Multipoint Temperature Measurement by Optical Fiber Sensor for Rationalization of Plant Condition Monitoring and Maintenance Planning

SHIGERU YOSHIDA*1 SHINICHIRO MORI*2
TAKASHI SAKAGUCHI*3 DAIKI MIYAMOTO*4
HIROTAKE KAWASHIMA*5 KAZUHIRO TAKEUCHI*6

Plant industries in the fields of power, chemical, oil, gas, etc., face problems such as aging equipment and a shortage of operators. Rational operation and maintenance based on condition monitoring and the maintenance of stable operations have become an issue. In response, Mitsubishi Heavy Industries, Ltd. has developed a multipoint temperature measurement technology that is useful for plant condition monitoring. This technology uses optical fiber thermometers with excellent heat resistance and can measure temperatures at multiple points with a single piece. For example, this technology enables early detection of abnormalities and optimization of inspection and renewal work when used to monitor the temperature of many heat transfer tubes used in thermal power generation boiler plants. In a long-term demonstration test being conducted on an actual boiler, it was confirmed that the technology can be installed at a lower cost in a shorter period of time than conventional technologies and that temperature distribution can be monitored during rated operation, and continuous measurement for more than one year was achieved. We will continue to verify the long-term durability and measurement performance of this technology and apply it to various plant equipment to contribute to solving the problems of condition monitoring and maintenance planning.

1. Introduction

In the power, chemical, oil, gas, and other plant industries, there is a need to respond to their industry-common problems and various environmental changes, such as aging equipment, aging operators and maintenance personnel, a shortage of human resources, a decline in the ability to pass on technology and skills, the development of a digital society, and the shift to a carbon-neutral society. Under these circumstances, companies in these industries are facing the need to continue stable plant operation with fewer personnel and limited maintenance costs compared to the past, and there is a growing need for early detection of abnormalities and rationalization of maintenance plans based on plant condition monitoring.

To address these issues related to stable plant operation, Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) developed a multipoint temperature measurement system that enables more efficient condition monitoring. This report presents an overview and features of the multipoint temperature measurement system using optical fiber thermometers, and then describes the concept of plant operation and maintenance utilizing the monitoring data, using a thermal power plant as an example. The status of a demonstration test using a boiler in operation and future prospects are also reported.

*1 Electron & Physics Research Department, Research & Innovation Center
*2 Research Manager, Manufacturing Technology Research Department, Research & Innovation Center
*3 Engineering Manager, Engineering Department, Steam Power Maintenance Innovation Business Division, Energy Systems
*4 Engineering Department, Steam Power Maintenance Innovation Business Division, Energy Systems
*5 Chief Manager, Engineering Department, Steam Power Maintenance Innovation Business Division, Energy Systems
*6 Engineering Manager, Business Department, Steam Power Maintenance Innovation Business Division, Energy Systems

2. Optical fiber thermometer

Technologies utilizing optical fibers as various sensors have been studied for a long time, and various optical fiber structures and measurement principles have been proposed to measure temperature, strain, pressure, vibration, etc. Some of them have been put into practical use for infrastructure monitoring of bridges, electric cables, etc. However, few optical fiber sensors can be used in high-temperature environments exceeding 300°C. On the other hand, MHI's products, such as power generation equipment and chemical plants, are used for long periods of time in harsh environments with high temperatures and high pressures. To apply optical fiber sensors to the condition monitoring of critical components of such products, it was necessary to improve the heat resistance of optical fibers. Therefore, MHI conducted joint research with the University of Adelaide and the University of South Australia, and developed an optical fiber thermometer with excellent heat resistance [(1)].

MHI's optical fiber thermometer is a sensor called an FBG (Fiber Bragg Grating) type. **Table 1** shows the characteristics of this optical fiber thermometer. When a laser beam is injected into the optical fiber, a light of specific wavelength is reflected at the FBG. By measuring this wavelength, which shifts with temperature, the optical fiber can be used as a temperature sensor. Arranging multiple FBGs with different reflection wavelengths in the longitudinal direction of an optical fiber enables temperature measurement at multiple points with a single optical fiber (**Figure 1**). Therefore, it is possible to improve the efficiency of sensor installation work and make a large-scale temperature measurement system at low cost.

Table 1 Features of optical fiber thermometer

Item	Specification
Temperature range	-200°C to 1,200°C
Temperature sensing part (FBG) size	Several millimeters
Number of measurement points on single fiber	Dozens of points (depending on measurement device specifications and temperature range measured)
Measurement cycle	1 to 60 seconds
Measurement device	Commercially available interrogators for FBG can be used
Data visualization	Real-time display on local and cloud dashboards
Other	Good immunity to electromagnetic interference, Remote configuration changes and maintenance

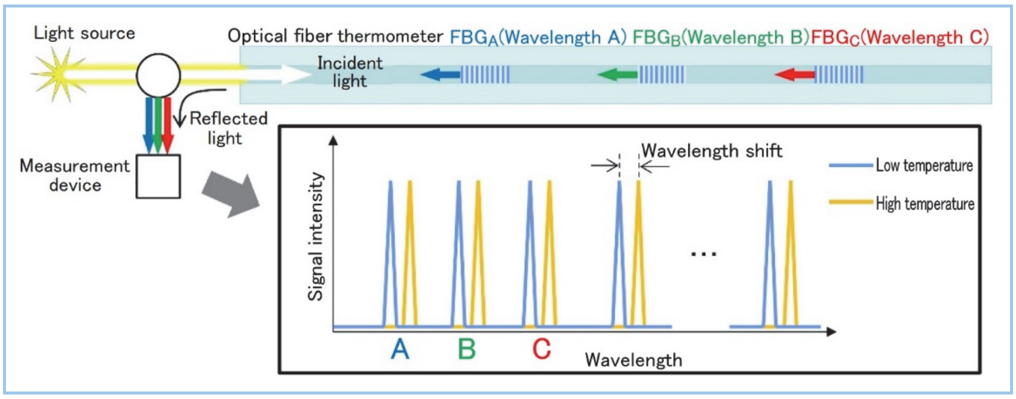

Figure 1 Principle of optical fiber thermometer (FBG type)

One of the best features of the MHI's optical fiber thermometer is that it has high heat resistance to operate in ultra-high temperature environments of 1,000°C or higher by drawing FBG on the optical fiber of special structure using a special process [(2)]. In addition, since no electrical signals are used, the optical fiber thermometer can be used even in locations where electromagnetic interference may be a concern. Furthermore, a large amount of measured time-series temperature data can be collected and visualized through MHI's or the customer's cloud or remote monitoring infrastructure, enabling real-time condition monitoring and analysis of equipment. Also, the FBG used in MHI's optical fiber thermometer is a "discrete" sensor in which multiple temperature-sensitive sections of several millimeters in length are arranged along the longitudinal direction of the fiber. On the other hand, another type of optical fiber thermometer called "distributed" measures the average temperature every several hundred millimeters (**Figure 2**). Therefore, in the case of the distributed type, a relatively long area must be in contact with the measuring object. In the case of our company's optical fiber thermometer, only the temperature-sensitive section needs to be fixed locally, which provides good workability.

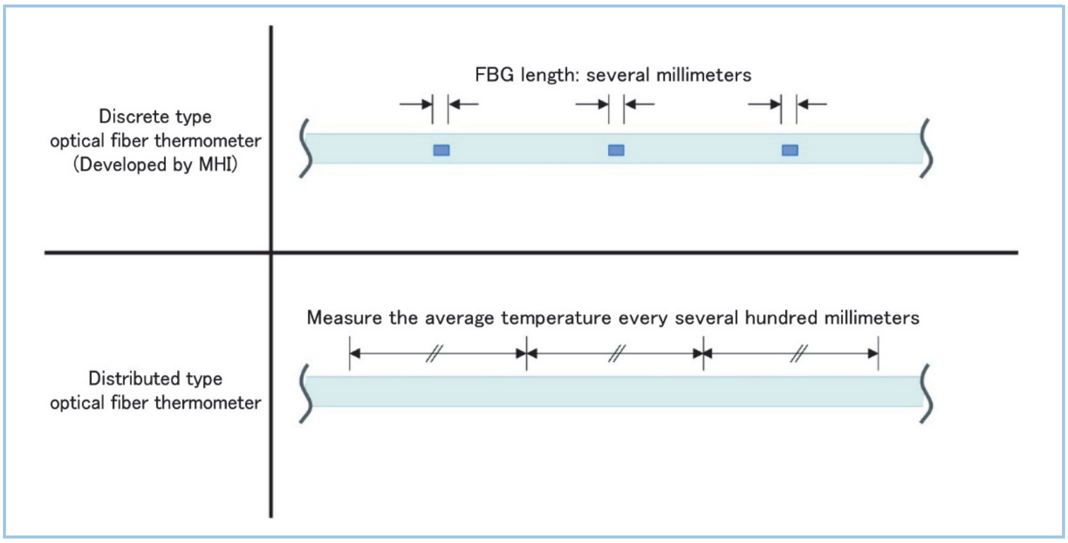

Figure 2 Differences in optical fiber thermometers by type

3. Utilization of multipoint temperature data in thermal power generation plants

Under the Ordinance for Enforcement of the Electricity Business Act, which was revised in 2017, thermal power plants can extend the periodic operator's inspection (currently, periodic voluntary inspections) period up to six years, provided that advanced and adequate maintenance management is implemented in addition to having an adequate inspection system. On the other hand, with the ongoing shift from thermal power generation to renewable energy sources as a countermeasure against global warming, and the difficulty of making large-scale capital investments in thermal power generation, ensuring efficient maintenance of aging equipment has become more important than ever before. This chapter describes how multipoint temperature measurement data can be used in thermal power plants (boilers) during operation and periodic inspections, respectively.

3.1 Condition monitoring during operation and operational enhancement

An important point during operation is to accurately monitor the condition of equipment to ensure proper operation and to detect problems and their signs at an early stage. By increasing the number of monitoring points using multipoint temperature measurement, it is made possible, for example, to grasp the detailed metal temperature distribution in the boiler's pressure-resistant section, thereby reducing the risk of overlooking abnormal overheating that can lead to boiler heat transfer tube creep damage leakage (resulting in long-term boiler stoppage) (**Figure 3**). Furthermore, with MHI's intelligent solution TOMONI® [3], it is possible to provide optimal operational guidance and to equalize temperature deviations to extend the service life of pressure resisting parts based on remote monitoring data and control status data for the entire plant.

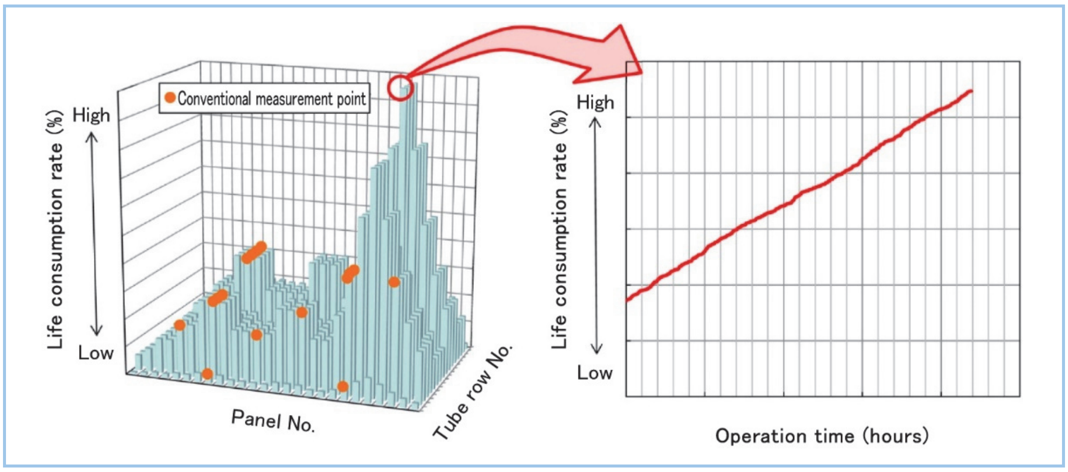

Figure 3　Schematic of detailed monitoring of boiler pressure resisting part metal temperature

In recent years, there have been cases of switching to various types of coal to reduce fuel costs, and cases of high-frequency load-fluctuation operation due to the spread of renewable energy sources. In addition, biomass co-firing and, in the future, ammonia co-firing are being considered for carbon neutrality. In these cases where the fuels and operations are diversified, understanding the combustion conditions and metal temperatures in detail is effective for high-efficiency operation with optimal operation of soot blowers (ash removal equipment using steam injection) for higher efficiency, prevention of problems, and stable operation, and can also contribute to CO_2 emissions reduction.

3.2　Rationalization of inspection and repair work in periodic inspections

During periodic inspections of boilers, visual inspections and nondestructive inspections are conducted on the heat transfer tubes and headers in high-temperature areas for the purpose of detecting creep damage, high-temperature oxidation thinning, fatigue damage, etc., at an early stage. If the inspection reveals significant damage, a detailed evaluation is conducted to estimate the remaining service life, and a decision is made on how to deal with the damage. In the planning and execution of inspection and repair work, it is important to identify the damaged areas and determine the inspection range. However, visual inspections have the risk of overlooking aged deterioration of the material. The issues also include the difficulty to conduct precise inspections of a large number of heat transfer tubes in a limited work period. Utilizing multipoint temperature measurement data to understand the deterioration state in more detail can avoid the risk of overlooking the inspection range and reduce inspection costs and work period by optimizing excessive inspections. In addition, not only by using temperature data, but also by comprehensively combining them with inspection results and operating conditions, the accuracy of life evaluation is improved, contributing to the establishment of maintenance plans.

Figure 4 schematically summarizes the rationalization of inspection quantities and maintenance plans through the implementation of multipoint temperature measurement. While a large number of inspections were necessary to properly assess the risk of damage due to the limited measurement data in the past, multipoint measurement enables a detailed understanding of a wide range of deterioration conditions, making it possible to plan the minimum necessary number of inspections at the appropriate time. In addition, by combining detailed inspections with damage risks evaluated based on multipoint measurements in each periodic inspection, the replacement quantities can be minimized and carrying over of work to the next periodic inspection can be done, enabling work to be leveled out. As a result, the number of critical work days is reduced, making it possible to shorten the total shutdown period more than before.

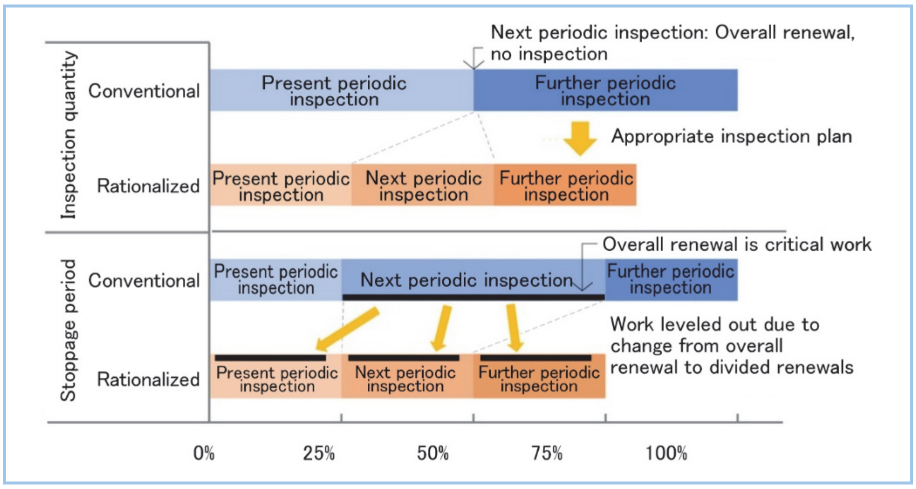

Figure 4 Reduction of inspection quantity and stoppage time

4. Demonstration test

4.1 Test status

This chapter describes the status of the demonstration test being conducted on a coal-fired boiler (650 MW Mitsubishi supercritical sliding pressure operation once-through boiler, radiant reheat type) to verify the measurement accuracy and long-term durability of the optical fiber thermometer in an actual plant operating environment. The tertiary superheater outlet header tube nozzle of the boiler is a pressure-resistant component that is used at the highest temperature in the superheater system and has approximately 700 tubes, making its life management difficult. In the demonstration test, an optical fiber thermometer was installed in the width direction of the furnace at the tertiary superheater outlet header tube nozzle in the boiler ceiling housing as shown in **Figure 5**. By inserting a heat-resistant optical fiber including the temperature-sensing part (FBG sensor) inside a metal protective tube, the fiber is protected from external forces and dust, and is easy to handle during installation. To accurately measure the metal temperature of the tube nozzle, the optical fiber contained in the metal protection tube was fixed to the tube nozzle surface using a special fixing method. And, regarding the laying of the fiber except for the sensor part, a route which is hardly affected by the thermal elongation of the structure with the temperature rise was adopted.

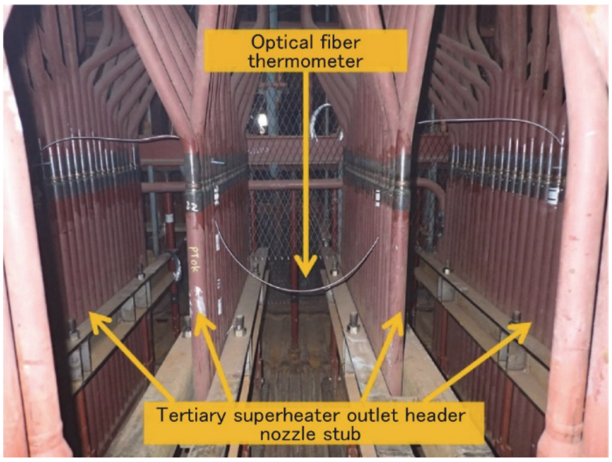

Figure 5 Installed optical fiber thermometer

4.2 Measurement system configuration and measurement example

Figure 6 shows the configuration of the multipoint temperature measurement system during the demonstration test. The optical fiber thermometer was drawn out of the furnace and connected to a measurement device installed in an on-site rack via an extension cable. The measurement device may be a commercially available one for FBG sensors. In this test, an interrogator EFOX-1000B (manufactured by Kyowa Electronic Instruments), which has a wide wavelength bandwidth of 160 nm, was used. The measurement device is controlled by an industrial edge computer, and the measurement data is transmitted to the TOMONI® server via Secure Sockets Layer (SSL) communication through an LTE router. In addition, the on-site rack contains a UPS, DC power supply, remote control relay, and cooling fan, enabling the system to continue measurement during power outages, cope with high outdoor temperatures in summer, and remotely reset the system if the instrumentation or software stops.

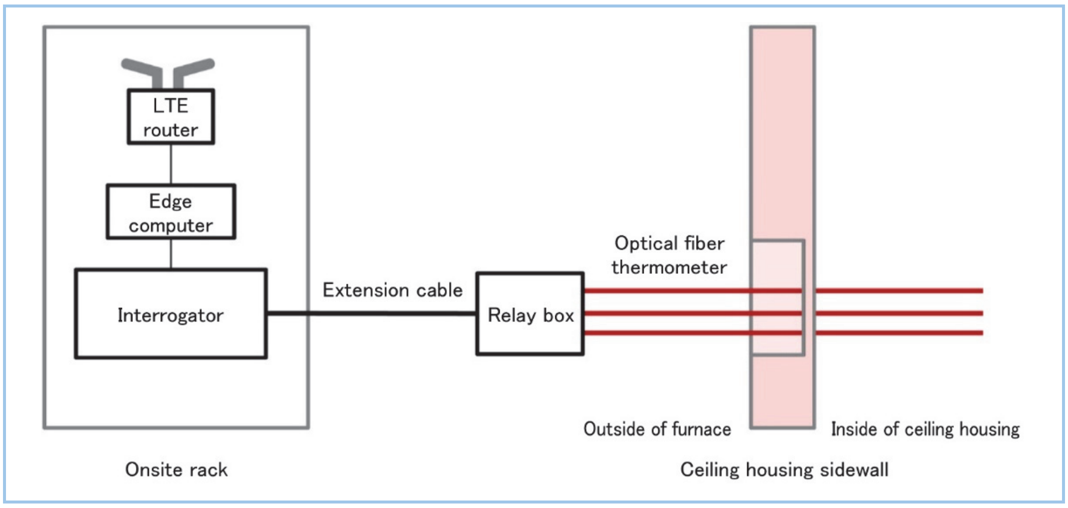

Figure 6 Configuration of optical fiber multipoint temperature measurement system

Figure 7 shows a dashboard screen built on the TOMONI® visualization software. As shown in the figure, it was confirmed that the temperature distribution of the tertiary superheater outlet tube nozzle in the furnace width direction can be understood. In addition to indicating data from the optical fiber thermometer, this dashboard can be customized freely according to the purpose of monitoring and analysis by combining other status values.

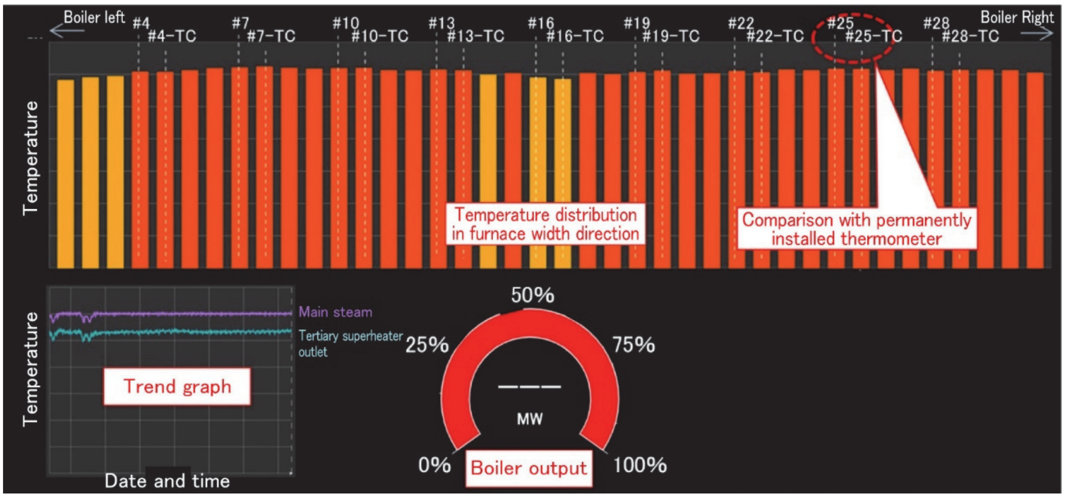

Figure 7 Temperature data visualization dashboard

4.3 Temperature measurement accuracy and durability

The accuracy evaluation of this fiber thermometer was performed by comparing with a pad-type thermocouple, which is permanently installed measuring equipment. **Figure 8** shows the evaluation results. The mean absolute error (MAE) of the temperature data for 4 hours (sampled at intervals of 5 seconds) during rated operation ranged from 1.3°C to 4.5°C, which is equivalent to the permissible error of 4.5°C for a JIS Class 2 thermocouple at 600°C. The mean absolute error (MAE) was obtained by calculating the absolute value (absolute error) of the difference between the measured values of the permanently installed thermocouple and the fiber thermometer and then averaging this absolute error over the entire evaluation period.

The durability of the fiber thermometer is being verified by testing its long-term durability over a span of several years against various concerns such as long-term exposure to high temperatures in the actual boiler environment, expansion and contraction due to startup and shutdown, combustion gas components, dust, and work during shutdown. Currently, continuous measurement for over one year has been achieved since the start of the verification (**Figure 9**). During the verification, fiber breakage occurred in some of the systems. In response to this, repair procedures including identification of the break points, end-face treatment, fusion splicing, and protection of fusion splices were considered. Then, repair of the break points, correction of the installation route and protective structures were carried out. We plan to continue the test to verify the durability and measurement performance over a longer period of time, keeping a close eye on the deterioration of the sensor, etc.

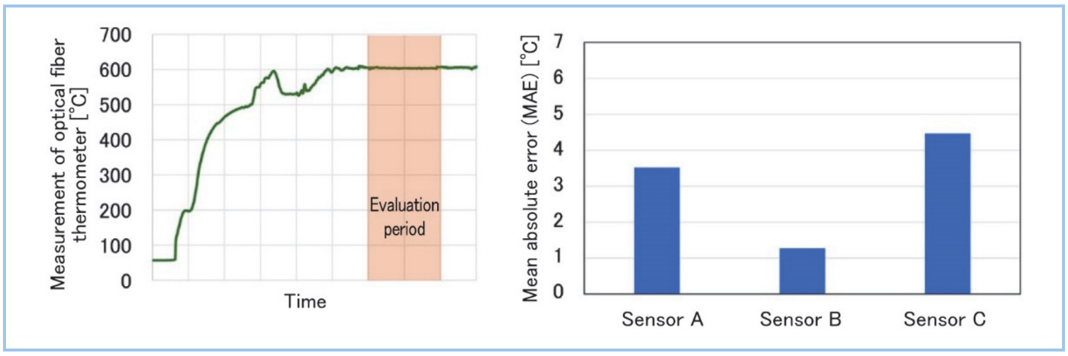

Figure 8　Evaluation of temperature measurement accuracy

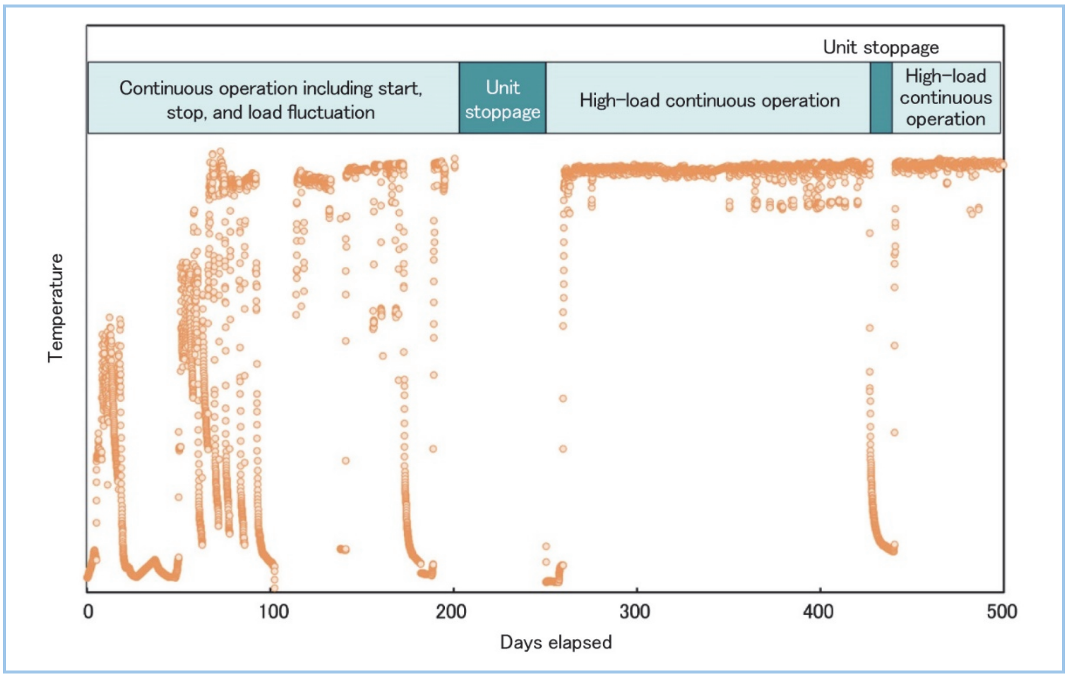

Figure 9　Long-term continuous measurement data

4.4　Installability and installation cost

In the demonstration test, not only the accuracy and durability of the optical fiber thermometer, but also the installability was evaluated based on the plan and actual results to accumulate knowhow for more efficient installation and maintenance. Although this was the first attempt to install the thermometer on an actual boiler, the actual net time required to install the sensor for 31 points was approximately 2 days, indicating that the work can be completed more smoothly than expected. We believe that the installation can be completed in a shorter period of time in the future with the enhancement of installation skills. **Figure 10** compares the installation cost of the optical fiber thermometer with that of the conventional method (thermocouple). The installation of thermocouples requires more man-hours for laying and curing sheath wires one by one, more parts for penetrations to draw sheath wires from the inside of the boiler to the outside, and more incidental work such as pre-weld treatment (polishing), welding, and PT inspection of the tip pad, which significantly increases installation costs as the number of temperature measurement points increases. On the other hand, the optical fiber thermometer can measure multiple points with a single fiber, thus man-hours required for laying and curing and the number of parts for penetrations can be reduced and incidental work such as pre-weld treatment (polishing), welding, and PT inspection can be eliminated. Therefore, the optical fiber thermometer can reduce the installation cost by about 30% compared to thermocouples, depending on the number of points, and is most suitable for large-scale multipoint measurement. In addition, this method can be installed in a short period of time and is effective when dealing with tube leaks and other problems.

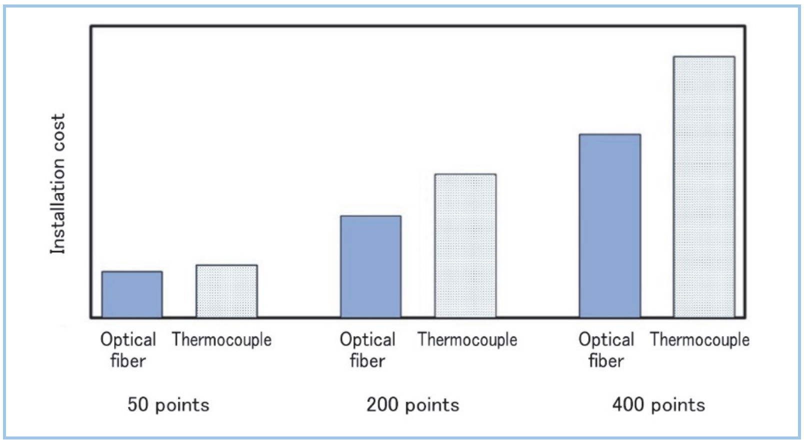

Figure 10 Comparison of installation costs

5. Conclusion

This report presented the features of MHI's optical fiber thermometer that can be effectively used for plant condition monitoring and maintenance planning, such as its excellent heat resistance and ability to easily perform multipoint measurement, and described utilization examples of multipoint temperature data during operation and periodic inspections, such as the reduction of risk of overlooking heat transfer tube creep damage, optimal operational guidance, optimization of inspection quantity and timing, and rationalization of work planning, using the application to a thermal power plant as an example. In addition, this report introduced an ongoing demonstration test of multipoint temperature measurement on an actual boiler in operation and the fact that continuous measurement for more than one year has been achieved. To promote the application to actual equipment, we plan to continue the test to demonstrate the long-term operation of the optical fiber thermometer, as well as to specifically study and trial the use of the data described in Chapter 3. We also plan to promote the application to plant equipment other than thermal power plants, such as chemical, oil, gas, cement, and steel plants, thereby contributing to solving the problems of condition monitoring and maintenance planning in the plant industry.

References

(1) https://www.adelaide.edu.au/news/news91324.html
(2) Warren-Smith, S. et al., Stability of Grating-Based Optical Fiber Sensors at High Temperature, IEEE Sensors Journal, Vol.19, Issue 8
(3) Y. Agata et al., Intelligent Solution TOMONI® for Advanced Maintenance and Operation of Critical Infrastructure, Mitsubishi Heavy Industries Technical Review, Vol.59, No.3 (2022)