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Classification of Boiling Flow Instabilities in a Vertical Annulus through Pressure Frequency

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1. Introduction

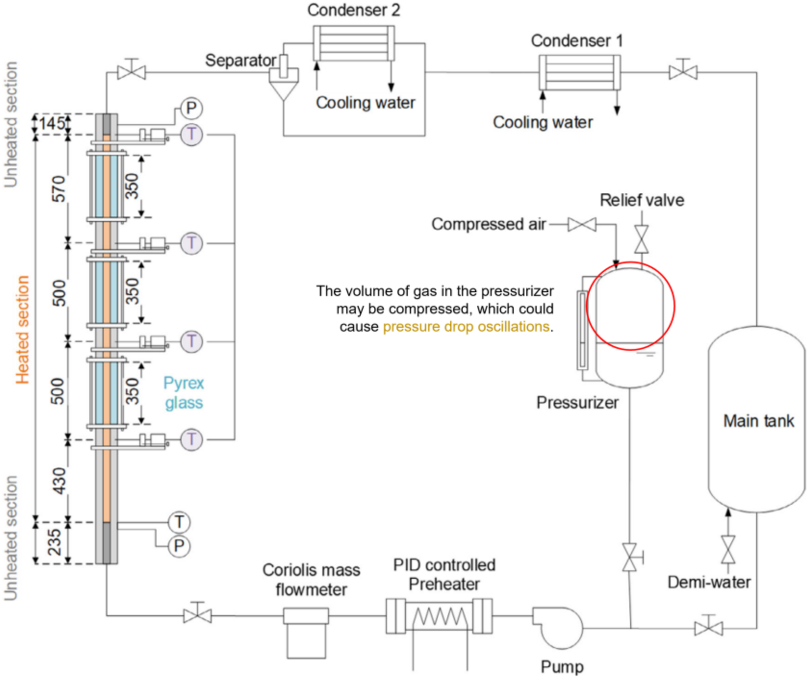
Two-phase flow instabilities in boiling systems serve as a critical factor compromising the operational safety of nuclear reactors. These instabilities arise from complex feedback loops involving heat flux, flow rate, and pressure drop. Specifically, high-frequency Density Wave Oscillations (DWO) and low-frequency Pressure Drop Oscillations (PDO) induce thermal fatigue and structural damage, respectively [4, 5]. While the physical mechanisms triggering DWO and PDO differ, PDO is typically accompanied by DWO under practical experimental conditions, exhibiting a complex superposition of the two phenomena. [1, 4, 5]

In this study, the evolving oscillation characteristics under different operating conditions are evaluated based on variations in heat flux. Given that conventional amplitude-based metrics may have limitations in detailing the complex transitions of flow states, Power Spectral Density (PSD) and Fast Fourier Transform (FFT) analyses are employed to observe the trends in energy distribution across frequency bands as operating parameters shift. This approach focuses on identifying how high-frequency DWO and low-frequency PDO develop and interact within the flow map, providing a comprehensive analysis of the tendencies in the system's dynamic instability transitions.

2. Experiment Method

The experimental study utilized the flow boiling test loop previously employed in prior research [1-3]. As illustrated in Fig. 1, the experimental setup consists of a main tank, pump, preheater, mass flow meter, pressurizer, heat exchanger, and heated section.

The experiments were conducted by varying only the mass flow rate and heat power, while maintaining a constant outlet pressure and subcooling temperature. The mass flow rate was controlled using a globe valve, and data were collected by adjusting the heat power of the heating rod. Furthermore, the outlet pressure was fixed at 150 kPa using a pressurizer. To precisely control the inlet temperature, a PID-controlled preheater was employed to maintain a consistent subcooling temperature throughout the procedure. To ensure the reliability of the results, a stabilization period of 15-20 minutes was observed. After verifying steady-state conditions, experimental data were then collected.



The volume of gas in the pressurizer may be compressed, which could cause pressure drop oscillations.

Fig. 1. Schematic diagram of the experimental apparatus

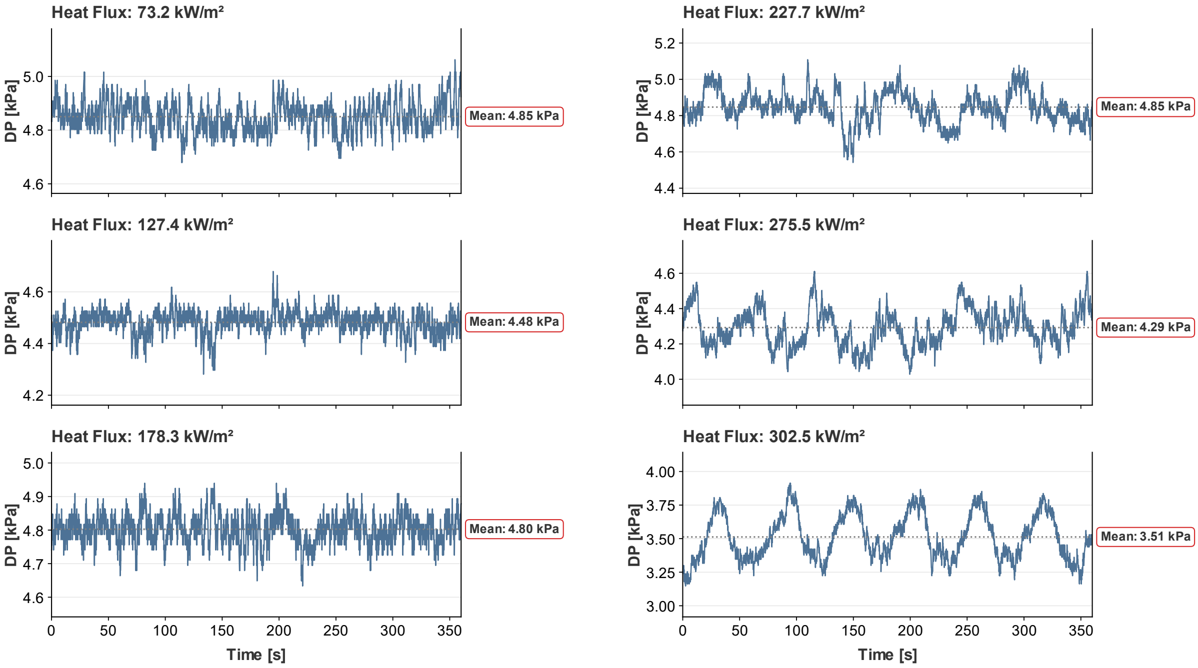


Fig. 2. Transient pressure drop signals under various mass flux and heat flux conditions

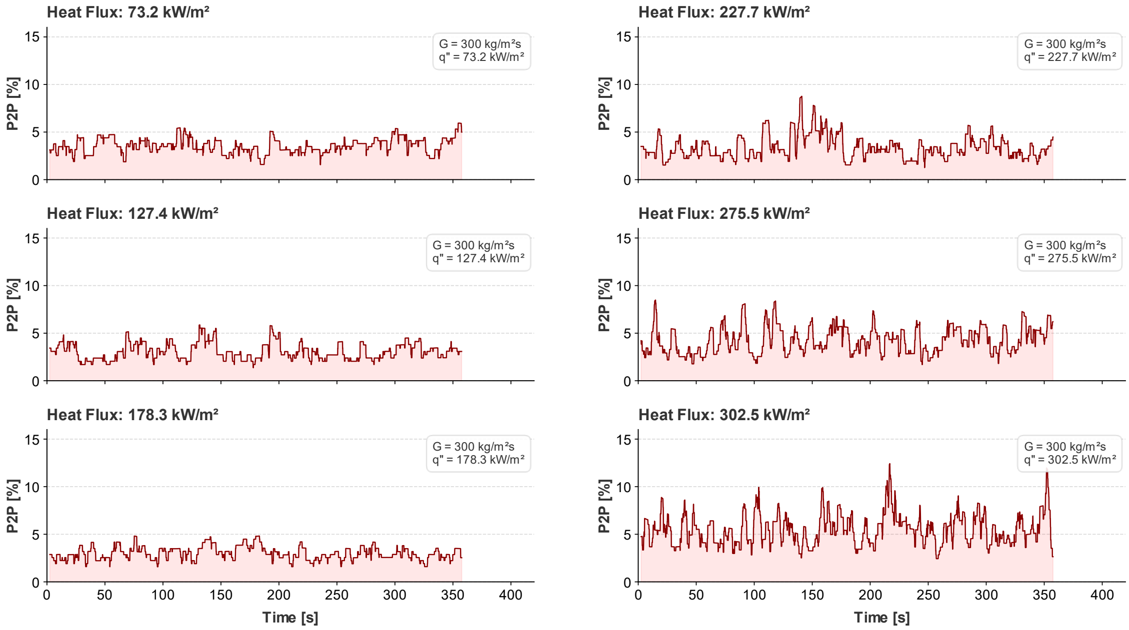


Fig. 3. Peak-to-peak oscillation amplitudes across the experimental matrix

3. Result and discussions

In this experiment, pressure drop data were collected while step-wise increasing the heat flux from 75 to 300 kW/m² with the mass flux fixed at approximately 300 kg/m²s. Based on the acquired pressure drop data in Fig. 2, the Peak-to-Peak percentage representing the amplitude variation in the time domain was derived in Fig. 3. While the time-domain Peak-to-Peak analysis effectively captures the macroscopic severity of the overall oscillations, it presents limitations in distinguishing between the specific instability mechanisms driving the system.

Therefore, based on the frequency scale difference between PDOs in the 0.01 to 0.02 Hz band and DWOs in the 0.13 to 0.25 Hz band, 0.1 Hz was set as the cutoff frequency to quantify the energy distribution ratio of the PSD across frequency bands in Fig. 4. This dual-domain approach is essential for decoupling the superimposed instability phenomena that operate on fundamentally different time scales [4].

By combining these two indicators, the top 5% average Peak-to-Peak and the frequency energy ratio, the instability transition trends according to heat flux were derived in Fig. 5. In the comprehensive analysis results in Fig. 5, a non-linear behavior was observed where the amplitude decreased at a heat flux of 178.3 kW/m². Checking the frequency energy confirmed that this section is not system stabilization but a precursor phenomenon where the internal flow structure is reorganized, showing a slight decrease in low-frequency PDO energy and a rebound in high-frequency DWO energy. Physically, this localized increase in DWO energy indicates intensified void fraction fluctuations and delayed feedback within the heated section, which continuously perturb the system's flow boundary conditions before a massive global instability is triggered.

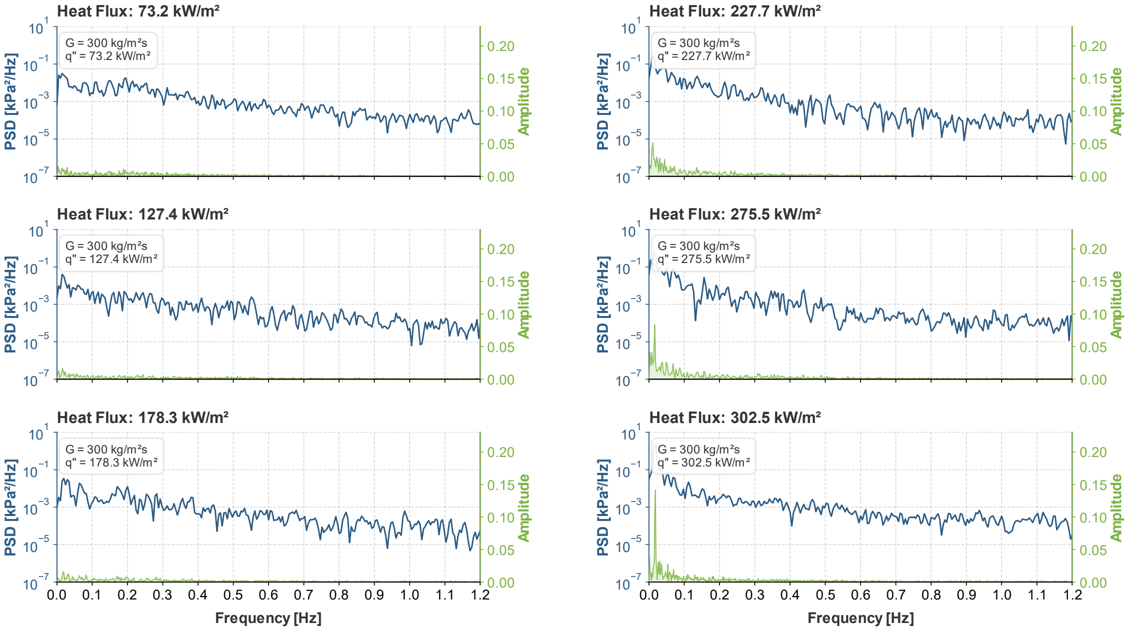


Fig. 4. Frequency-domain analysis (PSD and FFT) of pressure drop oscillations

Immediately after this precursor phenomenon, at the 227.7 kW/m² condition, the amplitude nearly doubled, and an energy cross-over occurred where the low-frequency PDO energy ratio exceeded the high-frequency DWO energy. This significant shift signifies that the interaction between the flow inertia and the compressible volume in the upstream pressurizer has begun to dominate the dynamic response of the entire system [4, 5]. In the high heat flux environment of 302.5 kW/m², DWO energy did not disappear but maintained a proportion of approximately 6%, even though PDO dominated 94% of the total oscillatory energy.

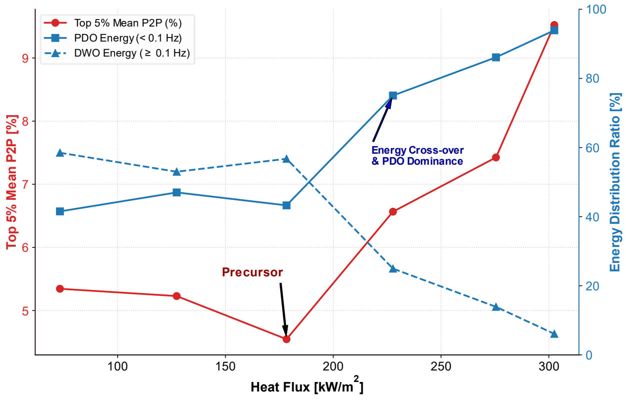


Fig. 5. Flow Instability Transition

This shows a compound instability mechanism where high-frequency oscillations are continuously superimposed on large low-frequency wavelengths. Specifically, during the low-flow phase of the macroscopic PDO cycle, the reduced flow rate renders the heated channel highly susceptible to localized density wave delays, thereby sustaining the high-frequency DWO component alongside the dominant PDO [4].

4. Conclusion

A multidimensional transition trend graph in Fig. 5 was derived by combining the results of the conventional simple Peak-to-Peak analysis in Fig. 3 and the frequency band analysis in Fig. 4. It was confirmed that the temporary amplitude reduction observed in a specific heat flux range of 178.3 kW/m² is not system stabilization, but a precursor phenomenon involving the redistribution of low-frequency and high-frequency energies. This proves that relying only on conventional simple amplitude time-domain analysis can underestimate the risks of flow instability.

Subsequently, at the 227.7 kW/m² heat flux section, the dominant frequency decreased sharply while the amplitude increased significantly, objectively identifying an energy cross-over phenomenon where PDO energy dominates the system. By confirming that a certain proportion of high-frequency DWO energy remains even in severe PDO-dominated environments, it was verified that the two instability mechanisms do not act independently but operate as a compound instability. Ultimately, this dual-frequency analysis serves as a objective basis for identifying energy transfer phenomena and classifying the complex transition processes of flow instability in environments where DWOs and PDOs overlap.

Furthermore, considering the practical application of helical tubes in Small Modular Reactors (SMRs), the influence of their geometric characteristics and associated minor pressure losses on these instability mechanisms remains a crucial subject for future experimental investigations.

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