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Comparison of MARS-KS and MARS-KS-Colombo Code in Predicting Density Wave Oscillation (DWO) Onset Under HTR-PM Helical Tubes in Steam Generators

Yeongjae Cho, Hyo Chan Kim, Jun Ha Hwang, Jeong Ik Lee
Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong Yuseong-gu, Daejeon 305-701, Republic of Korea
** Corresponding author: jeongiklee@kaist.ac.kr*

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1. Introduction

The HTR-PM utilizes helical coil steam generators due to their superior heat transfer coefficients and compact design[1]. Specifically, the centrifugal forces within the coils create secondary flows that alter the void fraction distribution and pressure drop compared to traditional straight-tube designs. Transient distribution of pressure drop along the pipe may induce self-sustained oscillation by the difference in the enthalpy perturbation which is caused by the inlet mass flow rate and the void fraction distribution[2]. The boundary condition of parallel pipes is sufficient to impose the pressure drop across the channels, which triggers the multiple feedback effects that cause the inception of instability. Among one of instability phenomena, the density wave oscillation (DWO) is an instability phenomenon that occurs in a boiling system by the interaction between the single-phase and two-phase flow pressure drops, the inlet mass flow rate and the void fraction distribution [2][3].

MARS-KS is a comprehensive nuclear reactor safety analysis code developed by KINS. MARS-KS-Colombo code is developed by integrating pressure drop correlations from Colombo [7] for helical coil geometries. This study aims to evaluate and compare the predictive performance of the MARS-KS code and the MARS-KS-Colombo code in simulating Density Wave Oscillations (DWO) and stability maps of DWO in the helical coils of steam generator in HTR-PM.

2. Methodology

This study utilizes MARS-KS to simulate two-parallel helical coils in steam generators under HTR-PM conditions, specifically focusing on the detection of the onset of Density Wave Oscillations (DWO) [4].

2.1 Helical steam generator modelling

This model is based on the two-parallel helical coil pipes in steam generator of HTR-PM reactor. Boundary condition included an inlet pressure of 13.24MPa, while modelling the outlet pressure of 13.24MPa through the engineering assumption of inlet pressure of 13.24MPa [1] and inlet mass fluxes of 0.142857kg/s per pipe, that calculated through the assumed total mass flow rate [10] divided by total helical pipes' number. Figure.1 shows the geometries in MARS-KS modelling, which helical coil separates equal length 64 nodes. Table.1 presents the configurations in this study for modelling the two parallel helical coils in steam generators of HTR-PM. The configurations of the helical coils are referred from the previous studies [4][10] and reference [1].

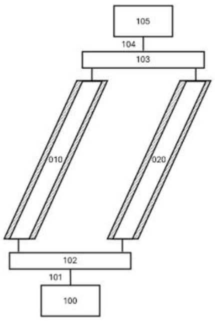

Figure 1: Parallel helical coils in S/G nodalization in MARS-KS and MARS-KS-Colombo codes

Table 1. parallel helical pipe input variable descriptions

HTR-PM Helical pipe parameters		**value**
Operation Condition value	T_{in}[°C]	205
	$\dot{m}$ [kg/s]	95
	T_{out}[°C]	523
	P_{in}[MPa]	15.2
Input variables	T_{in}[°C]	160 ~ 295
Helical Pipe Geometry	$\dot{m}$ [kg/s]	0.142857
	T_{out}[°C]	523
	P_{out}[MPa]	13.24
	Length[m]	24.2
	Vertical Height[m]	8.6
	# coils	36
	$d_{inner\ coil}$ [mm]	17
	$d_{outer\ coil}$[mm]	19
	Vertical incline angle	20.816
	Number of nodes	64

The threshold points of DWOs are identified in 1D thermal-hydraulic codes by observing time-dependent oscillations in power. These simulations employ a uniform heat flux along the pipe, which is gradually increased to determine the critical conditions.

2.2 Stability maps

The critical heat flux of DWO onset point is then converted into a phase-change number and subcooling number based on the inlet temperature, and inlet pressure which is calculated by MARS-KS code. Collected threshold data have been obtained in dimensionless stability maps on the stability plane by using *phase-change number* N_{pch} and *subcooling number* N_{sub}, introduced by Ishii and Zuber [3].

$$\boldsymbol{N_{pch}} = \frac{\Omega}{w_{in}/L} = \frac{v_{fg} \cdot q'''/h_{fg}}{w_{in}/L} = \frac{q}{\Gamma \cdot h_{fg}} \cdot \frac{v_{fg}}{v_f} \qquad (1)$$

$$\boldsymbol{N_{sub}} = \frac{\triangle h_{in}}{h_{fg}} \cdot \frac{v_{fg}}{v_f} \qquad \boldsymbol{N_{sub}} = \boldsymbol{N_{pch}} - \boldsymbol{x_{ex}} \frac{v_{fg}}{v_f} \qquad (2)$$

While the phase change number defines the ratio between the phase change frequency Ω and the inverse transit time, the subcooling number is used to quantify the thermal state of the inlet subcooling. Those numbers are calculated by equation (1) and (2).

2.3 MARS-KS code and MARS-KS-Colombo code

MARS-KS is a comprehensive nuclear reactor safety analysis code developed by KINS. In previous studies, as a modified version of the MARS-KS code by using Colombo correlations, MARS-KS-Colombo, is developed by integrating pressure drop correlations for helical coil geometries. To model single-phase flow, the code implements the correlations from Ito[6]. For two-phase flow conditions, it utilizes the equations from Colombo[7], which was derived based on experimental data from Santini [8] and Zhao [9]. Specifically, Santini [8] focused on vertical helical coils, while Zhao [9] investigated horizontal helical coils.

Table2. Heat Transfer and Pressure Drop Correlations used for Modeling HTR-PM in MARS-KS code

MARS-KS code model
Single-phase flow $\frac{1}{\sqrt{f}} = -2\log_{10}\frac{\epsilon}{3.7d} + \frac{2.51}{Re}[1.14 - 2\log_{10}(\frac{\epsilon}{d} - \frac{21.25}{Re})]$
Two-phase flow $(\frac{dP}{dx})_{2\Phi} = \frac{1}{2d} f_f \rho_f (\alpha_f v_f)^2 + C[f_f \rho_f (\alpha_f v_f)^2 f_g \rho_g (\alpha_g v_g)^2]^{\frac{1}{2}} + f_g \rho_g (\alpha_g v_g)^2$ $2 \leq C = -2 + f_1(G) T_1(\Lambda, G)$ $f_1(G) = 28 - 0.3\sqrt{G} \quad T_1(\Lambda, G) = \exp[\frac{(\log_{10}\Lambda + 2.5)^2}{2.4 - G(10^{-4})}] \quad \Lambda = \frac{\rho_g}{\rho_f}(\frac{\mu_f}{\mu_g})^{0.2}$
MARS-KS Colombo code model
Single-phase flow (Ito correlation) $f(\frac{D}{d})^{0.5} = 0.029 + 0.304\left[Re\left(\frac{d}{D}\right)^2\right]^{-0.25}$
Two-phase flow (Colombo correlation) $\Phi_l^2 = 0.0986(1 + \frac{20}{X_{tt}} + \frac{1}{X_{tt}^2}) De_l^{0.19} (\frac{\rho_m}{\rho_l})^{-0.4}$ $De_l = \frac{G(1-x)d}{\mu_l}\sqrt{\frac{d}{D}} \quad \rho_m = (\frac{x}{\rho_g} + \frac{1-x}{\rho_f})^{-1} \quad \Delta P_l = \frac{f_l G^2 (1-x)^2 L}{2\rho_l d} \quad \Delta P_{tp} = \Delta P_l \Phi_l^2$

3. Results and Discussions

The threshold for DWO was determined by using both MARS-KS and the modified MARS-KS-COLOMBO codes. In these simulations, the heat power was incrementally increased by 1 kW every 2,000 seconds to accurately identify the onset point of the DWO. Table.3 and Table. 4 are the results of DWO onset point using MARS-KS code and MARS-KS-Colombo codes.

Table3. Key parameter values prior to the onset of DWO using MARS-KS code

Input parameter variable		Output parameters				
# Order	T_{in}[°C]	P_{in}[MPa]	T_{out}[°C]	Critical Power[KW]	N_{pch}	N_{sub}
1	160.0	13.39	879	479	20.43	12.00
2	182.5	13.39	888	468	19.96	11.41
3	205.0	13.40	888	456	19.44	10.80
4	250.0	13.42	1026	476	20.25	9.52
5	272.5	13.38	754	367	15.67	8.89
6	295.0	13.36	594	296	12.62	8.20

Table4. Key parameter values prior to the onset of DWO using MARS-KS-Colombo code

Input parameter variable		Output parameters				
# Order	T_{in}[°C]	P_{in}[MPa]	T_{out}[°C]	Critical Power[KW]	N_{pch}	N_{sub}
1	160.0	13.39	583	370	15.79	12.01
2	182.5	13.39	561	354	15.10	11.42
3	205.0	13.39	547	336	14.34	10.81
4	250.0	13.40	522	300	12.79	9.55
5	272.5	13.40	504	279	11.90	8.88
6	295.0	13.40	476	253	10.78	8.16

In the simulations using MARS-KS-Colombo, the DWO threshold power for low inlet temperatures ranging from 160°C to 250°C are presented to be more than 100 kW lower than the results obtained from the standard MARS-KS code. Furthermore, even at higher inlet temperatures, the MARS-KS-Colombo consistently yielded a lower critical heat flux compared to the original MARS-KS. Consequently, the predicted fluid outlet temperatures in the COLOMBO simulations were lower than those observed in the standard MARS-KS results.

3.1 Stability maps

The stability characteristics of the density wave oscillations are represented on a stability map through the relationship between the subcooling number and the phase change number. This graphical representation provides a clear visualization of the marginal stability boundaries and highlights the discrepancies between the standard MARS-KS and the MARS-KS-Colombo version codes.

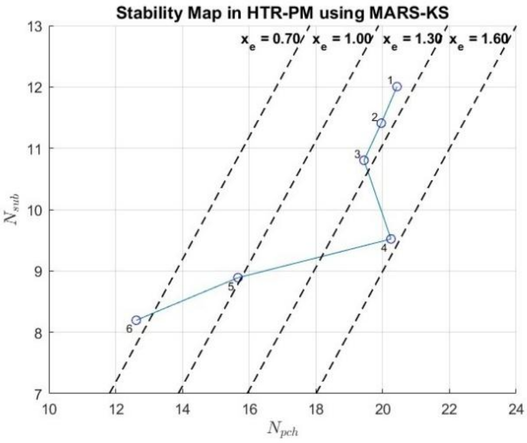

Figure 2. Stability maps of helical coils of HTR-PM in MARS-KS codes

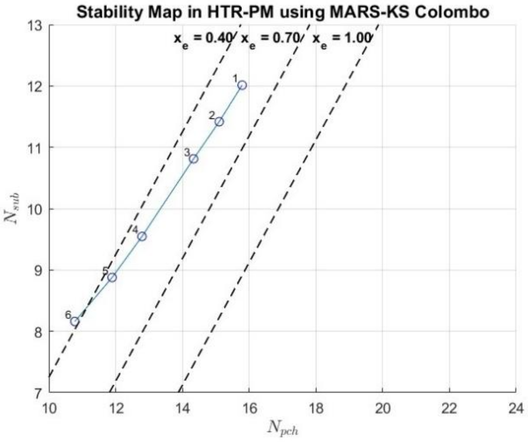

Figure 3. Stability maps of helical coils of HTR-PM in MARS-KS-Colombo codes

The DWO stability boundaries for the standard code show exit qualities rising from below 1.3 (ranging from 160 to 205°C) to nearly 1.6 at 250°C, before dropping to around 1.00 and around 0.70 at higher temperatures 272.5°C and 295°C. However, as shown in Figure 3, the MARS-KS-Colombo results exhibit significantly lower quality values than MARS-KS results (Figure. 2), ranging from nearly 0.4 to below 0.7. Notably, the quality continues to decline with increasing temperature, reaching values below 0.4 at 295°C.

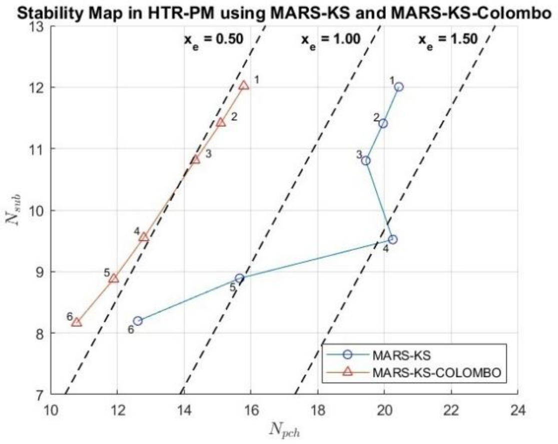

Figure 4. Stability maps of helical coils of HTR-PM in using MARS-KS code and MARS-KS-Colombo codes

The prediction of DWO in the HTR-PM helical tube steam generator using the MARS-KS-Colombo code yields more conservative results compared to those obtained from the MARS-KS code. Specifically, the COLOMBO code predicts a lower critical heat flux for the onset of DWO, resulting in a lower exit quality at the instability threshold. In contrast, MARS-KS predicts a relatively higher exit quality at the DWO onset point, suggesting that the flow at the outlet is more significantly superheated than the COLOMBO code calculation results.

4. Conclusions and Further Works

This study conducted a comparative analysis of the onset of density wave oscillations (DWO) in HTR-PM helical tube steam generators using the one-dimensional system code MARS-KS and modified MARS-KS-Colombo that applied Colombo correlations. The results demonstrated that the MARS-KS-Colombo code provides a more conservative prediction of DWO onset compared to MARS-KS. Specifically, MARS-KS-Colombo identified the onset of DWO at a lower critical heat flux, which resulted in a lower exit quality at threshold point. In contrast, MARS-KS predicted a higher exit quality for the DWO onset, indicating that the flow at the outlet reaches the greater degree of the superheating before the flow enters an unstable oscillation.

These differences are primarily attributed to the distinct numerical approaches and two-phase flow correlations implemented in each code. MARS-KS-Colombo estimation suggests a more stringent safety margin for steam generator operation.

The findings highlight that modeling choices in heat transfer and pressure drop correlations significantly influence the assessment of flow instability in helical geometries. As ensuring the thermohydraulic stability of the HTR-PM steam generator is vital for advanced reactor safety. Future research will conduct the collection of experimental data regarding DWO onset in helical coils under HTR-PM operating conditions. Such empirical evidence is essential to evaluate the predictive accuracy of current numerical models and to enhance the validation between experimental observations and simulated results.

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