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Preliminary Analysis of Two-Phase Instability in Helical Coiled Steam Generator for Advanced Reactor Using MARS-KS

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1. Introduction

Nuclear power has been a significant source of electricity worldwide, providing baseload power. However, in recent years, there has been growing interest in developing reactors that can be used for a range of applications, including industrial process heat supply, hydrogen production, and seawater desalination, in addition to electricity generation. The need to develop advanced reactors that are both safe and flexible has become more urgent in response to climate change. To reduce the size of the steam generator, recently developed advanced reactors have adopted a Helically Coiled Steam Generator (HCSG). This technology increases the heat exchange area density instead of using the U-tube steam generator commonly used in existing commercial Pressurized Water Reactors (PWRs).

Steam generators that produce superheated steam can experience a phenomenon known as two-phase flow, in which water and steam flow together. Two-phase instability is a common thermo-hydraulic phenomenon that should be avoided in the design of systems involving boiling heat transfer. It can cause unexpected oscillations in flow rate and system pressure, leading to mechanical vibration or disrupted heat transfer. Density Wave Oscillation (DWO) is a typical dynamic instability [1], which can occur in once-through steam generator with multiple tubes sharing the same inlet and outlet header, when they are operated under two-phase flow conditions [2]. This factor significantly reduces the stability of two-phase flow systems and requires accurate analysis.

Although most studies on two-phase instability have focused on straight tubes, some experiments have used helical tubes and compared their results with the RELAP5 [3-4]. These studies improve the RELAP5 by addressing its limitations and incorporating a helical tube thermo-hydraulic model. However, there is a lack of research analyzing two-phase instability in helical tubes using the MARS-KS. Therefore, this study uses MARS-KS to numerically analyze the two-phase instability phenomenon in the HCSG of the SMART reactor, which was developed by KAERI.

2. Numerical Simulation Using MARS-KS

This section introduces the helical tube geometry information used in this study and the helical tube model in MARS-KS. This study analyzes two-phase instability by varying the inlet flow rate, inlet subcooling, and geometry of the helical tube.

2.1 Helical tube geometry information

Fig. 1 depicts the HCSG design concept of SMART, which consists of 17 layers. Fig. 2 shows the geometry and design parameters of the helical tube. Each layer has a different helix diameter (D), pitch (p), helix angle (θ), and length (L), except for the tube inner diameter (d_i) and height (H). The geometry information for the 1st and 17th helical tubes is summarized in Table I.

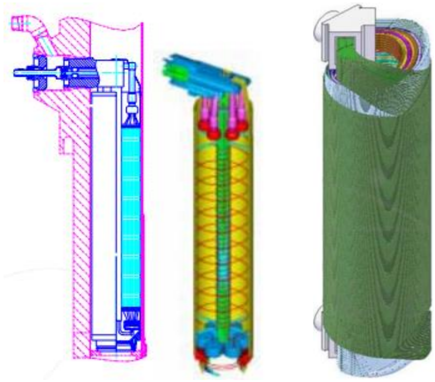

Fig. 1. SMART helical steam generator cassette design concept [5]

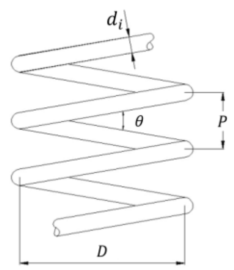

Fig. 2. Basic geometry of helical tube

Table I: Helical tube geometry information of SMART

		1st layer	17th layer
Open data [6]	d_i (mm)	12	12
	D (mm)	577	1297
	p (mm)	280	600
	θ (°)	8.78	8.38
Assumed data	H (mm)	4200	4200
	L (mm)	27513	28830

2.2 Helical tube simulation model in MARS-KS

MARS-KS is a system analysis code developed for detailed safety analysis of PWRs. While it is primarily designed for PWRs, MARS-KS also includes a helical tube heat transfer model, making it suitable for advanced reactor safety analysis [7]. Table II summarizes the correlations for the helical tube in MARS-KS. However, there is no pressure drop correlation available for the helical tube in MARS-KS.

Table II: Correlations for Helical Pipe [7]

Regime	Correlations
Single phase turbulent flow	Mori-Nakayama correlation
Laminar and Natural convection	Same correlation of default
Nucleate boiling heat transfer	Chen correlation (Owhadi)
Transition boiling	$x_s > 0.8$
Film boiling	Same correlation of default

In this study, MARS-KS v2.0 was used for numerical simulation of two-phase instability in helical tube. A nodalization of MARS-KS is shown in Fig. 3. The inlet subcooling was controlled using a time dependent volume (TMDPVOL). Since single junction (SNGLJUN) was used, the outlet TMDPVOL pressure was adjusted to control inlet flow rate with a constant inlet TMDPVOL pressure. While there is no helical geometry in MARS-KS, PIPE was used with vertical angle (helix angle) and the helical tube heat transfer option was used. The heating power was uniformly applied to each node of the PIPE and gradually increased until the onset of instability was observed. The operating parameters used in the numerical simulation are summarized in Table III.

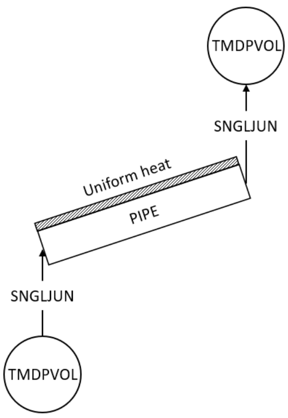

Fig. 3. MARS-KS nodalization of helical tube

Table III: Operating parameters

Mass flow rate (kg/s)	$\dot{m}$	0.03 ~ 0.05
Inlet subcooling (quality)	x_{in}	-0.20 ~ -0.02
Pressure (MPa)	P	5.00

3. Two-Phase Instability in Helical Tube

3.1 Density wave oscillation observation

The DWO refers to a phenomenon in which the system parameter oscillates periodically over time. The heating power was increased gradually, as shown in Fig. 4, and when threshold was reached, flow began to oscillate. As the heating power gradually increases, the amplitude of the oscillations progressively grows, as demonstrated by the flow rate and pressure drop oscillations depicted in Figs. 5 and 6. In addition, the sensitivity to time step is shown in Fig. 7. It was confirmed that the time step did not affect the MARS-KS results.

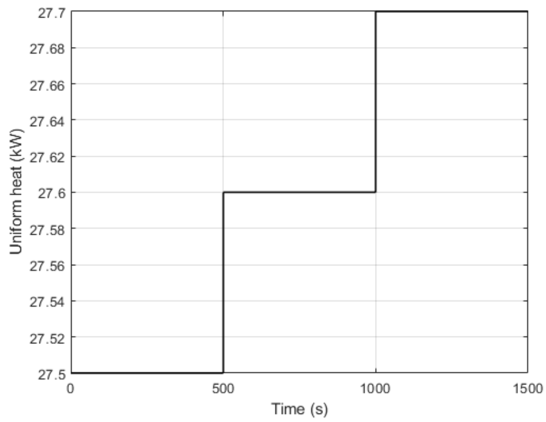

Fig. 4. Uniform heat change

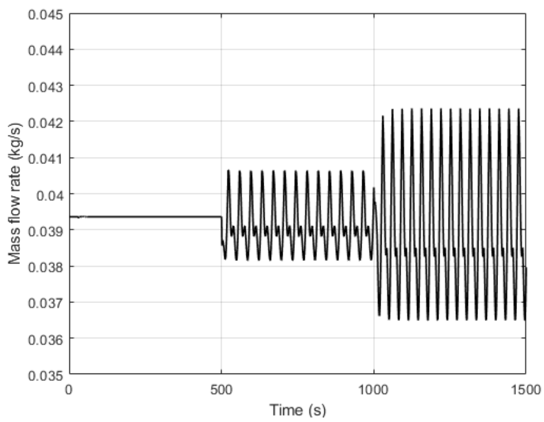

Fig. 5. Flow rate oscillation
($\dot{m} = 0.04kg/s, x_{in} = -0.1$, 1st layer)

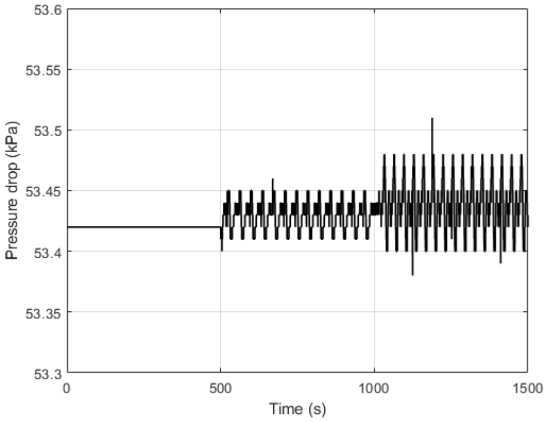

Fig. 6. Pressure drop oscillation
($\dot{m} = 0.04kg/s$, $x_{in} = -0.1$, 1st layer)

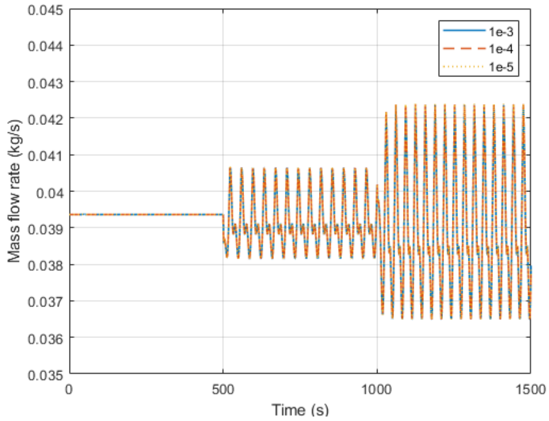

Fig. 7. Flow rate oscillation with respect to different time step

3.2 Stability maps

The phase change number (N_{pch}) and subcooling number (N_{sub}) are dimensionless parameters used to describe the behavior of boiling [8]. These number were introduced by Ishii and Zuber to develop a stability map that can represent data obtained under various operating conditions. These number are defined as follows and all the thermodynamic properties are defined at the inlet pressure.

$$N_{pch} = \frac{Q}{\dot{m}h_{fg}}\frac{\rho_{fg}}{\rho_g} \quad (1)$$

$$N_{sub} = \frac{h_f - h_{in}}{h_{fg}}\frac{\rho_{fg}}{\rho_g} \quad (2)$$

$$N_{sub} = N_{pch} - x_{ex}\frac{\rho_{fg}}{\rho_g} \quad (3)$$

Q: Heat input, $\dot{m}$: mass flow rate, h_{in}: inlet enthalpy, h_f: saturation liquid enthalpy, h_{fg}: latent heat of evaporation, ρ_g : saturation gas density, ρ_{fg} : density difference between saturation liquid and gas densities

Fig. 8 displays the stability map for the 1st layer helical tube and Fig. 9 compares the stability maps of each helical tube. The stability boundary shape is L shape, which is typically observed in straight tubes. This L shape implies that the stability of the system is enforced by increasing subcooling in the high inlet subcooling region, and by decreasing subcooling in the low inlet subcooling region.

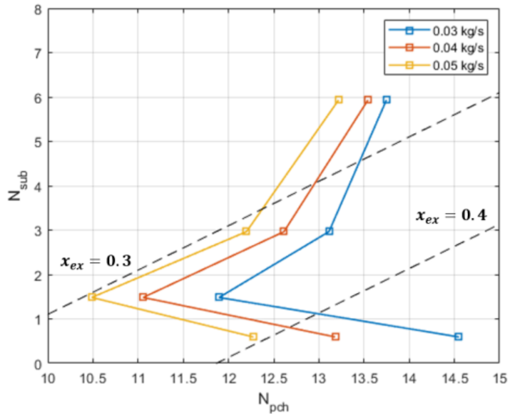

Fig. 8. Stability map at different flow rate and inlet subcooling (1st layer)

Destabilization of a stable system is generally caused by increasing heat flux or decreasing flow rate. It is widely accepted that increasing $Q/\dot{m}$ tends to destabilize a system. In the case of the same geometry, inlet pressure, and subcooling, a decrease in inlet flow rate leads to an increase in $Q/\dot{m}$. However, the difference in tube structure has little effect on $Q/\dot{m}$.

This may be due to the fact that the MARS-KS used in this study does not accurately reflect the centrifugal force and secondary flow in the helical tube flow. Therefore, it is important to consider the effects of centrifugal force and secondary flow when analyzing the stability of helical tube systems.

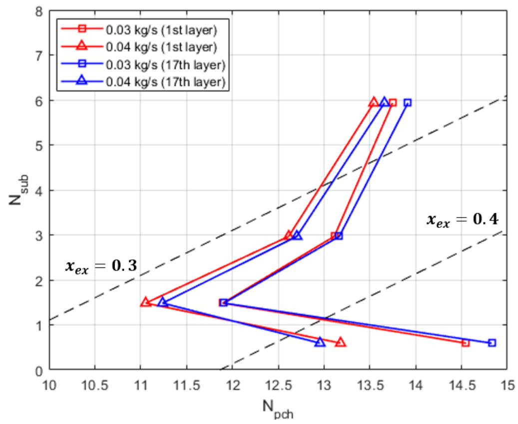

Fig. 9. Stability map at different flow rate in inlet subcooling (1st layer and 17th layer)

3. Conclusions

The numerical analysis of two-phase instability using MARS-KS has been presented in this study, featured as topic of interest in the steam generator design for advanced reactors. The onset of DWO was observed while gradually increasing the heating power under various inlet conditions. The stability boundary shape known to occur in a straight pipe as an L shape has also been found in a helical tube. Furthermore, the structural differences in the helical tube have little effect on the stability boundary condition. MARS-KS simulates the helical tube as a straight pipe that only uses heat transfer options, without using a helical tube pressure drop correlation. Therefore, the flow inside the tube is not different from that in a straight pipe, and it is necessary to analyze whether this has any effect. In addition, in power cycles with once-through steam generator, a method of reducing steam pressure is used during load-following operation. Therefore, the study on two-phase instability according to pressure should be performed.

ACKNOWLEDGEMENT

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