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Optical temperature measurement method of premixed flames using a multi-laser system

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Abstract The temperature distribution of a methane-air premixed flame was measured by the optical measurement technique. The absorption line was decomposed through 3rd order polynomial analysis, and the simultaneous multiplicative algebraic reconstruction technique (SMART) algorithm was adopted for computed tomography-tunable diode laser absorption spectroscopy (CT-TDLAS) data reconstruction. Methane-air premixed combustion system was used to construct laminar and turbulent flames. A double tube structure was adopted to solve combustion instability factors that occur when turbulent flames are generated. To overcome the high-temperature measurement limitations of a single laser system, two types of distributed feedback (DFB) lasers were mixed and measured. The relative error in temperature was largely confirmed at the central location of the burner. It was about 1.22 % for the laminar flame and 14.47 % for the turbulent flame.

1. Introduction

The efficient use of energy resources requires accurate measurement of the combustion gas composition. Also, precise gas control is required to improve product quality in industrial processes. Combustion quality can be managed through accurate measurement of factors that occur after combustion, such as temperature and concentration. It is essential to measure the temperature and concentration of combustion products in order to understand the number of harmful substances generated after combustion.

As measurement methods for this, recent advances are discussed for the use of metal oxide semiconductor sensors for the detection of a variety of gases (CO, NO_X, NH_3) and the particularly challenging case of CO_2 [1]. A wireless and passive surface acoustic wave SAW microsensor was used for simultaneous measurement of relative humidity RH and CO_2 [2]. All of these traditional measurements are not suitable for measuring irregularly distributed gases. On the other hand, there is an optical measurement method using a laser set. To measure temperature and concentration without being directly involved in the flow. Tunable diode laser absorption spectroscopy (TDLAS) measurement is known to measure temperature and concentration with fast response times [3-14]. In particular, CT-TDLAS measures two-dimensional and three-dimensional temperature distribution by adding tomography techniques to the existing TDLAS [15-24]. Kamimoto et al. performed CT-TDLAS measurements using a single laser set (1388 nm) and showed measurement limits for temperatures above 1000 K [24].

In this study, laminar and turbulent flames are generated using a double-tube burner tip [25, 26]. This effectively keeps the turbulent flame in the same condition. CT-TDLAS technology was applied to measure the two-dimensional temperature distribution of the methane-air premixed flame. By generating high temperature under complete combustion conditions, the temperature and concentration fields are realized through absorption spectrum analysis of H_2O gas at a combustion product. In particular, it overcomes the limitations of high-temperature measurement by using a multiple laser system (1388 nm+1343 nm). Measurement results were

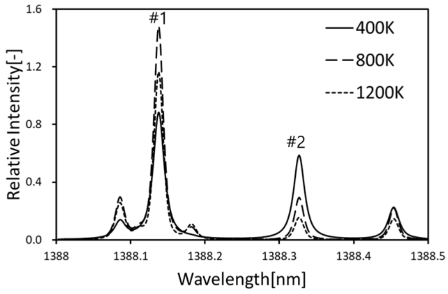


Fig. 1. The relative intensity of theoretical absorption spectra (1388 nm-1388.5 nm).

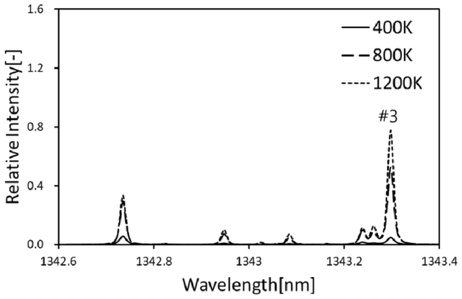


Fig. 2. The relative intensity of theoretical absorption spectra (1342.6 nm-1343.4 nm).

compared using CT-TDLAS and thermocouples. Also, the suitability of the technology in laminar and turbulent flame conditions was evaluated using a single laser system and a multi-laser system.

2. Optical measurement

2.1 Theory of TDLAS

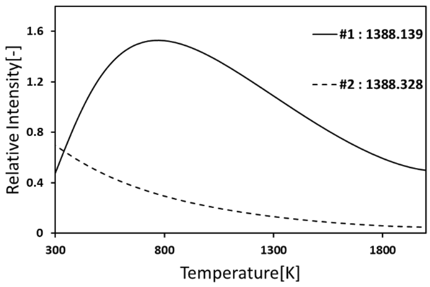
TDLAS is an optical technique that measures the absorption spectra of target gas using diode lasers based on Lambert Beer's law [3]. Wavelengths are adjusted to the range of absorptive wavelengths of the selected gas for high absorption spectra. Incident laser beam passes through the target gas, the unique characteristics are obtained from the attenuation of the transmitted light. The light absorbance information according to the measured gas type is expressed by the following Eq. (1):

$$\frac{I_t(\lambda)}{I_{in}(\lambda)} = \exp\{-A_\lambda\} = \exp\{-\sum_i (Pn_i L \sum_j S_{i,j}(T) G_{vi,j})\}\,. \tag{1}$$

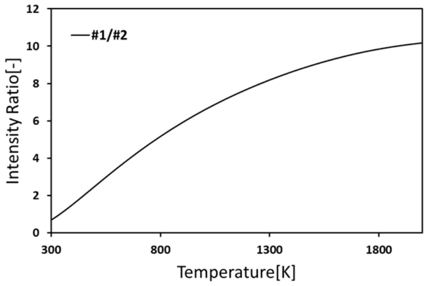
Here, I_t is the transmitted light intensity, I_0 is the incident light intensity, A_λ the absorbance, $G_{vi,j}$ the line broadening function, n_i the number of density, L the path length, $S_{i,j}$ the line strength of the absorption line j and P is the pressure. Broadening function $G_{vi,j}$ has been approximated by the Voigt profile [21].

Two types of lasers were used to measure the temperature in a combustion product. Especially, the intrinsic absorption wavelength of H_2O gas was used to measure the temperature measurement sensitivity of the combustion environment. Fig. 1 shows the absorption spectra of H_2O in the 1388 nm region, such as 1388.139 nm (#1) and 1388.328 nm (#2) using representative wavelengths. Fig. 2 shows the absorption spectra of H_2O in the 1343 nm region and uses 1343.298 nm (#3) as the representative wavelength. It shows that the absorbance intensity of a specific wavelength changes according to the temperature variation. For theoretical absorption spectrum analysis, the absorption spectra in the 1388 nm and 1343 nm regions were calculated by the HITRAN database [27].

Fig. 3(a) shows the variation in the theoretical absorption intensity according to the temperature change of #1 and #2 in the 1388 nm region. Fig. 4(a) shows the variation in the theoretical absorption intensity according to the temperature change of #1 and #3 when the 1388 nm and 1343 nm regions are used simultaneously.



(a) Temperature dependence of two-line strength of the absorbance



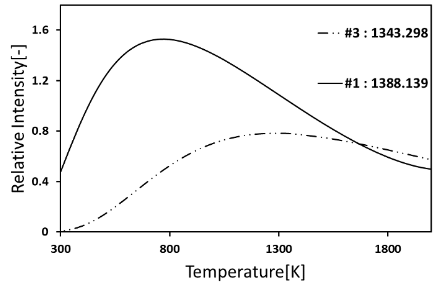
(b) The ratio of line strength intensity

Fig. 3. Theoretical temperature dependence of absorption spectra (1388 nm-1388.5 nm).

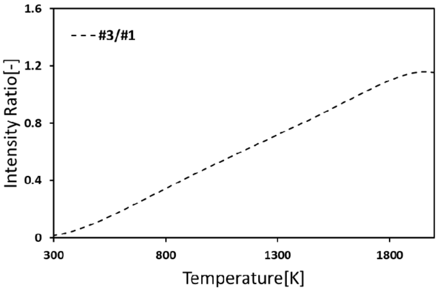
Fig. 3(b) represents the temperature dependence of the ratio (#1/#2) when used a single-laser set (1388 nm). Fig. 4(b) represents the temperature dependency of the ratios (#3/#1) when using a multi-laser set (1388 nm+1343 nm). In this way, we would like to evaluate the dominant wavelength suitable for high-temperature estimation of 1250 K over by comparing the case of using the 1388 nm laser alone and a combination of the 1388 nm and 1343 nm lasers.

2.2 Computed tomography reconstruction algorithm

The principle of TDLAS is the line of sight method to provide information only on the transmitted straight region. CT-TDLAS technique is used by adding computed tomography technique to this method. To measure the temperature distribution for CT



(a) Temperature dependence of two-line strength of the absorbance



(b) The ratio of line strength intensity

Fig. 4. Theoretical temperature dependence of absorption spectra (1342.6 nm-1343.4 nm).

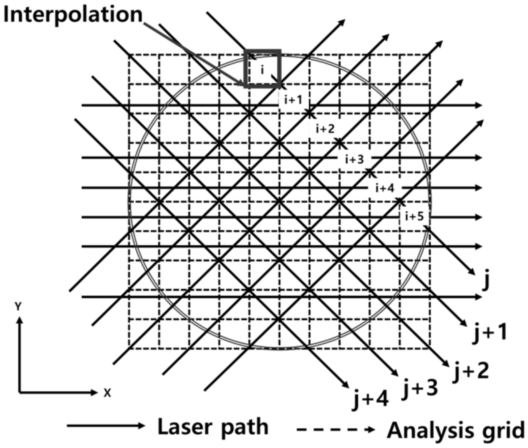


Fig. 5. Calculation grids for tomographic reconstructions.

calculation, we adopted laser beams set in the mesh form shown in Fig. 5. All laser intensity information was theoretically reconstructed at the grating point where the laser beam measured by the experiment overlaps. In this study, the CT grid was constructed using 10x10 for a measuring area with a diameter of 70 mm. This is the optimal resolution for the placement of a 16 paths laser light source. More light sources need to be placed to increase the number of grids.

The signal absorbance [18] of the laser path can be expressed by the following Eq. (2):

$$A_{\lambda,j} = -\sum_{i} n_i \cdot L_{i,j} \cdot \alpha_{\lambda,i} \,. \tag{2}$$

Here, $A_{\lambda,j}$ is the integrated absorbance, L_{ij} is the path length inside a single grid *i*, $\alpha_{\lambda,i}$ is the absorption coefficient of wavelength.

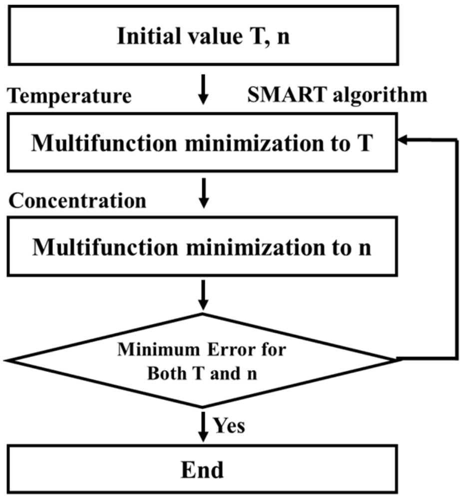


Fig. 6. Calculation grids for tomographic reconstructions.

Fig. 6 shows the CT calculation procedure. It can reconstruct the temperature and concentration in each grid point.

It is important to adopt the initial temperature values for all grids for CT calculations. We adopted the summation of line of sight (SLOS) method for initial temperature estimation [22]. At the initial stages of CT calculation, the initial values are used for the calculation of the SMART algorithm [23] like the following Eq. (3). It is used for the calculation of the absorption coefficients $\alpha_{\lambda,i}$.

$$\alpha_{\lambda,i}^{\;k+1} = \alpha_{\lambda,i}^{\;k} \cdot \exp\left(\sum_{j=1}^{J} \frac{L_{ij}}{\sum_{i=1}^{I} L_{ij}} \cdot \log \frac{A_{\lambda,j}}{\sum_{i=1}^{I} \alpha_{\lambda,i} \cdot L_{ij}} \right). \tag{3}$$

Iteratively until the differences between the experimental absorbance and the theoretical absorbance using the MSE (mean square error) function as shown in the Eq. (4) are minimized. Next, the final temperature and concentration are decided by using the SMART algorithm. During iterative calculations, the absorbance was decomposed by normalizing individual signals to the same intensity.

$$Error = \sum \left\{ (A_{\lambda,j})_{theory} - (A_{\lambda,j})_{\mathrm{experiment}} \right\}^2 . \tag{4}$$

Relative error evaluation for the temperature measurement results using a thermocouple and CT-TDLAS is represented by Eq. (5).

$$\mathrm{Re}T = \sqrt{\left(\frac{T_{CT-TDLAS,Max} - T_{Thermocouple,Max}}{T_{Thermocouple,Max} - T_{Thermocouple,Min}} \right)^2} \,. \tag{5}$$

Here, $T_{CT\text{-}TDLAS,\ \mathrm{Max}}$ is the maximum temperature by CT-

Table 1. Combustion experimental parameters (main flame).

Condition	Supplying gas	Surrounding air [l/min]	Main flame [l/min]	Equivalence ratio	Reynolds number
Laminar condition	Dry air	100	1.0	1.05	747.87
	Methane	-	0.11		
Turbulent condition	Dry air	100	5.7	1.01	4246.09
	Methane	-	0.6		

Table 2. Combustion experimental parameters (sub flame).

Condition	Supplying gas	Sub flame [l/min]	Equivalence ratio	Reynolds number
Laminar condition	Dry air	2.0	1.05	328.74
	Methane	0.22		
Turbulent condition	Dry air	2	1.05	328.74
	Methane	0.22		

TDLAS measurement, $T_{CT\text{-}TDLAS,\ \mathrm{Min}}$ is the maximum temperature by thermocouple measurement, $T_{Thermocouple,\ \mathrm{Min}}$ is the minimum temperature by thermocouple measurement.

3. Experimental setup

The current burner design, shown in Fig. 7, is a double tube structure for the jet premixed flame. A sub-flame is provided in laminar flow conditions to protect the central jet combustion process from the ambient air. Providing the sub-flame can ensure the combustion stability of the jet flame. Methane gas has been used as fuel, and it has been premixed with air supplied through a sintered bronze filter. The inner diameter of the central tube is 2 mm, sub-flow tube is 10 mm. The optical measurement cell as shown in Fig. 7 has been set at the position 45 mm above the burner. The experimental parameters are summarized in Tables 1 and 2.

H_2O gas absorption spectra are measured using two types of lasers. First diode laser (DFB type, NTT Electronics Co., NLK1E5GAAA) of which working wavelength is 1388 nm, second diode laser (DFB type, NTT Electronics Co., NLK1B5EAAA) of which working wavelength is 1343 nm were used to get H_2O gas absorption spectra. In order for two-dimensional measure, simultaneous absorption spectra using collimator (THORLABS Co., 50-1310-APC) and photodetector (Hamamatsu Photonics and G8370-01) were set on the 16-path cell. The laser beam was split using a fiber optic splitter (OPNETI Co., SMF-28e, 1x16). Laser paths have 7 to 12.3 mm spacing with each other for covering measuring space as shown in Fig. 8. The intensity of the transmitted light is detected by a photodiode and recorded in a recorder (HIOKI Co., 8861 Memory Highcoda). To verify the temperature measurement result using CT-TDLAS, the same point was measured using one thermocouple (ANBE SMT Co., BM-100-100-050, 100 µm).

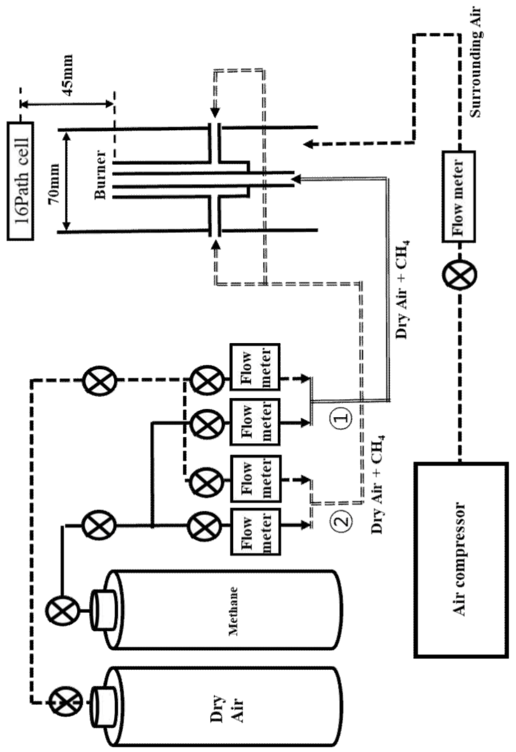


Fig. 7. Configuration diagram of an experimental device for 2D temperature measurement of a special flame burner.

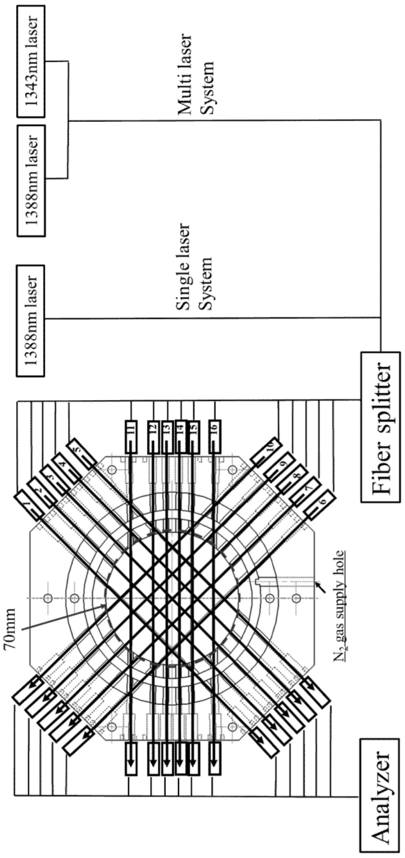


Fig. 8. Optical CT-TDLAS measurement cell.

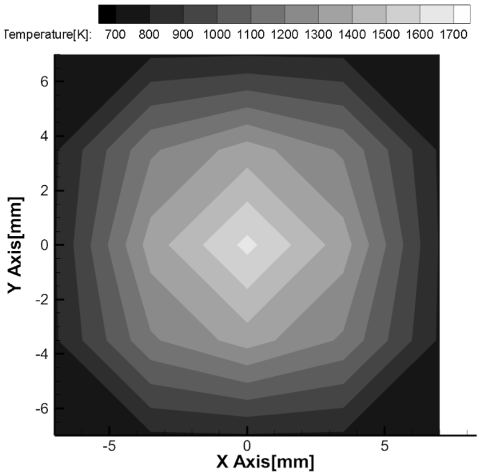


Fig. 9. Temperature distribution measured by thermocouple (laminar flame).

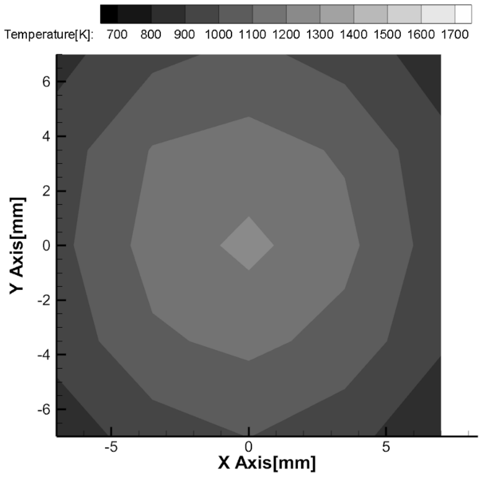


Fig. 10. Temperature distributions reconstructed by SMART algorithm (single laser, laminar flame).

Table 3. Comparisons of relative error of the temperature at Y = 0 mm and -3.5 mm (laminar flame).

Measuring point	Method	Maximum temperature [K]	Minimum temperature (room condition) [K]	Relative error [%]
Center	Thermocouple (single point)	1629.04	301.35	-
	CT-TDLAS (single laser)	1226.13	301.35	30.35
	CT-TDLAS (multi-laser)	1612.86	301.35	1.22
Side (X = -3.5 mm)	Thermocouple (single point)	1348.37	301.35	-
	CT-TDLAS (single laser)	1106.12	301.35	23.14
	CT-TDLAS (multi-laser)	1338.84	301.35	0.91

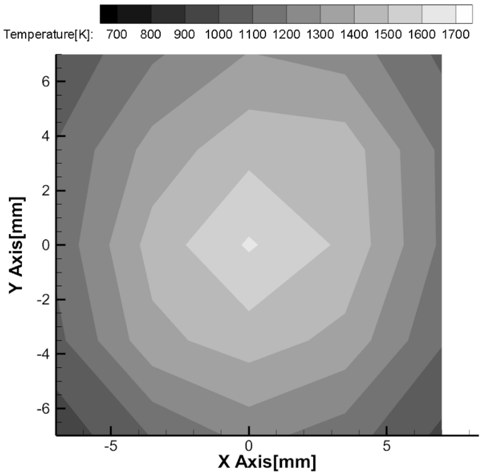


Fig. 11. Temperature distributions reconstructed by SMART algorithm (multi-laser, laminar flame).

4. Results and discussion

In this study, three absorption lines located at 1388.139 nm (#1), 1388.328 nm (#2), and 1343.298 nm (#3) were chosen for temperature reconstruction. Absorption spectra of H_2O at 1388.0-1388.5 nm and 1342.6-1343.4 were measured by the CT-TDLAS measurement cell.

4.1 Laminar flame test in real combustion

Fig. 9 shows the temperature field measured by a thermocouple experiment in laminar flame conditions. It shows the temperature field at the grids of 3.5 mm intervals at the measurement cell inside. It can be seen that the center area is the highest temperature.

Fig. 10 shows the results by the CT-TDLAS measurement using a single laser system (1388 nm). Fig. 11 shows the results by the CT-TDLAS measurement using a multi-laser system (1388 nm+1343 nm). In both of them, the temperature structure is similar to the thermocouple measurement results as shown in Fig. 9.

However, the relative error of the temperature by a thermocouple and a single laser system at the center position of the measurement cell was 30.35 % as shown in Table 3. Besides, the relative error at a point 3.5 mm away from the center of the cell was relatively high at 23.14 %. From these results, it can be estimated that the use of a single laser system for high temperature above 1250 K shows a large error in temperature measurement. The multi-laser system showed a relative error of 1.22 % between the CT-TDLAS and the thermocouple measured temperature results at the center of the measurement cell. Besides, the relative error at a point 3.5 mm away from the center of the measurement cell was relatively high at 0.91 %.

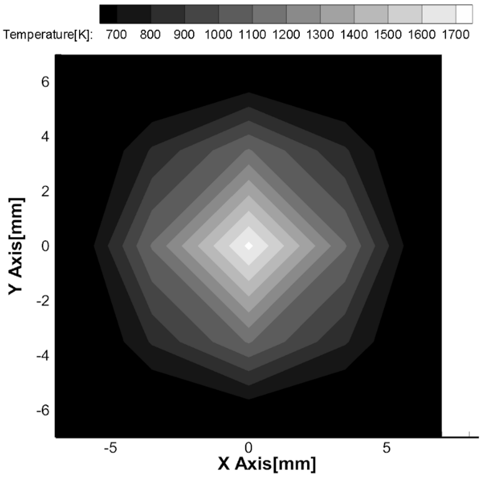


Fig. 12. Temperature distribution measured by thermocouple (turbulent flame).

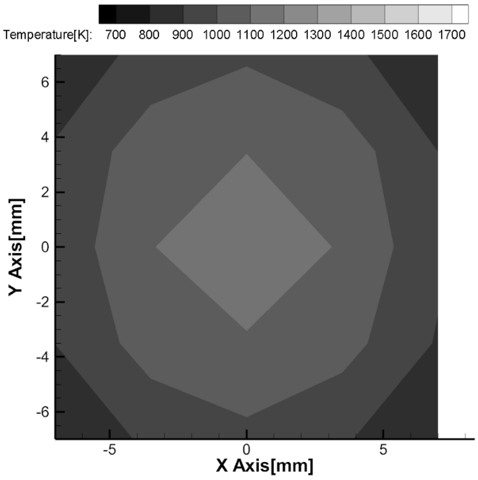


Fig. 13. Temperature distributions reconstructed by SMART algorithm (single laser, turbulent flame).

4.2 Turbulent flame test in real combustion

Fig. 12 shows the temperature field measured by a thermocouple experiment in turbulent flame conditions. It shows the temperature field at the grids of 3.5 mm intervals of the measurement cell. It can be seen that the center area has the highest temperature and sharp variation than laminar conditions.

Fig. 13 shows the results by the CT-TDLAS measurement using a single laser system (1388 nm). Fig. 14 shows the results by the CT-TDLAS measurement using a multi-laser system (1388 nm+1343 nm). In both of them, the temperature structure is similar to the thermocouple measurement results as shown in Fig. 13.

However, the relative error of the temperature measured by a thermocouple and a single laser system at the center position of the measurement cell was 38.33 %, as shown in Table 4. Besides, the relative error at a point 3.5 mm away from the center of the measurement cell was relatively high at 6.27 %. The multi-laser system showed a relative error of 14.47 % between the thermocouple and the CT-TDLAS measured temperature results at the center of the measurement cell. The relative error at a point 3.5 mm away from the center of the measurement cell was relatively high at 2.74 %. It can be seen that it is more advantageous to measure the temperature using a multi-laser system than a single laser system.

Table 4. Comparisons of relative error of the temperature at Y = 0 mm and -3.5 mm (turbulent flame).

Measuring point	Method	Maximum temperature [K]	Minimum temperature (room condition) [K]	Relative error [%]
Center	Thermocouple (single point)	1725.78	301.35	-
	CT-TDLAS (single laser)	1179.77	301.35	38.33
	CT-TDLAS (multi-laser)	1519.60	301.35	6.27
Side (X = -3.5 mm)	Thermocouple (single point)	1111.07	301.35	-
	CT-TDLAS (single laser)	1060.32	301.35	14.47
	CT-TDLAS (multi-laser)	1088.87	301.35	2.74

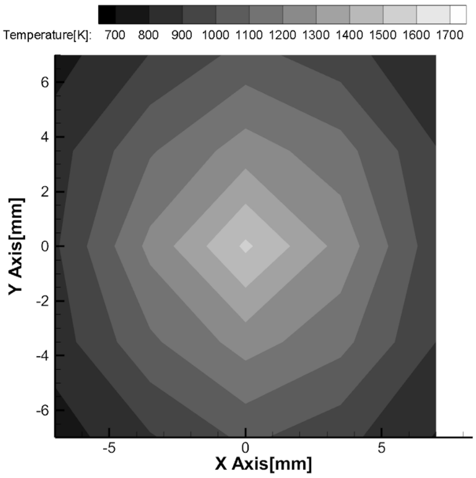


Fig. 14. Temperature distributions reconstructed by SMART algorithm (multi-laser, turbulent flame).

5. Conclusions

By using an optical measurement method, we measured the temperature distribution of the premixed flame. To realize both laminar (Reynolds No.; 747.87) and turbulent (Reynolds No.; 4246.09) flames, a double tube structure burner has been successfully constructed. The temperature field above the burner was compared and evaluated using a thermocouple and CT-TDLAS measurement method. In particular, it was found that the selection of the absorption wavelength is important for temperature estimation in the CT-TDLAS technique.

In the case of a single laser system in the laminar flame condition, the relative error at the center of the measurement cell was high as 23.14 %. It can be seen that the relative error is relatively low as 1.22 % in the case of using a multi-laser system. As a result of measuring the temperature using a single laser in a laminar flame condition shown, a large error occurred in the estimation of the temperature above 1250 K. So this an inappropriate measurement method in high-temperature conditions.

In the case of a single laser system in the turbulent flame condition, the relative error at the center of the measurement cell was as high as 38.33 %. It can be seen that the relative error is relatively low at 14.47 % in the case of using a multi-laser system. The disagreement between measurement results was found at the center of the measurement cell in turbulent flame conditions.

The results of measuring the temperature using a thermocouple and CT-TDLAS (multi-laser system) in a laminar heat flux environment were similar. However, it was confirmed that the thermocouple result was higher in the turbulent heat flux environment. It is estimated that an error in the thermocouple measurement result occurs due to the influence of the high radiant heat flux in turbulent flow conditions. Furthermore, it can be seen that a multi-laser system is more advantageous than a single laser system for measuring high-temperature heat sources.

Acknowledgments

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Nomenclature

I_t : Transmitted intensity
I_{in} : Incident intensity
A_λ : Absorbance
λ : Selected wavelength
P : Pressure
n_i : The number of density
L : Optical path length
i : Number of grid
j : Column direction
$S_{i,j}$: The line strength of the absorption line *j*
$G_{vi,j}$: The line broadening function (Voigt profile)
$\alpha_{i,j}$: Absorption coefficient
k : Iteration number
$T_{CT\text{-}TDLAS,\text{ Max}}$: The maximum temperature by CT-TDLAS measurement (K)
$T_{CT\text{-}TDLAS,\text{ Min}}$: The minimum temperature by CT-TDLAS measurement (K)
$T_{Thermocouple,\text{ Min}}$: The minimum temperature by Thermocouple measurement (K)
T : Absolute temperature (K)
l/min : Liter per minute

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