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Coupled Analysis of High-Resolution Localized Temperature Measurement Using an Optical Fiber Sensor and Bubble Dynamics in Pool Boiling

Seoyeon Park [a], Hyeonmin Choi [a], Dong Eok Kim [b], Hyungmo Kim [a*]
[a] *School of Mechanical Engineering, Gyeongsang National Univ.*
[b] *School of Energy System Engineering, Chung-Ang Univ.*
Corresponding author: hyungmo@gnu.ac.kr

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1. Introduction

Boiling heat transfer is a fundamental process in various fields, including nuclear reactor cooling, electronic device cooling, and industrial heat exchangers. In particular, precise measurement of local heat transfer characteristics and bubble dynamics on boiling surfaces is essential for improving critical heat flux (CHF) prediction models and designing high-performance cooling systems. However, conventional measurement techniques have limitations in accurately capturing local temperature variations. Resistance-based measurement methods can only measure the average surface temperature, making it difficult to detect local temperature fluctuations [1]. Infrared thermography cameras (IR) also face challenges in emissivity correction [2]. Furthermore, thermocouple sensors measure the temperature of the surrounding fluid rather than the actual surface temperature, failing to provide accurate surface heat transfer data.

To address these issues, this study proposes a novel measurement technique using an Optical Fiber Sensor (OFS). The OFS utilized in this study employs Optical Frequency Domain Reflectometry (OFDR) technology and the principle of Rayleigh scattering, enabling precise local temperature measurements with a resolution of less than 1 mm [3]. Additionally, a gold-coated OFS is used as a wire heater, allowing simultaneous heating and measurement through Joule heating. Moreover, a high-speed camera is synchronized with a Luna sensor to measure bubble departure diameter and growth time. AI-based object detection techniques are applied to automatically track bubble formation and departure [4].

Through this study, the complex heat transfer phenomena on boiling surfaces are analyzed in detail, contributing to the improvement of CHF prediction models and the enhancement of boiling heat transfer performance.

2. Method

In this study, an OFS was utilized as a wire heater to quantitatively measure localized boiling heat transfer characteristics. The system was designed to enable real-time surface temperature measurement using Joule heating. For precise data acquisition, the ODiSI 6000 model from Luna was employed as the OFS data collection system, and the experimental setup was configured as shown in Fig. 1.

During the experiment, thermocouples were used to monitor the internal temperature of the water tank, ensuring thermal stability. Additionally, silver paste was applied to minimize contact resistance between the sensor and electrodes, with the final measured resistance confirmed as 0.81 Ω.

This study provides a detailed analysis of heat transfer mechanisms on boiling surfaces, contributing to the improvement of Critical Heat Flux (CHF) prediction models and the enhancement of boiling heat transfer performance.

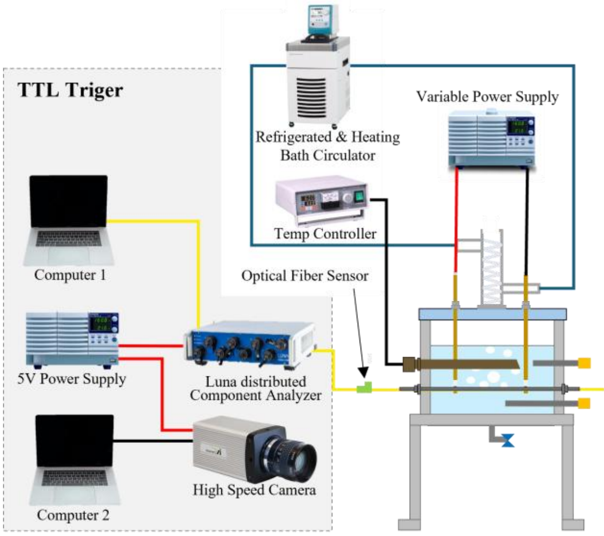


Fig. 1. Scheme of Pool Boiling Experimental Facility

The working fluid used in the experiment was deionized water (DI Water), which was heated using a cartridge heater to approximately 100°C to create a saturated boiling environment. The initial heat flux through the wire heater was set to 100 kW/m², and during the experiment, it was gradually increased by 50 kW/m² every 5 minutes to evaluate the boiling characteristics under varying heat flux conditions. The optical fiber sensor used in this study had a diameter of 0.155 mm and a gage pitch of 0.65 mm.

For a precise analysis of boiling dynamics, a high-speed camera was employed to capture real-time bubble dynamics. The camera operated at 1250 frames per second (fps) to accurately record the bubble behavior.

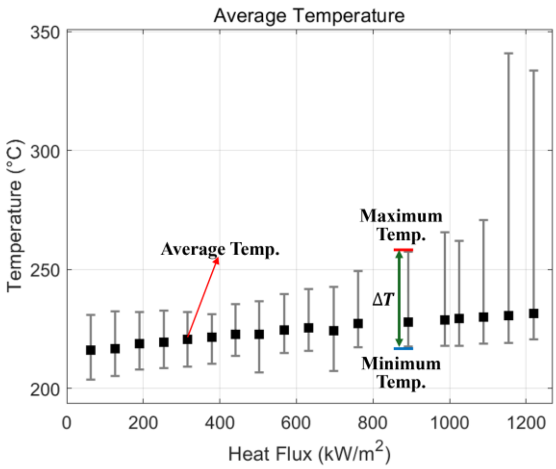
Item	Description	Remarks
Length	1 m	Short length enables fast response time
Measurement Rate (Max)	125 Hz	Real-time high-speed measurement possible

Table. 1. Sensor Response Characteristics

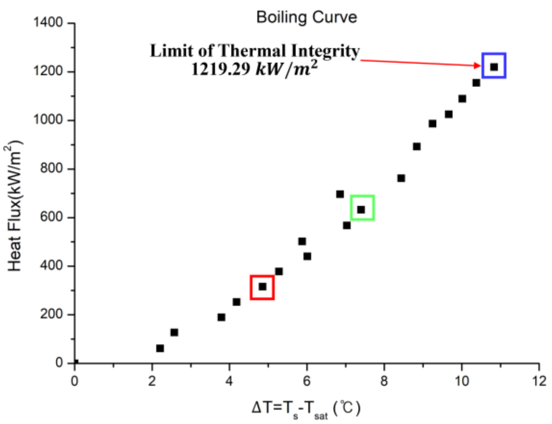
Sensor response speed is a critical factor in environments with rapid temperature changes. This sensor has a short length of 1 meter, which allows for fast thermal conduction, and supports a high measurement rate of up to 125 Hz for real-time temperature data acquisition. In this experiment, OFS data was acquired at 31.25Hz, allowing synchronized comparison with high-speed camera footage.

Through this study, the complex heat transfer phenomena on boiling surfaces are analyzed in detail, contributing to the improvement of CHF prediction models and the enhancement of boiling heat transfer performance.

3. Result



(a)



(b)

Fig. 2. Graph of average temperature and boiling curve
(a) Average Temperature
(b) Boiling Curve

Fig. 2 (a) Average Temperature graph represents the average surface temperature under different heat flux conditions, allowing observation of the maximum and minimum temperature values at each heat flux level. As shown in the graph, the deviation from the average temperature increases as the heat flux rises, indicating greater temperature variations.

Fig. 2 (b) Boiling Curve illustrates the relationship between heat flux and surface superheat. The experimental results align with the typical nucleate boiling behavior, showing that as the heat flux increases, the surface superheat also rises.

In summary, higher heat flux leads to greater temperature variations across the surface, which correlates with increased boiling intensity. Furthermore, when compared to the boiling curve, the experimental results follow nucleate boiling behavior, demonstrating that surface superheat increases with rising heat flux.

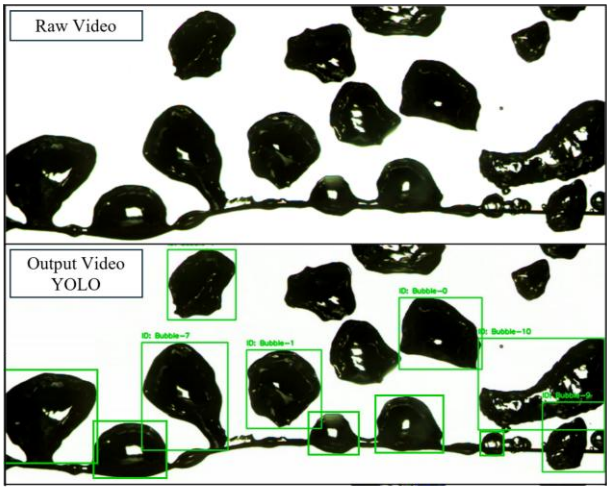


Fig. 3. AI-Based Measurement of Bubble Departure Diameter from High-Speed Imaging at 1219.29 kW/m²

Fig. 3. presents the analysis results obtained from an AI model developed to automatically measure bubble diameters using high-speed imaging. A deep learning-based object detection algorithm, YOLO (You Only Look Once), was adopted and implemented through the Ultralytics library. The detected bubbles were subjected to image preprocessing using OpenCV (cv2), after which their diameters were quantitatively extracted. This approach enables precise and real-time measurement of the morphological and dimensional variations of individual bubbles generated on the boiling surface. Furthermore, compared to traditional manual or threshold-based methods, the proposed technique offers enhanced consistency, improved processing speed, and greater applicability in the quantitative analysis of complex boiling phenomena.

Fig. 4. compares the variations in bubble departure diameter, as a function of heat flux based on the measured data. The experimental results indicate a trend of increasing bubble size with rising heat flux. This

phenomenon reflects the acceleration of bubble growth and departure processes under high heat flux conditions, resulting in the bubbles growing large.

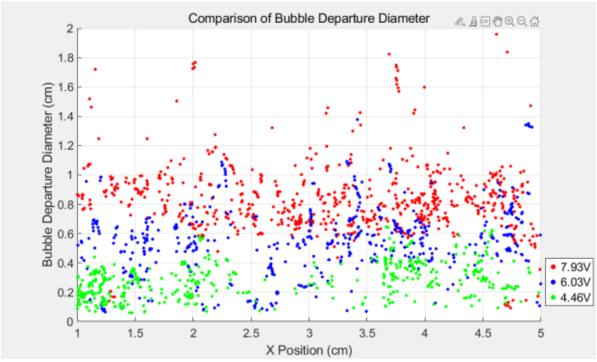


Fig. 4. Comparison of Bubble Departure Diameter at Different Locations as a Function of Heat Flux

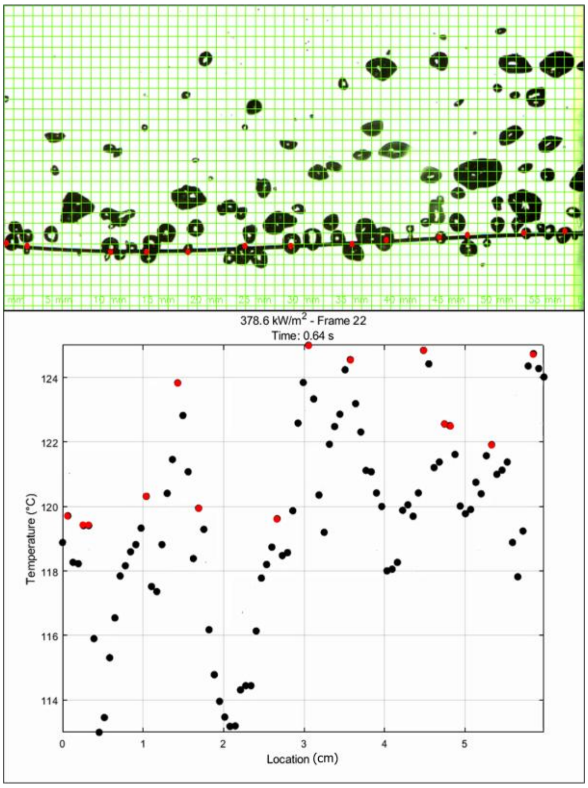


Fig. 5. Comparison of Bubble Dynamics and Temperature Distribution at 315.71 kW/m² Heat Flux

Fig. 5 presents an analysis of the local temperature distribution on the boiling surface. The results show that regions where bubbles formed had relatively high temperatures, while areas without bubbles exhibited lower temperatures. This pattern implies that localized heat transfer characteristics during bubble formation and departure influence the surface temperature distribution.

Notably, continuous bubble generation was observed in high-temperature regions, which can be attributed to localized superheating that promotes bubble nucleation and growth. Conversely, in lower-temperature regions, bubble formation was rarely detected, suggesting that heat transfer remained relatively stable. These findings confirm a strong correlation between bubble formation, dynamics, and localized surface temperature variations.

4. Conclusion

This study demonstrated that bubble growth and departure on a fully boiling heated surface are closely related to localized temperature variations and that increasing heat flux intensifies temperature distribution non-uniformity. In particular, localized superheating was observed in regions where bubbles formed. As heat flux increased, bubbles grew larger, coalesced, and caused abrupt changes in temperature distribution.

Additionally, real-time OFS-based localized temperature measurements were integrated with AI-driven high-speed video analysis. This approach enabled precise quantification of bubble departure diameter and growth rate. The correlation between surface temperature data and bubble dynamics was also examined.

AI-based object detection was used to automatically track bubble shape and behavior from high-speed imaging. This method ensured high reliability in the collected data. The results showed that bubbles grew faster and had larger departure diameters in high-temperature regions. This finding indicates that localized superheating significantly affects heat transfer characteristics and boiling intensity.

Through this study, the quantitative relationship between surface temperature distribution and bubble dynamics was clarified. This contributes to a more detailed understanding of boiling heat transfer mechanisms. Future research will focus on refining boiling conditions, evaluating heat transfer characteristics for different fluids and surface materials, and analyzing how bubble morphology and dynamic behavior impact heat transfer performance.

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