Distributed Optical Fiber Measurement of Temperature Distributions at CHF in Pool Boiling using a Directly Heated Rod

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1. Introduction

Nuclear energy continues to play significant role in the global energy mix , currently supplying more than 10% of the world's electricity and providing reliable low-carbon baseload power in many countries. As efforts to achieve carbon neutrality accelerate, the demand for stable and clean energy sources is expected to increase, and nuclear power is projected to remain an important component of future energy systems. In particular, the development of advanced reactors and small modular reactors(SMRs) has further emphasized the need for improved understanding of thermal-hydraulic safety phenomena under various operating conditions. Boiling heat transfer is a governing thermal-hydraulic phenomenon in nuclear systems and directly influences the thermal safety margins of nuclear fuel rods. In particular, Critical Heat Flux (CHF) represents a key thermal limit that can result in rapid surface temperature increase and potential cladding failure. Accurate understanding of the thermal behavior leading to CHF is essential for nuclear safety evaluation and thermal-hydraulic modeling. Previous studies have primarily relied on point-based temperature measurements such as thermocouples to investigate boiling heat transfer and CHF phenomena. While these approaches have provided valuable insights, they are limited in their ability to capture spatially non-uniform and transient thermal behavior along heated surfaces. Recent advances in optical fiber sensing offer the potential for distributed temperature measurements with high spatial resolution. Such techniques enable continuous temperature monitoring along heated surface and provide new opportunities to investigate spatial boiling behavior that has been difficult to observe experimentally.

The objective of this study is to investigate spatial temperature behavior during pool boiling on a directly heated rod using optical fiber sensing. By resolving axial temperature distributions and linking them to bubble transport and rewetting behavior, this work aims to provide improved physical insight into localized boiling phenomena relevant to CHF and nuclear thermal-hydraulic applications.

2. Methods

This section presents the experimental configuration and distributed temperature measurement approach, followed by key observations obtained under pool boiling conditions.

2.1 Pool Boiling Facility

A pool boiling facility was constructed using a stainless-steel test chamber equipped a visualization window, as shown in Fig. 1. A vertically oriented directly heated rod was installed at the center of the chamber to simulate rod-type heating conditions relevant to nuclear thermal-hydraulic studies. The heater rod had a diameter of 9.5mm and an effective heated length of 70mm. Electrical power was supplied using a DC power supply (SCR Rectifier, 75V 700A 62.5kW, SRTech., Korea) The heating system was designed such that electrical current was delivered through copper electrodes and directly introduced into an Inconel heater rod, enabling volumetric Joule heating within the rod. This configuration ensures stable high heat flux generation and provides a realistic representation of directly heated rod conditions for boiling heat transfer experiments.

Table I: Test matrix for the pool boiling experiments.

Subcooling (°C)	***Pressure (bar)***
0	***1***
10	
20	
30	
40	
50	

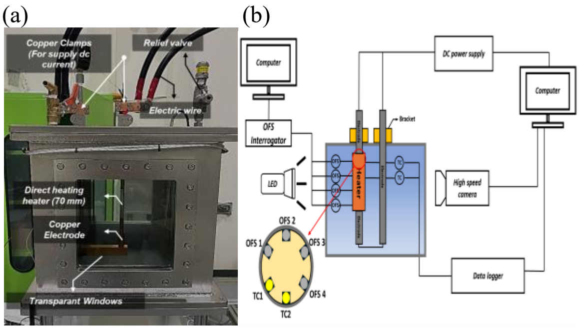

Fig. 1. (a) Pool boiling test facility and (b) P&ID of the experimental system.

2.2 Distributed Temperature Measurement

An optical fiber sensor was installed along the axial direction of the heater to obtain spatially continuous temperature measurements. A distributed optical fiber sensing system (ODiSI 7101, Luna, USA) with a sensor gage pitch of 1.3mm and a measurement rate of 62.5 Hz was used in this study. This configuration enables high spatial resolution temperature acquisition compared with conventional point-based thermocouple measurements. Thermocouples were additionally used to obtain reference temperature data.

3. Results

3.1 Axial Temperature Behavior

Representative distributed temperature profiles obtained from optical fiber measurements are shown in Fig.2. The data indicate axial temperature variations along the directly heated rod under increasing heat flux conditions.

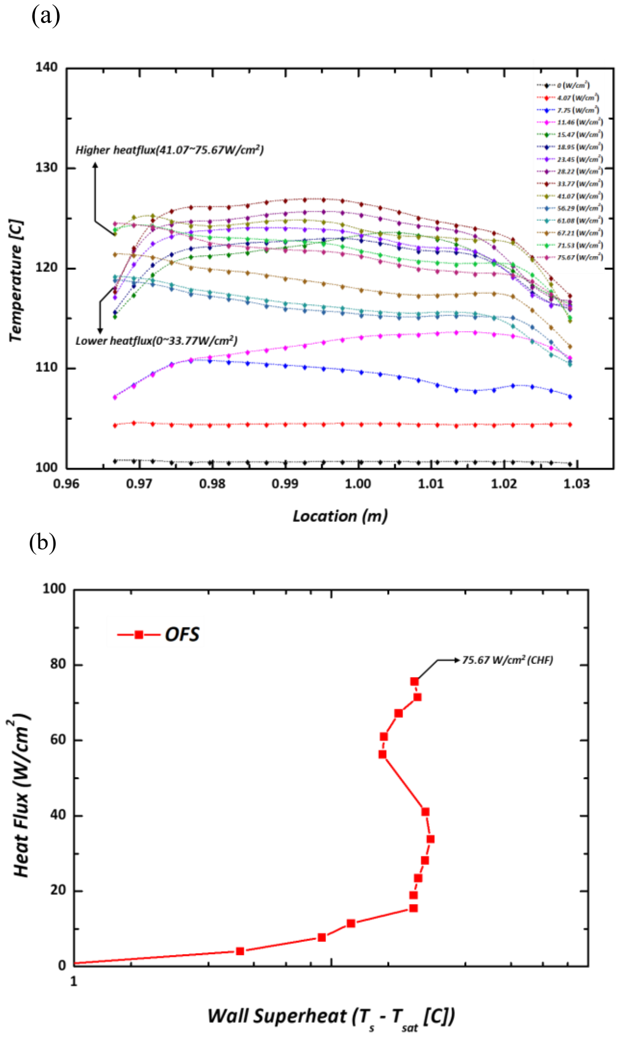

Fig. 2. (a) Axial temperature distributions and (b) corresponding boiling curve along the directly heated rod.

At relatively low heat flux conditions (0~33.77W/cm^2), bubble nucleation was primarily initiated near the lower region of the heater. The generated bubbles were transported upward by buoyancy-driven natural convection, sliding along the heater surface before departing into the bulk liquid. Under these conditions, limited vapor coverage was observed near the upper region of the heater, enabling effective liquid rewetting and resulting in relatively lower surface temperatures at higher axial locations.

As the heat flux increased(41.07~75.67W/cm^2), bubble size and interaction frequency increased substantially. Larger vapor structures tended to slide upward along the heater surface, leading to increased bubble crowding in the upper region. This behavior locally suppressed liquid rewetting near the upper section of the rod, resulting in elevated surface temperatures observed in the optical fiber measurements.

3.2 Boiling Visualization

To support interpretation of the distributed temperature measurements, visualization of boiling behavior was performed at elevated heat flux conditions, as shown in Fig. 3. The visualization captures large vapor structures and bubble coalescence along the heated rod surface.

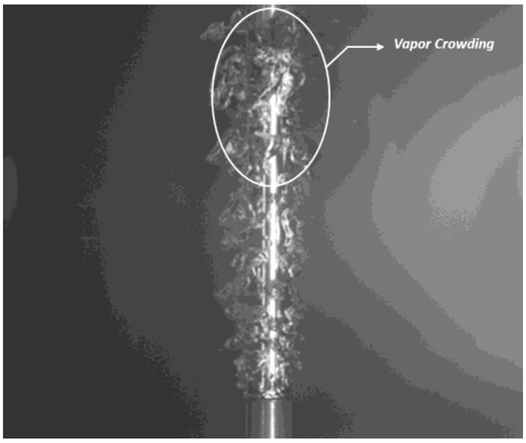

Fig. 3. Boiling visualization at elevated heat flux(67.21W/cm^2), highlighting large vapor structures and bubble coalescence along the heated rod.

These visual observations provide qualitative support for the spatial boiling behavior inferred from distributed temperature measurements. In particular, the observed upward bubble motion and vapor accumulation along the heater surface are consistent with the axial temperature variations identified from the optical fiber data. The visualization suggests that bubble sliding and localized vapor crowding contribute to reduced liquid rewetting in the upper region, supporting the interpretation of elevated surface temperatures at higher axial locations.

4. Conclusions

This study demonstrated that optical fiber sensing can be used to measure spatially resolved temperature distributions along a directly heated rod under pool boiling conditions. The measurements suggested axial temperature non-uniformities associated with bubble transport along the heated surface. The results suggest that localized temperature variations can arise from bubble sliding and reduced liquid rewetting, particularly at higher heat flux conditions relevant to CHF phenomena. These findings highlight the value of distributed temperature measurements for understanding spatial boiling behavior in nuclear thermal-hydraulic studies. Future work will focus on subcooling experiments and on extending the distributed sensing configuration by installing three optical fibers along the vertical heater. The measured signals will be processed in MATLAB to reconstruct a spatiotemporal temperature heat map over the entire heater surface, enabling time-synchronized comparison between the passage of large vapor structures and the local temperature drop and recovery behavior associated with rewetting.

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