Design and Development of a flow boiling experimental facility using optical fiber sensor

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1. Introduction

With the rapid advancement of artificial intelligence technologies, the deployment of high-energy-consumption facilities such as data centers has been increasing worldwide[1]. To ensure a stable and large-scale energy supply, nuclear power plants have been actively considered and deployed as a reliable baseload energy source. While nuclear power offers high energy density and operational stability, potential accidents can lead to severe consequences, emphasizing the critical importance of safety during reactor operation. In nuclear thermal-hydraulic systems, accurate identification of the critical heat flux (CHF) is essential for ensuring fuel integrity and preventing boiling crisis conditions. Precise detection of CHF requires reliable measurement of local wall temperature behavior along heater rods under flow boiling conditions. Conventional measurement techniques primarily rely on thermocouple; however, their application is limited by the difficulty of installing multiple sensors within a single heater rod, resulting in insufficient spatial resolution and incomplete temperature information. To overcome these limitations, this study proposes the use of optical fiber sensor capable of simultaneous multi-point temperature measurement with high spatial resolution(1 mm, 100 Hz) and accuracy. By integrating optical fiber sensing technology into a flow boiling experimental facility, the present work aims to identify the CHF location along a heater rod more effectively, thereby contributing to enhanced thermal-hydraulic safety assessment in nuclear reactor systems. This study focuses on the design and development of a flow boiling experimental facility and does not include CHF measurement results.

2. Methods

2.1 Experimental Facility Design

The flow boiling experimental facility was designed to investigate local wall temperature behavior along a heater rod under controlled flow boiling conditions. Figure 1 presents the three-dimensional CAD model of the experimental loop, developed using Autodesk Inventor to ensure accurate geometric representation and practical feasibility. The test section was designed to accommodate a cylindrical heater rod subjected to uniform heat flux, enabling the observation of vertical axial temperature variations associated with boiling inception and critical heat flux conditions. Special consideration was given to the integration of optical fiber sensor, allowing continuous temperature measurement along the heater rod without disturbing the flow. The overall loop configuration consists of primary circuit and secondary circuit. Primary circuit consists of a pump(~0.9 kg/s, MP221 ,SANWA) , heat exchanger(50 kW, Hanil Heat Exchanger Co., Ltd), pressurizer(~20.5 L, ~40 bar, Hanyang Engineering Co., Ltd), pressure gauge(Rosemount), differential pressure gauge(Rosemount), flow meters(~1.5 kg/s, Rosemount) and test section. Heater rod was designed by 90 kW power with 1 m(0.5 mm thickness) tube and test section channel width was designed 25 mm * 25.3 mm. The secondary circuit has a heat exchanger, chiller(~50 kW, Hanil Heat Exchanger Co., Ltd) and water tank. This loop forms a closed-loop system suitable for steady-state flow boiling experiments. The modular design of the test section facilitates sensor replacement and future experimental expansion. The 3D modeling process was utilized not only for visualization but also for verifying sensor placement, assembly feasibility, and experimental repeatability.

Table I: Test matrix

Mass flux (kg/m^2s)	Inlet temperature	Pressure (bar)
250 kg/m^2s 500 kg/m^2s	10°C subcooling 30°C subcooling 50°C subcooling	1 bar 5 bar 10 bar

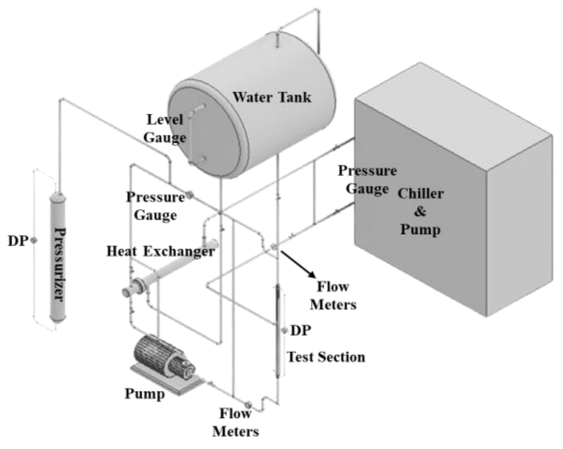

Fig 1. Three-dimensional design model of the entire flow boiling experimental loop

2.2 P&ID and Operational Concept

Figure 2 illustrates the P&ID and operational concept of the flow boiling experimental facility designed in this study[2]. The experimental system consists of a primary loop, in which flow boiling occurs, and a secondary loop dedicated to heat removal. The two loops employ different working fluids and are physically separated to prevent fluid mixing, ensuring stable and independent operation of each loop. The primary loop is configured as a closed circulation loop including a circulation pump, a test section with a heater rod, and a heat exchanger. The working fluid is driven by the circulation pump into the test section, where electrical heating is applied to the cylindrical heater rod, inducing flow boiling along the rod surface. After passing through the test section, the heated primary-loop into the heat exchanger, where thermal energy is transferred to the secondary loop, and subsequently returns to the circulation pump. The secondary loop is an independent cooling circuit responsible for removing heat from the heat exchanger. The working fluid in the secondary loop circulates through the heat exchanger, absorbs heat transferred from the primary loop, and releases it through the cooling system. Thermal interaction between the two loops occurs exclusively within the heat exchanger, while direct contact or mixing of the working fluids is strictly prevented. This dual-loop configuration allows the flow boiling conditions in the primary loop to be controlled independently of the secondary-loop operation conditions, thereby ensuring stable heat removal and safe operation during experiments. The experimental facility is operated following a stepwise procedure including startup, steady-state operation, and shutdown, enabling systematic observation of thermal-hydraulic behavior under flow boiling conditions.

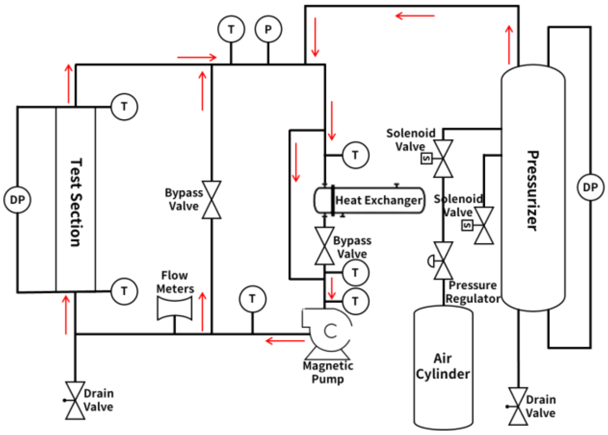

Fig 2. P&ID and operational concept of the flow boiling experimental facility. This schematic illustrates only the primary loop.

2.3 Optical Fiber Sensor

In this study, optical fiber temperature sensor(LUNA, 7101) will be applied to measure the axial wall temperature distribution along a heater rod under flow boiling conditions with high spatial resolution(1 mm, 100 Hz). Unlike conventional thermocouple, which provide temperature information only at discrete locations, optical fiber sensors enable simultaneous temperature measurement at multiple points along a single optical fiber, thereby significantly enhancing spatial resolution. The distributed sensing capability of the optical fiber temperature sensor allows continuous monitoring of axial wall temperature variations along the heater rod. This feature is particularly advantageous in flow boiling experiments, where localized temperature changes and steep temperature gradients are expected near the onset of boiling and the critical heat flux (CHF) condition[3]. By capturing temperature data at multiple locations simultaneously, the sensor provides detailed insight into local thermal behavior that can't be resolved using point-type sensors. In addition to multi-point measurement capability, the optical fiber sensor offers high spatial resolution, enabling detection of fine-scale temperature variations along the heater rod. This capability is essential for identifying local temperature excursions associated with the initiation of CHF and for distinguishing axial differences in boiling behavior under identical flow conditions. Furthermore, the compact size and flexibility of optical fibers facilitate sensor integration into the test section without significantly disturbing the flow or the heater rod structure. As a result, optical fiber sensing provides a reliable and effective measurement approach for acquiring detailed wall temperature information in flow boiling experiments, supporting improved assessment of CHF-related thermal-hydraulic phenomena.

3. Results

3.1 CHF Prediction Methodology

The critical heat flux (CHF) under the designed experimental conditions was estimated using a widely accepted Look-up table (LUT) approach[4]. The LUT method provides CHF values based on empirical data as a function of key operating parameters, including pressure, mass flux, and inlet temperature, and is commonly used for preliminary evaluation of flow boiling systems. In this study, CHF was predicted for the range of operating conditions corresponding to the designed experimental facility. The selected test matrix includes mass fluxes of 250 and 500 kg/m^{2}s, inlet temperature subcooling level of 10, 30, and 50 °C, and system pressure of 1, 5, and 10 bar. These conditions were selected to evaluate CHF behavior under thermal-hydraulic conditions that may occur during reactor operational accident scenarios. The predicted CHF range was used to assess the thermal operating limits of the heater rod and to support the design of the experimental facility, ensuring safe operation and appropriate measurement capability.

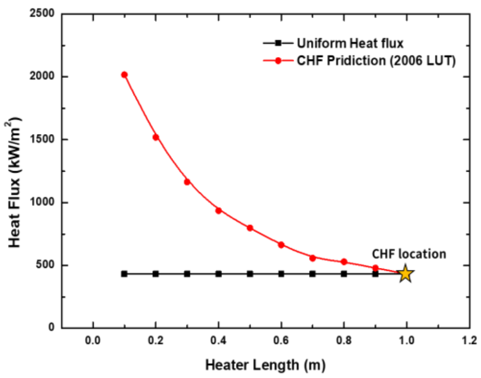

Fig 3. CHF prediction graph at a subcooling of 30 °C and a pressure of 10 bar using a LUT

Table II: CHF prediction on experimental set-up

Pressure	Inlet temperature	CHF prediction
1 bar	10°C subcooling	325 W/m^2
	30°C subcooling	338 W/m^2
	50°C subcooling	348 W/m^2
5 bar	10°C subcooling	355 W/m^2
	30°C subcooling	365 W/m^2
	50°C subcooling	382 W/m^2
10 bar	10°C subcooling	432 W/m^2
	30°C subcooling	445 W/m^2
	50°C subcooling	462 W/m^2

4. Conclusions

In this study, a flow boiling experimental facility incorporating optical fiber sensing was designed to enable high-resolution measurement of axial temperature distribution along a heater rod. The facility design was established through three-dimensional modeling to ensure practical feasibility, effective sensor integration, and experimental repeatability. The P&ID and operational concept were developed to provide stable and safe operation using separated primary and secondary loops with different working fluids. In addition, CHF prediction was conducted using LUT method based on established correlations to evaluate the expected CHF range under the designed experimental conditions. Overall, the proposed experimental facility offers a reliable platform for future high-resolution investigation of flow boiling heat transfer and CHF phenomena.

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