Real-time temperature measurement of flame using optical methods

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Research Outline

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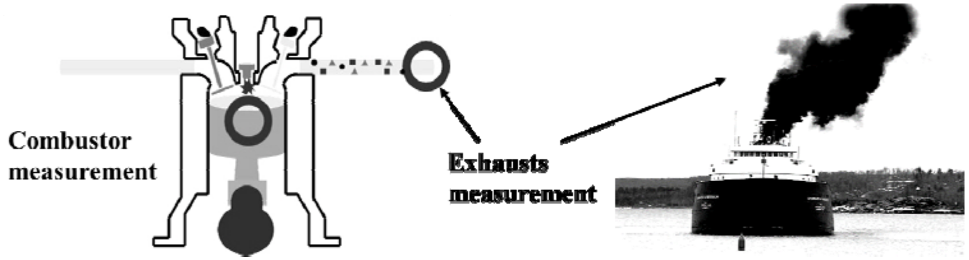
1. Background

Tighter regulation on substances such as NOx, CO_2 and CO

- Global warming and environmental problems
- Air pollution

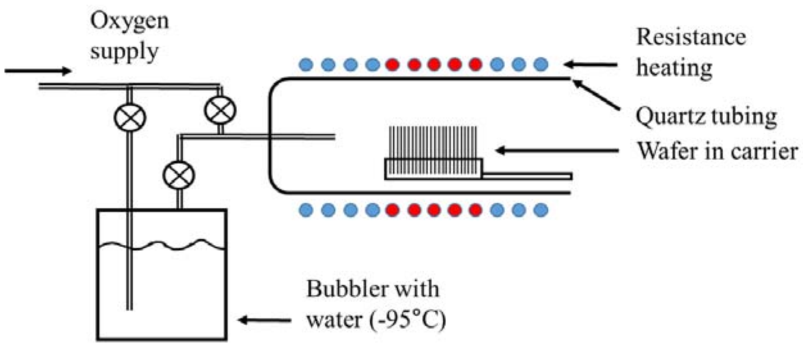


Especially, starting in 2015, cars need to be equipped with new engines or separate pollution-reducing devices to meet EURO 6 standards.

Carbon neutrality has become a hot topic around the world since 121 countries have joined the "Climate Ambition Alliance: Net Zero 2050" after the Paris Agreement into force in 2016.

Satisfy the requirements of high-quality and high-performance optimal material manufacturing process

- The quality of products is improved by controlling various gases



Precise measurement for the gases is important

- Comparison of a measurement technique

	LIF (Laser-Induced Fluorescence)	PIV (Particle Image Velocimetry)	PTV (Particle Tracking Velocimetry)	CT-TDLAS (Computer Tomography-Tunable Diode Laser Absorption Spectroscopy)
Measurement	Temperature, Concentration (Velocity, Pressure)	Velocity (Pressure)	Velocity (Pressure)	Temperature, Concentration (Velocity)
System cost	High	High	High	Low
Calibration Based on Theories	Difficult	Difficult	Difficult	Easy(self-calibrating)
Multi-Species Detection	Poor	Poor	Poor	Poor
In Situ Measurement	Excellent	Excellent	Excellent	Excellent

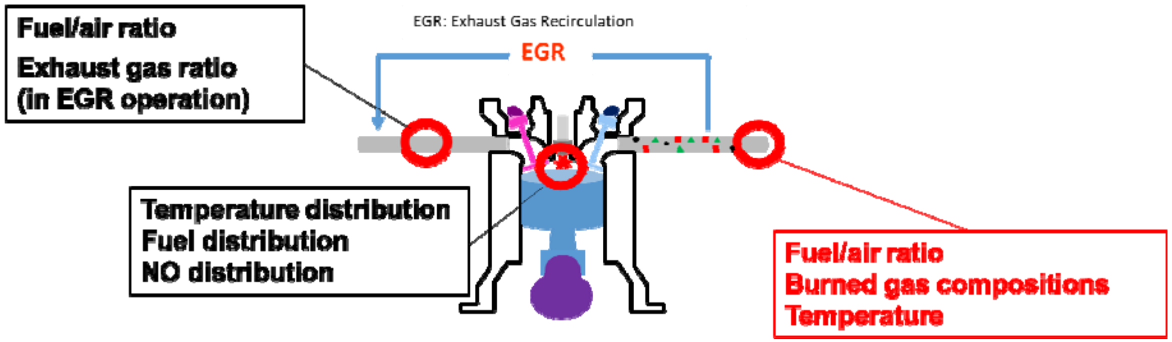
We have to choose the good method in the industrial application.

Can solve the problem using CT-TDLAS(Tunable Diode Laser Absorption Spectroscopy) system

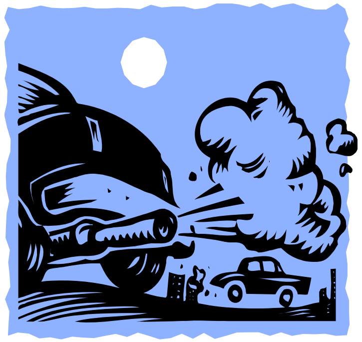
Necessary to understand irregular behavior in real-time, such as the combustion process.

1 point measurement (Thermocouple) → 2-dimensional CT-TDLAS

Application : Gas engine



Application : Exhaust gases

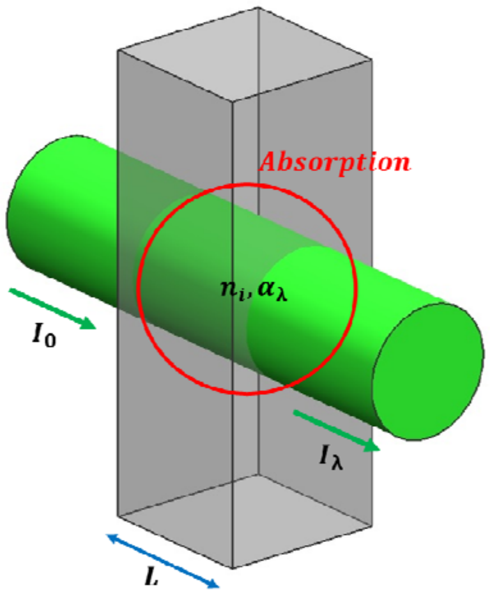


This study proposes a non-contact optical measurement method that does not interfere with the flow of combustion.

2. Theory

2.1 Principle of TDLAS

Tunable Diode Laser Absorption Spectroscopy(TDLAS)

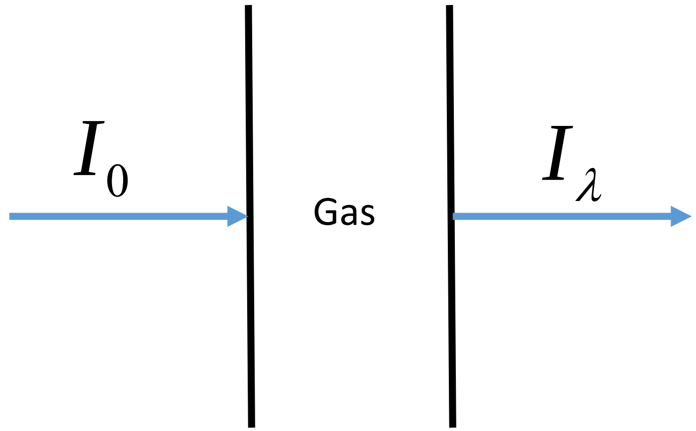


Lambert-Beer's law

$$\frac{I_t(\lambda)}{I_0(\lambda)} = exp\{A_\lambda\} = exp\{-\sum_i (P \cdot n_i \cdot L \sum_j S_{i,j}(T) G_{vi,j})\}$$

Here, I_o is the input laser light intensity, I_λ the transmitted light intensity at wavelength λ, n is the species number density, and L is the path length.

Experiment example

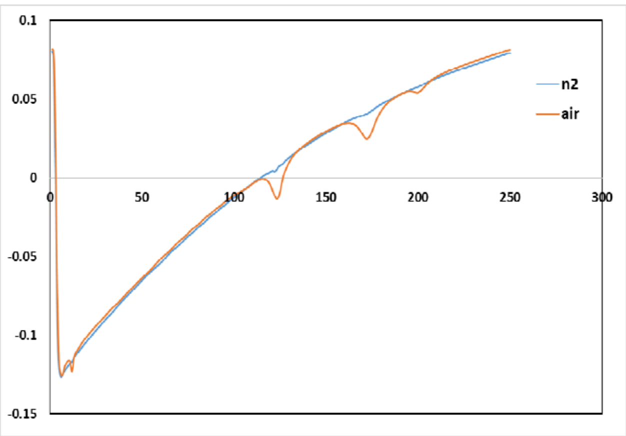


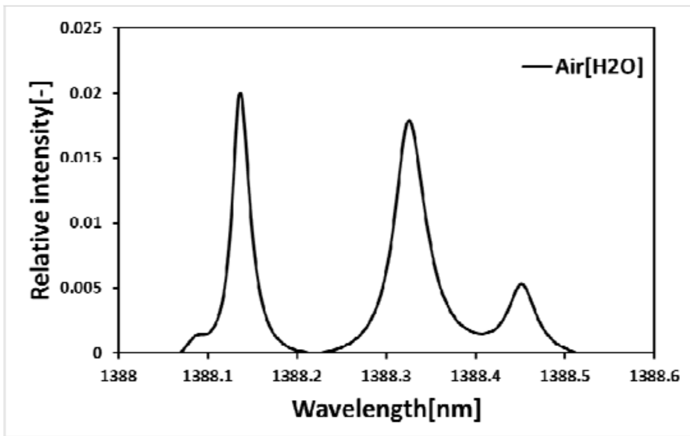
Absorbance of ratio : $A_r = \dfrac{I_\lambda}{I_0}$

here, $I_\lambda = Air_{AC}\ or\ Fire_{AC}$

$I_0 = N_{2DC}$

Absorbance : $A = 1 - \dfrac{I_\lambda}{I_0} = \dfrac{N_{2AC} - (Air_{AC}\ or\ Fire_{AC})}{N_{2DC}} = \dfrac{N_{2DC} - (Air_{DC}\ or\ Fire_{DC})}{N_{2DC}}$





- 0.1MPa
- Air
- Temperature : Room Temperature

Complete combustion Equation

$$CH_4+2(O_2+ (79/21)\ N_2) = CO_2+ 2H_2O+ 2*(79/21)N_2$$

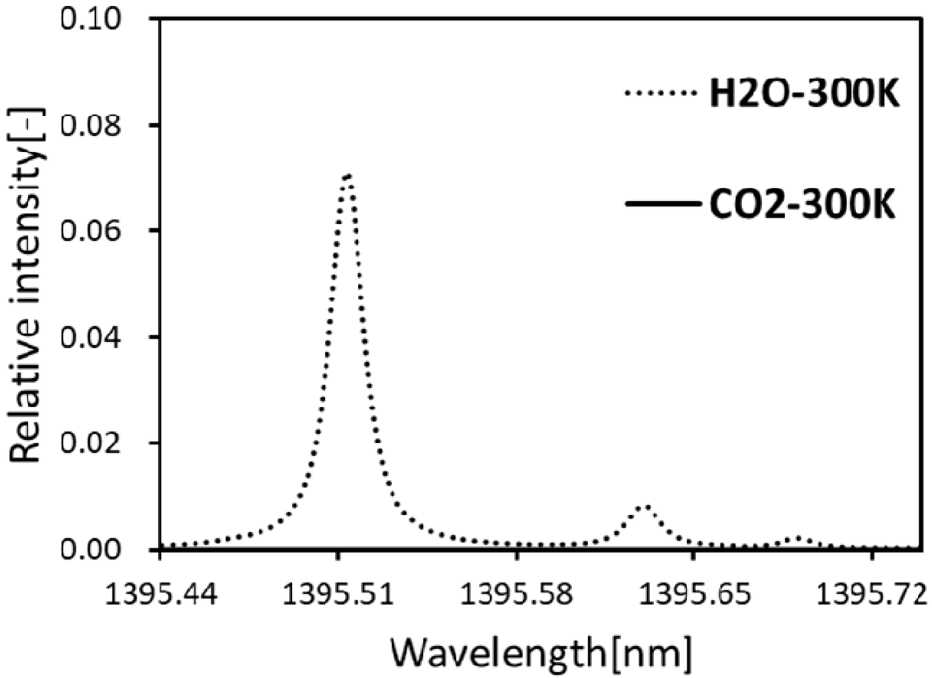
$16kg/1kmol$ $274.56kg/9.52kmol$ $44kg/1kmol$ $36kg/2kmol$ $210.56kg/7.52kmol$

Theoretical air required per 1kg of methane is 274.56/16=17.16 $kg/kg_{f.}$

Air-fuel ratio : $\frac{m_{air}}{m_{fuel}}$ **= 17.16** $\mathbf{kg/kg_f}$

The proportion of H_2O occupying in the combustion products is 12%.

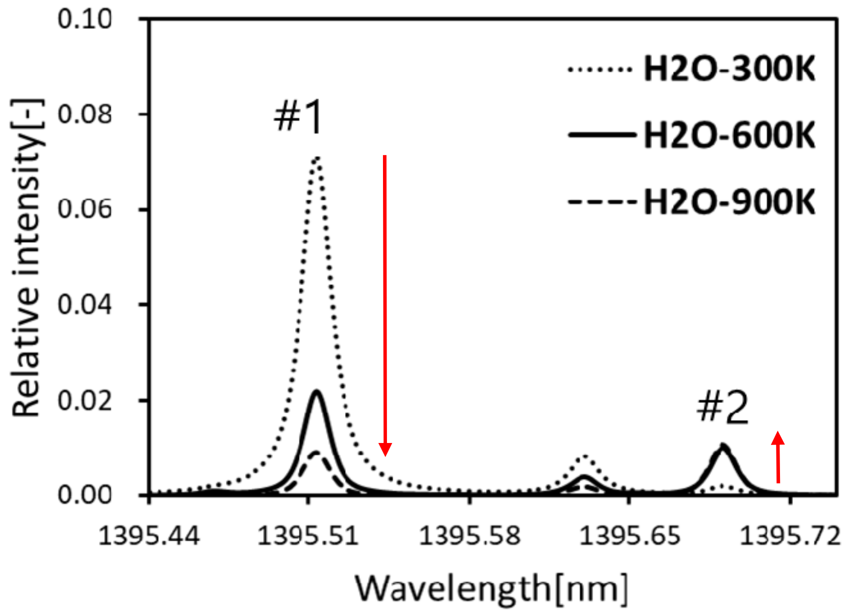
Depending on the type of target gas, the region of the representative wavelength where absorption appears large differs.

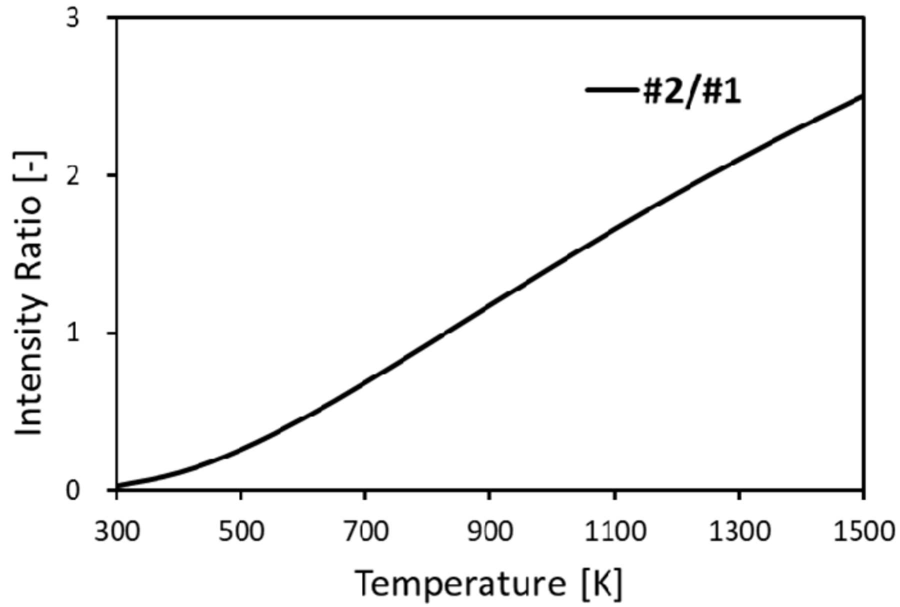


Interference confirmation of theoretical absorption spectra

The representative wavelength of the target gas

- H_2O : 1395nm
- CO : 1560nm
- CO_2 : 1580nm
- CH_4 : 1650nm
- NO : 225nm
- NO_2 : 405nm

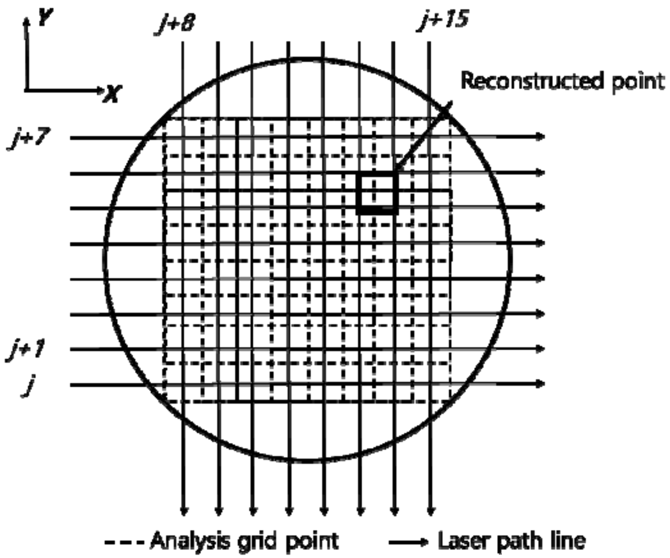




Relative intensity of theoretical H_2O absorption spectra(1395.44nm~1395.72nm)

Shows the absorption spectra at the temperatures of H_2O at 300K, 600K and 900K. These intensity profiles were calculated by using the **HITRAN(High Resolution Transmission) 2008 database**

2.3 Tomography reconstruction for TDLAS



How to divide the calculation area is most important.

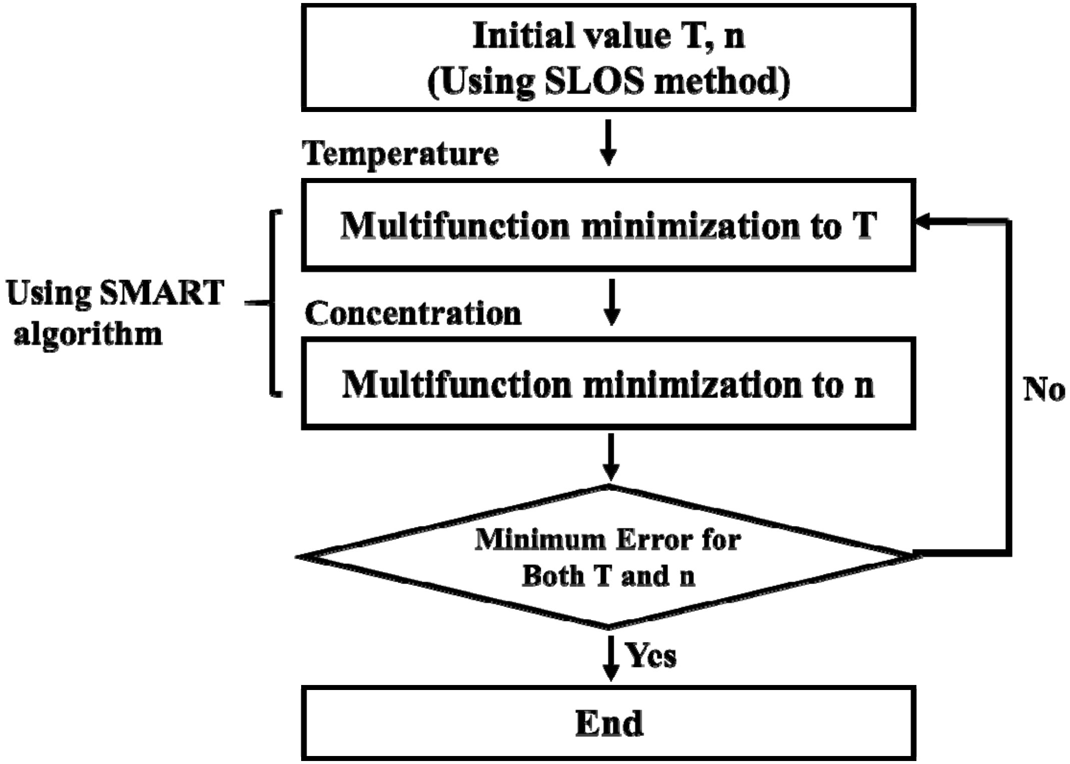
$$A_{\lambda,j} = -\sum_i n_i \cdot L_{i,j} \cdot \alpha_{\lambda,i}$$

Here, $A_{\lambda,j}$ is integrated absorbance of some wavelength λ in a path, $\alpha_{\lambda,i}$ is absorption coefficient of some wavelength λ inside a grid i on the path and is depend on temperature and density of species. $L_{i,j}$ is path length inside the grid i.

The conventional reconstruction algorithm for CT calculation, in which Fourier domain method is adopted.

- SMART algorithm (simultaneous multiplicative algebraic reconstruction technique)

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



SLOS (summation of line of sight) method

$$SLOS = \frac{A_{\#1,j1} + A_{\#1,j2}}{A_{\#2,j1} + A_{\#2,j2}}$$

SMART algorithm (simultaneous multiplicative algebraic reconstruction technique)

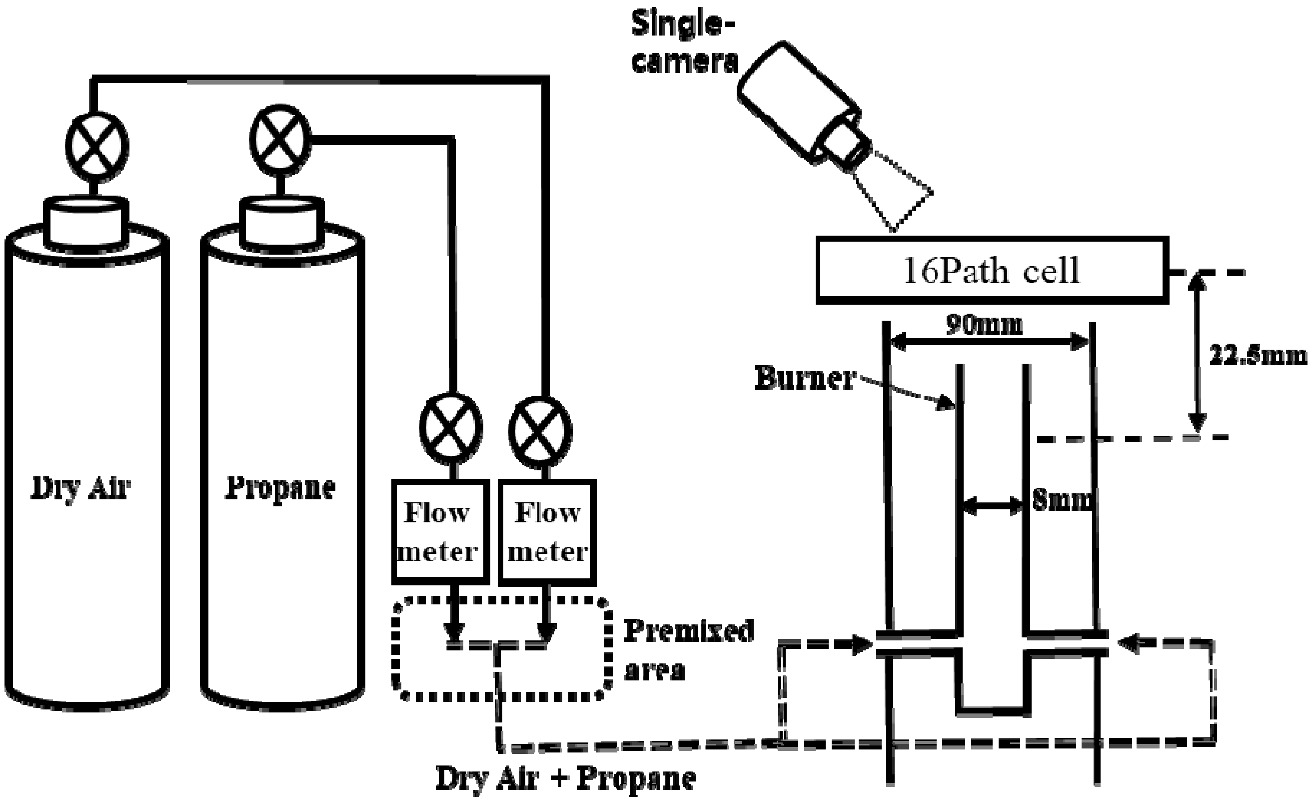
$$\alpha_{\lambda,i}^{k+1} = \alpha_{\lambda,i}^{k} \cdot exp\left(\sum_{j=1}^{J} \frac{L_{ij}}{\sum_{i=1}^{I} L_{ij}} \cdot log \frac{A_{\lambda,j}}{\sum_{i=1}^{I} \alpha_{\lambda,i} \cdot L_{ij}} \right)$$

MSE (mean square error)

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

3. Experimental setup

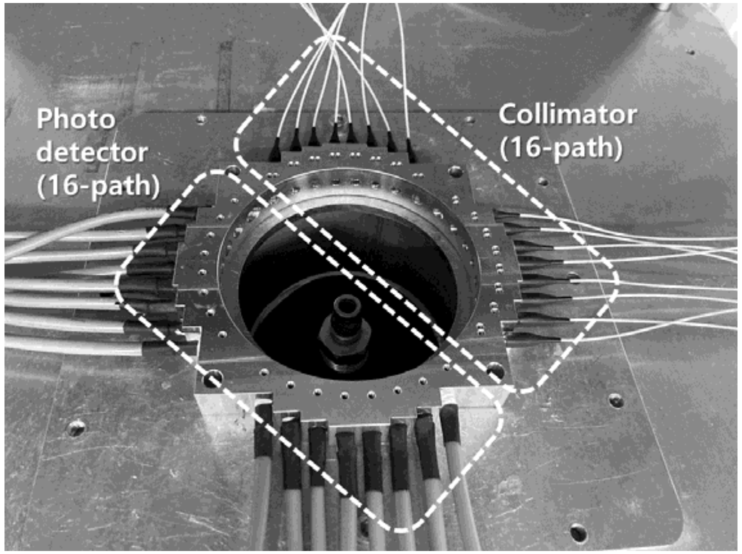
To measure the temperature was used thermocouples, a single camera, and the CT-TDLAS method during the combustion and extinguishing process.



Configuration diagram of optical system for two-dimensional temperature measurement of flame

Experimental parameters about premixed flame

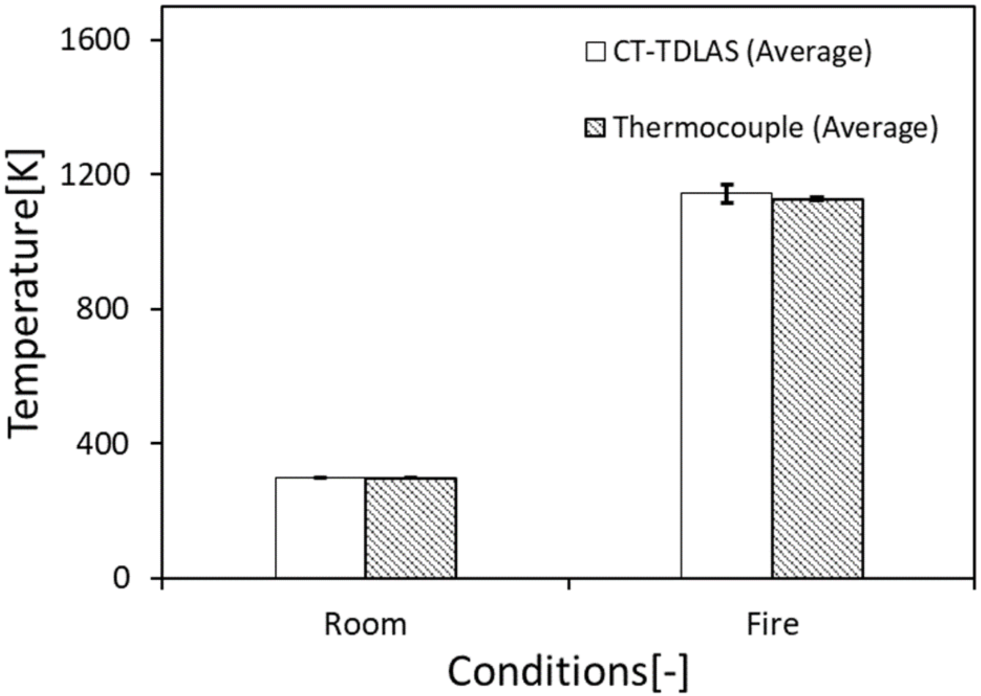
Condition	Propane (L/min)	Dry air (L/min)	Equivalence ratio	Reynolds number
Propane-Air premixed f lame	0.015	0.360	1.005	65.561



Optical CT-TDLAS measurement cell

4. Results and Discussion

A CT-TDLAS system uses to measure the temperature change that occurred during the combustion process. In addition, the changing in the intensity of light in the combustion field is compared together using a single camera system at the same time. A thermocouple is used as a verification of CT-TDLAS.

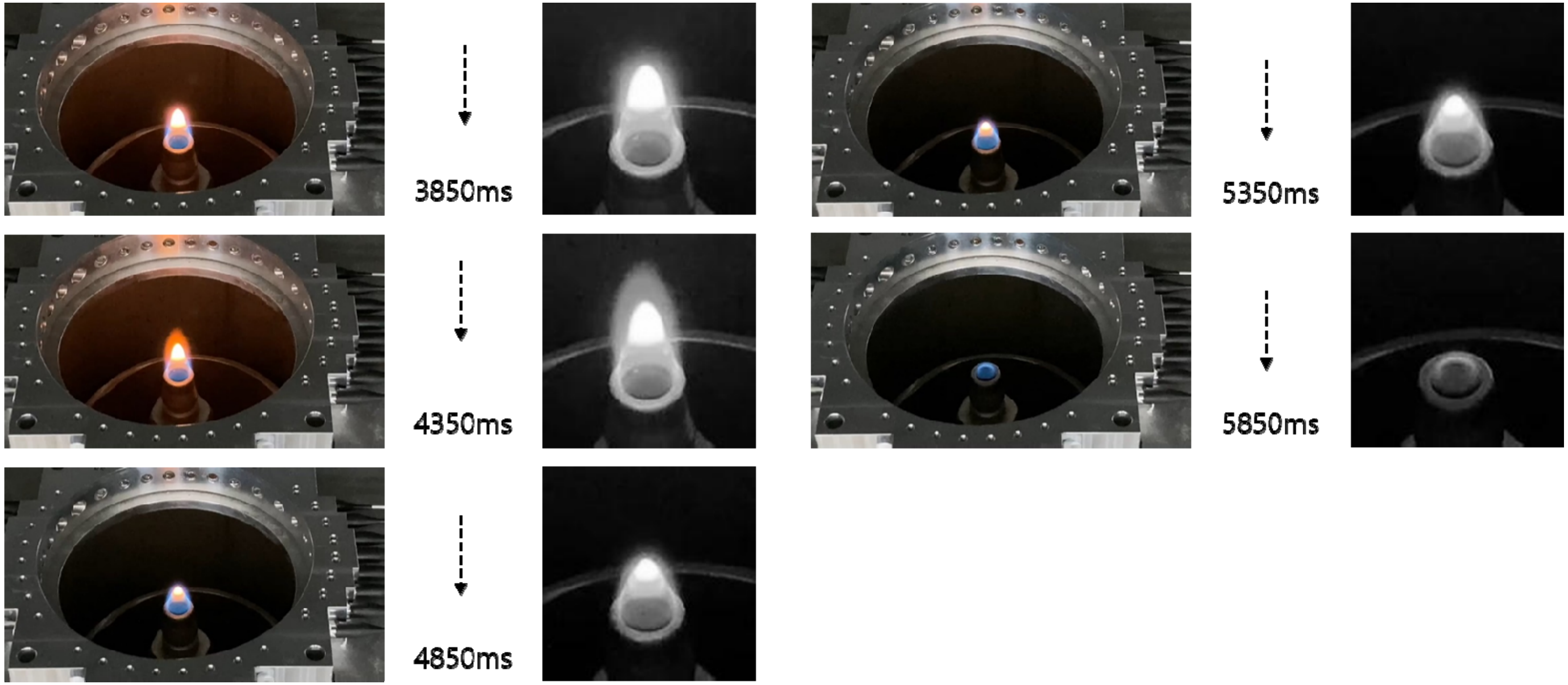


Relative evaluation of temperature measurement

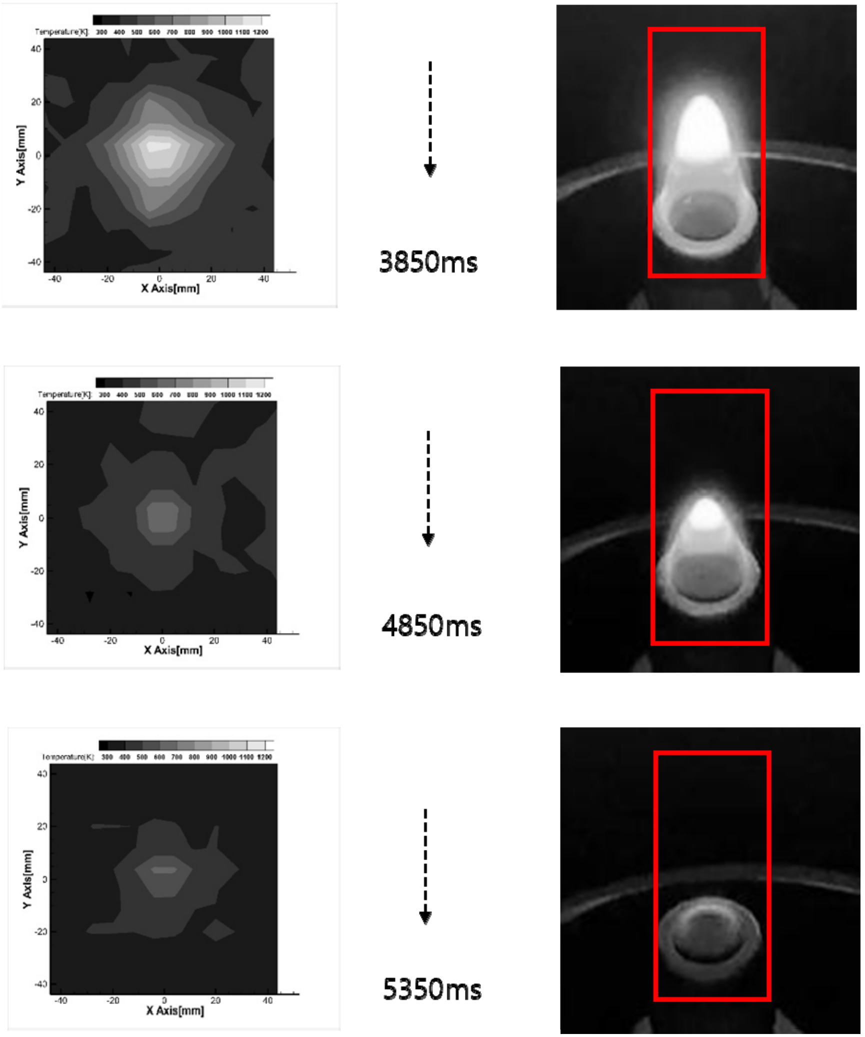
An error of 2% occurred in the relative temperature during flame maintenance. As a result of measuring the temperature change with a thermocouple for 5 seconds under flame conditions, the standard deviation is 4.056K. In the case of CT-TDLAS, the standard deviation was 27.123K, which was relatively high.

Comparison of phenomena that occur during fire extinguishing

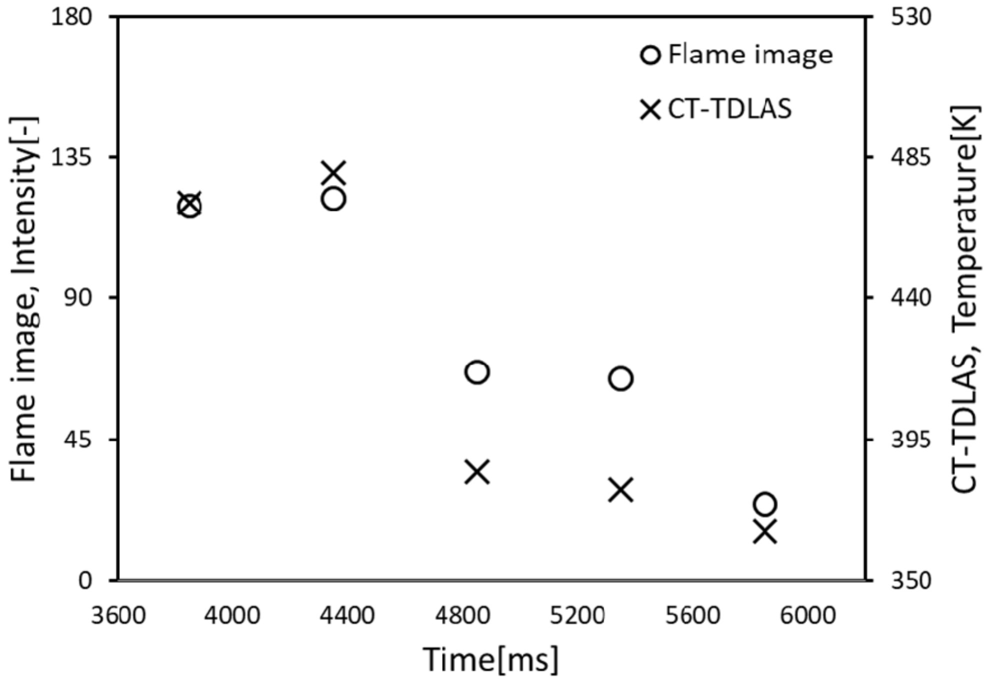
: The fire extinguishing process was compared using CT-TDLAS and a single-camera system.



Extinguishing process using the single-camera system



The CT-TDLAS results measured at the same time. It can confirm that the image information measured with a single camera system and the CT-TDLAS temperature field information behave the same. In particular, the area marked with a red box has pixels information, and the average value of the corresponding brightness information was used and compared with the CT-TDLAS result.



Extinguishing process according to time change

The digestion process as a function of time. It can confirm that the changing pattern of the average value of light and the changing pattern of the average temperature value of CT-TDLAS are similar.

5. Conclusions

- CT-TDLAS measurement was proposed to evaluate the fire extinguishing process in real-time. It was compared with a thermocouple for the same flame to validate the CT-TDLAS measurement. As a result, it was confirmed that the relative temperature error was reasonable at 2%. Also, in the case of CT-TDLAS, the standard deviation was 27.123K, which was more than 6 times higher than that of the thermocouple.

- Compare the CT-TDLAS result with the single-camera image at the same time. It was possible to evaluate the process of fire extinguishing at 500 ms intervals. In particular, it can be confirmed that the average brightness information of a single camera image and the behavior of the average temperature field of CT-TDLAS appear the same over time.

Thank you for your attention