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Validation of real-time 2D temperature measurement method using CT tunable diode laser absorption spectroscopy

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Abstract

Two dimensional (2D) temperature and concentration distribution plays an important role for the combustion structure and the combustor efficiency in engines, burners, gas turbines and so on. Recently, as a multi-species measurement technique with high sensitivity and high response, tunable diode laser spectroscopy (TDLAS) has been developed and applied to the actual engine combustions. With these engineering developments, transient phenomena such as start-ups and load changes in engines have been gradually elucidated in various conditions. In this study, the theoretical and experimental research has been conducted in order to develop the non-contact and fast response 2D temperature and concentration distribution measurement method. The method is based on a computed tomography (CT) using absorption spectra of water vapor at 1388 nm. The computed tomography tunable diode laser spectroscopy (CT-TDLAS) method was employed in engine exhausts to measure 2D temperature distribution. The measured 2D temperature shows a good agreement with the temperature measured by a thermocouple. The temporal and spatial resolutions of this method have also been discussed to demonstrate its applicability to various types of combustor.

Keywords: Measurement and instrumentation; Combustion; IC engines; 2D temperature measurement; Tunable diode laser absorption spectroscopy (TDLAS); CT

1. Introduction

It is necessary to make efforts to protect natural ecosystems and effectively utilize fossil fuels in various fields. Combustion is widely used for energy conversion technique in the world. The emission standards of harmful substances such as NOx, CO and particles from cars as well as several types of commercial thermal plants are strictly regulated for environmental preservation. In engines, for example, exhaust gas temperature distribution is an important factor in NOx, THC and PM emissions. Conventionally a thermocouple has been widely used as a temperature measurement device. However it is intrinsically a point measurement method and it is difficult to measure gas temperature distribution inside the combustion chamber and exhaust with sufficient time resolution. Compared to the point measurement, combustion chamber designs and fuelling strategies can be efficiently evaluated by visualizing two dimensional(2D) temperature and concentration distributions, which have effects on complex phenomena such as knocking, combustion instability and production of pollutants in combustors. Therefore, 2D temperature and concentration distribution plays an important role for the combustion structure, the combustion efficiency and reduction of pollutants including NOx, CO and particles in engines, burners, gas turbines and so on.

Recently, as a multi-species measurement technique with high sensitivity and high response, tunable diode laser absorption spectroscopy (TDLAS) has been developed and applied to the actual engine combustions [1-5]. With these engineering developments, transient phenomena such as start-ups and load changes in engines have been gradually elucidated in various conditions [6-12]. In this study, the theoretical and experimental research has been conducted in order to develop the non-contact and fast response 2D temperature and concentration distribution measurement method. The method is based on a computed tomography (CT) using absorption spectra of water vapor at 1388 nm. The CT-TDLAS method was applied to engine exhausts to measure 2D temperature distribution. The temporal and spatial resolutions of this method have also been discussed to demonstrate its applicability for various types of combustor.

2. Theory

Gas temperature and species concentration can be determined by measuring molecular absorbance at multiple wavelengths. Tunable diode laser absorption spectroscopy was used in this research. It is possible to continuously scan laser wavelengths and measure absorption spectra. Principle of TDLAS is based on Lambert Beer's law. When light permeates an absorption medium, the strength of the permeated light is related to absorber concentration according to Lambert Beer's law. TDLAS uses this basic law to measure temperature and species concentration. The number density of the measured species n is related to the amount of light absorbed as in the following formula [1, 2]:

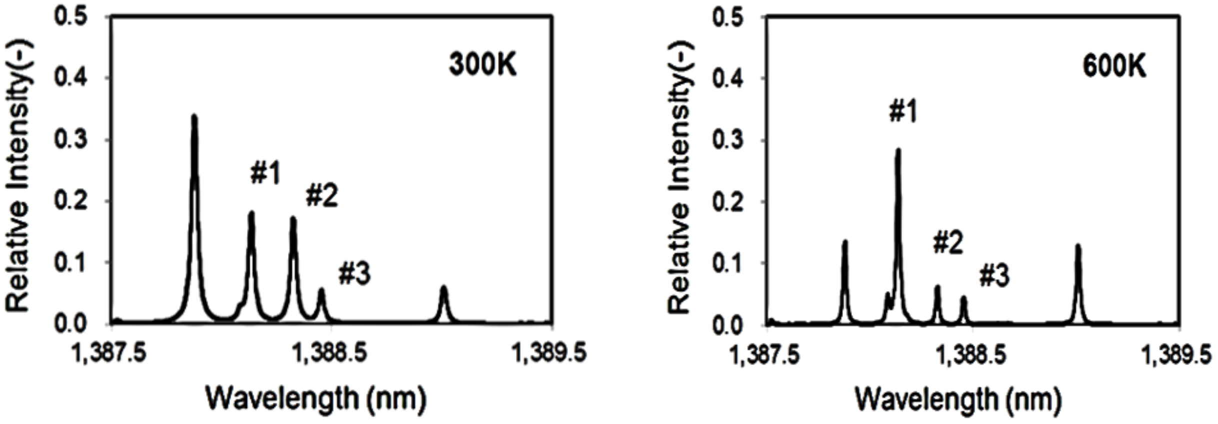
$$I_\lambda / I_{\lambda 0} = \exp\left\{-A_\lambda\right\} = \exp\left\{-\sum_i \left(n_i L \sum_j S_{i,j}(T) G_{\mathrm{v}i,j} \right)\right\} \qquad (1)$$

Here, $I_{\lambda 0}$ is the incident light intensity, I_λ the transmitted light intensity, A_λ the absorbance, n_i the number density of species i, L the path length, $S_{i,j}$ the temperature dependent absorption line strength of the absorption line j, and $G_{vi,j}$ the line broadening function.

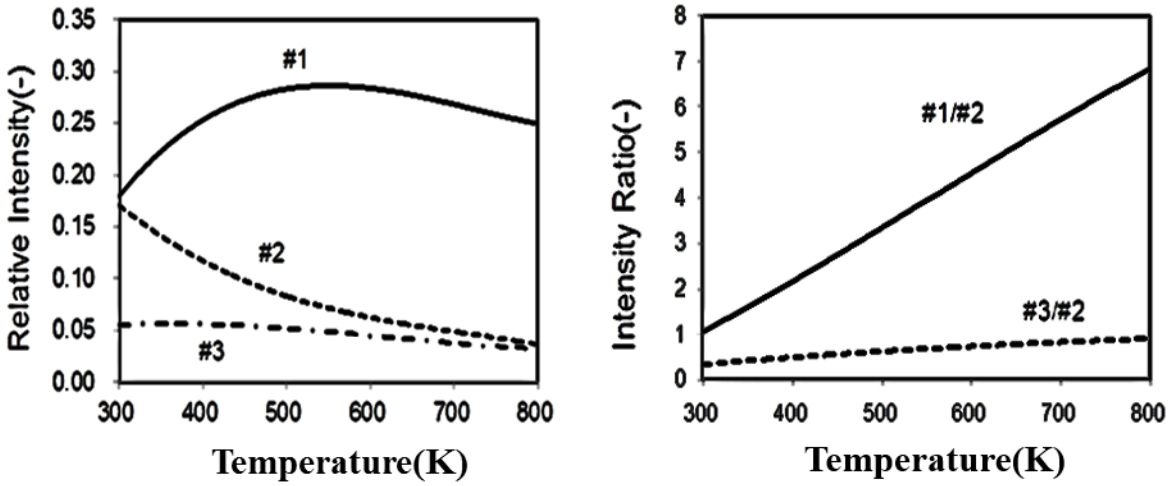
Theoretical H_2O absorption spectra using the HITRAN database [13] are shown in Fig. 1. In this study three absorption lines located at 1388.135 nm (#1), 1388.326 nm (#2), and 1388.454 nm (#3) were used to measure temperature and H_2O concentration. It is important to use several absorption lines with different temperature dependence to reduce the temperature error induced by a CT algorism.

Absorption of transmitted light through absorption medium occurs on the optical path. The absorption signal strength becomes an integrated value of the optical path. In this study, several optical paths are intersected to each other to form the analysis grids, reconstructing the 2D temperature distribution by a computed tomography method [14-17]. Concept of analysis grids and laser beam paths are shown in Fig. 2. The integrated absorbance in the path p is given by [14, 15].

$$A_{\lambda,p} = \sum_q n_q L_{p,q} \alpha_{\lambda,q} \qquad (2)$$



(a) 300K, 0.1MPa (b) 600K, 0.1MPa



(c) Temperature dependence of three absorption lines

(d) Temperature dependence of intensity ratio of two absorption lines

Fig.1 Theoretical H2O absorption spectra. (#1:1388.135nm, #2:1388.326nm, #3:1388.454nm)

Because the integrated absorbance is dependent on both temperature and concentration, the temperature distribution has to be calculated by more than two different absorbance values. Temperature and H_2O concentration at each analysis grid were determined using a multifunction minimization method to minimize the spectral fitting error at 1338.0-1338.6 nm.

$$Error = \sum \left\{ (A_{\lambda,q})_{theory} - (A_{\lambda,q})_{\exp erimet} \right\}^2 \qquad (3)$$

A set of measured H_2O absorption spectra was compared to the theoretical spectra to minimize the mean squared errors. Sets of H_2O densities and temperatures at analysis grids were determined separately by each minimization procedure shown in Fig. 3. A polynomial noise reduction technique [15,16] was also used to reduce noises such as the effect of laser beam steering.

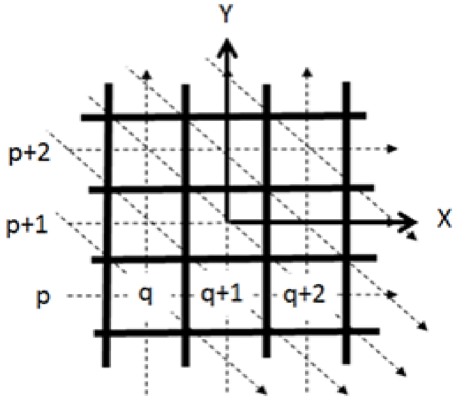


Fig. 2 CT grid and laser path.

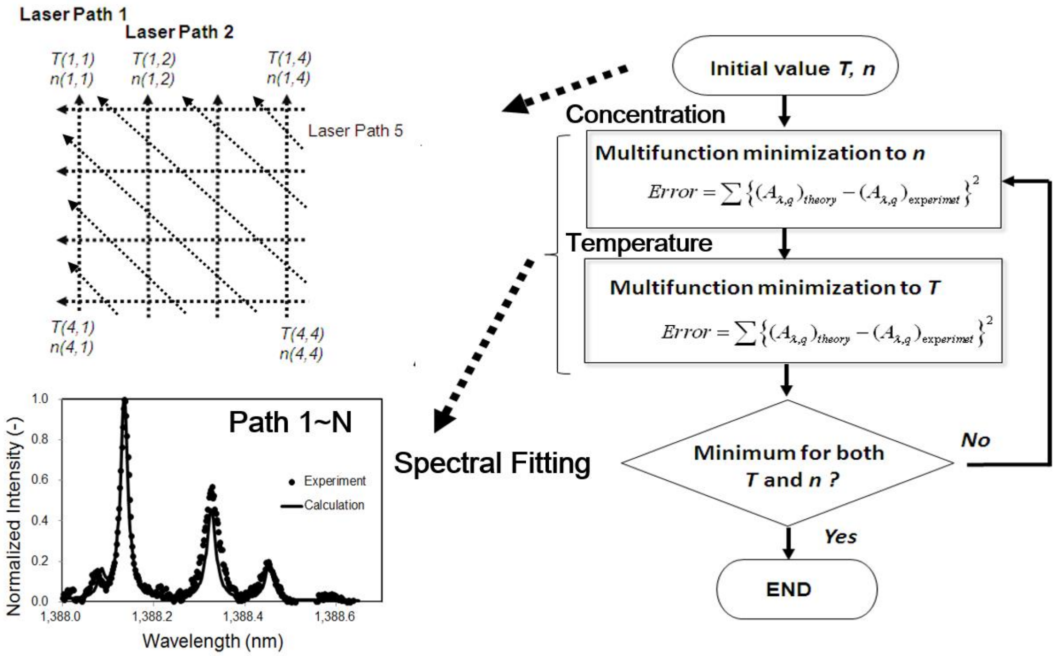


Fig. 3 CT –algorism.

3. Experimental apparatus

Fig. 4 shows the outline of an experimental apparatus used in this study. DFB lasers (NTT Electronics Co., NLK1E5GAAA) at 1388 nm with scanning range of 0.6 nm were used to measure water vapor absorption spectra. The lasers were scanned at 1 kHz and these outputs were mixed using a fiber combiner. Absorption spectra were simultaneously measured to calculate the instant 2D temperature using 16 path measurement cells shown in Fig. 4. Laser beam was separated by an optical fiber splitter (OPNETI CO., SMF-28e 1310 nm SWBC 1×16) and the separated laser beams were irradiated into the target area by 16 collimators (THORLABS Co., 50-1310-APC). The transmitted light intensities were detected by photodiodes (Hamamatsu Photonics and G8370-01), and taken into the recorder (HIOKI E.E. Co., 8861 Memory Highcoda HD Analog16). The data acquisition rate was 500 kHz (500 data points on every 1 scan of absorption spectra). Temperature in the measurement region was also measured by chromel-alumel thermocouples with a diameter of 100 μm (KMT-100-100-120).

Two types of experiment were performed using a Bunsen-type burner and a gasoline engine (FUJI HEAVY INDUSTRIES, Inc., EX13) as shown in Fig. 5. The laser paths were set at the position 95.5 mm above the burner and at the outlet of the engine exhaust pipes. The diameter of 16 path measurement cell was 70 mm. The diameter of the engine exhaust pipe is 22 mm with thickness of 3.5 mm and the pipe length was 160 mm.

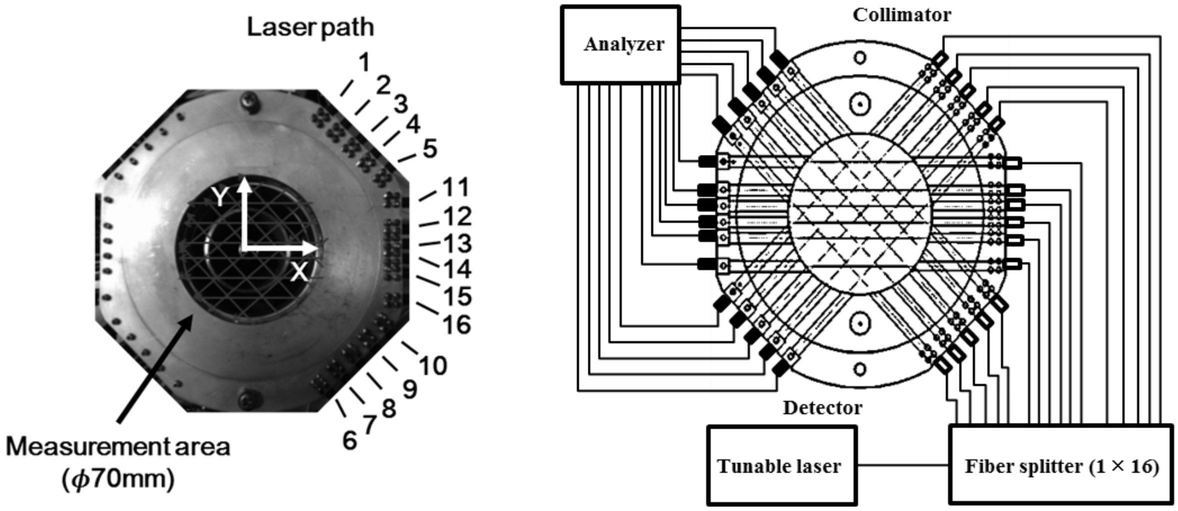
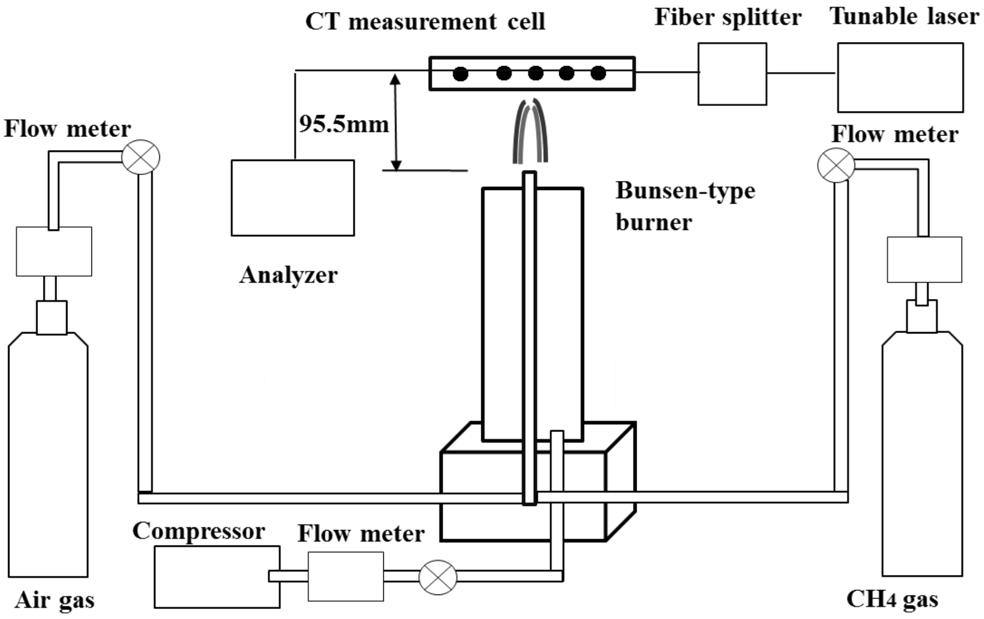
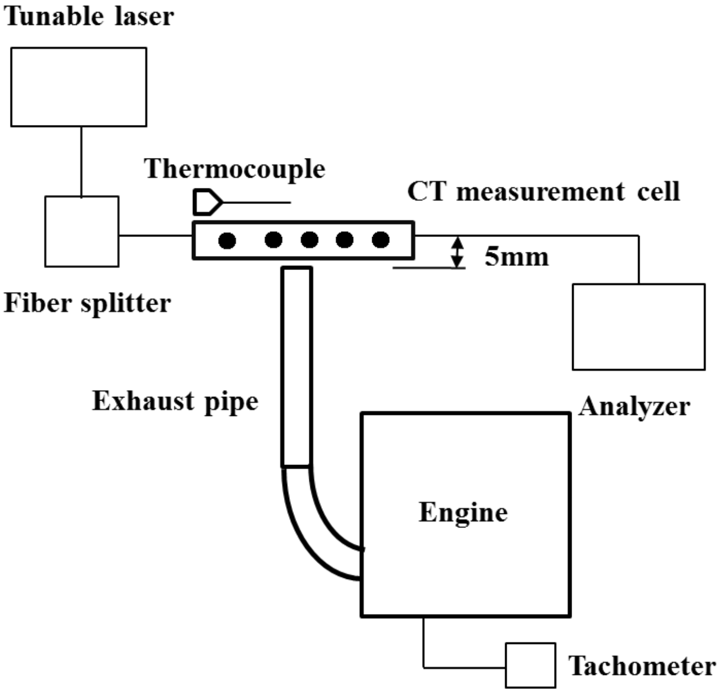


Fig. 4 16 path CT-TDLAS measurement cell.



(a) Burner experiment



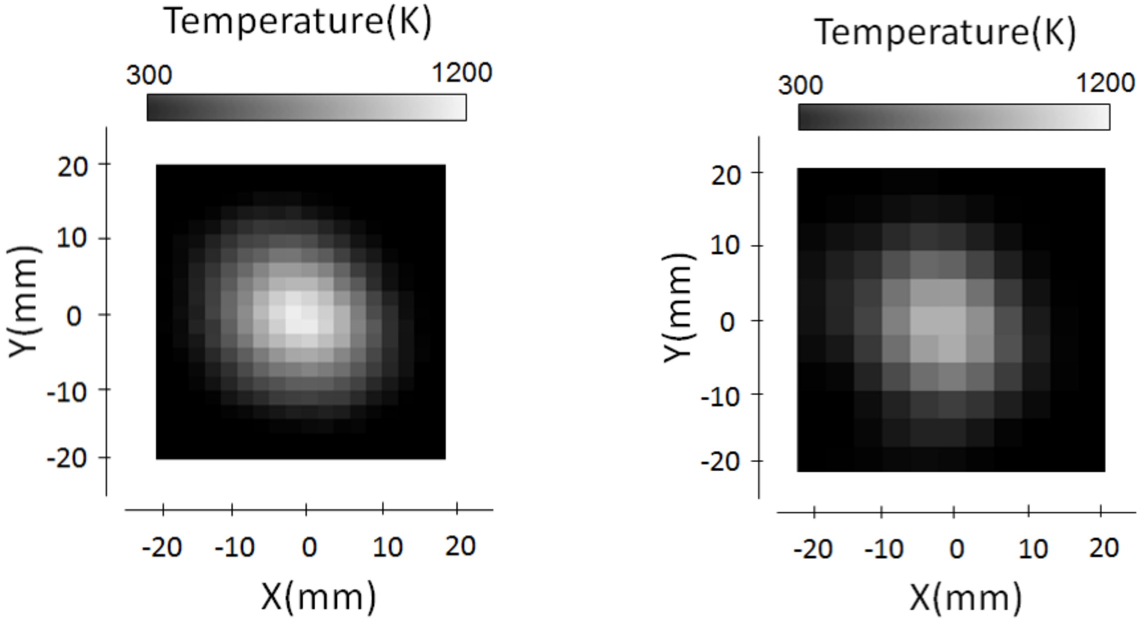
(b) Engine experiment

Fig. 5 Experimental apparatus.

4. Results and Discussion

4.1 Burner measurement results

2D temperature was measured by CT-TDLAS using the 16 path measurement cell shown in Fig. 4. In this experiment, 1388.135 nm (#1), 1388.326 nm (#2), and 1388.454 nm (#3) absorption lines were used to measure temperature. The 16 path cell was used in this experiment and 576 (24×24) points of temperature were analyzed using a multi-function minimization method. Fig. 6 shows the measurement results of temperature of the burner flame. Fig. 6(a) shows the results of temperature distribution measured by thermocouple. The burner was located at the center of the measurement cell (X=0, Y=0). The temperature was measured with interval of 2 mm by moving the thermocouple along the laser path surface. It shows that the highest temperature was about 1000 K and temperature became to the room temperature at X=20 mm. Fig. 6(b) shows the 2D temperature measured by CT-TDLAS.



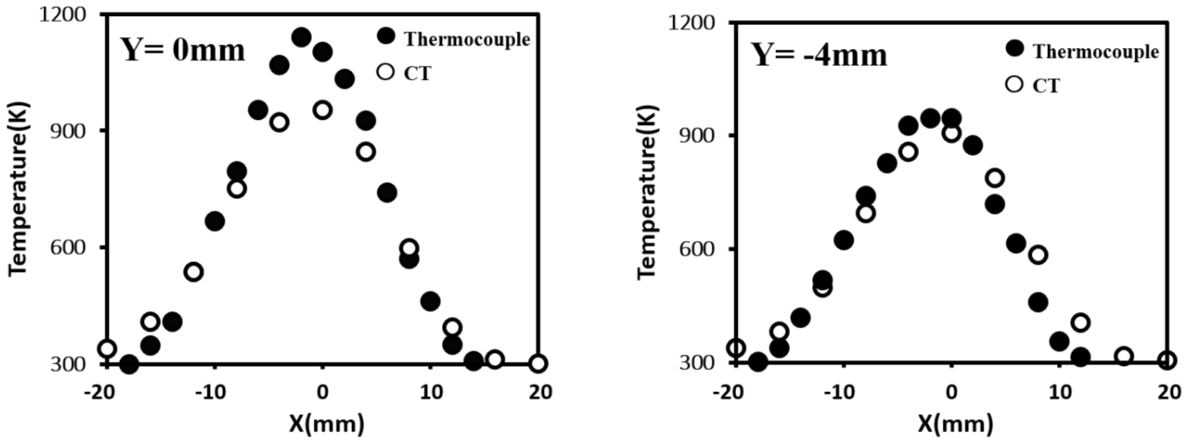
(a) Thermocouple

(b) CT-TDLAS

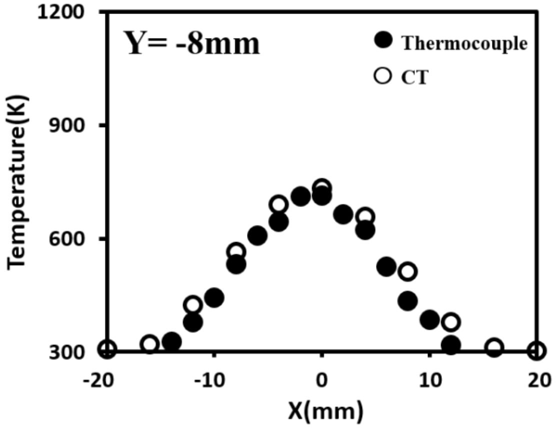
Fig. 6 2D temperature distributions measured by CT-TDLAS and thermocouple

(Bunsen burner : D=8mm, CH_4=1.2x10^{-5} (m^3/s) , Air=5.7x10^{-5} (m^3/s)).

The grid size was an important factor to reconstruct the precise temperature and concentration distribution. Comparison of measured temperature between thermocouple and CT-TDLAS at Y=0 mm, -4 mm, -8 mm is shown in Fig. 7. Measured temperatures are in a good agreement with each other in Fig. 7 (b) and (c). It means that the set of reconstructed temperature and H_2O concentration given by CT algorithm is valid. In Fig. 7(a), temperature distribution measured by thermocouple and CT-TDLAS shows the difference of temperature between X= -5 mm and 5 mm. The modification of CT grid, HITRAN database and selected absorption lines is necessary for more accurate 2D temperature measurement above 1000 K.



(a) Temperature distribution at Y=0mm (b) Temperature distribution at Y=-4mm



(c) Temperature distribution at Y=-8mm

Fig. 7 Comparison of temperature distributions measured by thermocouple and CT-TDLAS.

4.2 Engine measurement results

The center of an exhaust outlet was set at the center of the CT measurement cell. Exhaust gas temperature distribution was measured by CT-TDLAS. In this experiment, 1388.135 nm (#1), 1388.326 nm (#2), and 1388.454 nm (#3) absorption lines were used to measure temperature. Temperature was simultaneously measured by a thermocouple simultaneously. Exhaust gas temperature distribution was measured using the 16 path measurement cell. Fig. 8 show the 2D temperature measurement results at the engine revolution of 2400rpm. Better spatial resolution was achieved using the 16 laser paths compared with the results of 8 or 12 laser paths [17, 18]. The spatial resolution of CT-TDLAS can be easily improved to 2-3 mm by adding laser paths to the measurement area.

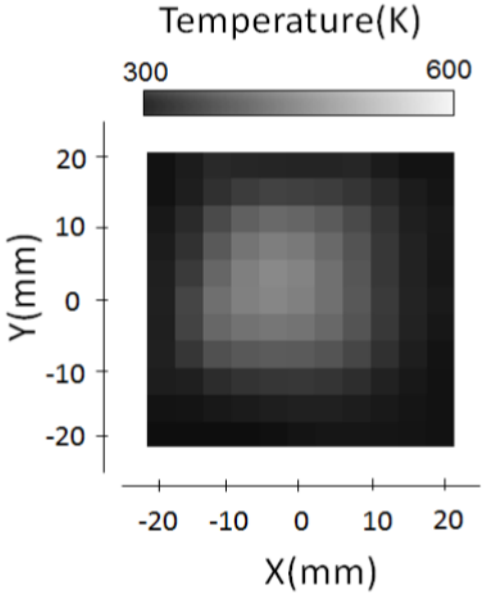


Fig. 8 2D temperature measurement results in engine exhausts using 16 path measurement cell.

4.3 Accuracy evaluation

Fig. 9 shows the comparison of measured temperature between CT-TDLAS and thermocouple. 1388.135 nm (#1), 1388.326 nm (#2), and 1388.454 nm (#3) absorption lines were used for the temperature measurement by CT-TDLAS. The linear relation between the measured temperatures by CT-TDLAS and thermocouple is confirmed under 800 K condition. On the other hand, the results measured by CT-TDLAS show lower temperature compared with those by thermocouple. The reasons for this discrepancy are uncertainties of the spectroscopic database used in this experiment and the spatial resolution of CT-TDLAS. The revision of these spectroscopic data to match the measurement results can lead to better measurement accuracy.

In high temperature (1000-2000 K) and pressure (1-5 MPa) fields such as the combustion chamber of an standard vehicle engine, expansion of the wavelength sweep width becomes important to cover the broadened absorption spectra. At high pressure conditions collisional broadening becomes predominant. There is also a need to revise spectroscopic data at high temperature and pressure conditions to measure accurate temperature and species concentration.

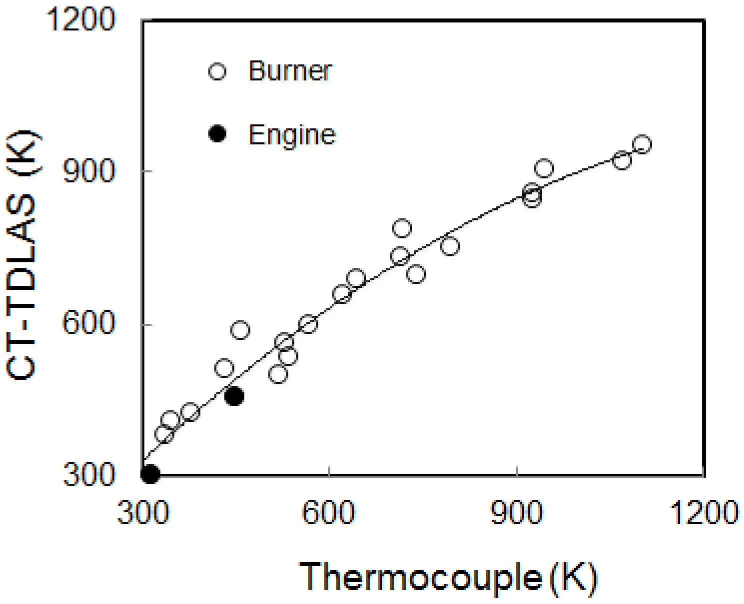


Fig. 9 Comparison of measured temperature between CT-TDLAS and thermocouple.

5. Conclusion

The 2D temperature measurement method using CT-TDLAS was developed and successfully demonstrated to measure 2D temperature distribution in combustion gas using 16 path measurement cell. Two types of experiment were performed using a Bunsen-type flame burner and a gasoline engine. 2D temperature distribution in Bunsen-type flame burner was measured by the CT-TDLAS method. The 2D temperature results of CT method were compared with the thermocouple measurements to evaluate quantitative measurements of temperature. The linear relation between the measured temperatures by CT-TDLAS and thermocouple was confirmed under 800 K condition. On the other hand, the results measured by CT-TDLAS show lower temperature compared with those by thermocouple. Considering the space averaged characteristics of the CT method, the results show a good agreement with the measurement results using the thermocouple. CT-TDLAS has a potential of the kHz response time and the method enables the real-time 2D temperature and species concentration measurement to be applicable in various fields.

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