Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 9-10, 2024

Exploring Two-Phase Flow Instabilities in Helical Steam Generators Using MARS-KS Code

Seunghwan Oh [a], Doh Hyeon Kim [a], Jeong Ik Lee [a*]
[a]*Nuclear & Quantum Engineering, Korea Advanced Institute of Science and Technology (KAIST), 291 Daehak-ro, Yuseong-gu, Daejeon, Republic of Korea*
[*]*Corresponding author: jeongiklee@kaist.ac.kr*

Keywords : Small modular reactor, Helical steam generator, Two-phase flow instability, MARS-KS code

1. Introduction

The integration of Helical Steam Generators (HSGs) into Small Modular Reactors (SMRs) is becoming increasingly significant due to their compact design and enhanced heat transfer efficiency. The operation of HSG, however, introduces challenges related to two-phase flow instabilities, such as Ledinegg instability and Density Wave Oscillation (DWO), which can impact the thermal-hydraulic performance and operational safety of SMRs. Recognizing and accurately predicting these instabilities are crucial for ensuring the reliability and safety of these reactor components.

Research efforts have been dedicated to exploring these phenomena, employing both experimental methods and simulations to understand the dynamics of two-phase flow instabilities within helical tubes. Previous studies have predominantly focused on helical tubes of identical configurations [1,2,3]. However, the structural characteristics of HSGs are their multi-layered composition with helical tubes of varying lengths across different layers [4,5]. This discrepancy highlights a gap in the research, as the influence of tube length and quantity on two-phase flow instability has not been thoroughly explored in previous investigations.

To advance the understanding of two-phase flow instabilities, this study employs the MARS-KS code, a thermal-hydraulic simulation tool developed in South Korea for nuclear reactor safety analysis. By analyzing the instability phenomena in two or more pipes of different lengths connected to the same headers, this study aims to provide a deeper insight to the behavior of two-phase flow instabilities in helical steam generators.

2. Methods and Results

In this section, the modeling of parallel helical tubes with the MARS-KS code is detailed, and summaries of helical tube shape data and the thermal-hydraulic model are provided. From this, two-phase flow instability is analyzed.

2.1 Parallel Helical Tubes Modeling

MARS-KS V2.0 code is utilized to examine the two-phase flow instabilities. Fig. 1 shows the nodalization of parallel helical tubes. The fluid enters with a constant subcooling by a time dependent volume (TMDPVOL 100), and the inlet flow rate is determined using a time dependent junction (TMDPJUN 101). Since MARS-KS models the helical tubes as inclined straight pipes (PIPE 10, 20 and 30), and the helical tube thermal-hydraulic model option is applied. The inlet and outlet of the pipes are linked to the inlet header (BRANCH 102) and the outlet header (BRANCH 103), respectively. The boundary for the outlet pressure is set by TMDPVOL 105. Uniform heat flux heats the fluid along the axial direction, and the tube inlet throttling is excluded in this investigation to understand the effect of multi-length tubes on the instability directly.

This study focuses on a helical steam generator used in the SMART reactor, which was developed by KAERI. It features 17 layers of helical tubes, each varying in length. Because of the restricted availability of detailed geometric data to the public, virtual helical tubes were conceptualized based on information accessible from public sources [5,6]. The dimensions and specifications of these virtual helical tubes are summarized in Table I.

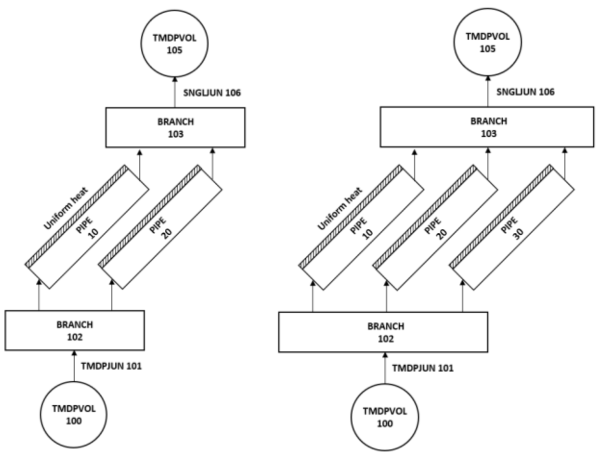

Fig. 1. Nodalization of parallel helical tubes

TABLE I. Geometric information of the helical tubes

	Tube1	Tube2	Tube3
Inner diameter (mm)	12.00	12.00	12.00
Outer diameter (mm)	17.00	17.00	17.00
Length (m)	24.35	25.14	25.51
Helical diameter (mm)	577.00	937.00	1297.00
Helical angle (°)	8.78	8.50	8.38

2.2 Heat Transfer and Pressure Drop Correlations for Helical Tube in MARS-KS Code

The MARS-KS code was developed to perform safety analyses on pressurized water reactors with its thermal-hydraulic model based on experimental correlations from straight tubes. To enhance the applicability of MARS-KS code, correlations suitable for helical tubes have been incorporated [7]. TABLE II provides a summary of the heat transfer correlations for helical tubes. At present, the original MARS-KS code does not include correlations for calculating the pressure drop in helical tubes.

In this study, a modified version of the MARS-KS code was employed, which incorporates pressure drop correlations for helical tubes. The Ito correlation [8] was applied for modeling single-phase flow, while the two-phase flow was modeled using the correlation developed by Colombo et al. [9]. This two-phase flow correlation was formulated using experimental data from studies by Santini et al. [10] and Zhao et al. [11], resulting in mean absolute percentage errors of 12.0% and 17.8%, respectively. Fig.2 displays the range of the helical tube shape conditions for each conducted experiment along with the conditions of the virtual helical tubes.

TABLE II. Heat transfer correlations

Single phase turbulent flow	
$h_c = 0.2439\frac{k_f}{d}Re_f^{0.8333}Pr^{0.4}\left(\frac{d}{D}\right)^{\frac{1}{12}}\left[1 + \frac{0.061}{\left[Re_f\left(\frac{d}{D}\right)^{2.5}\right]^{\frac{1}{6}}}\right] \; (Pr > 1)$	(1)
$h_c = 0.03846\frac{k_f}{d}Re_f^{0.8}\frac{Pr}{(Pr^{\frac{2}{3}} - 0.074)}\left(\frac{d}{D}\right)^{\frac{1}{10}}\left[1 + \frac{0.061}{\left[Re_f\left(\frac{d}{D}\right)^{2}\right]^{\frac{1}{5}}}\right] \; (Pr < 1)$	(2)
Laminar and Natural convection	
Same correlation of default	
Nucleate boiling heat transfer	
$q'' = h_{mac}(T_w - T_s)F + h_{mic}(T_w - T_s)S$	(3)
Transition boiling	
$x_s > 0.8$ (Dryout occurrence point)	(4)
Film boiling	
Same correlation of default	

TALBE III. Pressure drop correlations

Single-phase flow	Ito correlation [8] $f\left(\frac{D}{d}\right)^{\frac{1}{2}} = 0.029 + 0.304\left[Re\left(\frac{D}{d}\right)^{2}\right]^{-0.25}$ $0.034 < Re\left(\frac{d}{D}\right)^{2} < 300$	(5)
Two-phase flow	Colombo correlation [9] $\varnothing_l^2 = 0.0986\left(1 + \frac{20}{X} + \frac{1}{X^2}\right)De_l^{0.19}\left(\frac{\rho_m}{\rho_l}\right)^{-0.4}$ $De_l = \frac{G(1-x)d}{\mu_l}\sqrt{\frac{d}{D}} \quad \Delta P_l = \frac{f_l G^2 (1-x)^2 L}{2\rho_l d} \quad f: Ito\ cor.$	(6)

Fig. 2. Range of the helical tube geometric conditions

2.3 Two-phase Flow Instabilities

Two-phase flow instabilities manifest as variations in flow rate when the heat input surpasses the instability threshold under specific thermal-hydraulic conditions. Ledinegg instability leads to a shift in mass flow rate from one stable state to another, a process known as flow excursion. DWO is characterized by sustained periodic oscillations. By applying heat input as depicted in Fig. 3 and monitoring the flow rate in each tube as illustrated in Fig. 4. The simulation was conducted with conditions set at 5.2 MPa, 466.02 ℃, 0.0536 kg/s (each tube) in the parallel helical tubes of Tube1-Tube1. Given that the total flow rate remains unchanged, oscillations within each tube display a counter-phase. In the flow oscillation amplitude in response to heat input as depicted in Fig. 5 [12], the onset of DWO was determined when it exceeds 30% of the steady-state flow rate [13].

Fig. 6 shows flow change in the parallel helical tubes of Tube1-Tube3. Due to the variation in tube lengths, Ledinegg instability tends to occur. Since Tube1 is shorter than Tube3, more flow rate flows to maintain the same pressure drop. It diminishes with increased heat input. Subsequently, DWO emerges, with the flow rate between the two tubes exhibiting a minor difference.

The variations in flow within three parallel helical tubes are illustrated in Figures 7 and 8. When the tubes are of identical length, the oscillation amplitude of one tube equals the combined amplitudes of the other two tubes. This means that while two tubes oscillate in synchronized manner, the other tube oscillates in out of phase. When the lengths of the tubes are different, the phenomenon becomes more complex than the Ledinegg instability depicted in Figure 6. Two tubes share a similar flow rate, whereas the other exhibits a markedly different flow rate. Moreover, with an increase in heat input, DWO is observed only in the two tubes that share a lower flow rate. The Ledinegg instability with DWO diminishes with further increase in heat input, eventually leading to a state where all three tubes exhibit oscillations. In this case, all three tubes oscillate with identical amplitudes but with a phase difference of 120° between each tube. This flow behavior markedly contrasts with that observed in identical tube combinations.

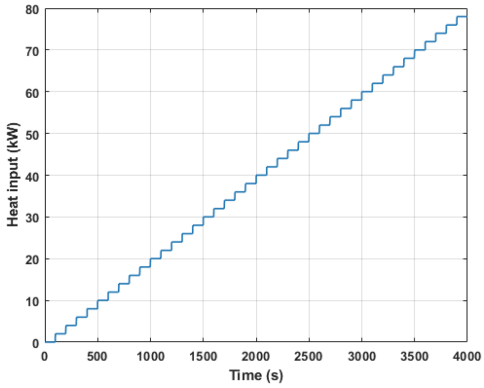

Fig. 3. Heat input of each tube

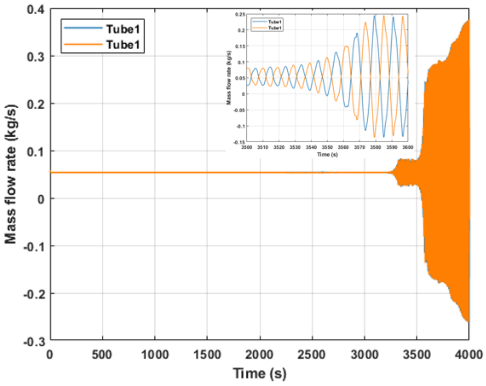

Fig. 4. Flow change of each tube (Tube1-Tube1)

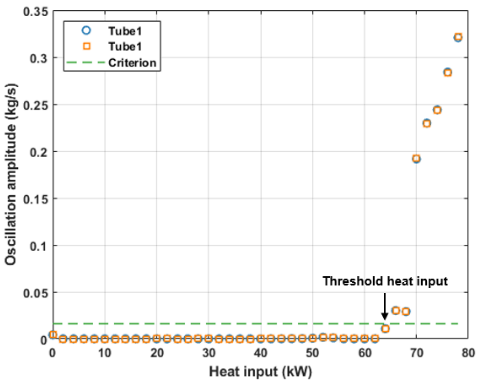

Fig. 5. Determination of the threshold heat input (Tube1-Tube1)

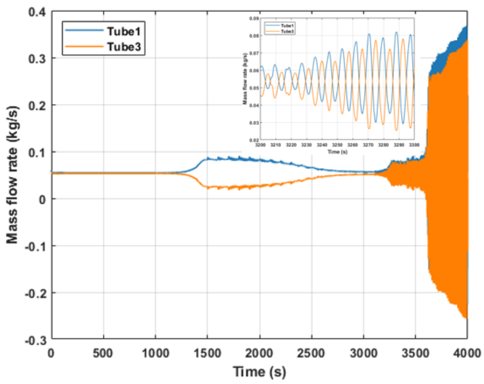

Fig. 6. Flow change of each tube (Tube1-Tube3)

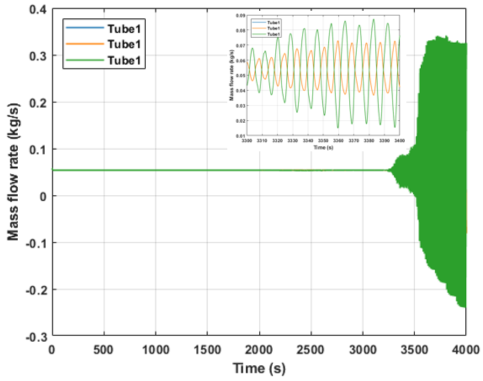

Fig. 7. Flow change of each tube (Tube1-Tube1-Tube1)

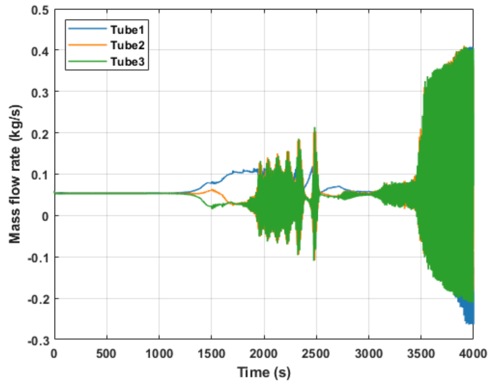

Fig. 8. Flow change of each tube (Tube1-Tube2-Tube3)

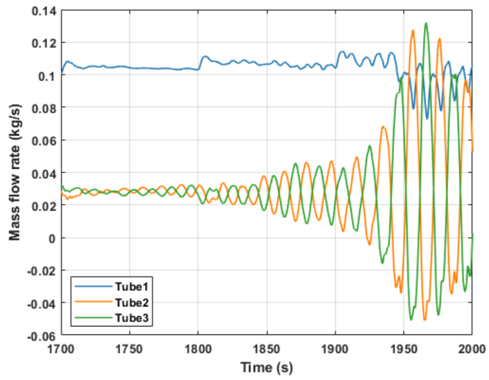

Fig. 9. Ledinegg instability with DWO (Tube1-Tube2-Tube3)

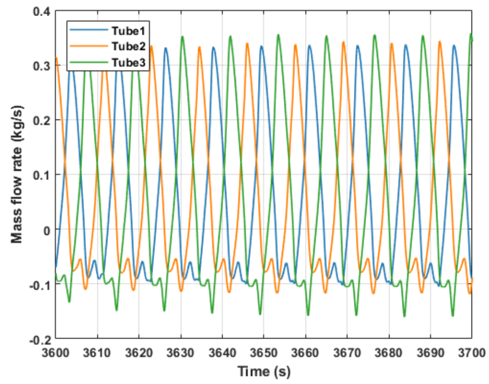

Fig. 10. DWO with 120° phase difference (Tube1-Tube2-Tube3)

2.4 Stability Map

After specifying the fluid properties, tube geometry, and operating pressure, it becomes possible to define the stable and unstable regions in a three-dimensional space by flow rate, heat input, and inlet subcooling. This three-dimensional plot can be simplified into two-dimensional plot with the use of dimensionless numbers. This is known as a stability map. The stability map developed by Ishii and Zuber is the most widely used [14]. The area to the left of the boundary line represents stability, whereas the area to the right indicates instability. Constructing a stability map necessitates identifying the threshold for instability, which can be achieved from experimental observations or simulations over various operational parameters.

Despite variations in the length and quantity of tubes, the threshold heat input for the occurrence of DWO remains relatively consistent, as illustrated in Figure 11. Regarding Ledinegg instability, it manifested solely at a subcooling number of 8, given identical tube lengths, and a notably higher threshold of heat input is required.

$$N_{pch} = \frac{Q}{\dot{m}h_{fg}}\frac{\rho_{fg}}{\rho_g} \tag{7}$$

$$N_{sub} = \frac{\Delta h_{in}}{h_{fg}}\frac{\rho_{fg}}{\rho_g} \tag{8}$$

$$N_{sub} = N_{pch} - x_e\frac{\rho_{fg}}{\rho_g} \tag{9}$$

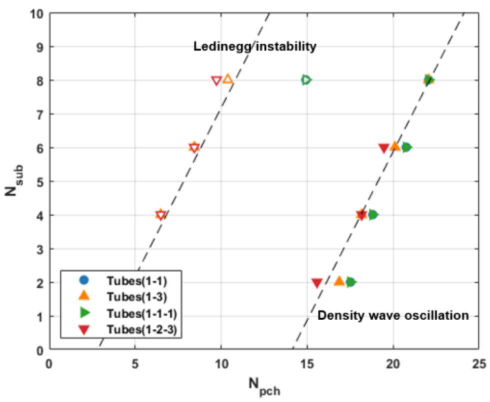

Fig. 11. Stability map

3. Conclusions

This study presents a comprehensive analysis of two-phase flow instabilities, particularly Ledinegg instability and DWO, within HSGs for SMRs using the modified MARS-KS code. Findings reveal that, despite variations in the length and quantity of tubes, the threshold heat input for the onset of DWO remains relatively consistent with the simple case. However, significant differences in flow behavior were observed within each pipe when the number and length of tubes changed. The variations in tube length facilitate the onset of Ledinegg instability earlier and allow for the localized occurrence of DWO in specific tubes. Moreover, when tube lengths vary, DWO with a phase difference 120° can manifest. Thus, analyzing two-phase flow instability in a helical tube using only two identical tubes presents limitations. The experiments will be conducted in near future to further understand the phenomenon of two-phase flow instabilities in helical tube steam generators better.

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. 00244146)

REFERENCES

[1] David Papini et al., Experimental and theoretical studies on density wave instabilities in helically coiled tubes, International Journal of Heat and Mass transfer, 2014.
[2] Minglu Wang et al., Experimental and numerical studies on two-phase flow instability behavior of a parallel helically coiled system, Annals of Nuclear Energy, 2022.
[3] Cong Shen et al., Study on two-phase flow instability of parallel helical tubes in steam generator of small modular reactors, International Communications in Heat and Mass Transfer, 2023.
[4] NuScale Power, Methodology for the Determination of the Onset of Density Wave Oscillations (DWO), TR-131981-NP Revision 1, 2023.
[5] KAERI, Heat transfer test for the steam generator and PRHRS Heat Exchanger of SMART, KAERI/CM-1199/2009.
[6] KAERI, Methodology for Failure Assessment of SMART SG Tube with Once-through Helical-coiled type, KAERI/CM-1351/2010.
[7] KINS, MARS-KS CODE MANUAL Volume V: Models and Correlations Manual, KINS/RR-1822 Vol.5
[8] H. Ito, Friction Factors for Turbulent Flow in Curved Pipes, Journal of Basic Engineering, 1959.
[9] L. Zhao et al., Convective boiling heat transfer and two-phase flow characteristics inside a small horizontal helically coiled tubing once-through steam generator, International Journal of Heat and Mass Transfer, 2003.
[10] Marco Colombo et al., A scheme of correlation for frictional pressure drop in steam-water two-phase flow in helicoidal tubes, Chemical Engineering Science, 2015.
[11] Lorenzo Santini et al., Two-phase pressure drops in a helically coiled steam generator, International Journal of Heat and Mass Transfer, 2008.
[12] Pradip Saha, Thermally Induced Two-phase Flow Instabilities, Including the Effect of Thermal Non-equilibrium between the Phases, Ph.D THESIS, Georgia Institute of Technology, 1974.
[13] Kenji Fukuda et al., Classification of Two-phase Flow Instability by Density Wave Oscillation Model, Journal of Nuclear Science and Technology, 1979.
[14] Mamoru Ishii et al., Thermally induced flow instabilities in two phase mixtures, International Heat Transfer Conference 4, 1970.