*Transactions of the Korean Nuclear Society Spring Meeting*
*Jeju, Korea, May 22-23, 2025*

# Preliminary Investigation of Density Wave Oscillation in Boiling Channel using Frequency-Domain Analysis

Haeram Jeong[a], Eunhee Jang[a], Chanmin Jeong[a], Yohan Kim[a], Hyungdae Kim[a*]
[a]*Department of Nuclear Engineering, Kyung Hee University, Republic of Korea.*
[*]*Corresponding author: hdkims@khu.ac.kr*

***Keywords :** Density wave oscillation, Frequency domain analysis, Small modular reactors

## 1. Introduction

Helical coiled steam generator (HCSG) possesses a larger heat transfer surface area compared to U-tube type steam generators, making it a preferred design in many small modular reactors (SMRs). However, the HCSG is susceptible to density wave oscillation (DWO) because i) the steam generator tubes share the same header at both the inlet and outlet, resulting in a constant pressure at the channel, and ii) the channel has a high ratio of tube length to tube diameter.

DWO may make system control complicated due to unintended heat transfer effects and can induce mechanical vibrations, potentially leading to mechanical damages in components. Therefore, predicting the initiating conditions of DWO is crucial for safety assessment of the components of interest, such as HCSG.

The onset of DWO is generally explored using two approaches: i) frequency-domain analysis and ii) time-domain analysis [1]. Frequency-domain analysis, known as linear analysis, employs classical control theory techniques, where the governing equations are linearized using the Laplace transform to derive transfer functions for stability assessment [2]. Time-domain analysis, also referred to as non-linear analysis, is a method for detecting flow instability using either theoretical investigations that do not involve linearization or numerical simulations with computational codes [3]. As shown in Table I, frequency-domain analysis offers advantages such as being free from numerical diffusion and having a lower computational cost. In contrast, time-domain analysis accounts for non-linear behavior and enables the assessment of how system parameters influence the instability threshold. Since the two methods have complementary effects in determining the initiation condition of DWO, both have to be used together to enhance reliability of the analysis [4].

In this study, a simple frequency-domain analysis method was developed and preliminary utilized to examine DWOs in a straight boiling channel before the comprehensive study of DWO in a HCSG.

## 2. Frequency-domain analysis method

### *2.1. Modeling of single boiling channel*

The modeling for frequency-domain analysis begins with the linearization of the mass, energy, and momentum conservation equations using the Laplace transform. The linearized equations are based on the approach proposed by Schlichting (2009) for analyzing the NASA-type test loop [5]. As shown in Figure 1, the model assumed one-dimensional flow and a uniform heat flux along the axial direction. The two-phase conservation equations are modeled using the Homogeneous Equilibrium Model (HEM), which provides a simplified representation of two-phase flow dynamics. The operating condition and channel geometry used in this study is summarized in Table II, which are typical operating conditions and geometry of boiling water reactor channel.

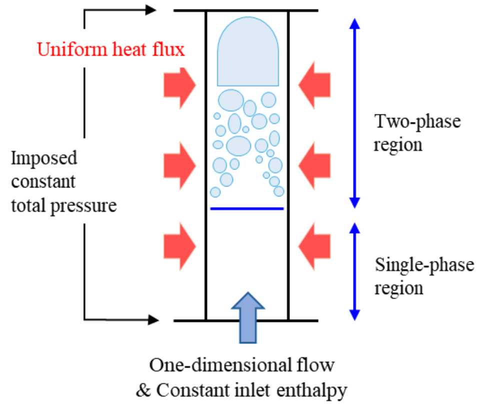


Fig. 1. Schematic diagram of simplified single boiling channel

Table I: Features in frequency-domain and time-domain stability analysis

| *Feature* | *Frequency-domain* | *Time-domain* |
|---|---|---|
| Computation speed | Fast | Slow |
| Numerical diffusion | No | Yes |
| Non-linear behavior | No | Yes |

Table II: Geometry and operating condition for the analysis

| | |
|---|---|
| *Channel geometry* | |
| Diameter (m) | 0.0124 |
| Length (m) | 3.658 |
| *Operating conditions* | |
| Pressure (bar) | 70 |
| Inlet temperature (°C) | 150-280 |
| Thermal Power (W) | 65000 - 110000 |

### *2.2. Transfer function*

The transfer function, which determines the flow instability characteristics under constant inlet and outlet pressure difference boundary conditions, is given in Eq. (1) [6].

(1) $$\frac{\delta j^{in}}{\delta P^{in}} = \frac{G_{1\emptyset}}{1+G_{1\emptyset}H_{2\emptyset}}$$

where:

(2) $$G_{1\emptyset} = \frac{\delta j_{in}}{\delta \Delta P_{1\emptyset}}$$

(3) $$H_{2\emptyset} = \frac{\delta \Delta P_{2\emptyset}}{\delta j_{in}}$$

The defined transfer function was utilized to predict instability boundaries using the Nyquist diagrams. The detailed procedures shall be explained in the following section at length.

## 3. Result

### *3.1. Determination of stability using Nyquist plot*

The stability threshold can be determined using the Nyquist diagrams of the transfer function. If the Nyquist diagram of the transfer function encircles the origin point in a counter-clockwise direction, the system is considered unstable. Otherwise, it means stable.

Figure 2 illustrates the Nyquist diagrams for cases with an inlet mass flow rate of 0.087 kg/s and an inlet temperature of 205.4 °C, showing (a) a stable case, (b) a neutrally stable case, and (c) an unstable case. From Fig. 2 (a)-(c), it can be observed that an increase in thermal power drives the system toward the unstable condition, as the plot evolves from not surrounding the origin, to passing through it, and finally enclosing it.

### *3.2. Stability map on $N_{pch} - N_{sub}$ plane*

A unified stability map does not exist. However, given the geometry and operating pressure of a boiling channel, the stability region can be generally represented in two-dimensional form using the dimensionless numbers $N_{pch}$ and $N_{sub}$, as proposed by Ishii (1970) [7].

(4) $$N_{pch} = \frac{Q}{\dot{m}h_{fg}} \cdot \frac{v_{fg}}{v_f}$$

(5) $$N_{sub} = \frac{\Delta h_{in}}{h_{fg}} \cdot \frac{v_{fg}}{v_f}$$

Figure 3 illustrates the stability map derived using the frequency-domain analysis model. The region to the left of the boundary represents a stable domain where oscillations are damped, while the region to the right corresponds to an unstable domain where oscillations grow. The stability boundary exhibits the characteristic L-shaped inclination, which is typically observed in DWOs. As mentioned in Section 1, since frequency-domain analysis involves the linearization of governing equations, it has limitations in capturing the detailed dynamic behavior of the DWO phenomenon. However, this method is free from numerical diffusion caused by numerical schemes such as time step and node size selection and provides an efficient means of detecting the stability threshold.

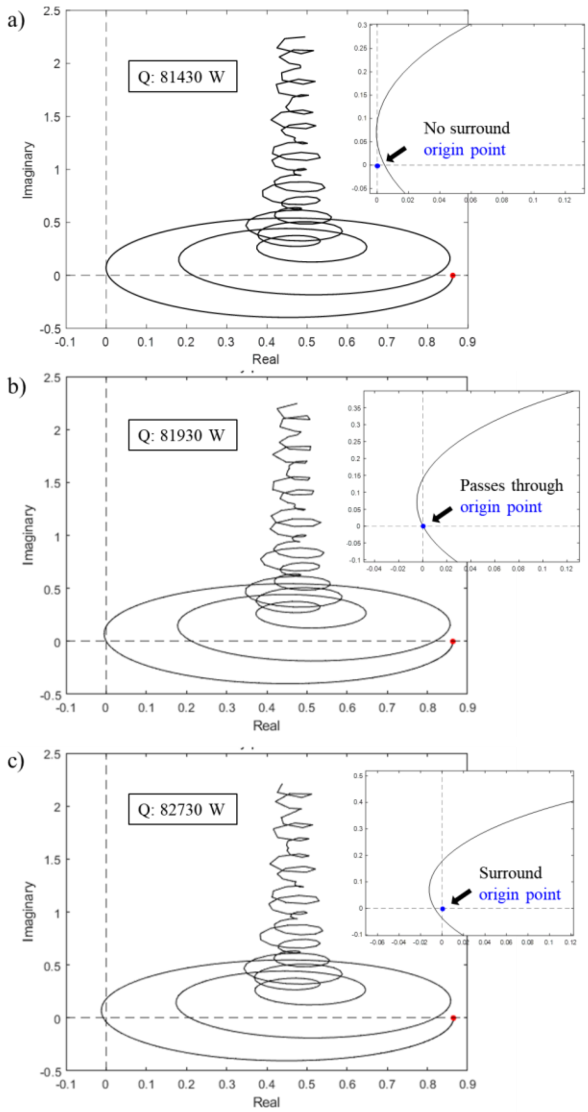


Fig. 2. Nyquist diagrams for (a) stable, (b) neutral stable, and (c) unstable systems

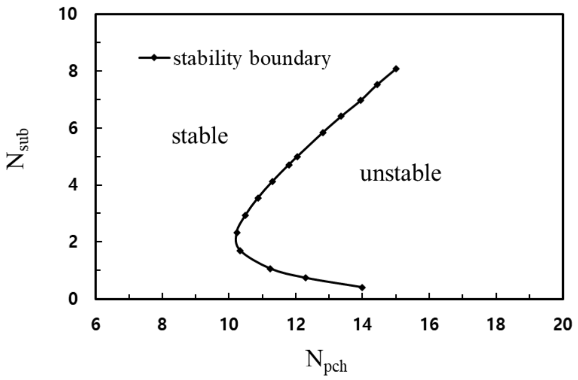


Fig. 3. Stability map in the $N_{pch}$-$N_{sub}$ plane

## 4. Conclusion

This work provides an analysis of DWO phenomena in a boiling channel using a frequency-domain model. The applied approach, based on the linearization of governing equations, readily enabled an establishment of instability occurrence in the boiling channel system. This study serves as a preliminary analysis for detecting flow instability in helical-coiled steam generators, and the model will be further developed to incorporate helical-geometric effects such as customized frictional pressure drop coefficients. Additionally, a comparison with time-domain analysis will be conducted to enhance reliability in predicting the onset of DWO.

## ACKNOWLEDGMENTS

This work was supported by the Nuclear Safety Research Program through the Regulatory Research Management Agency for SMRs (RMAS) and the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea. (No. RS-2024-00509653)

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