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Preliminary Testing of the Flow Loop in a High-Pressure Flow Boiling Test facility for a PWR Subchannel.

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1. Introduction

Subcooled flow boiling phenomenon refers to localized nucleate boiling at superheated surfaces while bulk fluid temperature remains below saturation temperature. Pressurized water-cooled reactors (PWRs), such as APR1400, employ subcooled water pressurized at 15.5 MPa as the primary coolant to remove heat from nuclear fuel rods. Under the operating conditions, subcooled flow boiling may occur from fuel rods at the hot channel. Thus an accurate prediction of subcooled flow boiling heat transfer is crucial for assessment of thermal margin and thermal-hydraulic safety in the hot channel of a PWR.

In many thermal-hydraulic system analysis codes and computational fluid dynamics (CFD) codes, a wall heat flux partitioning model is employed to predict heat transfer during subcooled flow nucleate boiling. The model was developed based on the mechanistic behavior of boiling bubbles and incorporates key physical parameters, including nucleation site density (N), bubble departure diameter (D_d), bubble departure frequency (f), and microlayer thickness (δ_m). Consequently, accuracy of heat transfer analysis in the codes is highly dependent on the precise modeling of bubble behavior and the accurate prediction of the aforementioned parameters.

Fig. 1 is a graph illustrating a comparison between the bubble nucleation site density predicted by the prediction models and experimentally measured data at various pressure conditions. Existing experimental validations of bubble behavior parameter models have been conducted under pool boiling conditions ranging from low pressures (~2.95 MPa) to high pressures (~19.8 MPa), thereby allowing for the comparison of experimental data with model predictions.[3] However, the experimental conditions at which the data were obtained do not properly replicate thermal-hydraulic conditions in a PWR subchannel though the dynamic behaviors of bubbles, such as sliding and lift-off, produced under subcooled flow boiling significantly vary according to the hydrodynamic conditions of the flowing coolant. Therefore, the wall heat flux partitioning models used in current thermal-hydraulic and CFD codes remain validated under actual PWR conditions. However, experimenting subcooled flow boiling and observing bubble dynamics at such high pressure and high temperature conditions is extremely challenging.

Advanced thermal-hydraulics laboratory (AdvanTH) at Kyung Hee University have recently designed and constructed a high-pressure flow boiling test facility for a PWR subchannel and have been conducting a set of preliminary tests for troubling shooting and stabilization of the facility. This study reports the preliminary test results conducted at non-boiling conditions.

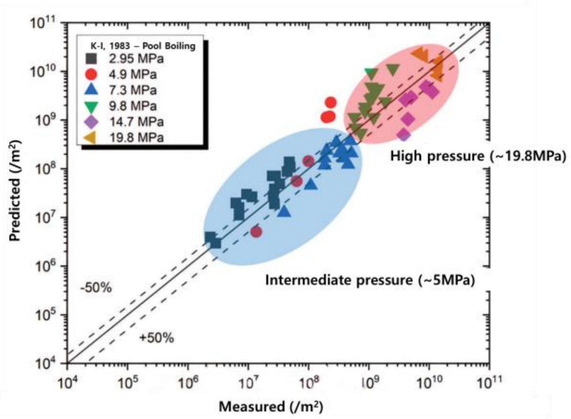

Fig. 1 Comparison between nucleation site density model and experimental data at different pressures [4]

2. High-Pressure Flow Boiling Facility

2.1 Flow Loop

The experimental facility comprises a flow loop divided into three sections: the pressurization loop, the high-pressure loop, and the nitrogen loop. Within the pressurization loop, the working fluid is pressurized to a maximum flow rate of 0.6 lpm and a pressure of up to 15.5 MPa. A preheater then heats the pressurized fluid to a maximum temperature of 320 °C before entering the high-pressure vessel. The high-pressure loop delivers the heated, high-pressure working fluid into the test section at a constant flow rate; a mixer within the high-pressure vessel augments the fluid's mass flux up to 3500 kg/m²s. The nitrogen loop introduces nitrogen gas, maintained at the same pressure as the working fluid, into the test section. A piston-type cylinder is employed to sustain pressure equilibrium between the working fluid and the nitrogen gas, thereby ensuring that the test specimen is subjected to a constant pressure.

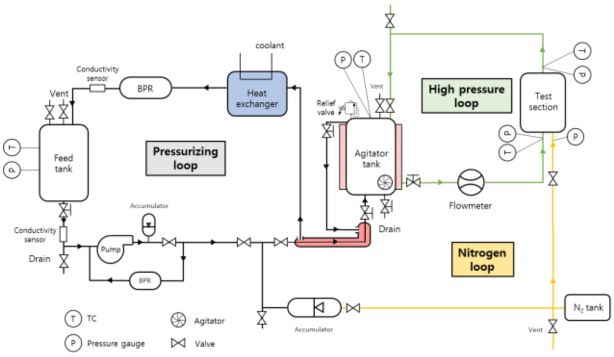

Fig. 2 Schematic diagram of the flow loop [4]

2.2 Test Section

The test section is comprised of a heater cartridge, a window cartridge, and a main body. The heater cartridge is designed both to secure the test specimen and to supply power to the heater element deposited on the specimen. The window cartridge, which is connected to the heater cartridge, forms a 5×5 mm² flow channel and secures an observation window for visual inspection while the test specimen in place. The main body, fabricated from stainless steel (SUS) to withstand high temperature and pressure conditions, a rectangular flow channel that accommodates the heater and window cartridges.

Fig. 3 shows the pressure balance of working fluid and nitrogen at the boundary of the visualization window. One side of this assembly is exposed to the high-pressure working fluid, whereas the opposite side is exposed to high-pressure nitrogen gas. The presence of nitrogen gas at an equivalent pressure to the working fluid within the flow channel prevents fracture of the visualization window. Two sapphire visualization windows are affixed to the exterior of the main body, thereby enabling both infrared and high-speed visual observation.

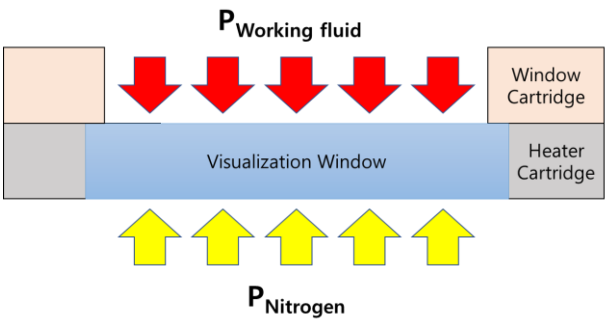

Fig. 3 Schematic of pressure balances for the visualization window

3. Preliminary Results

The experimental facility was fabricated in accordance with the design specifications and was evaluated through a flow rate test, a main loop pressurization test, and a nitrogen loop pressurization and leakage test.

Fig. 4 shows the results of a test performed to verify whether the mass flux within the loop can reach the design specification. The test was conducted by gradually increasing the mass flux at 30 bar. As a result, the mass flux of 3000 kg/m²s was achieved.

Fig. 5 shows the results of the pressurization test conducted on the main loop. The test was performed by gradually increasing the pressure, with measurements taken at the back pressurizer, test section, and pump outlet. As a result, the stabilization target of 100 bar was confirmed.

Fig. 6 shows the results of the leakage test conducted on the high-pressure loop. In this test, nitrogen was used as the working fluid while the pressure was gradually increased. The results confirm that the stabilization target of 100 bar was achieved, and that pressurization could be maintained without leakage even at pressures exceeding the subchannel conditions.

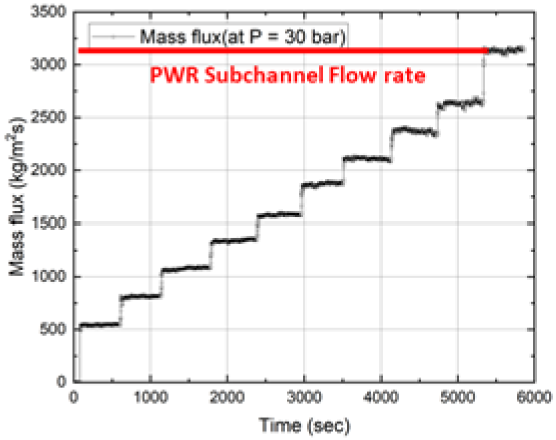

Fig. 4 Flow Rate Condition Establishment and Maintenance Test

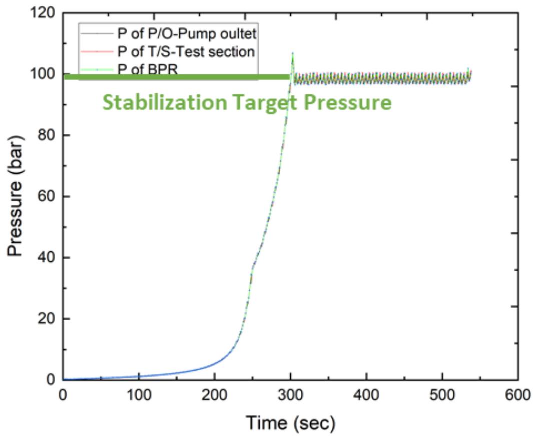

Fig. 5 Pressurization and Pressure Condition Maintenance Test

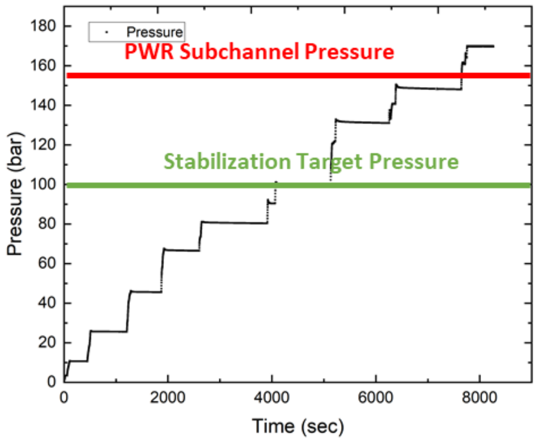

Fig. 6 Leakage Test Using Nitrogen Gas

4. Conclusion and Future Work

Preliminary tests of the high-pressure loop, which is designed for a maximum pressure of 150 bar, confirmed that pressurization beyond 150 bar is achievable without any leakage. Based on these results, it can be concluded that the experimental facility has been successfully constructed in accordance with its design specifications.

As future works, experiments will be conducted to achieve high-temperature conditions for the working fluid under high-pressure conditions, followed by flow visualization experiments employing high-speed and infrared cameras under high pressure conditions. Furthermore, experimental data will be acquired to validate the bubble behavior models utilized in system codes and CFD simulations under PWR subchannel conditions.

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REFERENCES

[1] Kurul, N. and Podowski, M. Z., 1991, "On the Modeling of Multidimensional Effects in Boiling Channels," ANS Proc. 27th National Heat Transfer Conference, MN

[2] Gilman, L. and Baglietto, E., 2017, "A Self-Consistent, Physics-Based Boiling Heat Transfer Modeling Framework for Use in Computational Fluid Dynamics," International Journal of Multiphase Flow, Vol. 95, pp. 35-53

[3]Takashi Hibiki, Mamoru Ishii, 2003, "Active nucleation site density in boiling systems," International Journal of Heat and Mass Transfer, Volume 46, Issue 14, Pages 2587-2601,

[4] Junha Kang (2023), PWR 노심 부수로 조건 고압 유동비등 열전달 실험장치 설계 및 제작, Master's thesis, Kyung Hee University

[5] Junha Kang, Donggyun Seo, Jonghwi Choi, Banseok Bae, & Hyungdae Kim (2022-11-30). Development of a High-Pressure Experimental Apparatus Simulating Reactor Core Sub-channel. Proceedings of the KFMA Annual Meeting, Jeju