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The Effect of Heat Flux Profile on Two-phase Flow Instability in Helical Tube Steam Generator

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1. Introduction

Helical tube steam generators have been widely used in various industries due to their compact and efficient heat exchange capabilities. Recently, these steam generators are adopted in advanced reactor designs. In a boiling system, the consideration of two-phase flow instability is crucial to guarantee service lifetime and reliability of the component.

Density Wave Oscillation (DWO) is a major two-phase flow instability. DWO can be caused by the interaction between single- and two-phase pressure drops, inlet mass flow rate, and void fraction distribution. This phenomenon can cause overheating and fatigue failure of the tube, causing serious problems to tube integrity. In parallel tubes such as steam generators, it is very difficult to detect local instabilities somewhere in the parallel tubes when the total mass flow rate is constant.

In the previous studies that experimented and analyzed DWO in helical tubes, mostly heat was uniformly applied [1,2]. However, it is known that the conditions for onset of DWO differ depending on the shape of the heat flux profile [3]. In a steam generator, when heat is transferred from primary side to secondary side, heat is not transferred uniformly. Therefore, the aim of this study is to analyze the differences in the onset of DWO with respect to the heat flux profile.

2. Numerical Simulation

In this section, the helical tube modeling with MARS-KS is explained. The helical tube geometric information and simulation range are also summarized.

2.1 Helical tube modeling in MARS-KS

In this study, the analysis of DWO was performed using MARS-KS v2.0. Fig. 1 shows the nodalization for parallel tubes analysis. Since the inlet temperature is controlled by a time dependent volume (TMDPVOL 100), the constant inlet subcooled fluid flowing through the tube is heated. A time dependent junction (TMDPJUN 101) is used to define inlet mass flow rate. Two inclined pipes (PIPE 10 and 20) have the same length and the same angle of inclination. MARS-KS cannot directly simulate a helical tube shape. The two pipes are connected with an inlet header and an outlet header (BRANCH 102 and 103). The outlet pressure is set by TMDPVOL 105. In this study, two types of heating are simulated. The first type is uniform heating (Fig. 1) and the second type is non-uniform heating using heat transfer between fluids (Fig. 2).

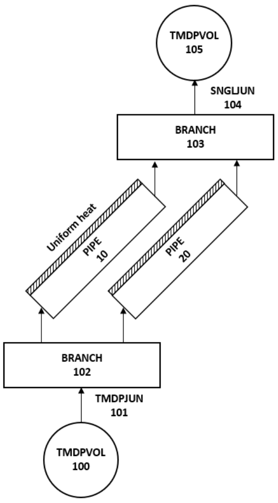

Fig. 1. MARS-KS nodalization of parallel helical tubes (uniform heating)

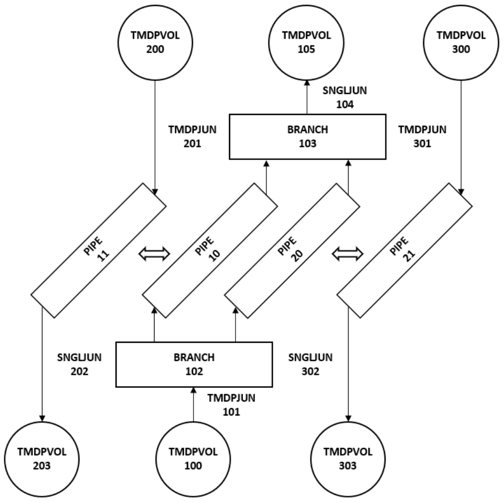

Fig. 2 MARS-KS nodalization of parallel helical tubes (non-uniform heating)

2.2 MARS-KS simulation conditions

MARS-KS was developed for the detailed safety analysis of Pressurized Water Reactors (PWRs). MARS-KS also includes helical tube heat transfer correlations, making it suitable for the advanced reactor safety analysis as well [4]. The heat transfer correlations for helical tubes in MARS-KS are as follows (TABLE I). However, there is no correlations available for pressure drop for helical tube.

TABLE I. Heat transfer correlations of helical tube [3]

Regime	Correlation
Primary side (Shell side)	
Single phase flow	Zukauskas
Secondary side (tube side)	
Single phase turbulent flow	Mori and Nakayama
Laminar and Nature convection	Same correlation of default
Nucleate boiling heat transfer	Chen correlation (Owhadi)
Transition boiling	$x_s > 0.8$
Film boiling	Same correlation of default

Fig. 3 shows the cross section of heat transfer between fluids for non-uniform heating. The helical coil geometry information (TABLE II) was based on the first layer in the helical steam generator of SMART reactor developed by KAERI [5,6]. The simulation ranges are summarized in TABLE III.

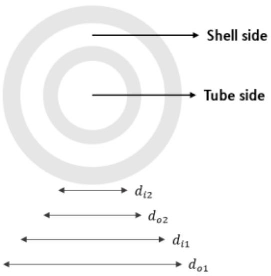

Fig. 3. Cross section of second type heat supply

TALBE I. Helical tube geometry information

	Variable	Value
Open data [5,6]	Inner diameter (d_{i2}) (mm)	12
	Outer diameter (d_{o2}) (mm)	17
	Helical diameter (mm)	577
	Helical angle (˚)	8.78
	Inner diameter (d_{i1}) (mm)	25
	Outer diameter (d_{o1}) (mm)	32
	Height (mm)	4200
	Length (mm)	27513

TALBE II. Simulation ranges per helical tube

Variable	Range
Primary side	
Mass flow rate (kg/s)	0.7
Outlet pressure (MPa)	15
Secondary side	
Mass flow rate (kg/s)	0.05
Inlet subcooled temperature (˚C)	155~245
Outlet pressure (MPa)	3~5

3. Density Wave Oscillation in Helical Tube

3.1 Density wave oscillation observation

The system was considered completely unstable when the amplitude of flow rate oscillation exceeds 100% of its steady-state value [1,2]. For the observation of DWO, the heating power was increased gradually in the uniform heating case and the shell side inlet temperature was increased in non-uniform heating case. Fig. 4 shows the case where shell side inlet temperature was increased under the conditions of a tube side outlet pressure set to 3MPa, an inlet subcooled temperature of 190˚C. As the shell side inlet temperature increases, the increased flow oscillations are shown in Fig. 5. The flow oscillation of each tube is in out-of-phase.

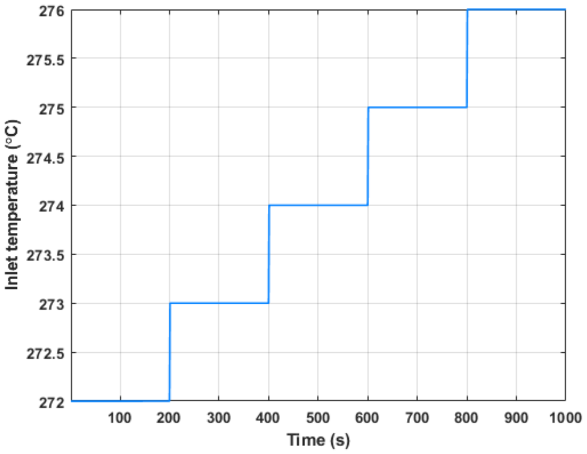

Fig. 4. Shell side inlet temperature change

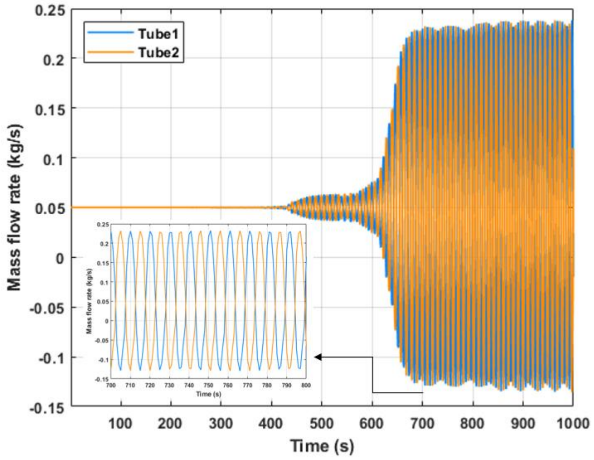

Fig. 5. Flow rate oscillation

3.2 Stability map

When the fluid characteristics, tube shape, and system operating pressure are determined, the flow rate, heating power, and inlet subcooling play an important role, so that the stable region and the unstable region can be defined in a three-dimensional space. A stability map is used to represent them in two-dimensional space using dimensionless numbers. The stability map (phase change number - subcooling number) proposed by Ishii and Zuber [7] is most frequently used stability map. The numbers are defined as follows. Based on the boundary, the left side is the stable region and the right side is the unstable region.

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

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

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

where, 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. 6 shows the stability map with respect to tube side outlet pressure and heating type. DWO occurs at lower heating power for the uniform heating case than for the non-uniform heating case. This difference is greater as the tube side pressure becomes lower. In other words, the heat transfer between fluids (i.e. non-uniform heating) provides better stability than the uniform heating.

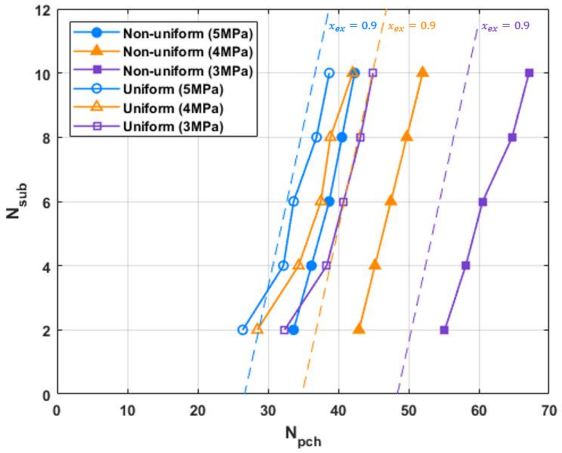

Fig. 6. Stability map with respect to tube side outlet pressure and heating type.

Fig. 7 shows the heat flux distribution at 400 seconds in Fig. 5. Blue dotted line means the heat flux when converting non-uniform heating to uniform heating while maintaining the same amount of heat. However, in actual uniform heating, flow oscillation occurs in the orange line, which is at lower heat flux level. Fig. 8 shows the quality distribution with respect to heating type. If heat is provided in uniform profile (orange line), the two-phase flow occurs at similar downstream position with the non-uniform case and the length of single-phase liquid region will be also similar. This is reason why the system becomes more unstable even at lower heating rate with uniform profile. Therefore, it is observed that instead of the heating level, the integrated heat to the occurrence of two-phase flow is more important for the two-phase flow instability.

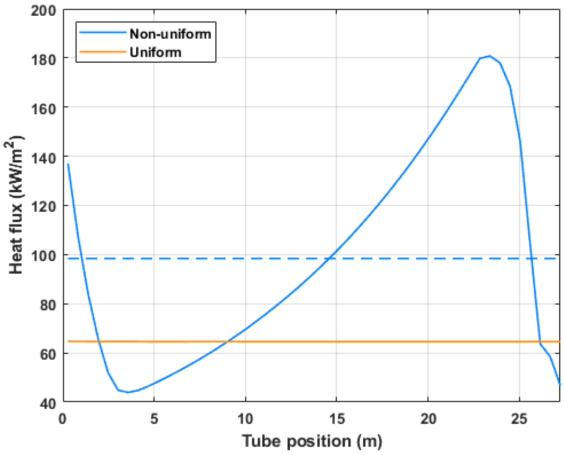

Fig. 7 Heat flux distribution according to heating type

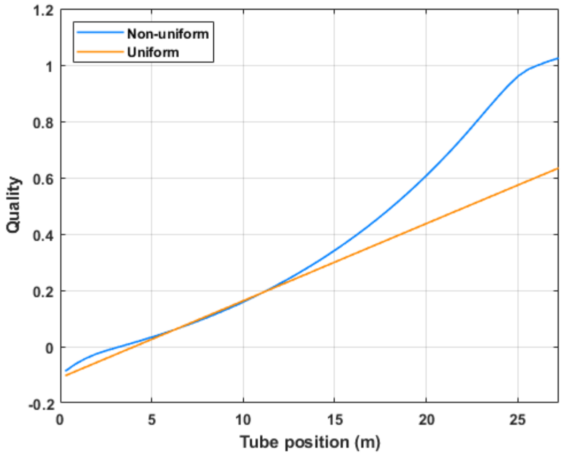

Fig. 8. Quality distribution with respect to heating type

3. Summary and Future Works

In the previous studies, the two-phase flow instability was analyzed for uniform heating, but in this study, the two-phase flow instability was analyzed for both uniform heating case and non-uniform heating case by using MARS-KS. As a result, the system became unstable at lower average heating powers for uniform heating case. It seems as if the constant vapor generation (linear increase in quality) destabilizes the system faster than the non-uniform generation of vapor. By observing the stability map, it can be claimed that the system is more stable because DWO occurs at higher exit quality for the non-uniform heating case. However, the previous studies stated that the system code results are less conservative than the experimental results, so the accuracy of the two-phase flow instability analysis and prediction using MARS-KS should be validated with future experiments.

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REFERENCES

[1] Papini, D., Colombo, M., Cammi, A., et al., Experimental and theoretical studies on density wave instabilities in helically coiled tubes, Int. J. Heat Mass Transf, Vol.68, pp.343-356, 2014.
[2] Minglu Wang, et al., Expeirmental and numerical studies on two-phase flow instability behavior of a parallel helically coiled system, Annals of Nuclear Energy, Vol.144, 107588, 2020.
[3] Xiaodong Lu et al., Theoretical investigations on two-phase flow instability in parallel channels under axial non-uniform heating, Annals of Nuclear Energy, Vol.63, pp75-82, 2014.
[4] KAERI, Development of Auditing Technology for Accident Analysis of SMART-P, KAERI/CR-179/2004.
[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] M. Ishii, N. Zuber, "Thermally induced flow instabilities in two-phase mixtures", Proceedings of Fourth International Heat Transfer Conference, Vol.5, 1970.