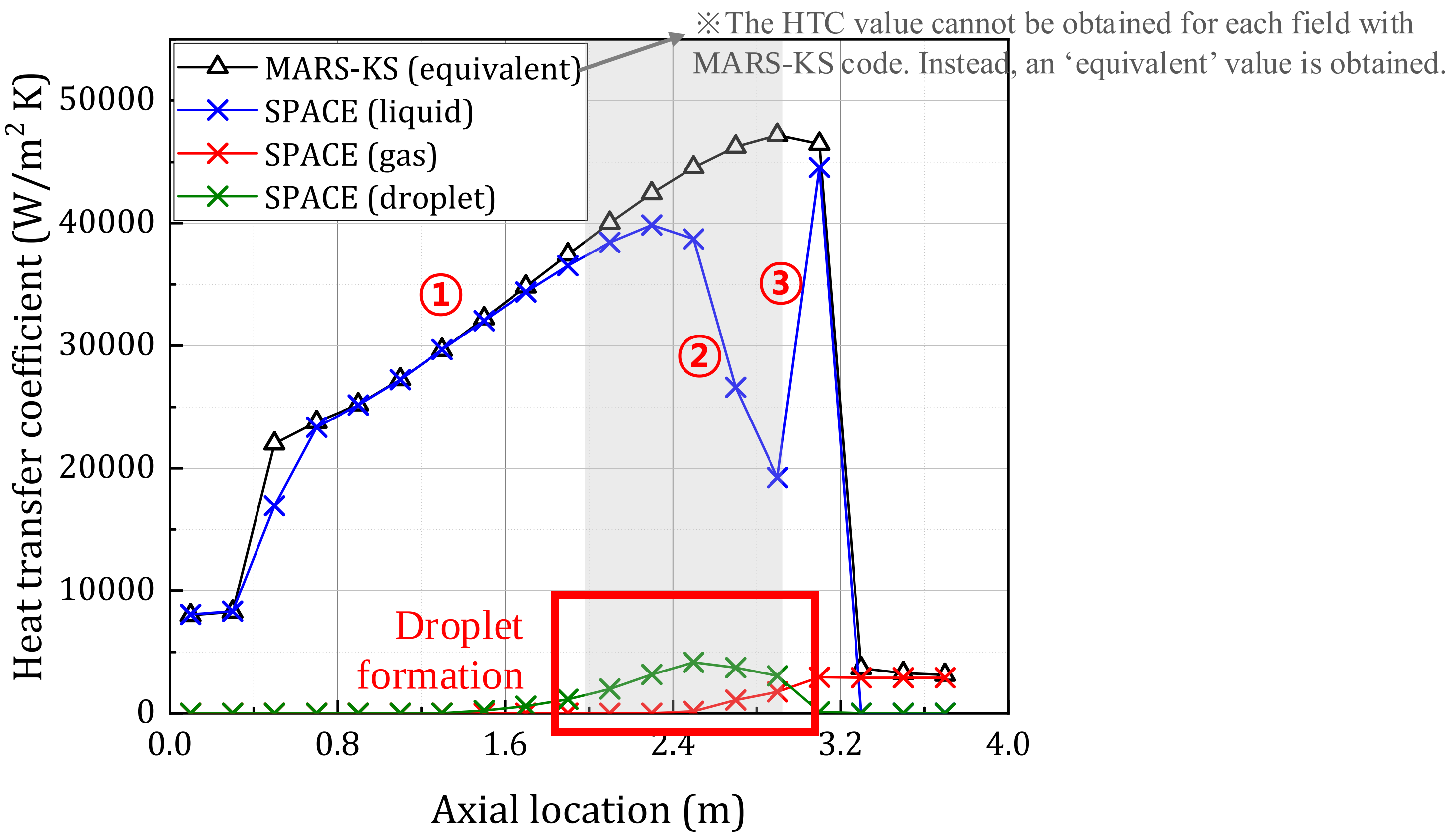


Fig. Secondary side HTC profile comparison

Flow Rate of Each Field

- Comparison of flow rate of each field (secondary side)
  - $\dot{m}_{gas}, v_{gas}$ is almost the same at both codes.
  - At the gray-boxed region, however, SPACE code predicts that:
    1. A portion of continuous liquid transforms into droplets.
    2. Droplet entrainment → $v_{droplet}$ increases gradually with v_{gas}.
    3. Meanwhile, v_{liq} decreases → Re_{liq} decreases → liquid HTC decreases (=Explanation for the sudden HTC drop)

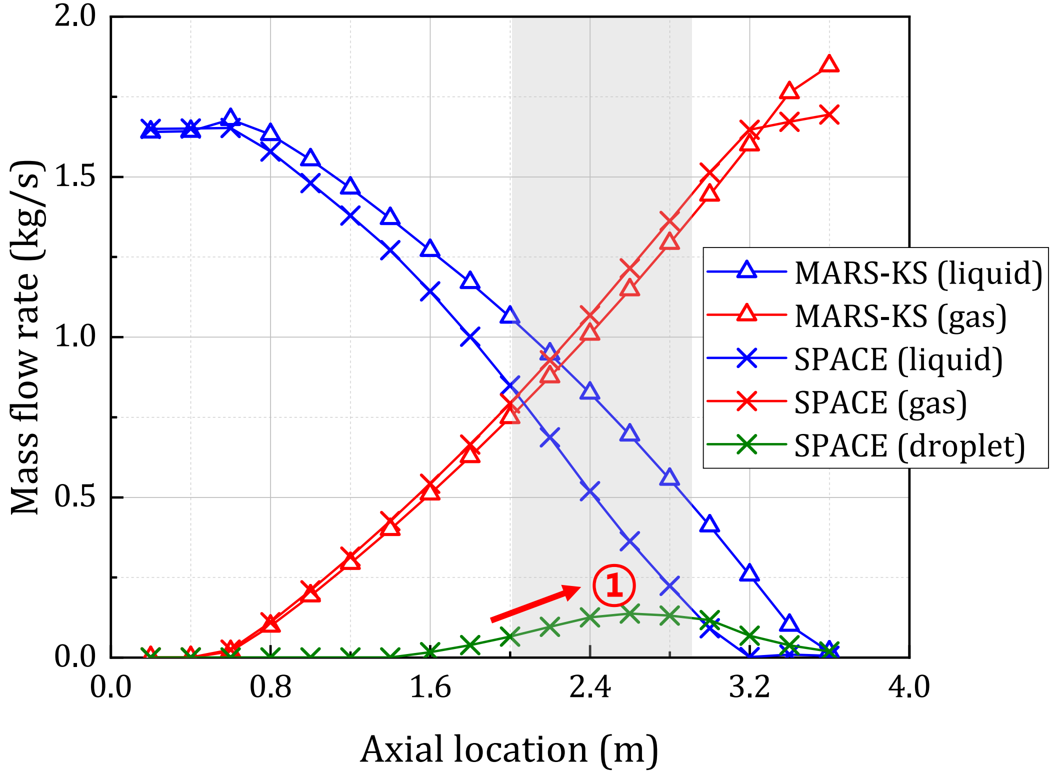


Fig. Mass flow rate profile at the secondary side

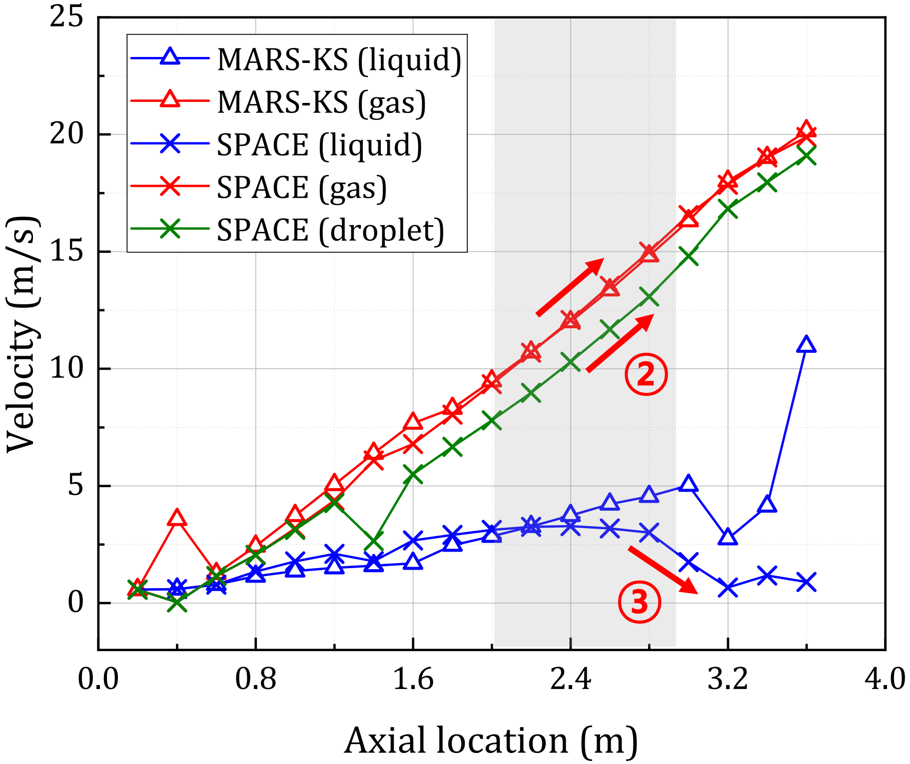


Fig. Velocity profile at the secondary side

04

Conclusions and Further Works

Summary

1 Comparison of steady-state calculation results for once-through helical SG with MARS-KS and SPACE code

- Depending on the TH code, the types of governing equations, heat transfer models, and correlations are different. Ex) Two-phase, two-fields (MARS-KS) vs Two-phase, three-fields (SPACE)
- Region where two-phase flow and droplet formation is prominent = Once-through steam generator like SMART SG

2 Differences in heat transfer mode selection and governing equations led to variations in heat transfer phenomena in the two-phase region.

- The temperature profile, heat transfer coefficient, and flow rates of each phase were calculated differently at the secondary side.
- However, the calculated inlet/outlet conditions were similar.

Limitations and Further Works

1 Effect of droplet formation

- SPACE code might be more accurate in calculating annular region where distinct droplet formation occurs.
- But does that mean the results are close to actual physical phenomena?
- Even if the results from SPACE are closer to the actual phenomena than those from MARS-KS, is that enough to justify the long computation time of SPACE?

2 Unstable calculation of superheated steam in helical tubes (SPACE)

- The pressure and HTC calculations of the secondary side superheated steam are unstable at SPACE.

```
***WARNING: h020-01-018, hv[0] = -1330.54, Pres = 5.22308e+006
***WARNING: h090-01-019, hv[0] = -4111.38, Pres = 5.19785e+006
***WARNING: h110-01-019, hv[0] = -1058.03, Pres = 5.19661e+006
***WARNING: h110-01-019, hv[0] = -1053.22, Pres = 5.19491e+006
```

3 Advanced correlations and models for helical geometry

- Both SPACE V3.3 and MARS-KS V2.0 have heat transfer correlation models for helical tube & bundle.
- The models for pressure drop, critical heat flux, etc. should be integrated into the codes, to better account for the unique flow within helical geometries.

Q & A

Appendix

- Heat transfer coefficient correlations used in MARS-KS and SPACE code

Heat transfer mode	MARS-KS (helical tube mode)	SPACE (default mode)	SPACE (helical tube mode)
Single phase liquid	Mori-Nakayama (1967)	Dittus-Boelter (1930)	Unknown
Nucleate boiling	Chen (1963)	Chen (1963), Thom (1965) for P > 70 bar	Unknown
Critical heat flux	Quality > 0.8	AECL look-up table (Groeneveld et al., 2007)	Unknown
Transition boiling	Chen-Sundaram-Ozkkaynak (1977)	Bjornard & Griffith (1977)	Unknown
Film boiling	Bromley (1950)	2004 film boiling look-up table (Groeneveld et al., 2003)	Unknown

Interfacial Heat and Mass Transfer (SPACE)

- Interfacial heat transfer at droplet
  - Two types of droplet
    1) Involved in the continuous liquid. Flows together with continuous liquid.
    2) Droplet that is separated from the continuous liquid. Its volume fraction is used for solving the 9 governing equations.
       → Only this type of droplet is treated as a separate droplet, and thus the interfacial heat transfer models are applied.
  - Heat transfer between droplet and gas

$$\mathrm{Re}_d = \frac{We \cdot \sigma \cdot \alpha_d^3}{\mu_g \sqrt{v_{dg}^2 \alpha_d}}$$

$$Nu_{drp} = 2 + 7\min\left(1 + cp_d \left|T_{sat} - T_d\right| h_{fg}, 8\right)$$

$$H_{id} = h \cdot a_i = \frac{Nu_{drp} s_{drp} k_d}{d_d}\left(1 + \frac{1}{4} dT_{\sup}^2\right)$$

$$dT_{\sup} = \max\left(0, T_d - T_{sat}\right)$$

For droplet from dispersed flow (Lee-Ryley)

$$trmm = \left|\max\left(-2, T_{sat} - T_g\right)\right|$$

$$f = 1 - 5 \times \min\left(0.2, \max\left(0, T_{sat} - T_g\right)\right)$$

$$\phi = \max\left(0, \min\left(10^{-5}, \alpha_d\right) 10^5 \times f + 1 - f\right)$$

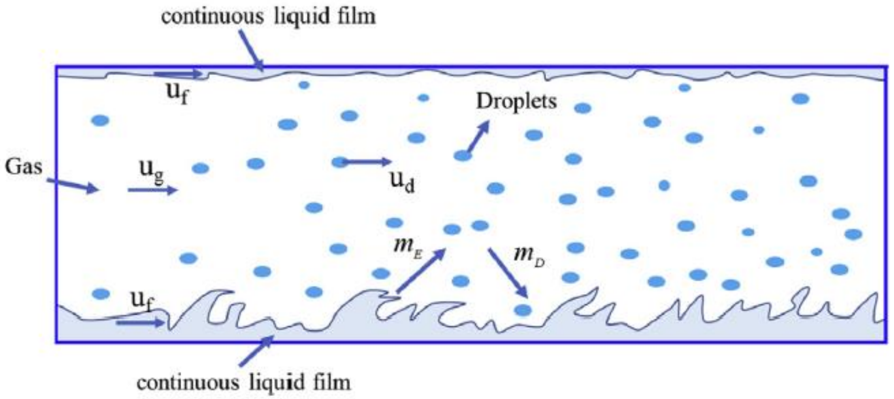
$$H_{ig} = \left[\left(2 + 0.5\sqrt{\mathrm{Re}_d}\right)\frac{k_g}{d_d} + 10^4\left(1 + trmm\left(100 + 25\,trmm\right)\right)\right] s_{drp} \times \phi$$

Droplet Entrainment & Deposition Model (SPACE)

- Generally, droplet forms when $v_{gas} > v_{liq}$. Thus, droplet is formed at annular and stratified flow regimes.

  - Entrainment rate correlation: Lopez de Bertodano et al. (1997)

$$m_E = k_E \frac{\mu_l}{D_h} \left[We_g \left(\frac{\rho_l - \rho_g}{\rho_g} \right)^{1/2} (\mathrm{Re}_{lf} - \mathrm{Re}_{lfc}) \right]^{0.925} \left(\frac{\mu_g}{\mu_l} \right)^{0.26}$$



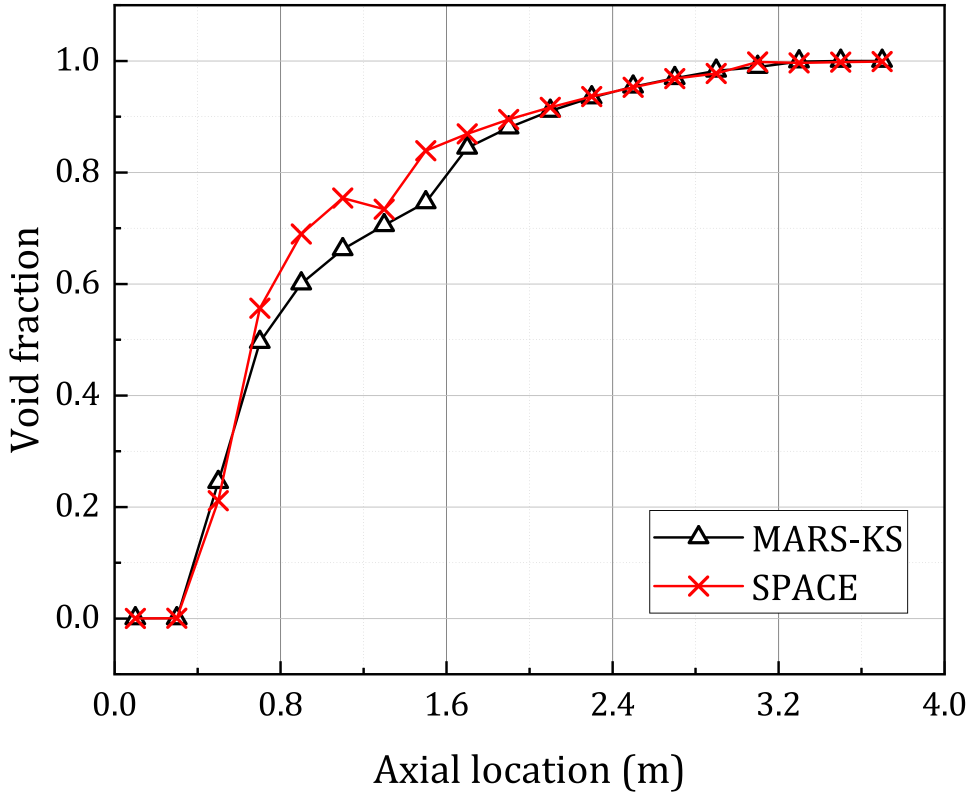
  - Deposition rate correlation: McCoy & Hanratty (1977)

$$m_D = C k_D$$

$$C \approx \rho_g \frac{m_d}{m_g} \qquad \frac{k_D}{v^*} = \begin{cases} 3.25 \times 10^{-4} (\tau^+)^2, & \tau^+ \leq 22.87 \\ 0.17, & 22.87 < \tau^+ \leq 8340 \\ 20.7 (\tau^+)^{-1/2} \times 0.75, & \tau^+ > 8340 \end{cases} \qquad v^* = \sqrt{\frac{1}{2} v_g^2 f_i} \qquad \tau^+ = \frac{d_d^2 (v^*)^2 \rho_l \rho_g}{18 \mu_g^2}$$

Appendix

❑ Void fraction profile (secondary side)



❑ HTC profile (primary side)