

Introduction

Helical coil heat exchangers are increasingly used for advanced reactors such as SMRs and HTGRs due to their superior thermal efficiency, compactness, and mechanical durability.

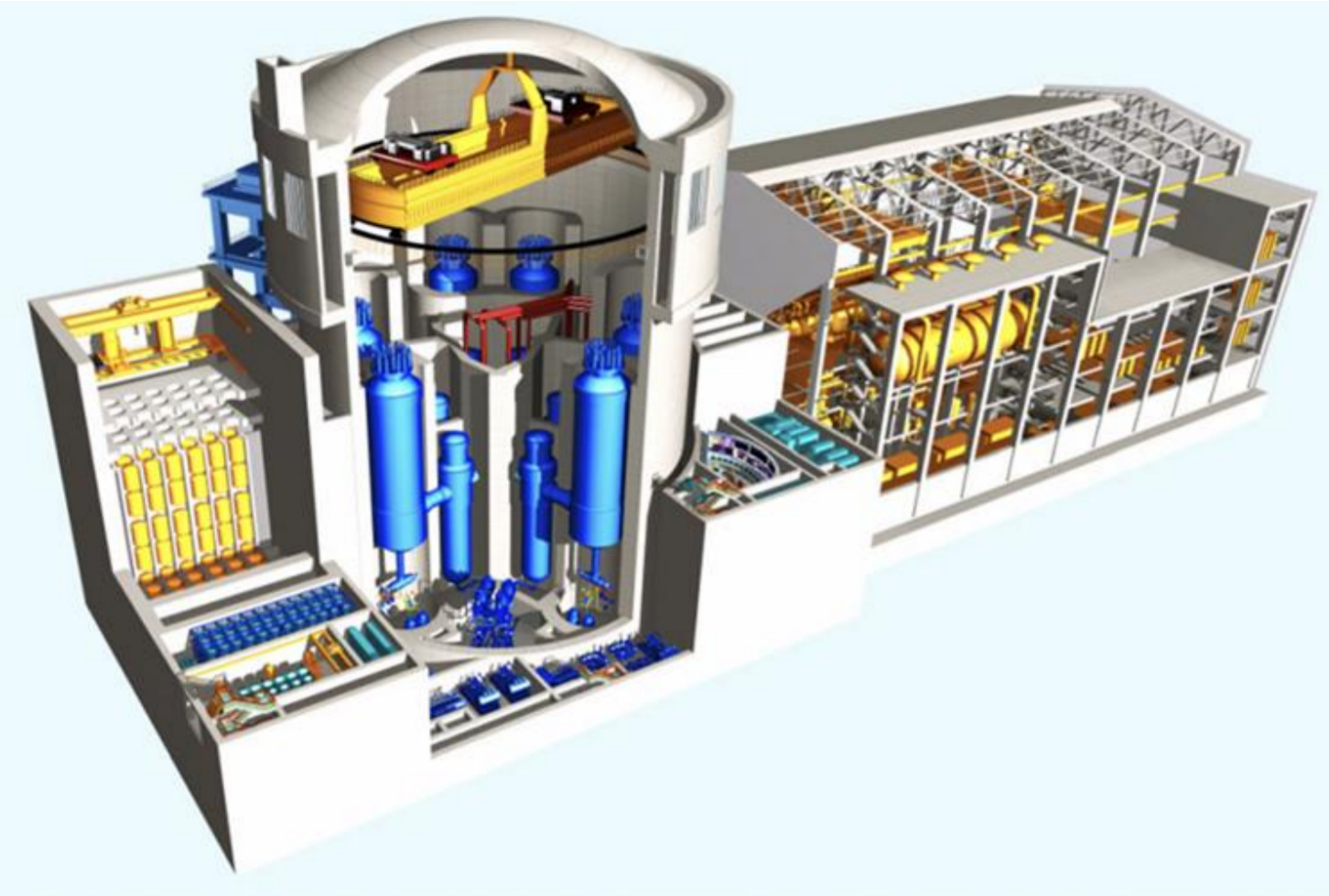


Fig. 1. Design of the HTR-PM600 nuclear power plant

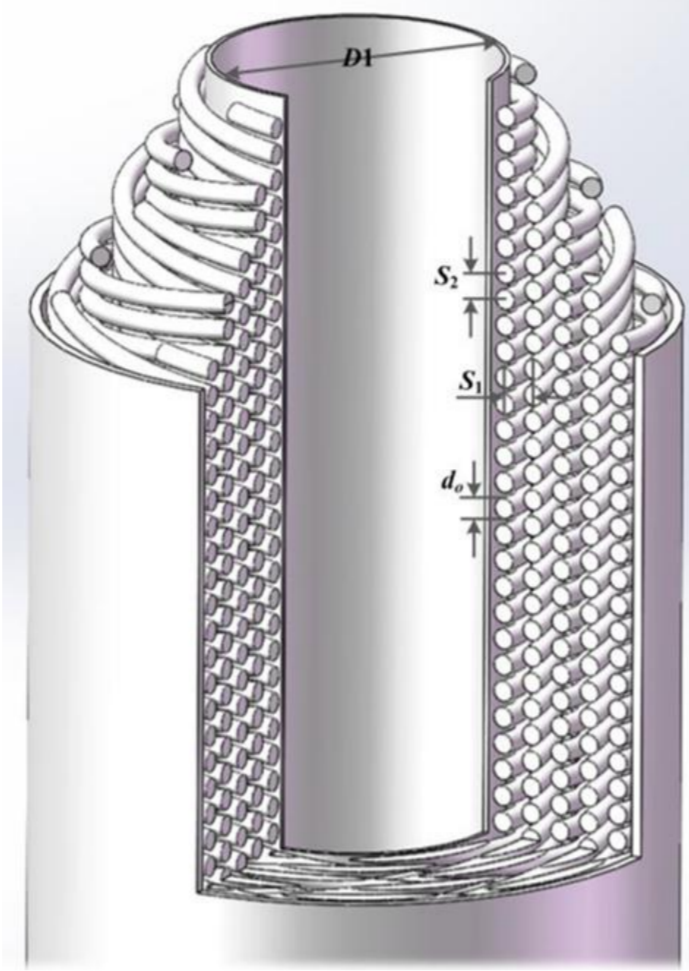


Fig. 2. Physical model of helical coils in HTR-PM steam generators

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.

This work focused on comparison of MARS-KS and MARS-KS-Colombo Code in Predicting Density Wave Oscillation (DWO) Onset Under HTR-PM Helical Tubes in Steam Generators.

Density Wave Oscillation

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.

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.

Collected threshold data have been obtained in dimensionless stability maps on the stability plane $N_{pch}-N_{sub}$, introduced by Ishii and Zuber:

$$N_{pch} = \frac{\dot{m}}{w_{in}/L} = \frac{v_{fg} \cdot q''' / h_{fg}}{w_{in}/L} = \frac{q}{\Gamma \cdot h_{fg}} \cdot \frac{v_{fg}}{v_f} \quad (1)$$

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

Dimensionless N_{pch} , N_{sub} equations

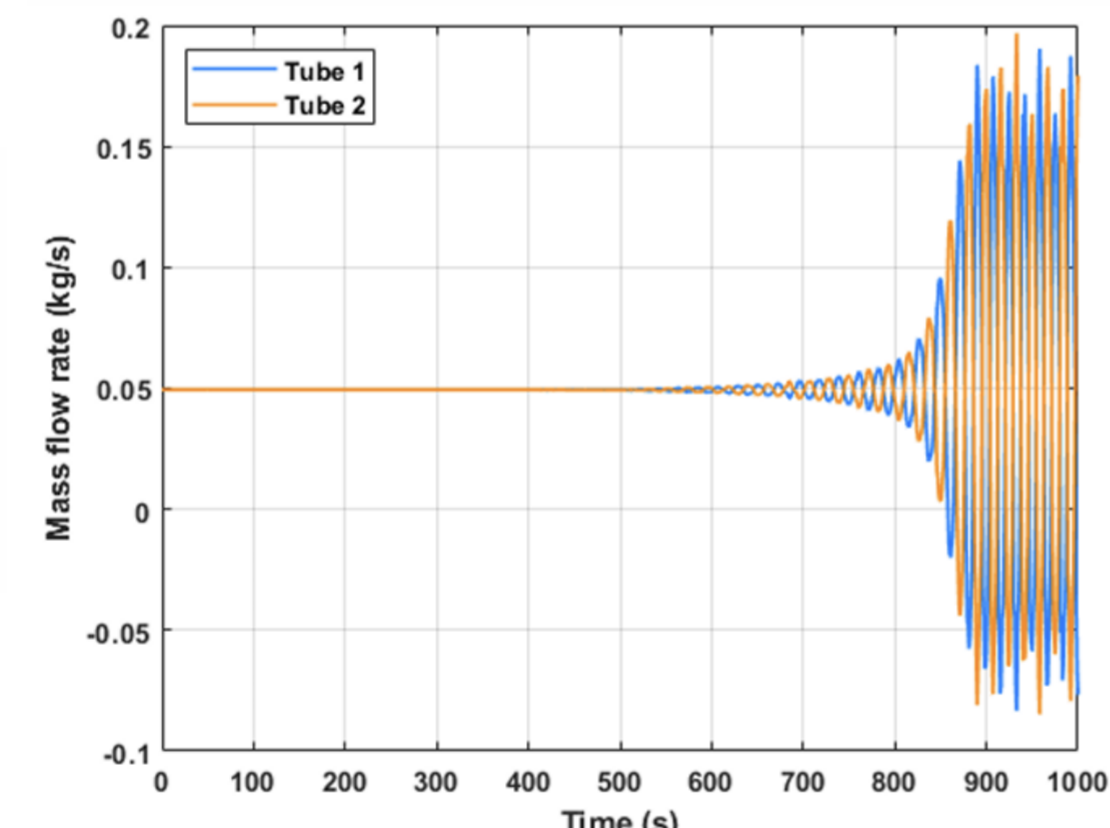


Fig. 3. Mass Flow Rate Change versus power depends on time [5]

Helical Coil Modeling

This study model is based on the two-parallel helical coil pipes in steam generator of HTR-PM reactor in MARS-KS and MARS-KS-Colombo code.

Table 1. HTR-PM S/G Input variable description

HTR-PM Helical pipe parameters		value
Operation Condition value	T_{in} [°C]	205
	\dot{m} [kg/s]	95
Input variables	T_{out} [°C]	523
	P_{in} [MPa]	15.2
Helical Pipe Geometry	T_{in} [°C]	160 ~ 295
	\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	

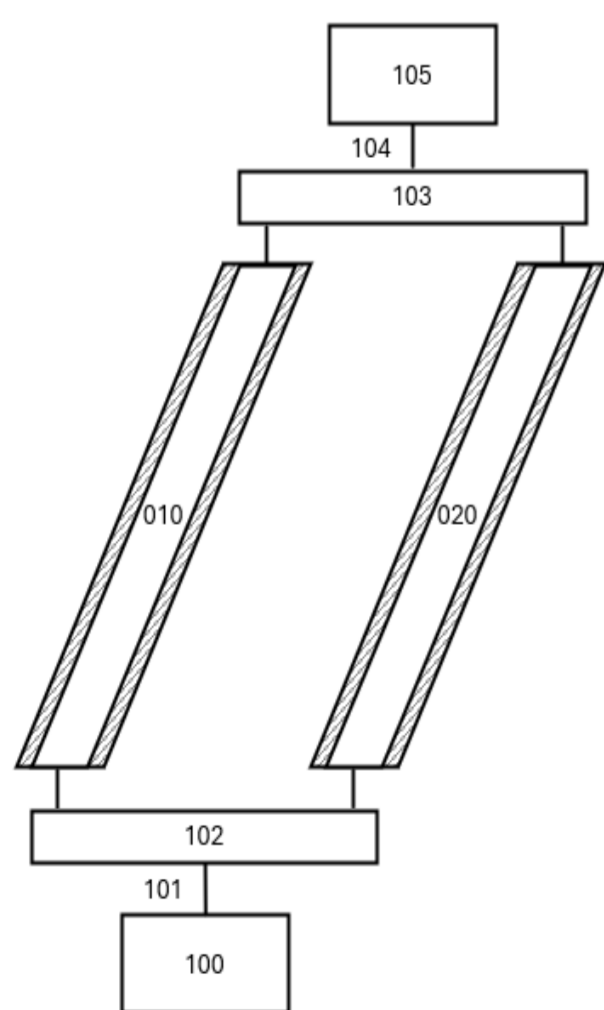


Fig. 4. Parallel helical coils in S/G nodalization

The onset of DWOs is identified in 1D thermal-hydraulic codes by observing time-dependent oscillations in power. These simulations employ a uniform heat flux along the pipes, which is gradually increased to determine the critical conditions. (1kw increases for every 2000 second time steps)

This critical power is then converted into a phase-change number and subcooling number based on the inlet temperature, and inlet pressure.

A stability map is constructed by non-dimensional critical subcooling number and phase change number to visualize the onset boundary of DWOs.

MARS-KS code and Colombo code

Table 2. The Pressure-drop Correlations in MARS-KS and MARS-KS-Colombo code

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

- Single-phase: Considering helical tube effects for calculating friction

- Two-phase: Considering helical tube effects for calculating friction factor to estimate the pressure drop

Results and Discussion

The onset of DWOs in HTR-PM Helical Tubes in Steam Generators

Table 3. N_{pch} , N_{sub} and key parameters prior to the onset of DWO according to T_{in} by 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

Table 4. N_{pch} , N_{sub} and key parameters prior to the onset of DWO according to T_{in} by MARS-KS-Colombo

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

Stability Maps in HTR-PM using MARS-KS and MARS-KS-Colombo

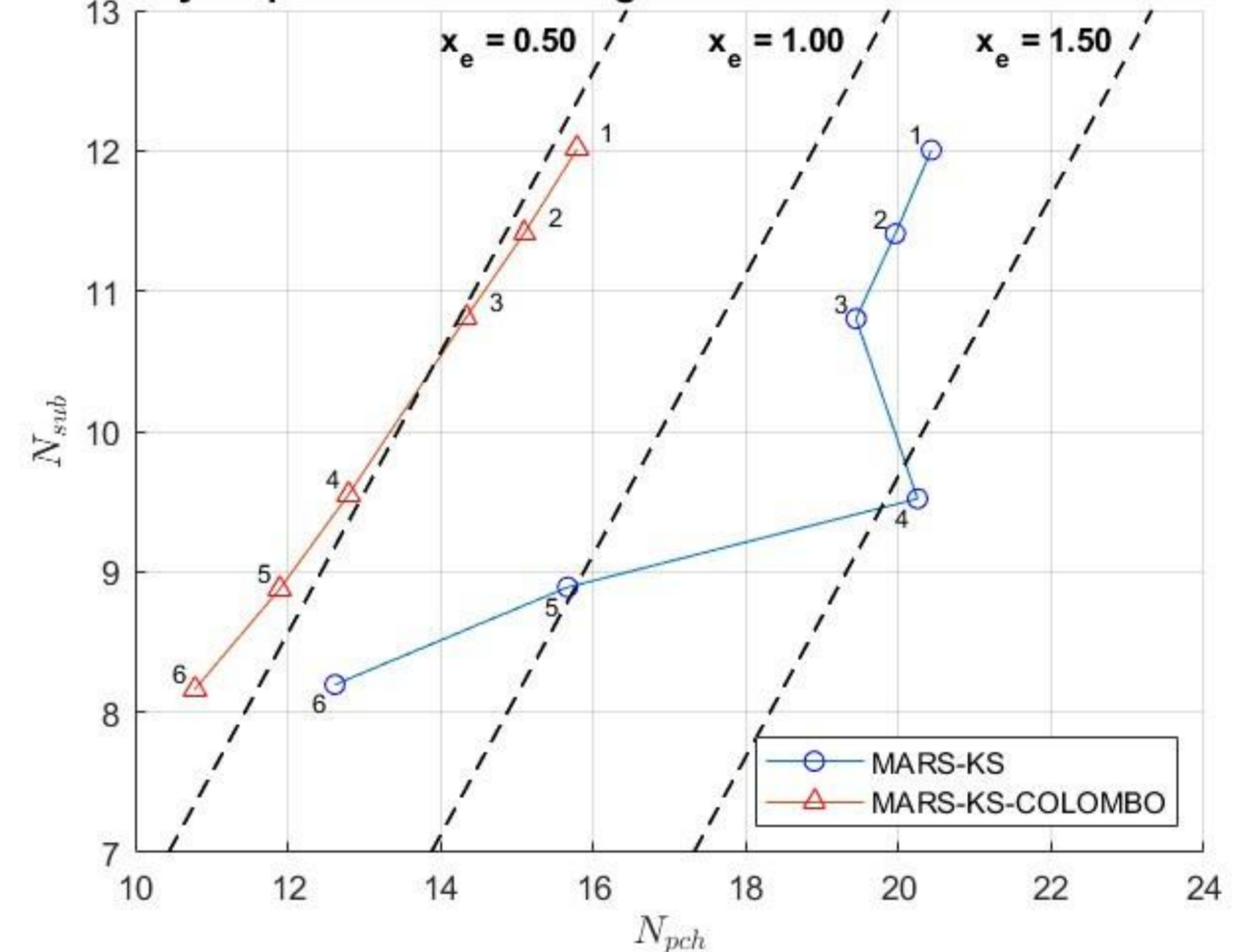


Fig. 5. Comparison of stability maps by using MARS-KS and MARS-KS-Colombo Code Under HTR-PM Helical Tubes in Steam Generators

Compared to the standard MARS-KS code, MARS-KS-Colombo predicted a DWO threshold power that was lower by more than 100 kW.

MARS-KS-Colombo code estimates a lower critical heat flux for the onset of DWO, resulting in a lower exit quality at the instability threshold.

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 MARS-KS-Colombo code calculation results.

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.

Conclusions

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.

MARS-KS-Colombo identified the onset of DWO at a lower critical heat flux, which resulted in a lower exit quality at threshold point.

MARS-KS-Colombo estimation suggests a more stringent safety margin for steam generator operation.

Future research will be required to conduct the experimental data regarding DWO onset in helical coils under HTR-PM operating conditions.