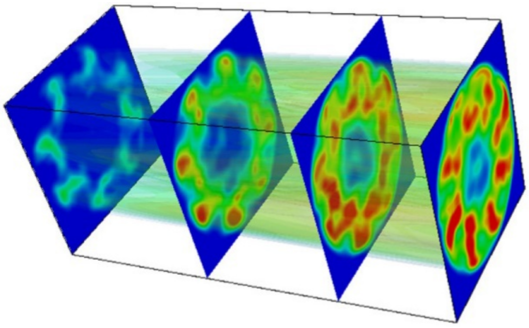
Mitsubishi Heavy Industries Technical Review Vol. 60 No. 1 (March 2023)

Three-dimensional Visualization of Flame in Gas Turbine Combustor



ICHIYU FUJIO[*1] **SHINSUKE TAJIRI**[*2]

ATSUSHI MORIWAKI[*3] **HIROTAKA OKA**[*4]

TAKURO IKEDA[*5] **TATSUYUKI NISHIMIYA**[*2]

Mitsubishi Heavy Industries, Ltd. (MHI) has been developing a Gas Turbine Combined Cycle (GTCC), which is more efficient and operable than conventional thermal power plants. The combustor of a large gas turbine has technological issues such as suppressing combustion instability and reducing NOx emissions, and it is important to evaluate the state of the flame in the combustor in order to solve these issues. In this report, we introduce "three-dimensional visualization of flame in gas turbine combustor", one of the measurement technologies we have developed to understand the flame distribution in a combustor.

1. Introduction

Large gas turbines apply a lean premixed combustion method to suppress the increase in NOx emissions caused by higher combustion temperatures for the purpose of higher efficiency. However, this method has a higher risk of combustion instability and flashback due to unstable combustion conditions compared to the diffusion combustion method, which is a technological issue. Combustion instability are caused by the interaction between pressure fluctuations and heat release rate fluctuations, and are considered to be closely related to the heat release rate distribution in the combustor. NOx emissions are also considered to be closely related to the heat release rate distribution because they are strongly affected by the local combustion gas temperature. Therefore, in order to achieve both stable combustion and low NOx emissions, it is important to evaluate the heat release rate distribution in the combustor.

OH radical chemiluminescence measurement is a simple measurement method for evaluating the distribution of heat release rate in a combustor. This method obtains the relative distribution of heat release rate in a flame based on the fact that the intensity distribution of chemiluminescence of OH radicals (OH*) excited by combustion is correlated with the heat release rate distribution. For example, the blue flame of a gas stove is also derived from excited chemiluminescence of CH radicals (CH*), and visualization of this chemiluminescence intensity distribution is equivalent to visualization of the flame shape.

We have evaluated the relationship between heat release rate fluctuations and combustion instability using the OH radical chemiluminescence measurement and the OH Planar Laser-Induced Fluorescence (OH-PLIF) method (1)~(3). However, the conventional OH radical chemiluminescence measurement can only measure the integrated value in the optical path direction and cannot evaluate the three-dimensional heat release rate distribution. The OH-PLIF method is a planar distribution measurement and cannot evaluate three-dimensional heat release rate distribution as well. Therefore, we have developed a measurement technology to visualize the three-dimensional relative heat release rate distribution in a combustor by combining OH radical chemiluminescence measurement with the computed tomography (CT) method, which is a three-dimensional distribution reconstruction method. This report presents an overview of the technology and the

[*1] Combustion Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.

[*2] Team Manager, Combustion Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.

[*3] Team Manager, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.

[*4] EPI Department, Digital Innovation Headquarters, Mitsubishi Heavy Industries, Ltd.

[*5] Service Engineering Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.

results of three-dimensional visualization of a flame in an actual combustor.

2. Development and validation of chemiluminescence CT reconstruction program

In order to apply chemiluminescence CT measurement to an actual combustor, it is necessary to introduce an appropriate CT processing method for the flame of the combustor to be measured. In this chapter, we describe the development of a reconstruction program for CT processing and the results of its validation.

First, the Ordered Subset Expectation Maximization (OS-EM) method (4), one of the successive approximation methods, was used as the basic algorithm for the reconstruction program. The OS-EM method is a reconstruction method that produces reconstruction results with fewer artifacts (processing errors that occur when reconstructing images), and is a faster version of the Maximum Likelihood Expectation Maximization (ML-EM) method, which is also used in medical CT reconstruction. **Figure 1** shows an overview of the CT process for the chemiluminescence distribution of a flame in a combustor.

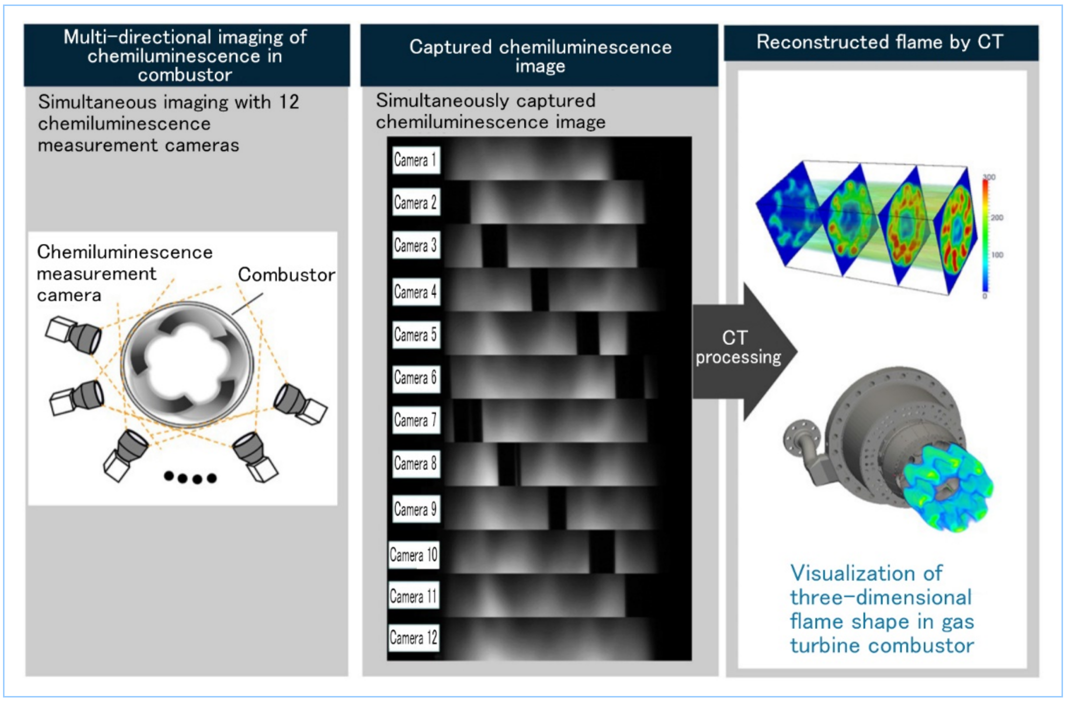
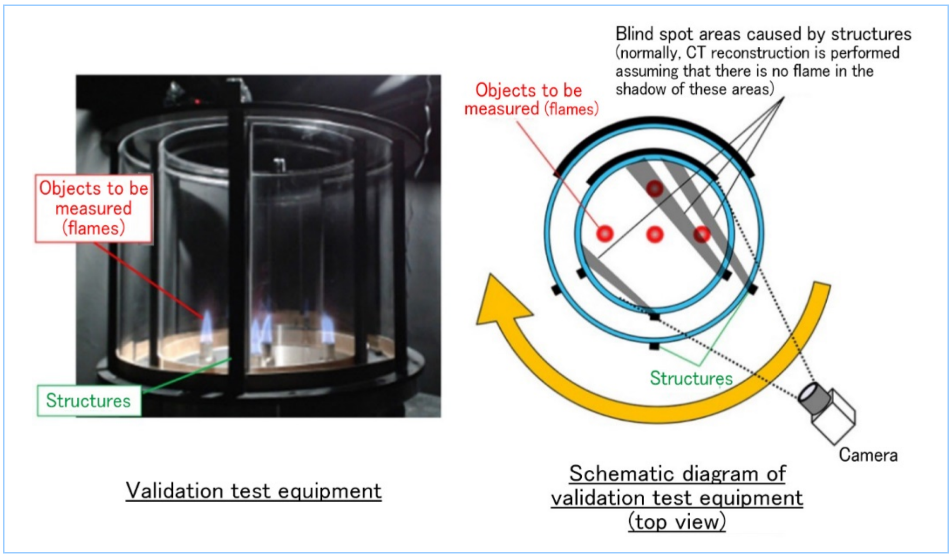


Figure 1 Overview of CT processing of flame chemiluminescence in combustor

To perform CT reconstruction processing, images taken from multiple directions are required. For example, X-ray CT used in the medical field acquires images taken from multiple directions by rotating the X-ray tube and detector. However, this assumes that the object does not change over time, making it difficult to apply it to flames in a combustor, which may change over time. Therefore, the measurement system presented in this report uses 12 cameras for simultaneous imaging to eliminate the influence of time-related changes. Since OH radical chemiluminescence is ultraviolet, special bandpass filters and cameras were used to measure the ultraviolet chemiluminescence. The 12 chemiluminescence images were reconstructed by the OS-EM method described above to obtain the three-dimensional distribution of the flame.

In the development of this measurement technology, the validity of the CT processing program was confirmed using several simple flames (Bunsen burners). When multi-directional imaging is used for the purpose of CT measurement, it is desirable that there are no structures in the field of view that would create blind spots for flame imaging. However, when this method is applied to an actual combustor such as a gas turbine combustor, a pillar is structurally necessary to hold the optical window, which creates a blind spot in the field of view. Therefore, we developed a method to reconstruct the image without the effect of these structures. When conventional CT process method is applied, the data of blind spot area in the image is processed as valid data. For this reason, the CT process treats the area as if there is no flame, and the intensity of the flame in the blind spot is evaluated low in the reconstructed image. On the other hand, in our newly developed CT process method, blind spot areas are identified in advance, and the data of blind spot areas in the image can be processed as invalid data in the reconstruction process. For example, when a certain area of flame enters the blind spot in images taken from three directions among the images taken from twelve directions, the chemiluminescence distribution in that area is reconstructed using constraint conditions based on data obtained from the images taken from the remaining nine directions.

The CT processing program that took into account blind spots was validation-tested to confirm its validity. **Figure 2** shows an overview of the test simulating blind spot areas. The measurement objects were four Bunsen burners and structures forming blind spot areas were placed around the objects. In this test, a single camera was revolved around the burners to capture images from multiple directions. Based on the captured images, the three-dimensional distribution was reconstructed using the CT processing program.



Validation test equipment

Schematic diagram of validation test equipment (top view)

Figure 2 Validation test simulating blind spot areas caused by structures

Figure 3 shows the results of the validation test. In all cases, four Bunsen burners were image-captured and reconstructed. In the case of only quartz tubes without structures, the reconstruction was made with no problem. In the case of the blind spots caused by structures, when the above-mentioned blind spots are not taken into account, some of the flames were reconstructed with low luminescence intensity and the flame shape was broken and not correctly reconstructed, even though the equivalent ratio and flow rate were almost the same as those of the other flames. On the other hand, when the processing taking into account the blind spots was applied, the resultant chemiluminescence intensities of the four burners were almost equal, which was a reasonable result.

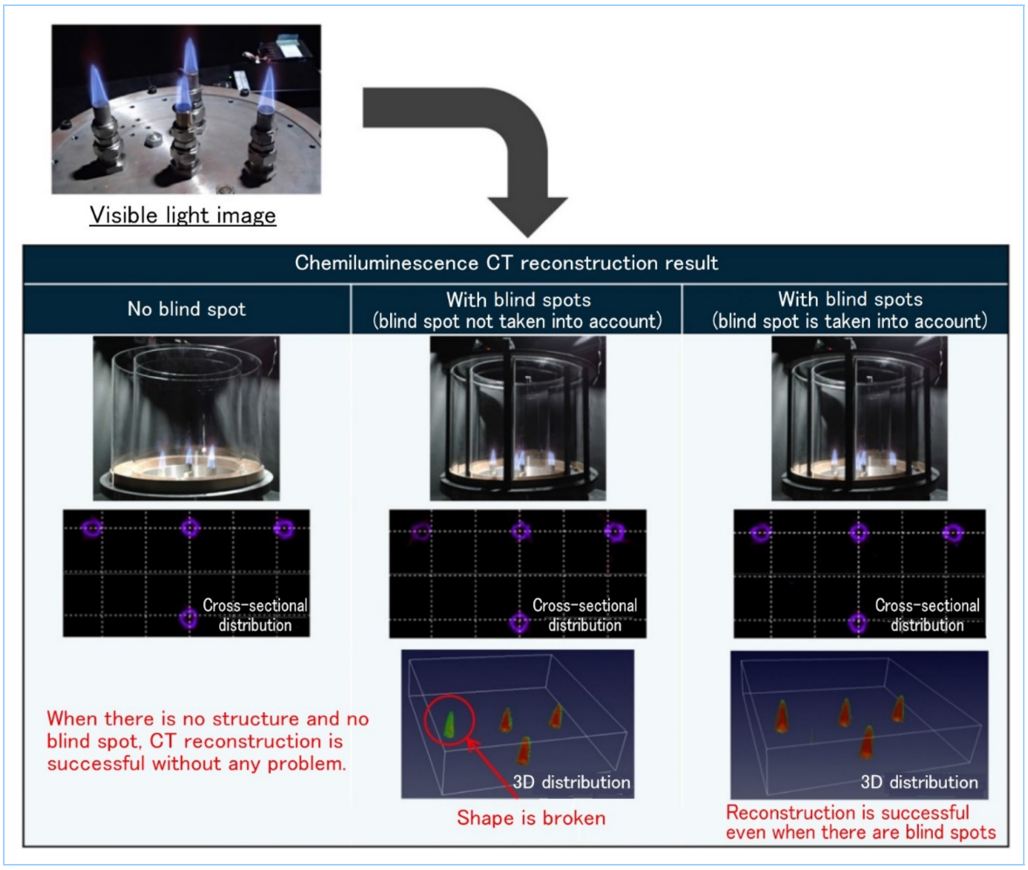


Figure 3　Validation results of CT processing program using simple flames

3. Development of chemiluminescence CT measurement system for actual-scale combustor

In order to acquire the images necessary for CT processing, we constructed a large image acquisition system capable of capturing images of an actual combustor flame from multiple directions. **Figure 4** shows the chemiluminescence CT measurement system we developed. The measurement system is constructed by aluminum frames, and twelve cameras are mounted circumferentially around the axis of the combustor so as to surround the combustor. This measurement system is self-standing and can be traversed in the direction of the combustor axis. **Figure 5** shows a configuration diagram of the measurement system. Two cameras are controlled by one camera control PC, and each control PC is controlled by an analysis PC via an Ethernet hub.

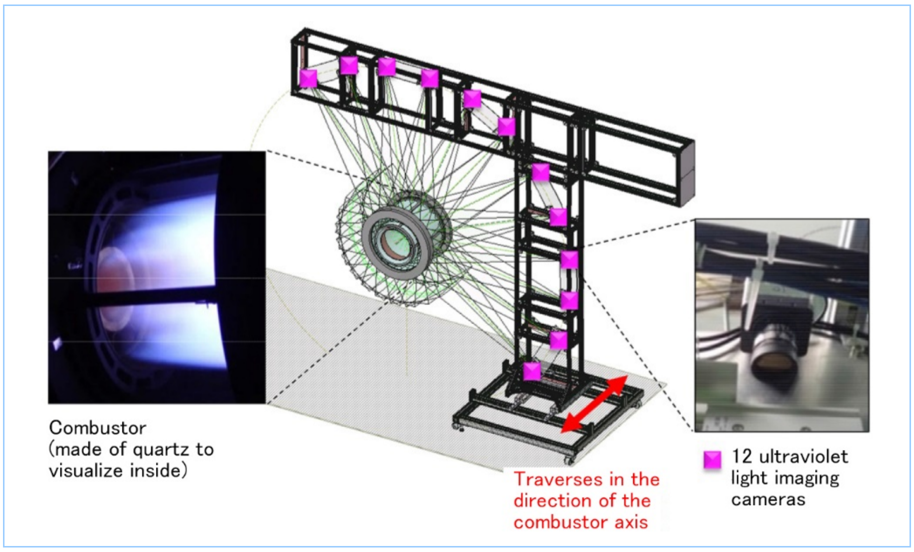


Figure 4　Overview of chemiluminescence CT measurement system

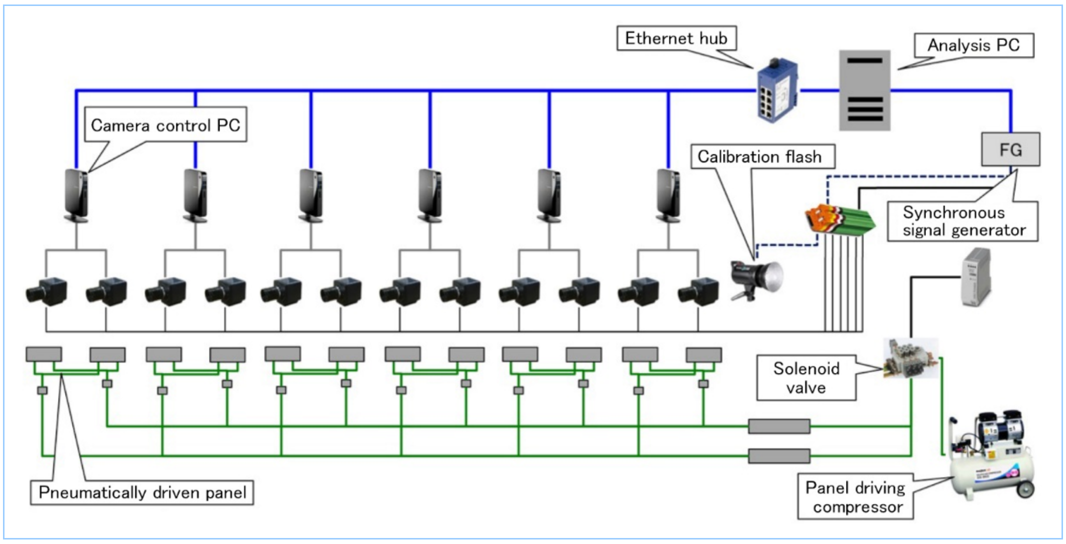
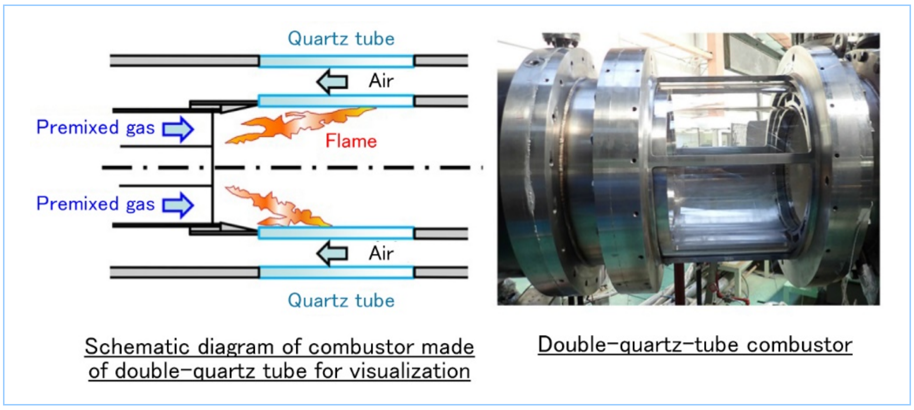


Figure 5 **Configuration of chemiluminescence CT measurement system**

4. Application to atmospheric pressure combustion test

We visualized flames in our gas turbine combustor using the developed chemiluminescence CT measurement system. For the validation test, we used our gas turbine combustor atmospheric pressure combustion test rig, and as the measurement target, an actual combustor developed by us (5). In a normal combustion test, the flames inside the combustor are not visible, but in this validation test, the flames inside the combustor were made visible by using a combustor made of quartz in order to measure the chemiluminescence in the combustor. **Figure 6** shows a schematic diagram and a photograph of the quartz combustor. The quartz combustor is double-tubed, and the inner quartz tube is cooled by air flowing between the inner and outer quartz tubes.



Schematic diagram of combustor made of double-quartz tube for visualization

Double-quartz-tube combustor

Figure 6 **Double-quartz-tube combustor**

Figure 7 shows our atmospheric pressure combustion test rig incorporating the chemiluminescence CT measurement system. The chemiluminescence CT measurement system is arranged to surround the combustor described above.

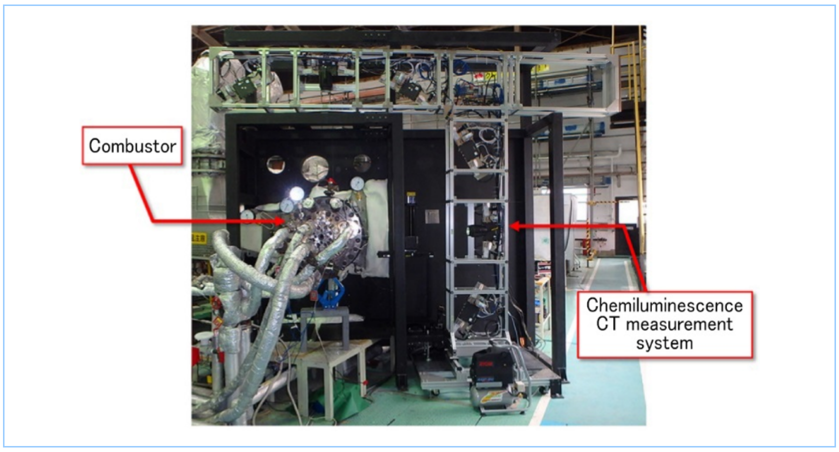


Figure 7 Our atmospheric pressure combustion test rig incorporating chemiluminescence CT measurement system

Figure 8 shows the results of chemiluminescence CT measurement under premixed flame conditions. In the premixed flame, a petal-like flame is formed by the swirling flow, and a three-dimensional flame structure with finely varying distribution in the circumferential direction can be observed. Such a three-dimensional and complex flame structure has also been observed in combustion CFD analysis, and it was confirmed that this measurement method is capable of acquiring complex flame shapes such as those in a gas turbine combustor.

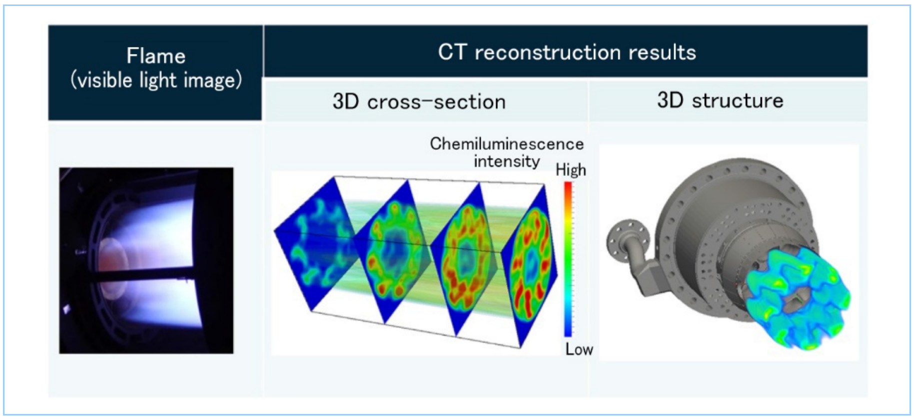


Figure 8 Visualization results of premixed flame in combustor

To confirm that the obtained three-dimensional distribution of relative heat release rate is reasonable, we compared it with the result of combustion CFD analysis. **Figure 9** compares the flow-directional distribution of integrated values of heat release rate and chemiluminescence intensity in the cross-section. The peak positions of the heat release rate in both cross-sections with different phases are coincident. This indicates that the chemiluminescence CT measurement can be used to properly identify the high heat release rate area in the combustor.

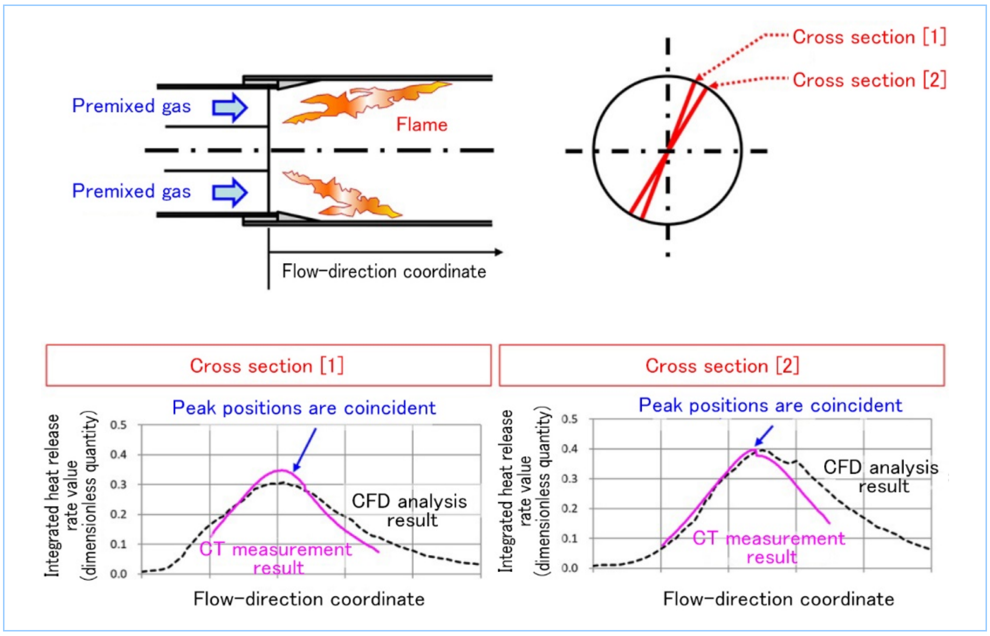


Figure 9 Comparison of heat release rate distribution obtained by combustion CFD analysis and chemiluminescence intensity distribution obtained by chemiluminescence CT measurement (Flow-direction distribution of integrated values in cross section)

5. Conclusion

This report introduced the three-dimensional visualization of flames in a gas turbine combustor using chemiluminescence CT measurement. By applying this technology, we were able to visualize the three-dimensional flame shape of our actual combustor for the first time. In addition, we have established a technology that enables us to actually visualize and evaluate the heat release rate distribution of the designed combustor for the development of combustors in the future. Furthermore, by using the data obtained by this measurement technology as validation data for combustion CFD analysis, it is expected to be useful for improving the accuracy of combustion CFD analysis technology. We will consider applying this technology to combustion evaluation in the development of hydrogen and ammonia-fired combustors in the future.

(Acknowledgment)

Part of the results presented here were obtained as a result of the High-efficiency Gas Turbine Technology Demonstration Project (the development of ultra-high efficiency 1700°C-class gas turbines, JPNP16002), which was subsidized by the New Energy and Industrial Technology Development Organization (NEDO). We would like to express our gratitude for their support.

References

(1) Saito, T. et al., Measurement of Flame Dynamics of a Gas Turbine Combustor by Using Optical Method, Proc. of ACGT2014, ACGT2014-0093.

(2) Isono, M. et al., Numerical and Experimental Investigation of the Flame Transfer Function in the Full-Scale Gas Turbine Combustor, Proc. of IGTC 2015, pp. 1438-1447.

(3) Fukuba, S. et al., Experimental and Numerical Investigation of DLN combustor for A Heavy-Duty Gas Turbine, Proc. of GPPF 2017, GPPF-2017-165.

(4) Hudson, H. et al., Accelerated Image Reconstruction Using Ordered Subsets of Projection Data, IEEE Trans Med Imaging vol.13 (1994) pp. 601−609.

(5) Tanimura, S. et al., Advanced Dry Low NOx Combustor for Mitsubishi G Class Gas Turbines, Proc. of ASME Turbo Expo 2008, GT2008-50819.