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Preliminary Assessment of SPACE Code for DWO in Helical Coils

Dong-Young Lee*, YoungJae Park , Jungjin Bang, Jan Hruškovič, Seong-Su Jeon
FNC Tech. Co. Ltd., Floor 32, Heungdeok IT Valley, 13 Heungdeok 1-ro, Giheung-gu, Yongin-si, Gyeonggi-do, 16954, South Korea
**Corresponding author: dylee273@fnctech.com*

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1. Introduction

Small modular reactors (SMRs) have gained significant attention as a promising solution for safe and efficient nuclear power generation, with their compact and modular designs offering enhanced flexibility and safety features. Within SMRs, the helical coil steam generator (HCSG) is employed for its compactness and superior heat transfer [1–3]. However, two-phase flow instabilities, such as Density-Wave Oscillations (DWOs), arise from pressure drop delays and void fraction changes, potentially causing mechanical vibrations and compromising system stability [4, 5]. Therefore, the DWOs have become an issue as SMR components can be affected by these oscillations.

As SMRs continue to develop, particularly with the incorporation of HCSGs in designs such as NuScale, the occurrence of DWO has drawn increasing attention. This is due to its potential impact on SMR components, which has prompted further investigation into the phenomenon [6]. To address this, NuScale developed an evaluation v-ramping methodology for DWO, including demonstration experiments [7, 8] and Oh et al. [1] simulated HCSG behavior using the MARS-KS code with an alternative pressure drop and heat transfer model. Similarly, the i-SMR, which features a similar HCSG design, may also experience similar instabilities [9]. Given these concerns, it is essential to assess the prediction capability of system analysis codes for DWO in order to validate the design and stability of helical-coiled steam generators in SMRs [5].

Although numerous experimental and computational studies have been conducted, discrepancies between observed DWO behavior and code predictions remain, particularly due to limitations in accurately reflecting the dynamic instabilities of helical coil systems [1]. This study employs the SPACE 3.3 code to simulate DWOs in a HCSG. The experimental setup adopted as the basis for this simulation is derived from Wang et al. [10], which provides detailed experimental data for observing dynamic instabilities in helical coil systems. The apparatus described by Wang et al. replicates two-phase flow conditions, including pressure drop and heat transfer characteristics, and this study aims to simulate these using the SPACE 3.3 code to conduct a preliminary evaluation of its predictive accuracy."

2. Calculation Method

2.1 Reference experimental facility

The experimental facility described by Wang et al. [10] consists of a two-helical coil system with a closed circulation loop. Fig. 1 shows the schematic diagram of the facility and Table I shows the detail data of helical coil geometry. Under operating conditions, key parameters are precisely controlled: inlet throttling is managed by a valve before the inlet header, system pressure by a pressure regulator, mass flux by a piston pump, and inlet subcooling by a pre-heater. The coil is heated via joule heating.

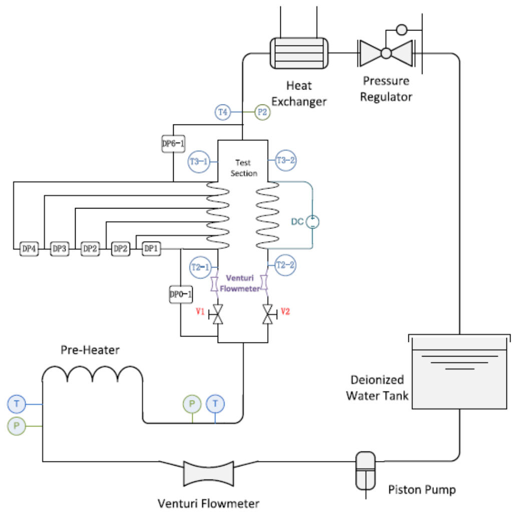


Fig. 1. Schematic diagram of experimental facility [10].

Table I: Geometry parameter

	Parameter	Unit
Inner diameter (d)	0.009	m
Coil diameter (D)	0.35	m
Diameter ratio (d/D)	0.0257	-
Coil length (L)	4.79	m
Helix angle (θ)	10	deg.

2.2 Calculation method

To evaluate the DWO prediction capability of the SPACE 3.3 code, the experimental facility Was modeled as shown in the nodalization in Fig. 2. The helical coil was discretized into 24 nodes. The mass flow rate and working fluid conditions were controlled using time-dependent flow boundary conditions (TFBC) at the inlet, while the system pressure was regulated by TFBC at the outlet. The loss coefficient (k-factor) was set to 0.0 in the helical coil to isolate the predictive ability of the SPACE 3.3 code without additional frictional effects, while a k-factor of 35.0 was applied at the inlet header to simulate the pressure drop due to inlet throttling.

Since flow disturbances can significantly influence DWO initiation, some studies have applied perturbation-based methods, such as the v-ramping approach, to assess stability boundaries more accurately [7, 8]. However, in this study, no external perturbation was introduced in the numerical simulation, focusing solely on the natural occurrence of DWOs under given conditions.

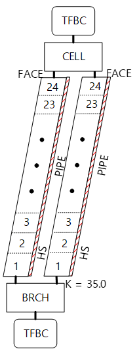
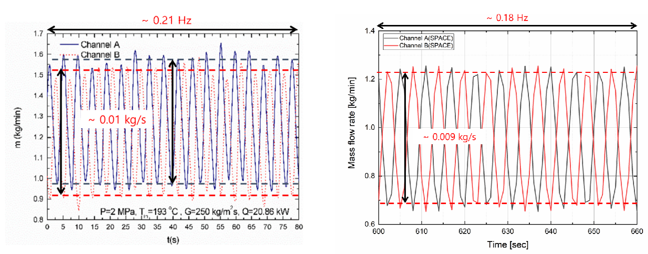


Fig. 2. Nodaliztion of experimental facility.

3. Results and Discussion

3.1 Comparison with reference DWO Case

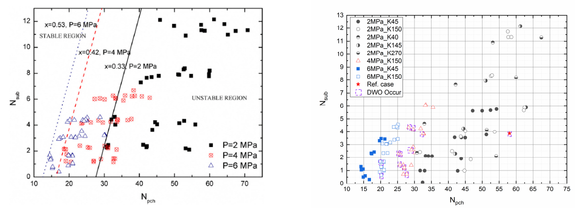
The reference DWO case from Wang et al. [10] was characterized by a mass flux of 250 kg/m²·s, an inlet temperature of 193 °C, and a heater power of 20.86 kW. The calculation results for this case were compared with the experimental mass flow rate oscillations, as shown in Fig. 3. Based on approximate values, the simulation yielded a frequency of 0.18 Hz and an amplitude of 0.09 kg/s, while the experiment showed a frequency of 0.21 Hz and an amplitude of 0.01 kg/s. These results indicate differences of about 22% in frequency and 10% in amplitude, respectively.



(a) Experimental data (b) Calculation data
Fig. 3. Comparison the calculation results with reference [10].

3.2 Comparison of stability map

As shown in Fig. 4, the calculated stability map was compared with experimental data from Wang et al. [10] to assess discrepancies in DWO boundary predictions across operating conditions. These calculations were performed specifically for cases where inlet throttling was clearly defined. While most experimental results indicate the presence of DWOs under the tested conditions, the calculated results exhibit a reduced tendency to reproduce these instabilities in several cases. This trend aligns with findings from past studies using RELAP5, where simulations of the same experimental setup showed DWO occurrence only within a heater power variation of ±30% [10]. These differences suggest the need for enhanced techniques in system codes to fully reproduce the dynamic behavior of helical coil systems [7, 8, 11, 12].



(a) Experimental data (b) Calculation data
Fig. 4. Comparison stability map of calculation results with experimental data [10].

4. Conclusions

In this study, the prediction capability of the SPACE 3.3code for DWOs in a helical coil was evaluated using experimental data from Wang et al. [10]. The comparison of mass flow rate oscillations demonstrated that the simulation predicted a DWO frequency of 0.18 Hz and an amplitude of 0.09 kg/s, whereas the experimental results showed 0.21 Hz and 0.10 kg/s, indicating discrepancies of approximately 22% in frequency and 10% in amplitude. Furthermore, the stability map comparison revealed that the SPACE 3.3 code exhibited a reduced tendency to capture DWOs under certain operating conditions.

These differences suggest that further refinement of the system modeling approach may be beneficial for improving the prediction of DWOs in helical coil systems. In particular, flow disturbances are known to play a role in DWO initiation, and incorporating perturbation-based methods could be useful for better capturing the onset conditions.

5. Further Work

This study evaluated the prediction capability of the SPACE code for naturally occurring Density-Wave Oscillations (DWOs) in a helical coil steam generator. To further improve prediction accuracy, additional methodologies will be explored.

Future work will assess the applicability of perturbation-based methods, such as the v-ramping approach used in past studies, as well as an alternative A-ramping method, where heater power is temporarily increased and restored [7, 8]. A comparative analysis of these methods will provide deeper insights into DWO onset conditions and enhance the predictive reliability of system codes for helical coil system applications.

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