

Uncertainty Analysis of Wall-Temperature Measurement using Distributed Optical Fiber Sensors

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ABSTRACT

This study presents an uncertainty evaluation of optical fibre sensor (OFS)-based wall-temperature measurement under steady-state conditions. The representative analysis was performed for the 50 °C condition, and the wall temperature was defined as the 3-min averaged value at the OFS point corresponding to the reference thermocouple location. The total uncertainty was separated into bias and precision components. The bias terms considered in this study were the uncertainty associated with the reference thermocouple accuracy, the OFS temperature-conversion and data-acquisition process, and the local spatial nonuniformity or location mismatch around the representative OFS point. The precision terms included the within-run uncertainty of the 3-min steady-state average and the repeatability error obtained from five repeated tests. The combined bias error and combined precision error were evaluated as 1.6001 °C and 0.0223 °C, respectively, resulting in an overall uncertainty of 1.6003 °C for the OFS-based wall-temperature measurement. The results showed that the overall uncertainty was strongly dominated by the bias component, whereas the precision-related contributions were relatively small. Among the quantified terms, the reference thermocouple accuracy and the OFS temperature-conversion process were identified as the dominant contributors to the total uncertainty. These findings indicate that further improvement of OFS-based wall-temperature measurement should focus primarily on reducing bias-related terms, particularly through improved reference thermocouple accuracy and refinement of the OFS frequency-to-temperature conversion procedure. The present study provides a practical uncertainty-evaluation framework for OFS-based wall-temperature measurement and may serve as a basis for further refinement of OFS temperature-conversion and measurement-location modelling.

Keywords: Uncertainty Analysis, Distributed Optical Fiber Sensor, Rayleigh Backscattering, Bias Error, Precision Error

1 INTRODUCTION

Wall temperature is one of the most important parameters in thermal-hydraulic experiments because it is directly related to local heat transfer behaviour, boundary conditions, and the thermal response of the test section. In particular, when axial temperature distributions or local thermal non-uniformities must be resolved, the accuracy of wall-temperature measurement has a direct influence on the reliability of the experimental results. Thermocouples have long been used for wall-temperature measurements because of their simple structure and ease of implementation. However, thermocouples provide temperature data only at discrete locations and therefore have inherent limitations in resolving continuous wall-temperature distributions, especially in narrow test sections where a large number of measurement points is required.

Distributed optical fibre sensing has attracted attention as an alternative to conventional pointwise measurement because continuous temperature information can be obtained along a single sensing line [1]. In particular, Rayleigh-backscattering-based optical fibre sensors can provide

temperature data with high spatial resolution, making them suitable for resolving axial temperature gradients and local thermal non-uniformities [2]. The applicability of fibre-optic temperature sensing has also been demonstrated in nuclear thermal systems [3,4]. However, the availability of distributed measurement does not necessarily guarantee accurate wall-temperature evaluation. In practical thermal-hydraulic experiments, the measured OFS temperature may be influenced by the accuracy of the reference instrumentation, the frequency-to-temperature conversion procedure, the selection of the representative comparison location, and the actual installation configuration of the fibre. Therefore, the reliability of OFS-based wall-temperature measurement should be examined not only in terms of spatial resolution but also in terms of measurement uncertainty [5].

The present study focuses on the uncertainty evaluation of OFS-based wall-temperature measurement under steady-state conditions. Repeated tests were conducted at 10 °C, 25 °C, and 50 °C, and the final uncertainty analysis was performed using the 50 °C condition as the representative case. The representative wall temperature was defined as the 3-min averaged value at the OFS measurement point corresponding to the reference wall thermocouple location. The total uncertainty was separated into bias and precision components, and the major contributions were quantified on the basis of the reference thermocouple accuracy, the OFS temperature-conversion and data-acquisition process, the local spatial non-uniformity around the representative OFS point, the within-run steady-state fluctuation, and the run-to-run repeatability. Through this approach, the present study aims to organise an uncertainty-evaluation procedure applicable to OFS-based wall-temperature measurement.

2 EXPERIMENTAL SETUP

2.1 Test section and instrumentation layout

The present experiment was conducted to evaluate the applicability and measurement uncertainty of OFS-based wall-temperature measurement in a pipe-type test section. Reference wall thermocouples were installed on the outer surface of the test section, and a Rayleigh-backscattering-based OFS was applied along the same section to enable distributed temperature measurement. This arrangement allowed a direct comparison between the conventional pointwise wall-temperature measurement and the distributed OFS measurement within the same test section.

The wall thermocouples were used to provide the reference wall-temperature values and served as the primary basis for comparison with the OFS data. Since the OFS provided continuous temperature information along the axial direction of the test section, representative OFS temperatures were defined by selecting the OFS points corresponding to the axial locations of the wall thermocouples. Through this position-matching procedure, the local wall-temperature measurements obtained from the OFS were compared directly with those from the reference wall thermocouples. Additional thermocouples were also installed to measure the fluid temperature; however, these data were used only for supplementary interpretation of the local thermal condition inside the test section and were not used as the reference for the wall-temperature uncertainty evaluation in the present study.

Repeated tests were performed at 10 °C, 25 °C, and 50 °C, and steady-state data were obtained for each condition. Among these cases, the final uncertainty evaluation was conducted using the 50 °C condition as the representative case. Accordingly, the instrumentation layout in the present study was designed to enable a direct comparison between the reference wall thermocouples on the outer surface of the test section and the corresponding OFS data at matched axial locations, which served as the basis for quantifying the bias and precision errors of the OFS-based wall-temperature measurement.

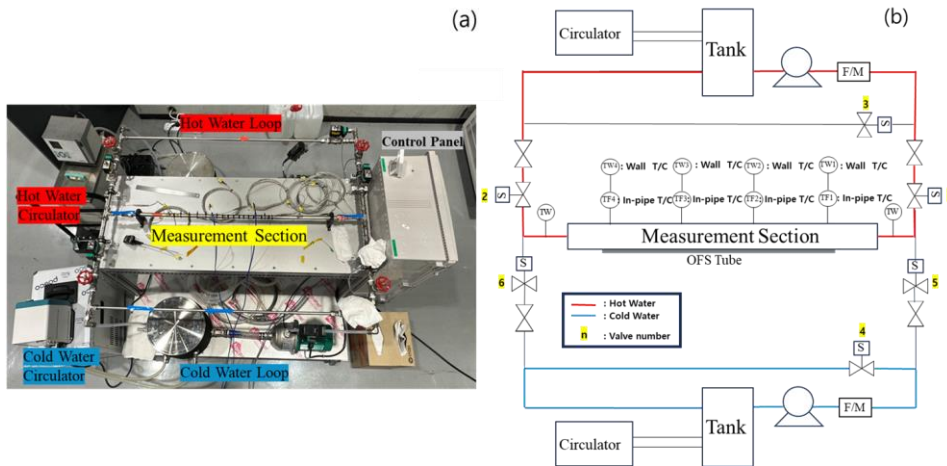


Figure 1: Experimental setup and test loop schematic: (a) Facility Photograph, and (b) Loop Schematic.

2.2 OFS installation configuration

In the present study, a Rayleigh-backscattering-based OFS was applied to measure the wall-temperature distribution along the outer surface of the test section. The OFS was installed inside an STS capillary tube for mechanical protection. As shown in Figure 2(a), the optical fibre was placed within the metallic capillary and applied to the test section in this configuration. The final confirmed outer and inner diameters of the STS capillary tube were 0.6 mm and 0.3 mm, respectively. In addition, the end of the OFS sensing line was configured in the form of a loop-shaped termination, as shown in Figure 2(b). The uncertainty analysis in the present study was performed using the coated OFS configuration, and the representative temperature was extracted from the OFS point corresponding to the location of the reference wall thermocouple.

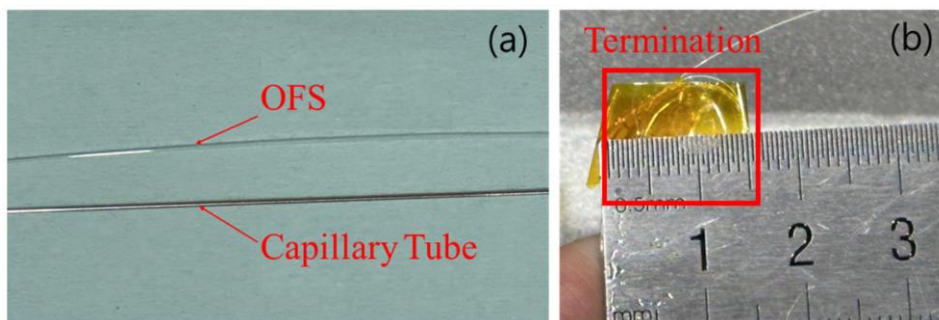


Figure 2 : Close-up views of the OFS configuration: (a) OFS and STS capillary tube, and (b) loop-shaped termination

2.3 Measurement conditions and data acquisition

The measurements in the present study were conducted under steady-state conditions at 10 °C, 25 °C, and 50 °C. Repeated tests were performed at each condition to obtain the temperature responses of the OFS and the reference wall thermocouples, and the final uncertainty analysis was carried out using the 50 °C condition as the representative case. In the present study, the representative

wall temperature was defined as the 3-min averaged value at the OFS point corresponding to the location of the reference wall thermocouple. The OFS signal was acquired using an ODiSI interrogator, and temperature data from the OFS and the reference wall thermocouples were collected during the steady-state period. For each repeated test, a stabilised 3-min interval was selected to determine the representative temperature, and the comparison between the reference thermocouple and the OFS measurement was performed on this basis. The steady-state data obtained from the repeated tests were subsequently used as the basis for the uncertainty evaluation by separating the bias and precision components. The quantitative uncertainty analysis in the present study was performed using the coated OFS configuration.

3 DATA REDUCTION AND TEMPERATURE CONVERSION

3.1 Frequency-to-temperature conversion

The OFS signal used in this study was acquired in the form of raw frequency data using an ODiSI 6 series interrogator and was subsequently converted into temperature using the frequency-to-temperature relation provided by LUNA. In this study, the manufacturer-provided conversion equation was applied directly to the raw OFS signal, and no additional empirical correction or curve fitting was introduced. The OFS temperature was calculated using Eq. (1).

$$T = T_0 - 0.667 \times f - 8.18 \times 10^{-5} \times f^2 \quad (1)$$

Here, T is the converted temperature, f is the measured frequency change, T_0 and is the reference temperature at the moment when tare was applied. In this study, T_0 does not simply represent room temperature, but rather the reference temperature at the time of tare after the low-temperature condition had sufficiently stabilised. Therefore, the tare reference temperature acts as a reference value that directly affects the converted OFS temperature.

The OFS temperature data obtained through this procedure were subsequently used for comparison with the wall thermocouple measurements. In the present analysis, the OFS point corresponding to the reference wall thermocouple location was selected, and the 3-min averaged value at that point was defined as the representative OFS temperature for the subsequent wall-temperature comparison and uncertainty evaluation.

3.2 Processing of Distributed OFS Data

While thermocouples provide pointwise temperature measurements at discrete locations, the OFS provides continuous temperature data along the sensing line. Therefore, in order to compare the OFS measurement directly with the reference wall thermocouple, it was necessary to select the OFS data corresponding to the thermocouple location. In this study, the OFS point corresponding to the axial location of the reference wall thermocouple was selected, and the temperature at that point was defined as the representative OFS temperature. For each repeated test, the OFS temperature data at the selected point were extracted over the stabilised 3-min interval, and the averaged value over this period was used as the representative temperature for comparison with the reference thermocouple.

In addition, the temperatures at the adjacent front and rear OFS points around the representative point were also examined. This was done to assess the possible effect of slight position mismatch between the thermocouple location and the selected OFS point, as well as the presence of local spatial temperature non-uniformity. These neighbouring OFS data were later used in the uncertainty analysis to evaluate the bias associated with location mismatch and spatial non-uniformity. Accordingly, the data processing in this study was not limited to distributed-data reduction, but also included a representative point-selection procedure for direct comparison between the reference wall thermocouple and the OFS measurement.

3.3 Steady-State Data Processing

The uncertainty evaluation in this study was based on data obtained from repeated steady-state tests. Stabilised temperature intervals were selected from the measurements conducted at 10 °C, 25 °C, and 50 °C, and a consistent 3-min interval was extracted for each repeated test. The averaged temperatures of the reference wall thermocouple, the representative OFS point, and the adjacent front and rear OFS points were then calculated over the selected interval. These steady-state averaged data were used for the direct comparison between the OFS measurement and the reference wall thermocouple and served as the basis for the subsequent uncertainty evaluation in terms of bias and precision. Although repeated tests were conducted at three temperature conditions, the final overall uncertainty evaluation was performed using the 50 °C data as the representative case.

4 UNCERTAINTY ANALYSIS

4.1 Uncertainty Framework

In this study, the uncertainty of the OFS-based wall-temperature measurement was evaluated by separating the total error into bias error and precision error [6]. The final uncertainty analysis was performed using the 50 °C condition as the representative case. Although repeated measurements were also conducted at 10 °C and 25 °C, the 50 °C condition was selected because the main objective of this study is the evaluation of wall temperature under relatively high-temperature conditions. For each repeated test, the representative wall temperature was defined as the 3-min averaged value at the selected OFS measurement point corresponding to the reference thermocouple location. The bias terms were defined to account for systematic deviations in the temperature measurement system, including the reference thermocouple accuracy bias, the data-acquisition bias, and the bias associated with local spatial nonuniformity or location mismatch around the representative OFS point. The precision terms were defined to represent the statistical variability of the measured temperature and included the within-run uncertainty of the 3-min steady-state average and the repeatability error obtained from five repeated tests. In this study, the bias terms associated with wall-temperature measurement are denoted by B_T, while the precision terms associated with wall-temperature measurement are denoted by P_T.

$$U_T = \sqrt{B_T^2 + P_T^2} \quad (2)$$

where B_T is the combined bias error and P_T is the combined precision error. The combined bias error was calculated from the root-sum-square of the quantified individual bias terms, while the combined precision error was determined from the within-run steady-state fluctuation and the run-to-run repeatability [6,7]. For the selected 50 °C condition, the combined bias error was evaluated as 1.6001 °C, and the combined precision error was 0.0223 °C. Therefore, the overall wall-temperature uncertainty was estimated to be 1.6003 °C. These results indicate that the uncertainty of the present OFS-based wall-temperature measurement is strongly dominated by the bias component rather than the precision component.

4.2 Definition and Quantification of Bias Error Terms

In this study, the systematic deviations associated with the OFS-based wall-temperature measurement were defined as bias error terms and quantified individually. Bias errors represent non-random components that may appear in a consistent direction due to instrument accuracy, the data-acquisition process, and the selection of the representative measurement location. For the selected 50 °C condition, the major bias components considered in this study were the uncertainty associated

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with the reference thermocouple accuracy, the data-acquisition process, and the local spatial nonuniformity or location mismatch around the representative OFS point. Although the OFS frequency-to-temperature conversion procedure may also introduce additional uncertainty, it was not included as an independent quantified bias term in this study.

The first bias term, BWT1, represents the uncertainty associated with the accuracy of the reference thermocouple. Since an individual calibration certificate was not available for the thermocouple used in the present study, the general limit of error for a standard type K thermocouple was adopted. In the relevant temperature range, the allowable error was taken as ± 2.2 °C, and a rectangular distribution was assumed. Therefore, BWT1 was converted into a standard uncertainty form as $2.2/\sqrt{3}$, resulting in a value of 1.27 °C. The second bias term, BWT2, represents the systematic error associated with the data-acquisition process. In the present study, the value previously determined for this contribution was directly adopted, and BWT2 was taken as 0.95 °C. The third bias term, BWT3, represents the uncertainty associated with local spatial nonuniformity or location mismatch around the representative OFS point. To estimate this contribution, the 3-min averaged OFS temperatures at the representative point and its adjacent front and rear points were examined for each of the five repeated tests, and the largest local temperature spread was conservatively adopted. As a result, BWT3 was evaluated as 0.2123 °C. Accordingly, the combined bias error was determined using the three quantified terms, BWT1, BWT2, and BWT3, as follows:

$$B_T = \sqrt{BWT1^2 + BWT2^2 + BWT3^2} \quad (3)$$

Using the evaluated values of BWT1 = 1.27 °C, BWT2 = 0.95 °C, and BWT3 = 0.2123 °C for the 50 °C condition, the combined bias error was calculated to be 1.6001 °C. This result indicates that the overall uncertainty of the present OFS-based wall-temperature measurement is predominantly governed by systematic bias contributions.

Table 1: Bias components

Code	Description	Value [°C]
BWT1	Reference thermocouple accuracy bias	1.27
BWT2	Data-acquisition bias	0.95
BWT3	Location-mismatch / local spatial nonuniformity bias	0.2123
B_T	Combined bias error	1.6001

4.3 Definition and Quantification of Precision Error Terms

In the present study, the statistical variability of the OFS-based wall-temperature measurement was defined as the precision error and quantified through individual components. Unlike bias errors, which represent systematic deviations in the measurement system, precision errors represent the statistical dispersion of the measured values caused by temporal signal fluctuations during the steady-state period and by scatter among repeated tests. For the selected 50 °C condition, the major precision components considered in this study were the uncertainty of the 3-min steady-state average within a single run and the repeatability error obtained from five repeated tests.

The first precision term, PWT1, represents the uncertainty of the mean value within a single repeated test during the 3-min steady-state period. This term reflects the statistical uncertainty of the 3-min averaged temperature caused by small temporal fluctuations in the measured OFS signal under nominally identical conditions. In the present study, the sample standard deviation of the 3-min time-series data at the representative OFS point was first calculated for each repeated test, and the uncertainty of the averaged value was then evaluated using Student's t-distribution. Among the results obtained from the five repeated tests, the largest value was conservatively selected as the representative PWT1. As a result, PWT1 was evaluated as 0.0024 °C. The second precision term,

PWT2, represents the repeatability error among five repeated tests performed under the same condition. In the present study, the mean temperature difference between the reference thermocouple and the OFS measurement was calculated for each repeated test, and the sample standard deviation of these five values was obtained. Student's t-distribution was then applied to estimate the precision error of the mean value. As a result, PWT2 for the 50 °C condition was evaluated as 0.0221 °C. Accordingly, the combined precision error was determined by combining PWT1 and PWT2 as follows:

$$P_T = \sqrt{PWT1^2 + PWT2^2} \quad (4)$$

Using the evaluated values of PWT1 = 0.0024 °C and PWT2 = 0.0221 °C for the 50 °C condition, the combined precision error P_T was calculated to be 0.0223 °C. This result indicates that the absolute magnitude of the precision error in the present OFS-based wall-temperature measurement is very small and that the final uncertainty is mainly governed by the bias component.

Table 2: Precision components

Code	Description	Value [°C]
PWT1	Reference thermocouple accuracy bias	0.0024
PWT2	Data-acquisition bias	0.0221
P_T	Combined bias error	0.0223

4.4 Overall Uncertainty Estimation

In the present study, the overall uncertainty of the OFS-based wall-temperature measurement was estimated using the bias and precision errors quantified for the 50 °C condition. As evaluated in the previous sections, the combined bias error was $B_T = 1.6001$ °C, and the combined precision error was $P_T = 0.0223$ °C. The overall uncertainty was calculated according to Eq. (2), and the resulting overall uncertainty of the OFS-based wall-temperature measurement at 50 °C was 1.6003 °C. This value may be rounded and reported as 1.60 °C.

A comparison of the relative magnitudes of the bias and precision components shows that the combined bias error is significantly larger than the combined precision error. In other words, the overall uncertainty of the present OFS-based wall-temperature measurement is dominated by the bias component rather than the precision component. This indicates that the temporal fluctuation within the steady-state period and the statistical scatter among repeated runs were both relatively small. In contrast, the systematic contributions associated with the reference thermocouple accuracy, the data-acquisition process, and the selection of the representative measurement location had a much larger effect on the final uncertainty. Therefore, further improvement in the accuracy of the present OFS-based wall-temperature measurement should focus primarily on reducing the bias-related terms rather than the precision-related terms. In particular, improving the reference thermocouple accuracy and reducing the data-acquisition-related uncertainty are expected to be the most effective approaches for lowering the overall uncertainty.

Table 3: Summary of uncertainty components

Code	Description	Value [°C]
B_T	Combined bias error	1.6001
P_T	Combined precision error	0.0223
U_T	Overall uncertainty	1.6003

5 RESULTS AND DISCUSSION

In this study, an uncertainty evaluation was performed for OFS-based wall-temperature measurement by separating the total uncertainty into bias and precision components. The final analysis was conducted using the 50 °C condition as the representative case, and the representative wall temperature was defined as the 3-min averaged value at the OFS measurement point corresponding to the reference thermocouple location. Based on this framework, the major uncertainty sources associated with the OFS-based wall-temperature measurement were systematically identified and quantified. The bias error terms considered in this study included the uncertainty associated with the reference thermocouple accuracy, the data-acquisition process, and the local spatial nonuniformity or location mismatch around the representative OFS point. The precision error terms included the within-run uncertainty of the 3-min steady-state average and the repeatability error obtained from five repeated tests. As a result, the combined bias error was evaluated as 1.6001 °C, while the combined precision error was evaluated as 0.0223 °C. Accordingly, the overall uncertainty of the OFS-based wall-temperature measurement was estimated to be 1.6003 °C. The results indicate that the overall uncertainty of the present measurement is strongly dominated by the bias component rather than the precision component. The temporal fluctuation within the steady-state period and the scatter among repeated runs were both relatively small, whereas the systematic contributions associated with the reference thermocouple accuracy and the data-acquisition process had a much larger influence on the final uncertainty. In addition, the uncertainty related to local spatial temperature variation around the representative OFS point was found to be non-negligible.

These findings suggest that further improvement in OFS-based wall-temperature measurement should focus primarily on reducing the bias-related terms rather than the precision-related terms. In particular, improving the reference thermocouple accuracy and reducing the data-acquisition-related uncertainty are expected to be the most effective approaches for reducing the overall uncertainty. In addition, further refinement of the OFS frequency-to-temperature conversion procedure remains a subject for future work. Although an additional bias contribution associated with the heat-transfer path through the STS tube and coating layer may exist, it was not quantified separately in the present study because the relevant coating-thickness and thermal-resistance information were not sufficiently available. Future work should include these thermal-path effects and further refinement of the OFS temperature-conversion relation to establish a more comprehensive uncertainty-evaluation framework for OFS-based wall-temperature measurements.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. RS-2025-25445840), the Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Ministry of Climate, Energy & Environment (MCEE) of the Republic of Korea (No. RS-2024-00398425), and the Korea Planning & Evaluation Institute of Industrial Technology (KEIT) grant funded by the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. RS-2024-00444697).

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