Comparison of MARS-KS and SPACE in Predicting Density Wave Oscillation (DWO) Onset Under Different Mass Flux Conditions

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Keywords : Helical Tube, MARS-KS, SPACE, Density Wave Oscillation, Instability

1. Introduction

Nuclear power has long been recognized as a reliable baseload energy source. Recently, its applications have expanded beyond electricity generation to include industrial process heat, hydrogen production, and seawater desalination. Alongside these developments, global efforts to mitigate climate change have driven an increased demand for advanced reactors that offer enhanced safety and operational flexibility.

The design of advanced reactors prioritizes miniaturization to enable modular transportability and reduce construction costs. Helical tube steam generators have gained significant attention as a promising alternative due to their high heat transfer area density and compact design.

However, because helical tube steam generators operate in a once-through configuration, where multiple heat exchanger tubes share common inlet and outlet headers, they are particularly susceptible to density wave oscillations (DWO) under two-phase flow conditions. This can lead to flow instability, potentially compromising the structural integrity of the steam generator.

Despite extensive research on two-phase flow instability since the 1960s, studies specifically focused on helical tube steam generators remain limited [1&2]. Widely used 1D thermal-hydraulic codes for reactor safety assessments can also be applied to the analysis of helical tube steam generators. In Korea, MARS-KS and SPACE are representative 1D codes. Both codes solve mass, momentum, and energy conservation equations. However, MARS-KS uses a 6-equation two-phase flow model, while SPACE incorporates an additional droplet phase, solving a set of 9 conservation equations. These methodological differences can significantly impact the prediction of phase-change dynamics and two-phase flow instability in helical tube steam generators.

This study compares and analyzes the DWO onset stability maps and thermal-hydraulic variables at critical conditions, evaluated using MARS-KS and SPACE under different flow boundary conditions. The results aim to enhance the understanding of two-phase flow instability in helical tube steam generators and contribute to the optimization of next-generation steam generator designs.

2. Methodology

This section introduces the fundamental concept of stability maps for assessing density wave oscillations, reviews key previous studies, and describes the modeling approaches employed in MARS-KS and SPACE, including the methodology for determining the critical conditions for density wave oscillations.

2.1 Parallel Helical Tube Modeling

To simulate Density Wave Oscillations (DWO) using a 1-D thermal-hydraulic code, a conceptual design and geometry were used based on relevant previous studies before modeling the identical parallel helical tube test section. The referenced experimental study is that of Papini (2014) [3], and Table I shows the geometric specifications of the helical tubes used in his experiments.

Table I: Papini's Helical Tube Geometry

Inner diameter [mm]	12.53
Outer diameter [mm]	17.24
Coil diameter [mm]	1000
Tube length [m]	24
Coil pitch [mm]	800
Inlet throttling	82

In the helical tube test section, both the upper and lower headers are shared, and direct current (DC) heating is applied. The boundary conditions used in Papini's study include an outlet pressure of 4.0 MPa and inlet mass fluxes of 200 and 600 kg/(m²·s). The corresponding experimental stability map is shown in Figure 1.

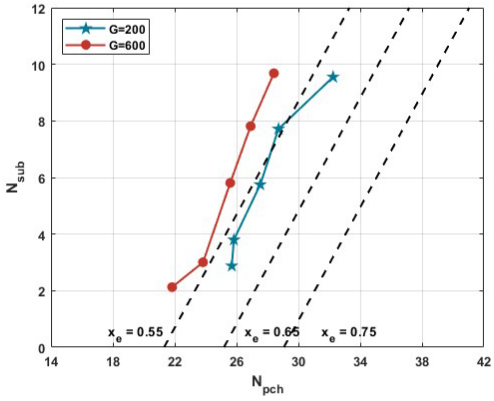

Fig. 1. Stability Map from Papini's Experiment.

The nodalization approach used to model the identical parallel helical tube test section is illustrated in Figure 2. In MARS-KS, the fluid enters with a specified temperature and mass flow rate at a time-dependent volume (TMDPVOL) and junction (TMDPJUN), where boundary conditions are imposed [4]. The BRANCH component, representing the headers, splits the flow into two streams, directing each stream into separate helical tubes.

The PIPE components, which include an inclination angle, define the flow paths within the helical section and consist of 80 nodes per pipe [5]. The connected heat structures simulate the surrounding helical tubes, with heating applied based on predefined tables. After passing through the helical tubes, the fluid merges again at a BRANCH component and exits through a single junction into a time-dependent volume, where the specified outlet pressure boundary condition is applied.

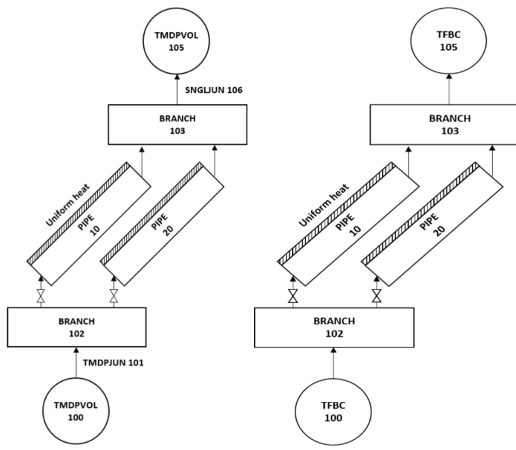

Fig. 2. Nodalization of Parallel Helical Tube Test Section with MARS-KS & SPACE.

The nodalization approach in SPACE is similar to that of MARS-KS; however, a key difference is that time-dependent volumes and junctions are integrated into a unified Temporal Face Boundary Condition. Both codes incorporate heat transfer models to determine the heat transfer coefficient within the helical tube steam generator. However, since neither code includes hydrodynamic components for pressure drop calculations appropriate for the helical tube geometry, the pressure loss in the helical coil is corrected using the form loss coefficient of a 180° bending tube, accounting for the number of rotations.

For the heat transfer model of the helical tube steam generator, MARS-KS employs the Mori-Nakayama and Chen models. In contrast, the specific heat transfer model used in SPACE is not publicly disclosed. However, the heat transfer coefficient in the single-phase region has been observed to closely align with that of MARS-KS.

2.2 Density Wave Oscillations Detection Using 1D Thermal-Hydraulic Codes

DWO in 1D thermal-hydraulic codes is identified through flow oscillations [6]. The heating power in the test section can be incrementally adjusted over time while maintaining specified boundary conditions, as shown in Figure 3.

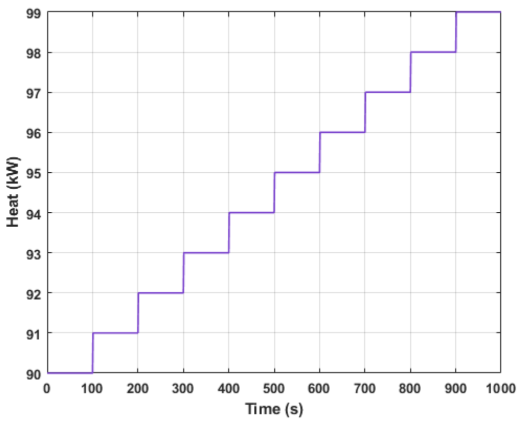

Fig. 3. Increment of Heating Power over Time.

When the heating power exceeds the critical level, flow oscillations, as shown in Figure 4, are observed. In this analysis, the heating power is adjusted in 1 kW increments every 500 seconds, and the corresponding flow response is monitored. The computed critical heating power, corresponding to the inlet temperature, can be converted into the critical phase-change number and subcooling number. This enables the construction of a stability map for density wave oscillations, with the axes representing the phase-change number and subcooling number.

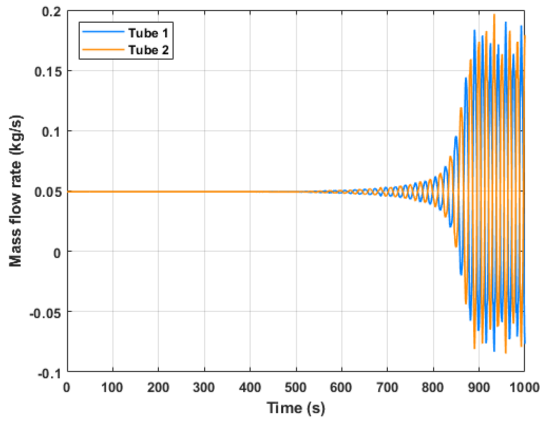

Fig. 4. Mass Flow Rate Change over Time.

3. Results and Discussion

This section presents the predicted density wave oscillation (DWO) results and stability maps for the previously specified boundary conditions using MARS-KS and SPACE. Additionally, it discusses the results and trends observed in each code.

3.1 DWO Onset for Each Code

The computational results for DWO onset reveal significantly different trends between the two codes, even in the absence of a dedicated pressure drop thermal-hydraulic model for helical tube steam generators. The legend in Figure 5 and 6 denotes cases where the mass flux is 200 kg/(m²·s) and 600 kg/(m²·s), respectively.

Figure 5 indicates that, in MARS-KS, unlike Papini's experimental stability map, lower mass flux conditions generally predict a more conservative DWO onset than higher mass flux conditions, except at a subcooling number of 2. Conversely, as shown in Figure 6, SPACE predicts a more conservative instability onset under higher mass flux conditions across all subcooling numbers. The corresponding results from each code are presented in Tables II and III.

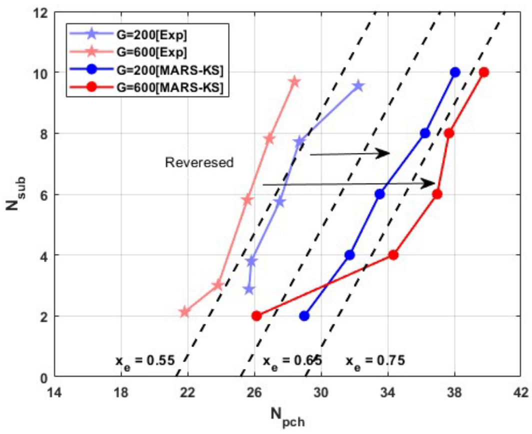

Fig. 5. Stability Map Computed by MARS-KS.

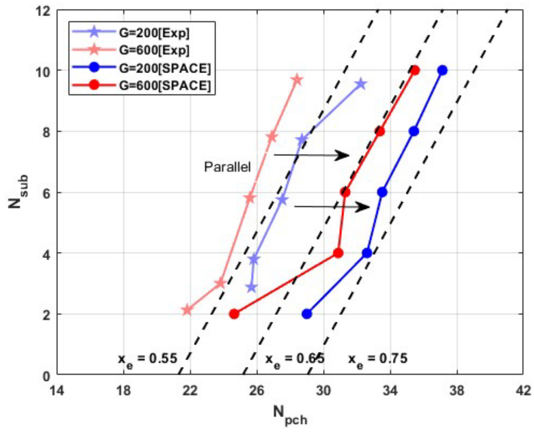

Fig. 6. Stability Map Computed by SPACE.

Table II: Computed Onset of DWO with MARS-KS

Subcooling No.	2	4	6	8	10
Inlet Temperature [K]	504.9	485.8	466.1	446.0	425.6
Critical Phase-Change No. [G=200 kg/(m²·s)]	29.01	31.73	33.53	36.25	38.05
Critical Phase-Change No. [G=600 kg/(m²·s)]	26.15	34.35	36.99	37.42	39.77

Table III: Computed Onset of DWO with SPACE

Subcooling No.	2	4	6	8	10
Inlet Temperature [K]	504.9	485.8	466.1	446.0	425.6
Critical Phase-Change No. [G=200 kg/(m²·s)]	29.01	32.62	33.53	35.43	37.14
Critical Phase-Change No. [G=600 kg/(m²·s)]	24.65	30.89	31.31	33.41	35.48

3.2 Difference between MARS-KS and SPACE

Additionally, the thermal-hydraulic variables just before the onset of DWO provide insight into the critical point predictions of MARS-KS and SPACE. Tables IV and V present the thermal-hydraulic variables at the critical onset conditions for each mass flux boundary condition in both codes.

A comparison of MARS-KS and SPACE under different mass flux conditions shows that at lower mass flux, both codes yield relatively similar results. However, at higher mass flux, a significant discrepancy in static quality is observed between the two codes. Despite the increase in equilibrium quality due to higher heating power, MARS-KS exhibits higher static quality than SPACE, indicating a greater degree of thermal equilibrium.

A lower degree of thermal equilibrium can suppress vapor generation, leading to nonlinear density variations and strong feedback effects, including localized nucleation burst, which contribute to DWO onset. This phenomenon helps explain the observed DWO prediction results.

Table IV: Key Parameter Values Prior to the Onset of Density Wave Oscillations for Each Code (G=200 kg/(m²·s))

Subcooling No.	2	4	6	8	10
Inlet Pressure [MPa] (MARS-KS)	4.041	4.041	4.042	4.043	4.043
Inlet Pressure [MPa] (SPACE)	4.041	4.042	4.042	4.043	4.043
Equilibrium Quality (MARS-KS)	0.682	0.701	0.696	0.716	0.711
Equilibrium Quality (SPACE)	0.682	0.725	0.696	0.693	0.688
Static Quality (MARS-KS)	0.399	0.438	0.421	0.451	0.444
Static Quality (SPACE)	0.325	0.361	0.337	0.334	0.33
Two-phase Length [m] (MARS-KS)	22.5	21.3	19.8	18.9	18
Two-phase Length [m] (SPACE)	22.5	21.3	19.8	18.9	17.7

Table V: Key Parameter Values Prior to the Onset of Density Wave Oscillations for Each Code (G=600 kg/(m²·s))

Subcooling No.	2	4	6	8	10
Inlet Pressure [MPa] (MARS-KS)	4.194	4.22	4.217	4.203	4.198
Inlet Pressure [MPa] (SPACE)	4.203	4.22	4.203	4.204	4.191
Equilibrium Quality (MARS-KS)	0.647	0.826	0.847	0.817	0.818
Equilibrium Quality (SPACE)	0.616	0.731	0.688	0.693	0.695
Static Quality (MARS-KS)	0.54	0.762	0.788	0.744	0.75
Static Quality (SPACE)	0.377	0.501	0.448	0.456	0.455
Two-phase Length [m] (MARS-KS)	22.5	21.6	20.7	19.5	18.6
Two-phase Length [m] (SPACE)	22.5	21.3	19.8	18.9	18

The higher static quality observed in MARS-KS compared to SPACE can be attributed to the fundamental difference between the two codes: the treatment of the droplet phase. Figure 7 presents the total vapor generation from the droplet phase in each tube over time in SPACE. The results indicate that, despite the inclusion of a droplet phase in SPACE, it does not contribute to vapor generation.

As a result, vapor formation occurs exclusively in the liquid phase. At high quality, the droplet phase transitions back into the liquid phase before evaporating. This process suppresses vapor generation, leading to increased thermal non-equilibrium in SPACE.

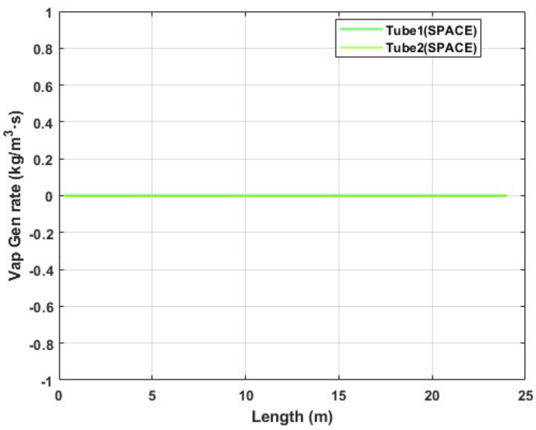

Fig. 7. Vapor Generation Rate Computed by SPACE

Additionally, Figure 8 presents the liquid and droplet phase velocities for each code under the same heating conditions. The results indicate that SPACE predicts a lower liquid velocity, which, due to an increased slip ratio, reduces interfacial area and enhances phase separation. This inhibits energy transfer between the liquid and gas phases, thereby increasing thermal non-equilibrium. In contrast, MARS-KS, with its higher liquid velocity, prolongs the contact time between the liquid and gas phases, facilitating thermal equilibrium.

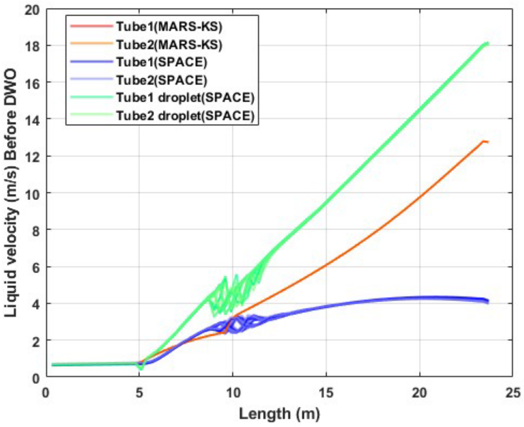

Fig. 8. Liquid Velocity including Droplet for Each Code

4. Conclusions

This study conducted a comparative analysis of the onset of density wave oscillations (DWO) in parallel helical tube steam generators using the one-dimensional thermal-hydraulic codes MARS-KS and SPACE. The results revealed significant discrepancies in DWO onset predictions, highlighting the impact of numerical modeling approaches on flow instability assessment, particularly in the absence of a dedicated pressure drop model for helical tube steam generators.

The computed stability maps exhibited contrasting trends between the two codes. MARS-KS predicted a more conservative DWO onset at lower mass flux conditions, whereas SPACE predicted a more conservative instability onset at higher mass flux conditions. These differences suggest that the conservation equations and phase-change models in each code play a critical role in defining stability boundaries.

Further analysis of thermal-hydraulic variables at critical conditions showed that MARS-KS consistently predicted higher static quality than SPACE, indicating a greater degree of thermal equilibrium in two-phase flow. This discrepancy is attributed to SPACE's droplet phase treatment, which suppresses vapor generation and enhances thermal non-equilibrium effects.

These findings suggest that modeling choices, particularly in phase-change dynamics and interfacial heat transfer, significantly influence flow instability predictions in helical tube steam generators. As accurate stability assessment is crucial for next-generation steam generator design and safety analysis, future research should focus on experimental validation and improved modeling approaches, particularly through the integration of dedicated helical tube pressure drop models to enhance predictive accuracy.

ACKNOWLEDGEMENT

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea. (No. RS-2023-00244146)

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