Numerical Study of MARS-KS in Predicting Density Wave Oscillation (DWO) Onset Under Different Heat Flux Profile Conditions

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1. Introduction

Next-generation nuclear plants are being designed with load-following capability, enhanced safety, and greater operational flexibility, expanding their role beyond traditional baseload electricity to industrial process heat, hydrogen production, and seawater desalination. Within this context, helical-tube steam generators (HSGs) are increasingly adopted owing to their high heat-transfer area density and compact form factor. However, because HSGs operate in an once-through configuration, multiple parallel tubes connected to common inlet and outlet headers, they are particularly susceptible to density-wave oscillations (DWO) under two-phase flow. Ensuring stable operation and structural integrity across the wider operating envelope envisioned for advanced reactors therefore requires a quantitative understanding of this instability.

Despite extensive examination of two-phase flow instabilities since the 1960s[1], studies that explicitly account for the geometry and system coupling of HSG remain scarce, and numerical investigations using one-dimensional (1D) system thermal-hydraulic codes exhibit a comparable gap [2]. Prior HSG–DWO experiments, exemplified by the works of Papini[3], Wang[4], Shen[5], and Oh[6], have largely been conducted under uniform heat-flux conditions with DC heating, whereas actual HTSGs commonly experience axially non-uniform heat-flux distributions.

In this study, the 1D system code MARS-KS, augmented with Colombo's pressure-drop model for helical coils, was used to predict the onset of DWO in HTSGs subjected to axially non-uniform heat-load and heat-transfer profiles[2]. As a pre-test scoping exercise, simulations were conducted with R-245fa under a simplified configuration to define a representative axial heat-transfer profile. Instead of constructing a full stability map, instability onset was compared across inlet temperatures (i.e., degrees of subcooling) at a fixed inlet mass flux, with the remaining boundary conditions held constant. The results extend understanding of DWO behavior in HSGs and provide guidance for the design and operation of next-generation steam generators.

2. Methodology

2.1 MARS-KS Modelling

Using the one-dimensional (1D) system thermal-hydraulic code MARS-KS, the parallel helical-tube test section for simulating density-wave oscillations (DWO) was modeled with the design and geometry derived from the helical tube test facility of Oh's study [6]. Table I summarizes the geometric specifications of the helical tube used in that experiment.

Table I: Oh's Helical Tube Geometry

Inner diameter [mm]	6
Outer diameter [mm]	8
Coil diameter [mm]	288.5
Tube length [m]	12.83
Inclination angle [°]	8.52
Tube turns	14

Each helical coil in the test section comprises three DC-heating zones delineated by four electrodes, as shown in Fig. 1. With respect to the internal flow direction, the zone-wise heat inputs at the inlet, middle, and outlet sections are denoted $Q1$, $Q2$, and $Q3$, respectively. The electrical resistance of each zone was specified to scale linearly with its axial length based on the material resistivity; accordingly, the applied heat input was apportioned in proportion to the zone length. The zone lengths and the assigned power fractions are summarized in Table 2.

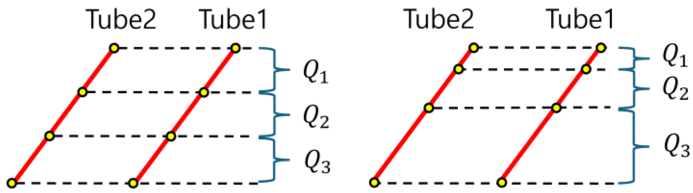

Fig. 1. Tube Segmentation with Electrodes

Table II: Tube Length Segmentation and Power Fractions

Case	$L_1 : L_2 : L_3$	$Q_1 : Q_2 : Q_3$
1	33 : 33 : 33	33 : 33 : 33
2	25 : 49 : 25	40 : 20 : 40
3	35 : 29 : 35	31 : 38 : 31
4	49 : 30 : 20	20 : 32 : 48

5	20 : 30 : 49	48 : 32 : 20

MARS-KS was augmented with Colombo's pressure-drop model to more accurately account for geometry-induced hydraulic effects in helical coils. Simulations were then performed under the boundary conditions reported by Oh: an outlet pressure of 4.6 bar, an inlet mass flux of 395 kg m^{-2} s^{-1}, an inlet temperature of 314.2K and R-245fa as the working fluid. Figure 2 illustrates the nodalization adopted for the parallel helical-tube configuration. In MARS-KS, the fluid enters the loop through a time-dependent volume (TMDPVOL) with a prescribed inlet temperature and a time-dependent junction (TMDPJUN) with a prescribed mass flow rate [7]. The BRANCH component represents the headers and splits the flow into two streams, each routed to an individual helical tube. The helical coil in the test section is modeled with a PIPE component comprising 99 axial nodes. A heat structure coupled to the PIPE applies an axially prescribed heating profile according to a predefined table. Downstream of the coils, the streams recombine in a BRANCH and discharge into a time-dependent volume at the outlet, where the specified outlet-pressure boundary condition is imposed.

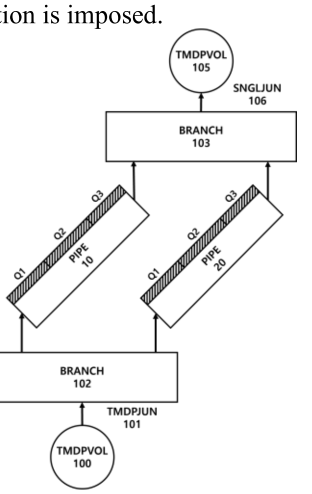

Fig. 2. Nodalization of Parallel Helical Tube Test Section with MARS-KS

2.2 Detection of DWO

Density-wave oscillations (DWO) are identified by sustained, anti-phase, quasi-periodic oscillations of the channel mass flow rate. The coil heating power is ramped in time while maintaining the prescribed boundary conditions, as illustrated in Figure 3. When the applied load exceeds a critical level, self-excited flow oscillations emerge, as shown in Figure 4. In the present analysis, the total heating power, defined as the sum of the three heating sections, is increased in 0.1 kW increments every 500 s, and the corresponding mass-flow response is monitored. Upon confirmation of DWO, the phase-change number and subcooling number corresponding to the inlet temperature and applied heating power are evaluated.

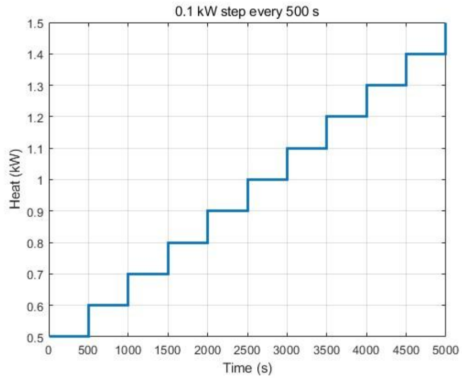

Fig. 3. Increment of Heating Power over Time.

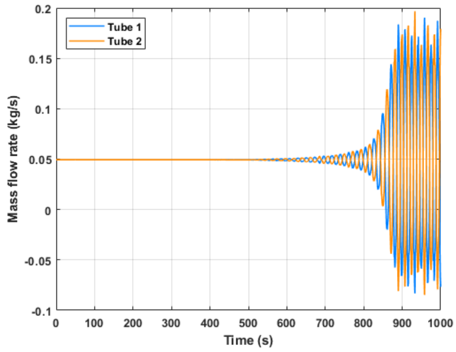

Fig. 4. Mass Flow Rate Change over Time.

3. Result and Discussion

Comparative analysis of the five cases in Table 3 indicates a clear inverse relationship between the inlet-zone heating share and the phase-change number: as $Q1/Qtotal$ ratio increases, critical onset Npch of system decreases. For example, Case 5 ($Q1$=48.2%) yields the lowest value, Npch=16.07, whereas Case 4 ($Q1$=19.7%) attains the highest, Npch=30.76. Relative to the uniform heating condition (33.3:33.3:33.3) in Case 1, which gives Npch=29.7, stronger inlet peaking systematically lowers critical Npch.

Table III: Tube Length Segmentation and Power Fractions

Case	$Q_1 : Q_2 : Q_3$	$Qtotal$ [kW]	Npch
1	33 : 33 : 33	1.3	29.7
2	40 : 20 : 40	1.0	22.7
3	31 : 38 : 31	1.3	29.2
4	20 : 32 : 48	1.3	30.76
5	48 : 32 : 20	0.6	16.07

From Figure 5, the step changes in the nodal critical power (at electrode boundaries) delineate the three axial zones, allowing the corresponding inputs $Q1$, $Q2$, and $Q3$ to be identified. The cases that trigger instability at lower total heat input and smaller Npch, Case 2 and Case 5, exhibit higher inlet per-node power than the cases whose critical total power is 1.3 kW. A direct comparison between Case 2 and Case 5 further indicates that, despite a substantial difference in the outlet-zone heating $Q3$, the inlet fraction $Q1$ exerts the primary influence on the DWO onset power. Conversely, when $Q1$ is comparable to or smaller than $Q2$ or $Q3$, the critical total heat input remains at 1.3 kW.

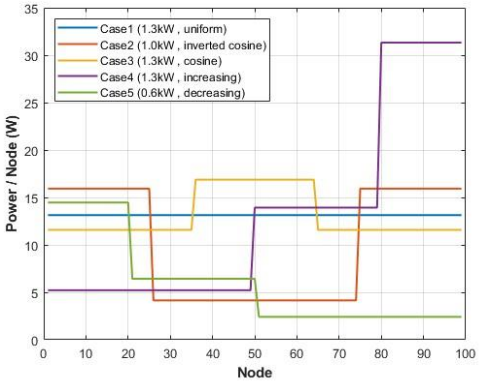

Fig. 5. Critical axial power distribution for each case

Consistent with Fig. 6, the observations accord with the general result that a larger axial two-phase extent increases susceptibility to instability. In particular, as the inlet heating fraction $Q1/Q$total increases, the phase-change region advances upstream at a lower total heat input than for smaller inlet fractions. Strengthening inlet heating accelerates the approach to saturation and shifts boiling incipience upstream, thereby reducing subcooling, expanding the two-phase region, and shifting the DWO onset to smaller Npch. The apparent reversal between Case 1 and Case 2 arises because, although DWO is triggered at similar critical total heat inputs in both cases, the computed Npch differs owing to the pressure dependence embedded in its definition (via reference saturation properties). Moreover, when the inlet fraction $Q1$ is comparable to or smaller than $Q2$ or $Q3$, the downstream allocation ($Q2$+$Q3$) becomes the controlling quantitative factor in attaining the converged critical total heat input for onset.

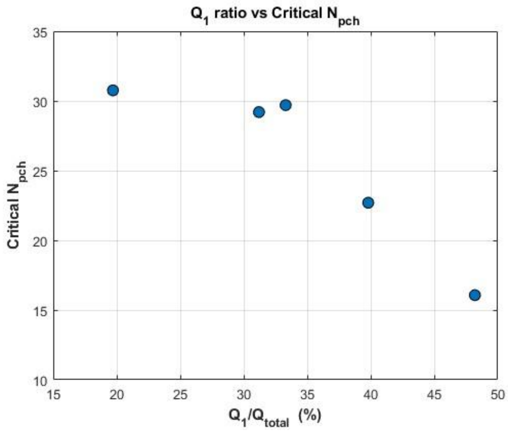

Fig. 6. Critical Phase Change Number against Q1/Qtotal

4. Summary Conclusion

Stronger inlet heating pulls boiling incipience upstream, lengthens the axial two-phase region, and triggers DWO at lower total heat input, yielding a smaller onset indicator (e.g., Npch). Conversely, when inlet heating does not exceed mid/outlet heating, transition to instability requires higher total heat input, with the downstream heating distribution acting as a secondary constraint. Differences in the reported onset indicator among cases are partly attributable to the pressure dependence embedded in the indicator's definition (via reference saturation properties).

This study was conducted as a preliminary scoping analysis using 0.1 kW power increments and a limited case set. For finer trend resolution and more robust inference, subsequent work should employ smaller power steps, standardize total heat input across cases, and expand the case matrix to cover a broader range of axial zone-length ratios. In addition, like-for-like simulations and dedicated experiments under matched axial zoning (identical zone lengths along the coil) are recommended to decouple geometric segmentation effects from power peaking and to validate the observed trends.

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