Inhomogeneous Mixing Behavior of Recirculated Exhaust Gas in a Lean Premixed Flame

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Contents

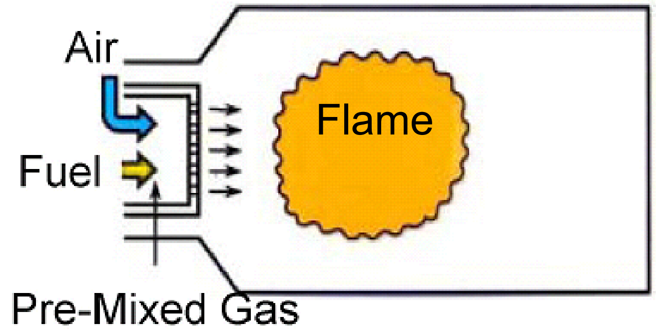
1. Background

reduce environmental loads

Premixed Combustion

Fuel and air are mixed before they burn

- Homogeneous flame is formed
- Reduce NOx emissions



Premixed combustion

EGR (Exhaust Gas Recirculation)

Recycle a part of the exhaust gas to the compressor

- Low oxygen concentration combustion
- Reduce the amount of oxygen combined with nitrogen
- Reduce NOx emissions

However …

The inhomogeneous oxygen distributions will be formed.

2. Objectives

To clarify the flame characteristics under the inhomogeneous oxygen concentrations

Approach

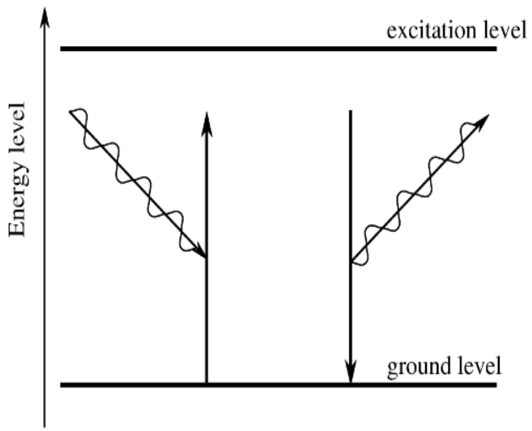
- Instantaneous measurements of 2-D flame temperature, OH-LIF and oxygen concentration distributions
- Using N_2 as a recirculated exhaust gas in order to reduce O2 concentration

Methods

Flame temperature	Rayleigh scattering method
OH-LIF and O_2	Laser-Induced Fluorescence(LIF) method
NOx emissions	Gas analyzer

(a) Rayleigh Scattering Method

Rayleigh scattering is the elastic scattering of light



- The wavelength of the scattering light = that of the incident light
- The wavelength of the scattering light doesn't change depending on gas species
- The intensity of the scattering light
  $\propto$ The number density of the gas molecules,
  The effective Rayleigh scattering cross section

Intensity of Rayleigh scattering light

↓ The effective Rayleigh scattering cross section

Number density of gas molecules

↓ The ideal gas equation

Temperature (is inversely proportional to scattering intensity)

Raleigh Scattering Intensity I_R

$$I_R = \varepsilon P_L N_s \sigma_{\mathrm{Re}\,ff} L$$

I_R : Rayleigh scattering intensity

ε : Detection efficiency

P_L : Laser intensity

N_s : Number density of molecules $N_s \propto T^{-1}$

$\sigma_{\mathrm{Re}\,ff}$: Effective Rayleigh scattering cross section

L : Length of measuring volume

Effective Rayleigh scattering cross section : σ_{Reff}

$$\sigma_{\mathrm{Reff}} = \sum_i \kappa_i \sigma_i$$

κ_i : mole fraction of species i

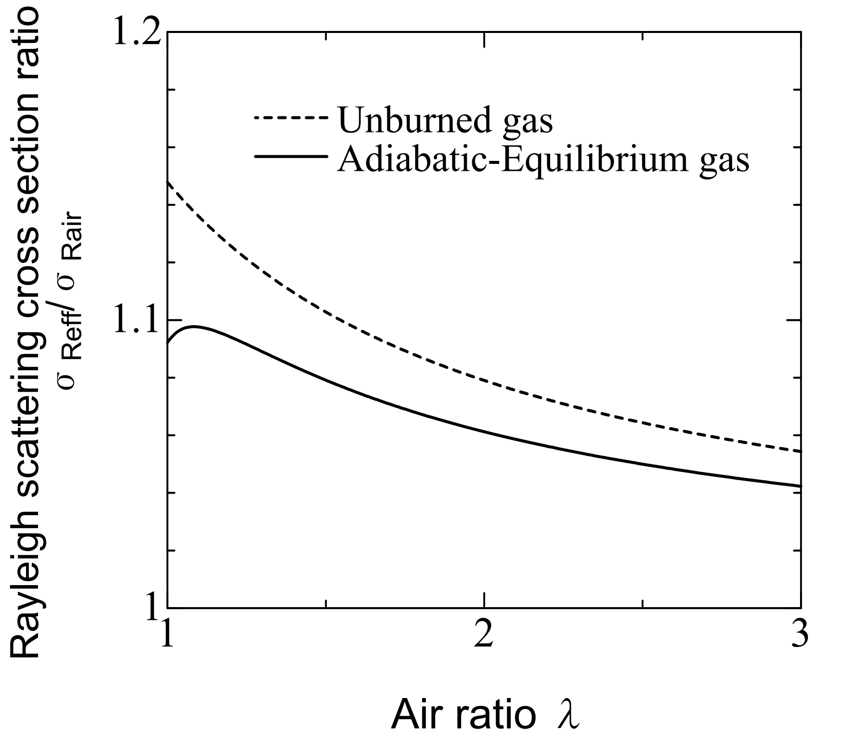
σ_i : Rayleigh scattering cross section of species i

The composition of species changes in combustion process

→ σ_{Reff} changes in combustion process

→ This technique is limited to the fuel whose σ_{Reff} varies only slightly

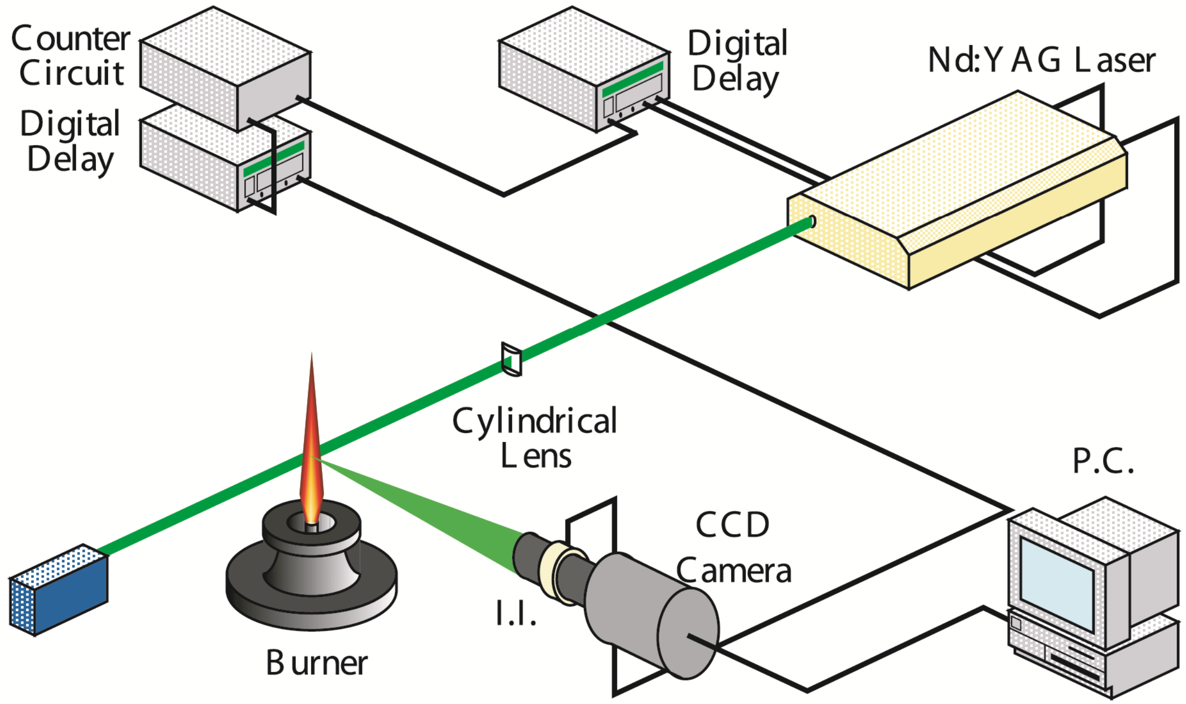
Effective Rayleigh scattering cross section : σ_{Reff}



➢ Relationship between air ratio λ and Rayleigh scattering cross section, σ_{Reff} normalized by that of air, σ_{Rair} in the CH_4-Air flame.

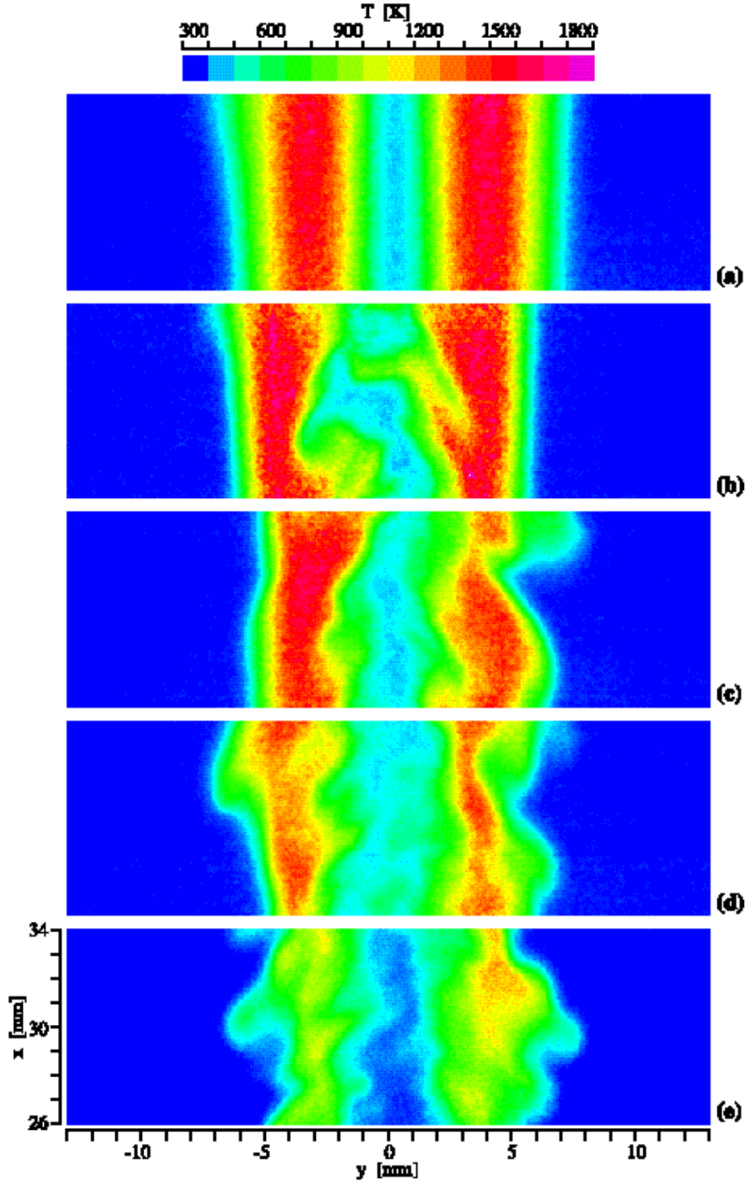
- CH_4 90 % + N_2 10 % /Air premixed flame
- Change of effective Rayleigh scattering cross section of the unburned mixture gas and burned gas within 3 %.
- Change of effective Rayleigh scattering cross section of the mixture gas in the reaction zone and burned gas within 4 %.

Optical Apparatus for Rayleigh Scattering



•Temperature measurement by Rayleigh scattering:
Nd:YAG laser (λ=532 nm, 300 mJ)
CCD camera with 512×512 square pixels with single I.I. and a normal lens (f 1.2)

Instantaneous Temperature Profiles in a Turbulent Flame

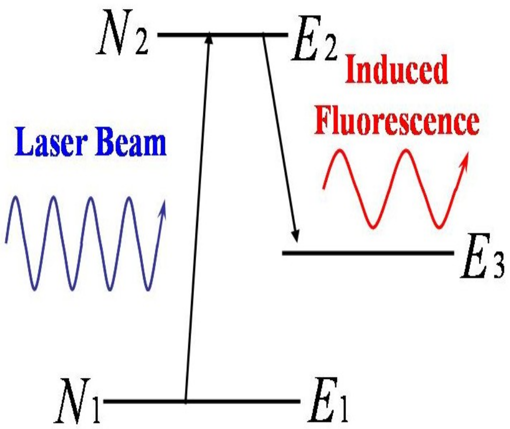


H_2 30%+N_2 70% Diffusion Flame
(a) Re=1000, (b) Re=4000,
(c) Re=8000, (d) Re=12000,
(e) Re=17000

(b) Laser-Induced Fluorescence (LIF)

Laser–induced fluorescence (LIF) is a spectroscopic method used for detective of selective species and flow visualization and measurements

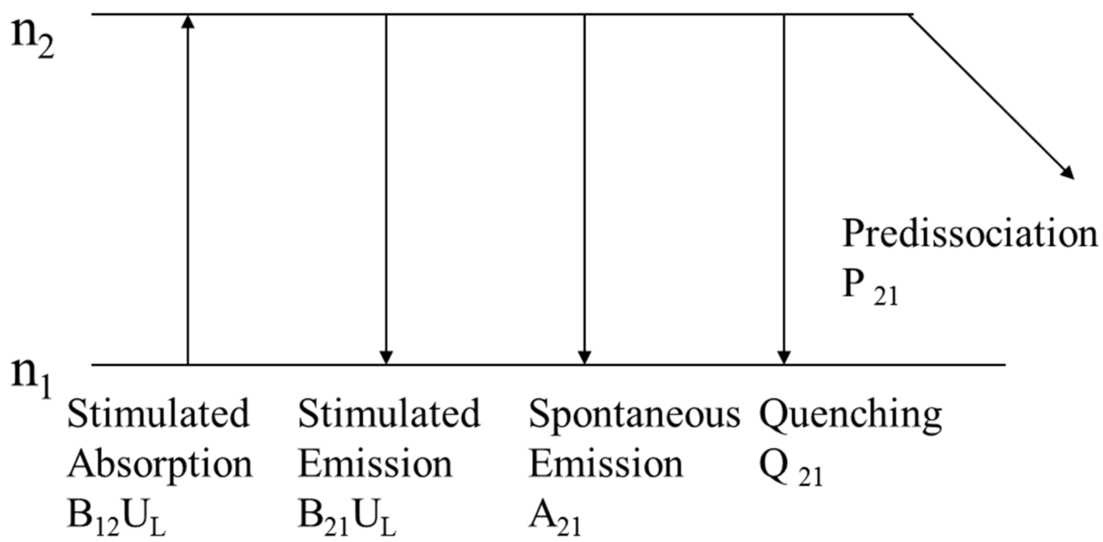
The excited species will de-excite and emit light at a wavelength larger than the excitation wavelength in few ns to μs.



<Advantages>

- It is possible to get two- and three-dimensional images.
- The signal-to-noise ratio of the fluorescence signal is relatively high, providing a good sensitivity to the process.
- It is possible to distinguish between more species .

Two level transition equation of molecules for LIF



$$\frac{dn_1}{dt} = n_2(B_{21}U_L + Q_{21} + A_{21}) - n_1 B_{12} U_L$$

$$\frac{dn_2}{dt} = n_1 B_{12} U_L - n_2(B_{21}U_L + Q_{21} + P_{21} + A_{21})$$

$$n_0 = n_1 + n_2$$

LIF intensity of OH molecules: I_F

$$A^2\Sigma^+(v'=1) \leftarrow X^2\Pi(v''=0) \;\; P_2(7): \;\; 285.43\text{nm}$$

$$I_F = \frac{A_{21}B_{12}U_L h\nu_{21}V}{B_{12}U_L + B_{21}U_L + Q_{21} + A_{21}} f_B(T)N$$

n_1 : number density of OH molecules in the ground state

n_2 : number density of OH molecules in the excithed state

n_o : total number density of OH molecules

B_{12} : Einstein coeffiient of stimulated absorption

B_{21} : Einstein coefficient of stimulated emission

A_{21} : Spontaneous emission rate

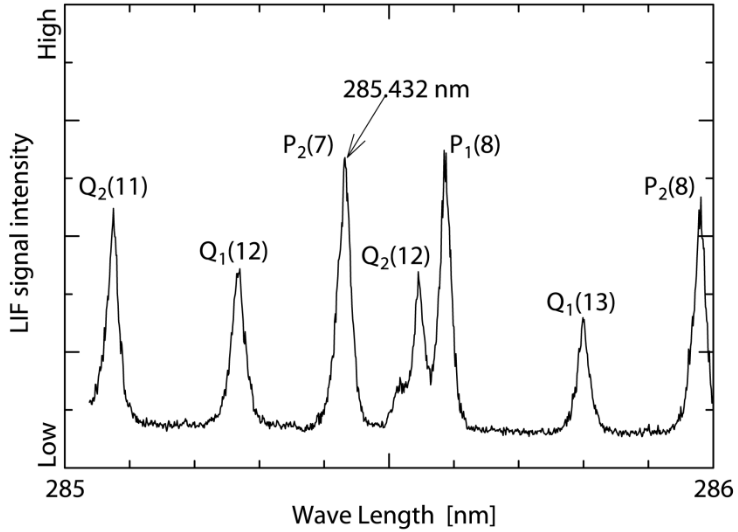
Q_{21} : electronic quenching rate

U_L : Energy density of laser light

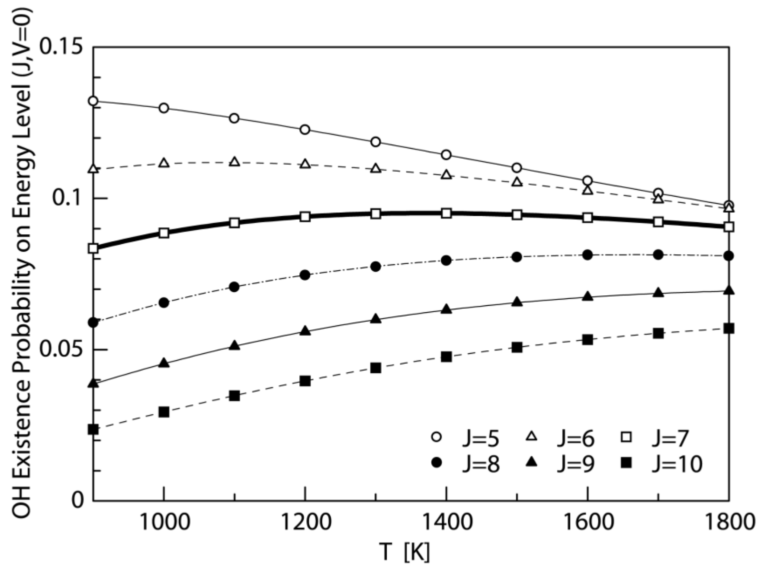
P_{21} : Predissociation rate

LIF intensity of OH A-X (1,0) System

- $P_2(7)$ A-X (1,0) has relatively weaker temperature dependency compered by other absorption lines.

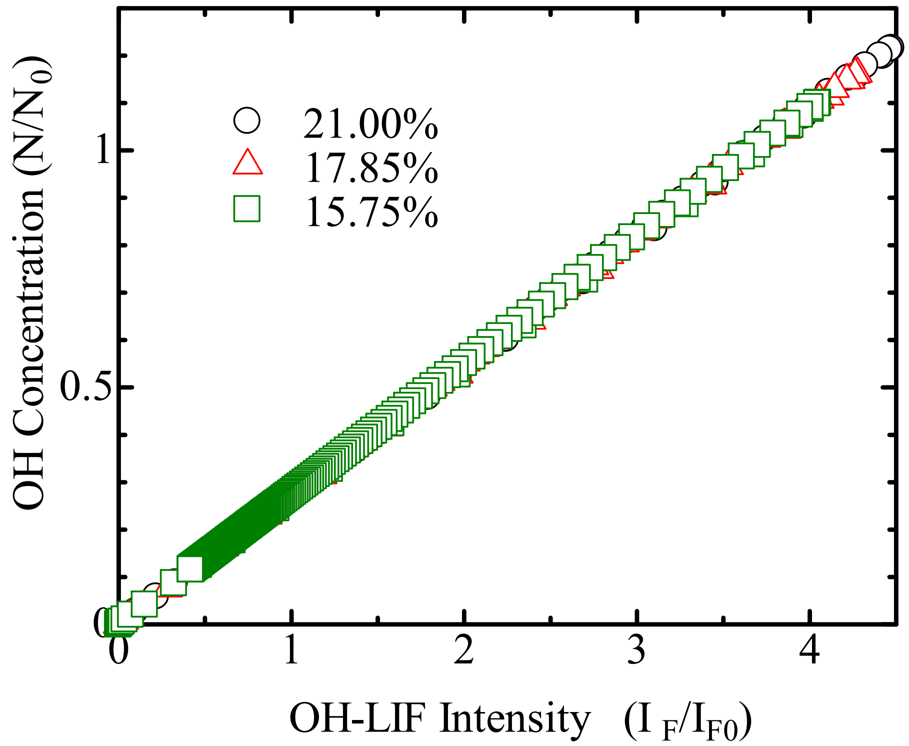


LIF signal intensity of OH A-X (1,0) system



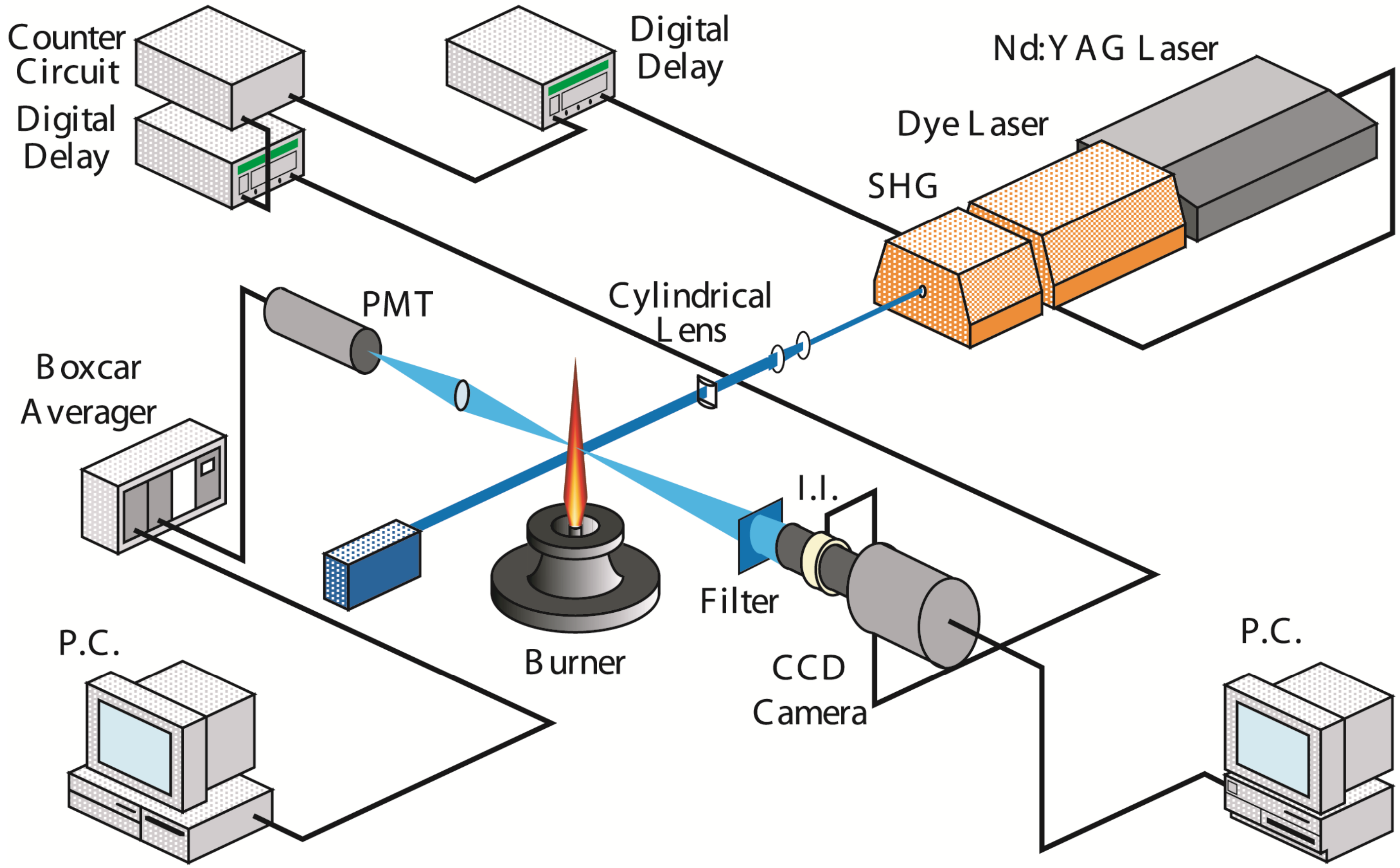
Relationships between OH existence probability on energy level and temperature

Relationship between OH-LIF and OH Concentration



- OH-LIF and OH concentration for air ratios of 2.0 with various oxygen concentrations.
- Calculated for the case of 1D PREMIX and GRI-Mech 3.0.
- Relationship between OH-LIF and OH Concentration keeps a linear one.

Optical apparatus for OH LIF



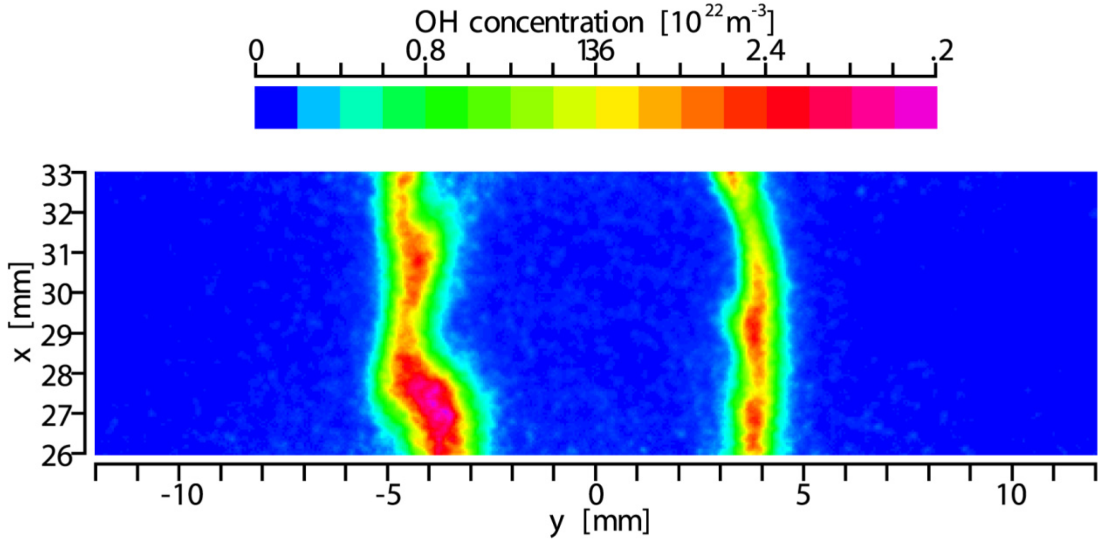
•OH-LIF:

Nd:YAG pumped dye laser (λ= 285.43 nm, 10 mJ) to excite the $P_2(7)$ line of the (1-0) band of $A^2\Sigma^+ - X^2\Pi$.

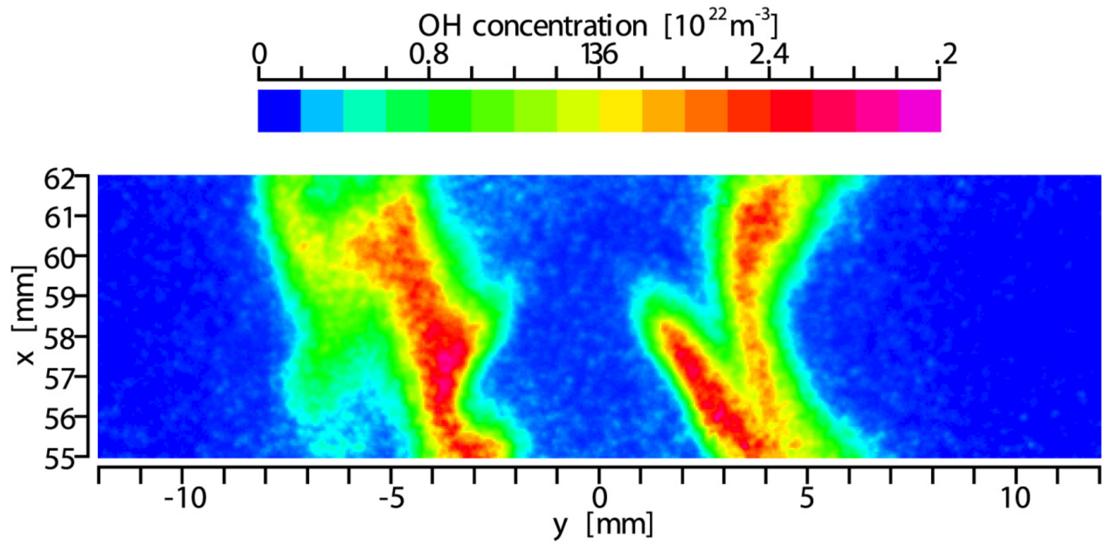
CCD camera with 512×512 square pixels with single I.I. and a UV camera lens (f3.5)

OH Concentration Profiles in a Turbulent Flame

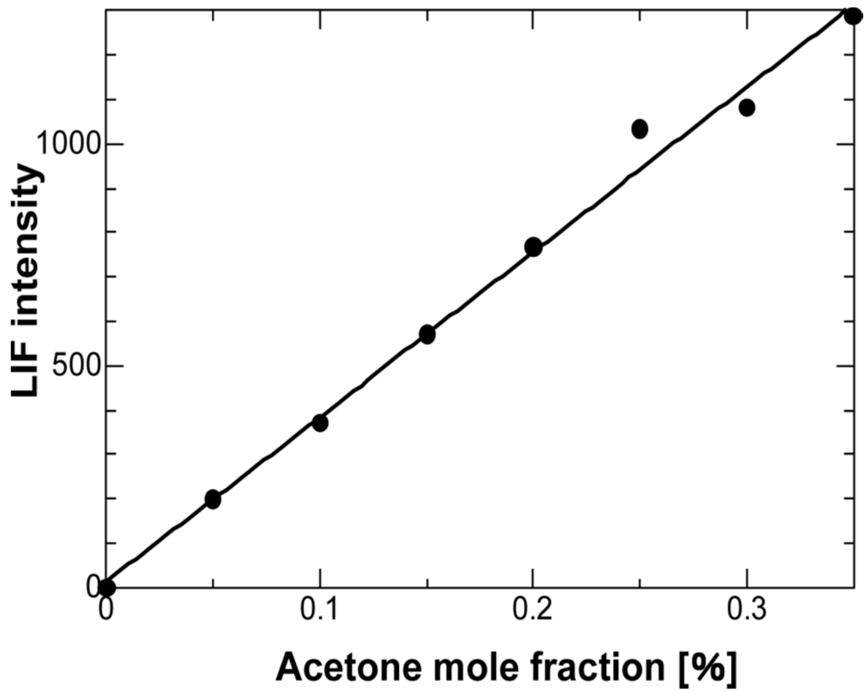
X=30 mm



X=60 mm



Acetone LIF for N_2 Concentration Measurement

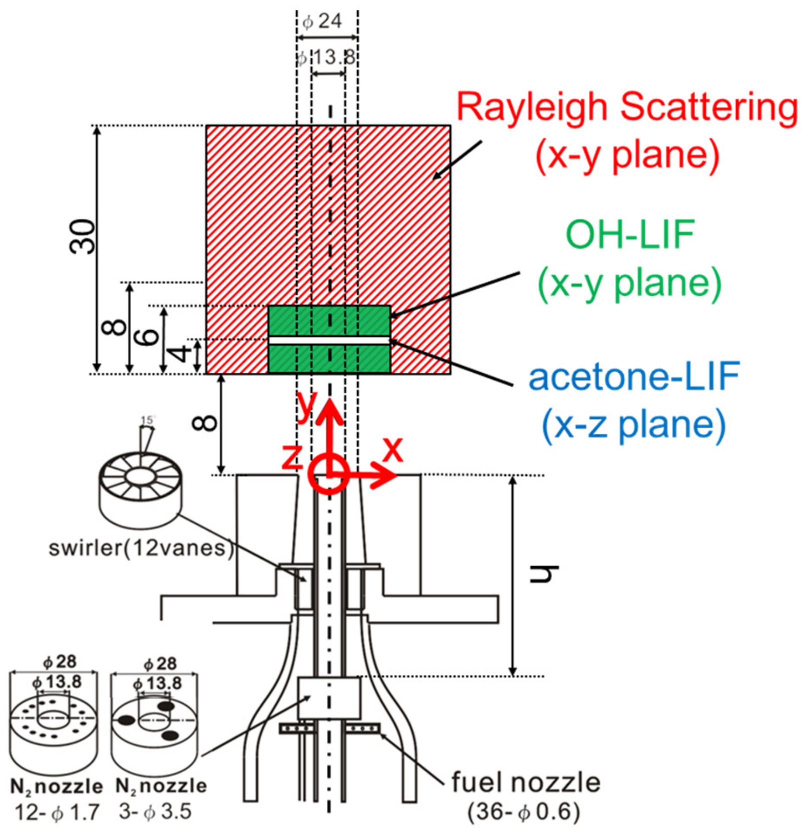


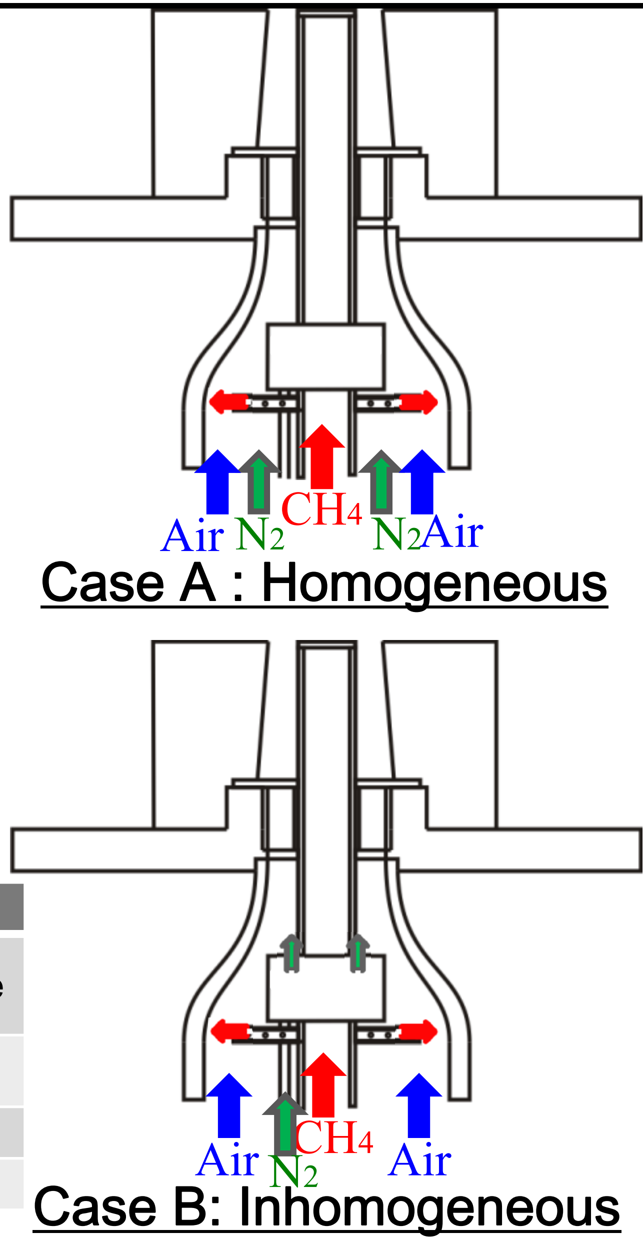
Acetone mole fraction is proportional to its LIF intensity in an unburned region in this experimental acetone mole fraction range.

•Nitrogen gas saturated with 1 % acetone vapor was used as a recirculated exhaust gas.

•Fluorescence intensity modified by the homogeneous acetone-LIF image of air.

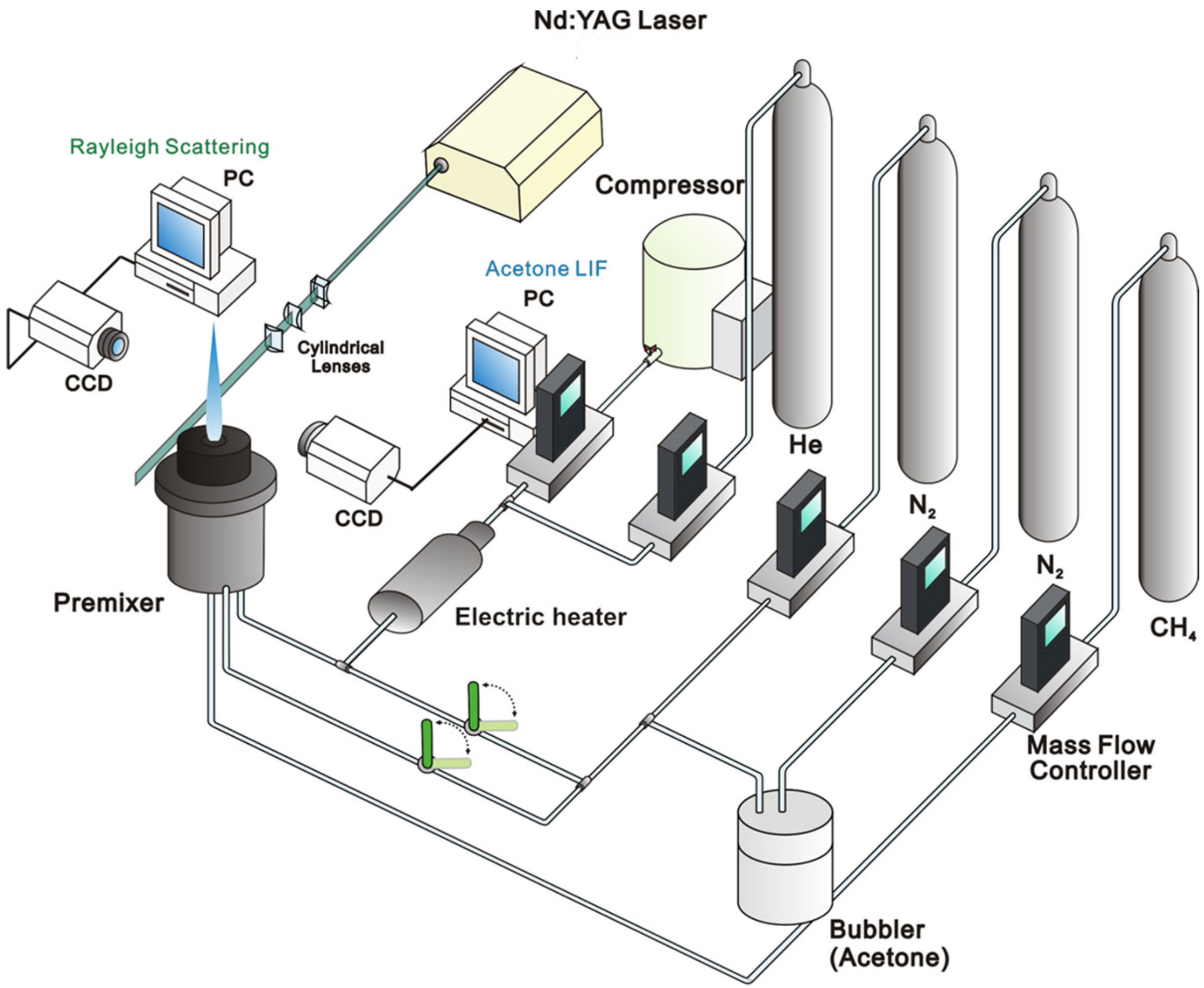
Schematic view of premixer for inhomogeneous mixing





Condition	Fuel	Oxidizer			
	CH_4	Air	N_2	O_2 concentration	Temperature
	NL/min	NL/min	NL/min	%	K
A	5	80.7	14.3	17.9	570
B	5	71.2	23.7	15.8	570

Experimental Apparatus for inhomogeneous mixing



Rayleigh: Nd:YAG 532nm, 400mJ
Acetone-LIF: Nd:YAG 266nm, 100mJ
OH-LIF: Nd:YAG pumped Dye laser 285.43 nm, 10mJ

- Air supplied from a compressor after cleaning moisture and dust.
- Nitrogen added to reduce oxygen concentration of an oxidizer.
- Methane as a fuel is supplied to fuel nozzle.
- A Nd:YAG laser
- CCD cameras for Rayleigh scattering and LIF are located at facing of the test section.

Inhomogeneity of oxygen concentration

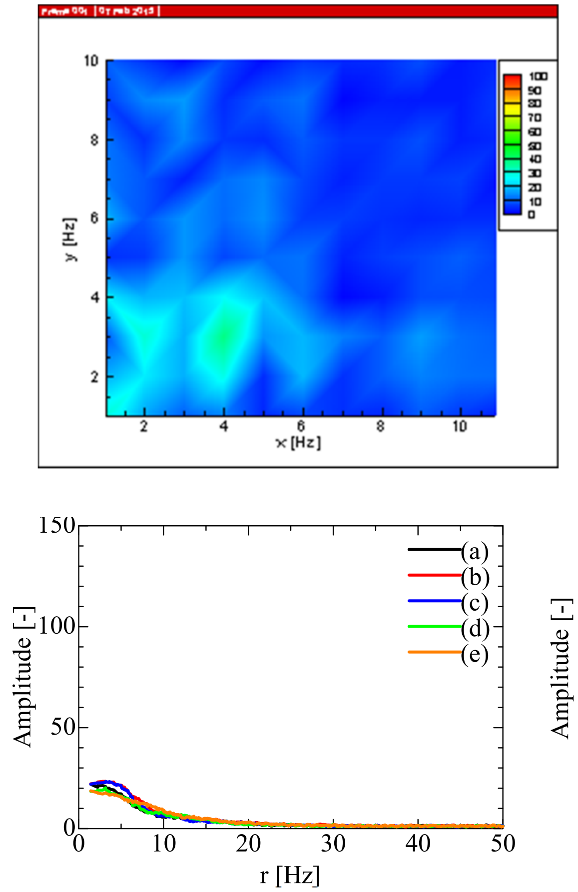
To evaluate inhomogeneity of oxygen concentration quantitatively, we used the *Unmixedness* : ***G*** given by the following equation.

$$G = \frac{\overline{Z'^2}}{\bar{Z}(1-\bar{Z})}$$

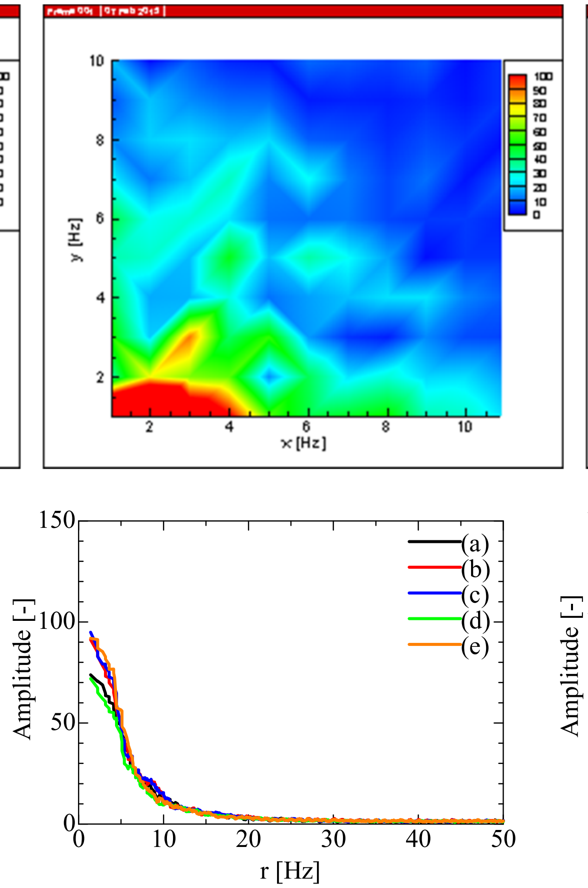
$\bar{Z}$: the average of LIF signals
Z': the variance of LIF signals

Spatial Scale λ of Concentration Fluctuation Using 2D FFT

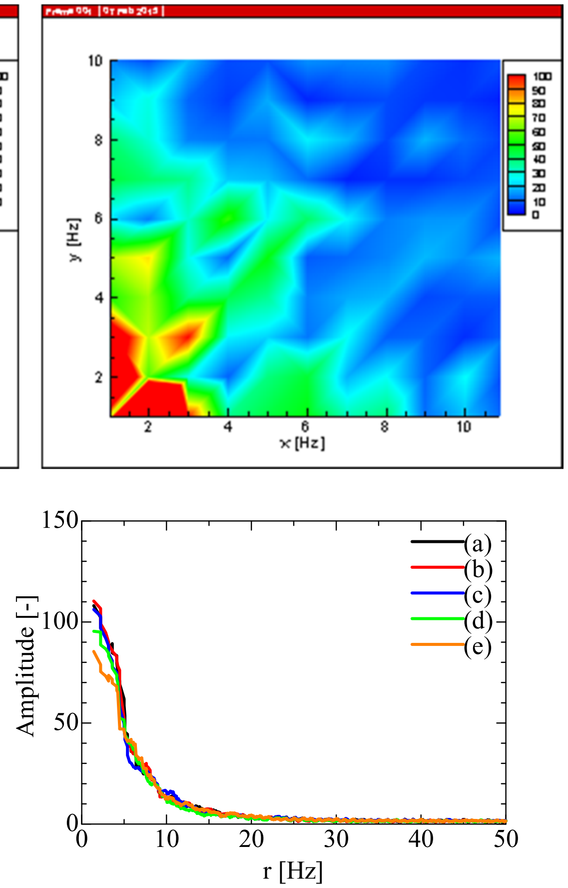
- 2DFFT→Relationships between Amplitude of Concentration fluctuation and Wavenumber
- Spatial scale λ ← Wavenumber based on Measuring Area



$\lambda = 0.900$ mm

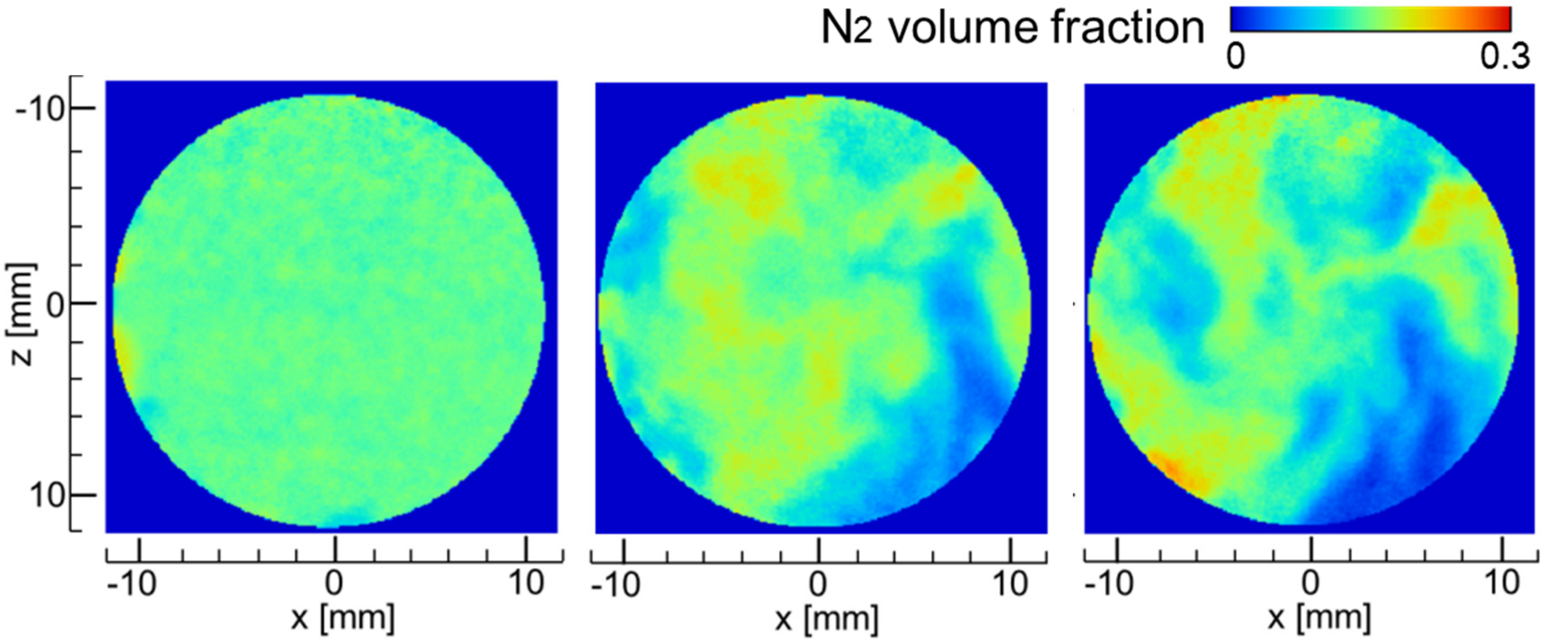


$\lambda = 1.945$ mm



$\lambda = 2.476$ mm

N_2 profiles under unburned conditions in x-z plane (Condition A)



(a) $G = 5.19 \times 10^{-4}$ (b) $G = 6.57 \times 10^{-3}$ (c) $G = 1.15 \times 10^{-2}$

$\lambda = 0.900$ mm $\lambda = 1.945$ mm $\lambda = 2.476$ mm

No N_2 Nozzle N_2 : $h = 90$ mm N_2 : $h = 70$ mm

(a) N_2 concentration mixed with air from upstream of the premixer homogenously

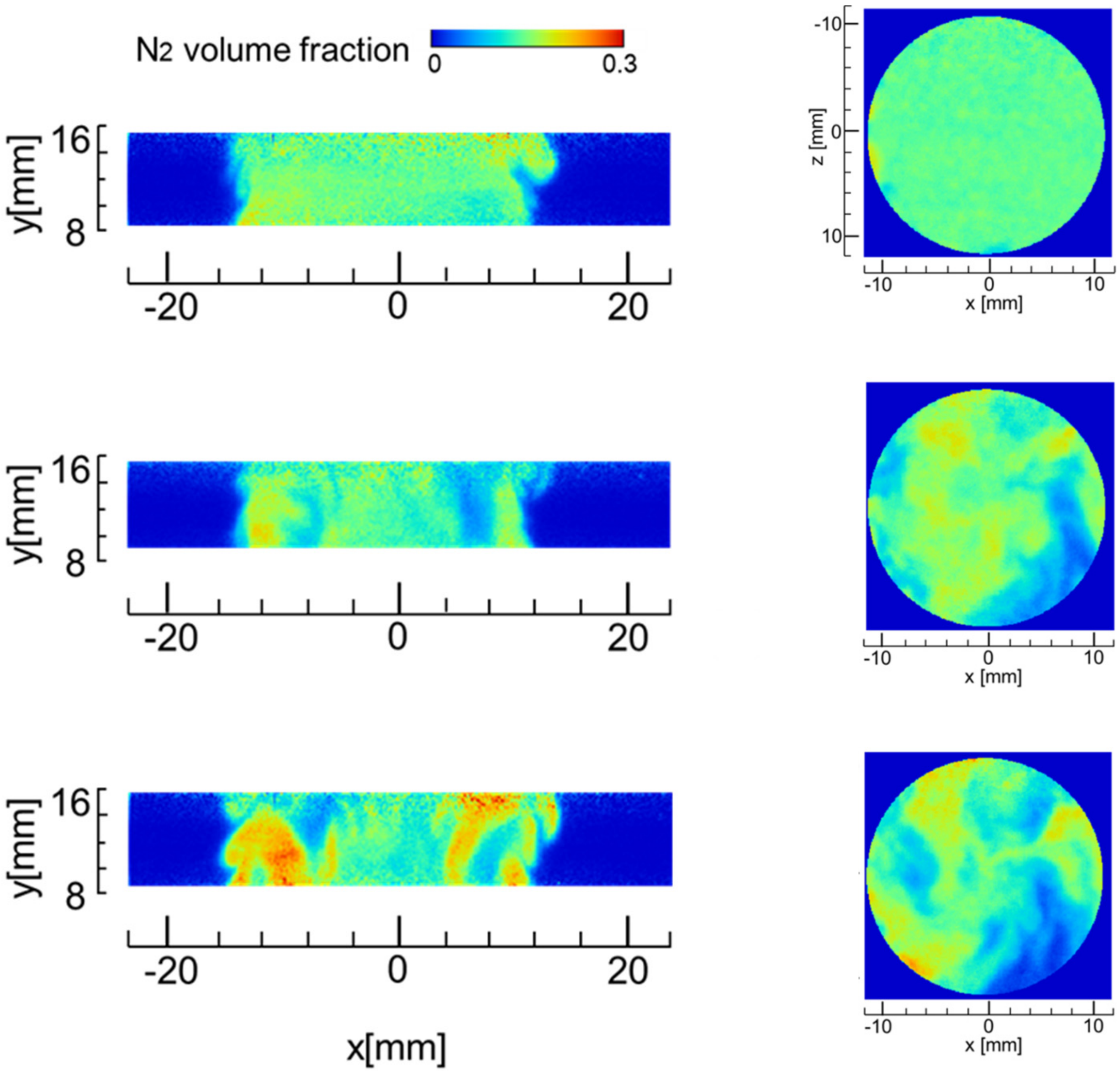
Lager G and λ in (b) and (c) rather than in (a).

N_2 profiles under unburned conditions in x-y plane (Condition A)

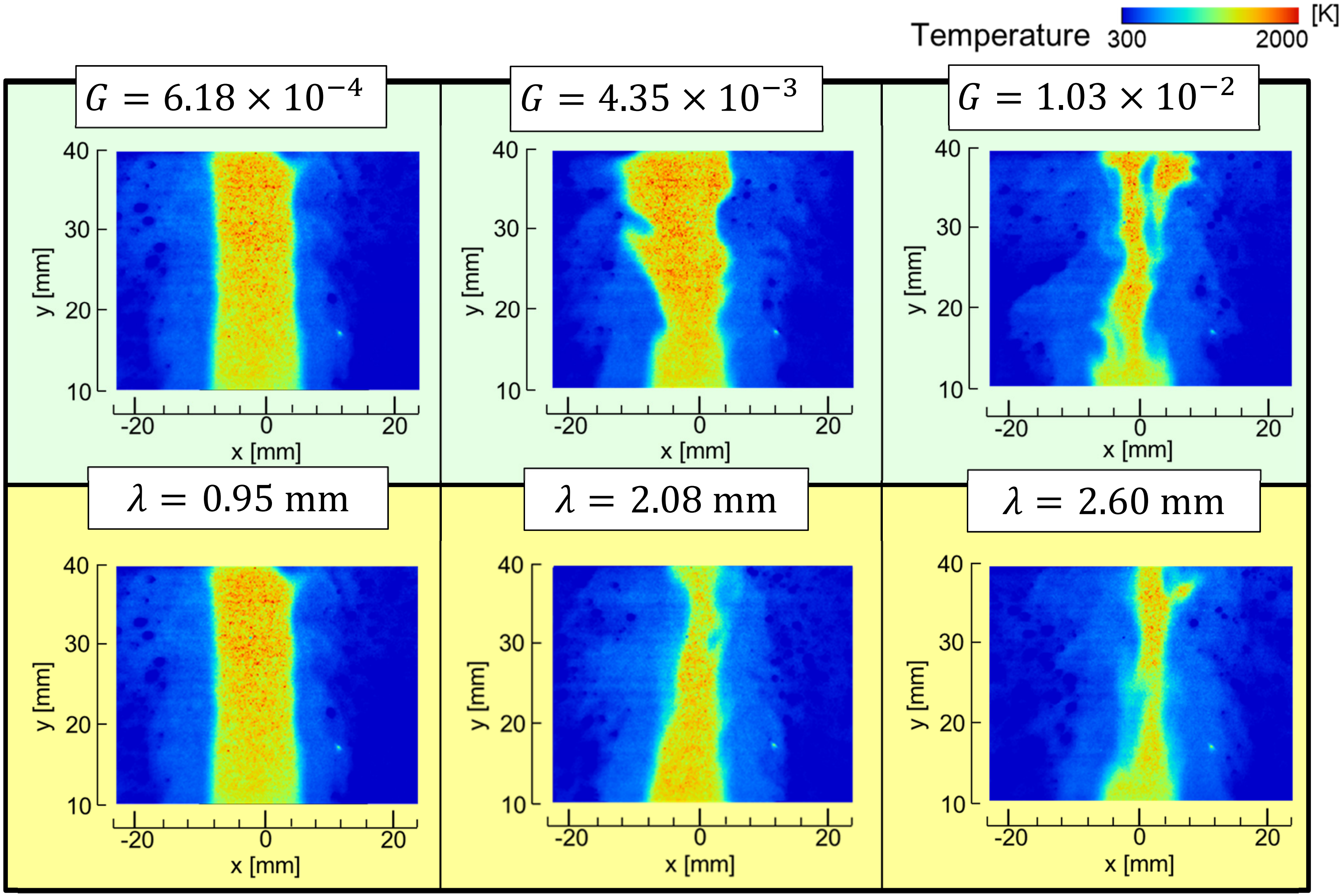
(a) $G = 5.19 \times 10^{-4}$, $\lambda = 0.900$ mm

(b) $G = 6.57 \times 10^{-3}$, $\lambda = 1.945$ mm

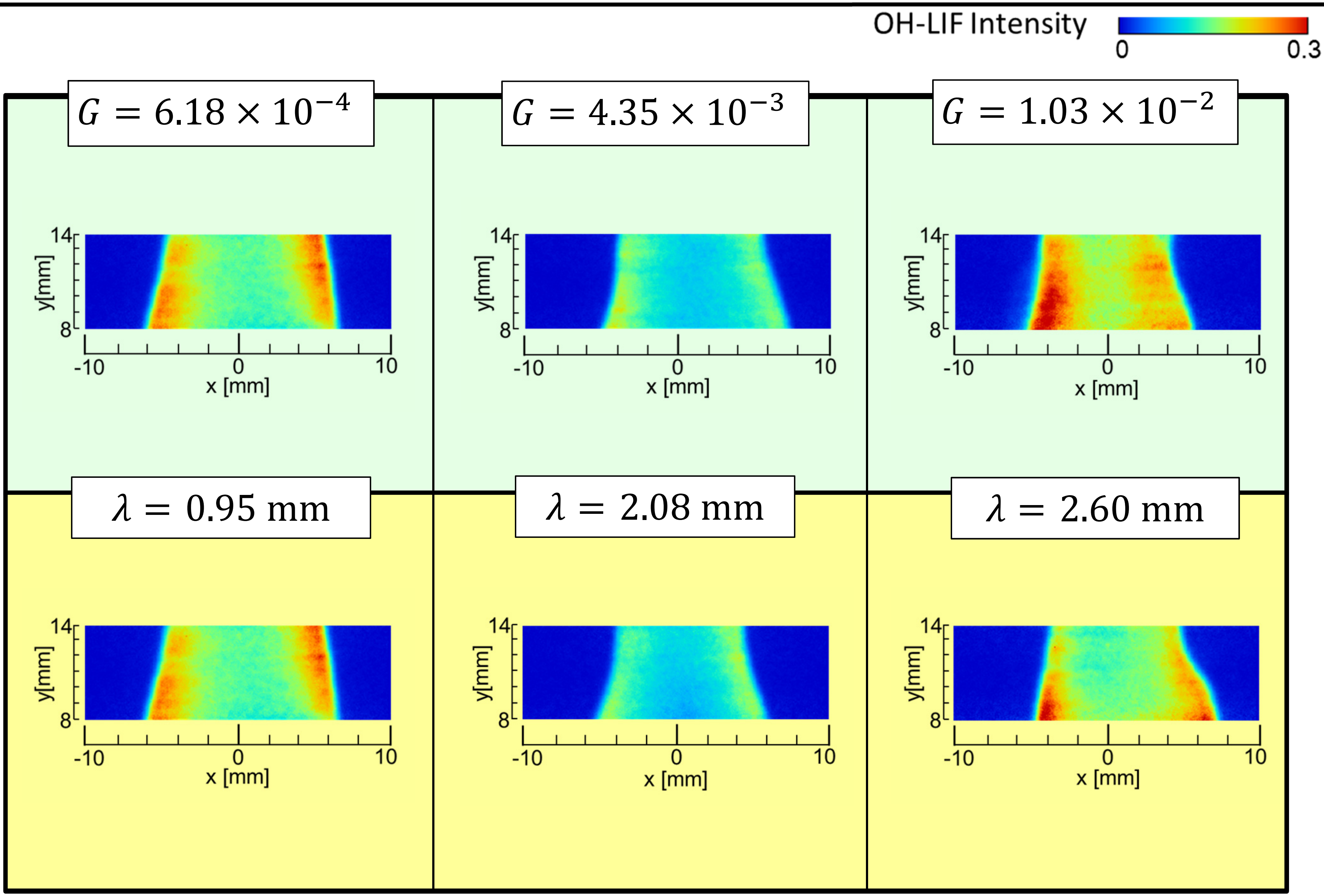
(c) $G = 1.15 \times 10^{-2}$, $\lambda = 2.476$ mm



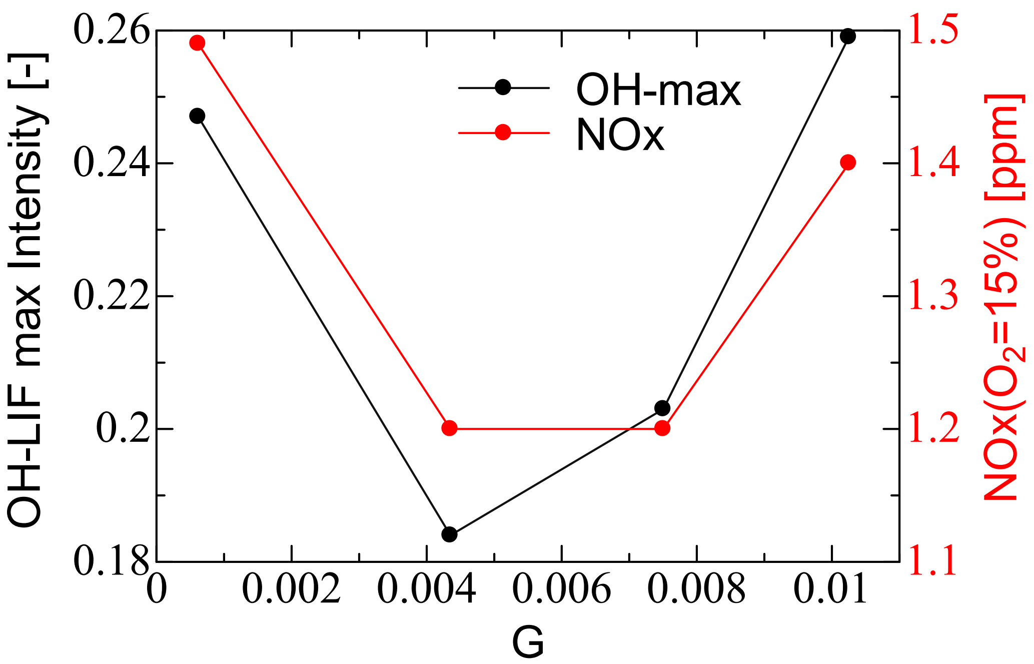
Instantaneous Temperature Profiles (Condition B)



Instantaneous OH-LIF Intensity (Condition B)

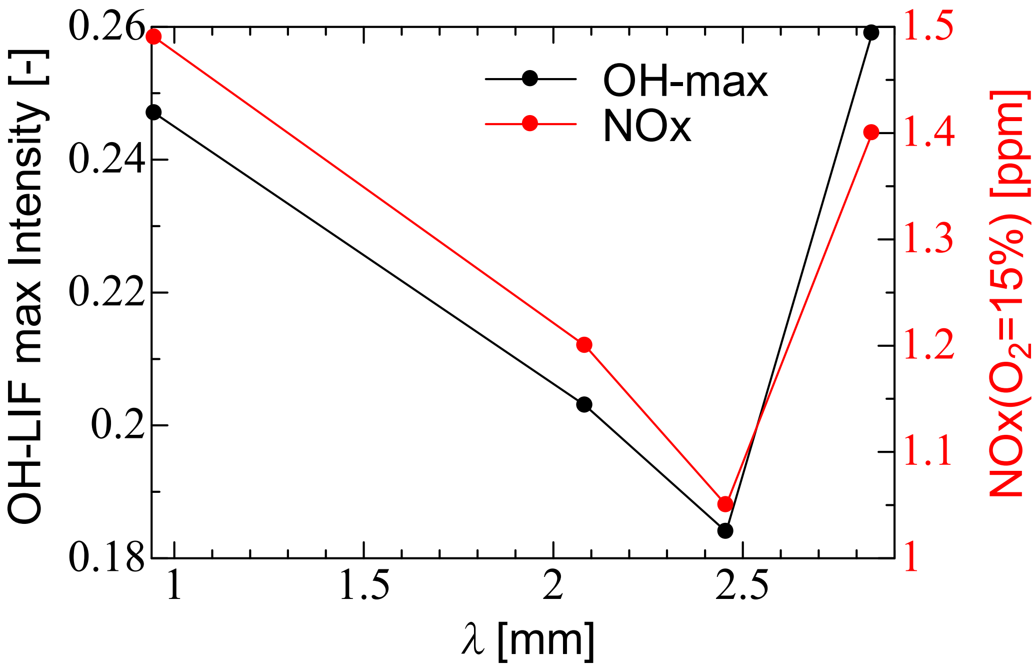


Relationship between Max OH-LIF, NOx and Unmixedness G



- When G increases, OH-LIF intensity and NOx concentration decreases in the beginning. When G increases more, OH-LIF intensity and NOx concentration increases conversely.
- Moderate reaction in lower oxygen concentration regions is predominant when the unmixedness increases, active reaction in higher fuel concentration regions might become predominant when the unmixedness increases more.

Relationship between Max OH-LIF, NOx and Spatial Scale λ



- When spatial scale increases, OH-LIF intensity and NOx concentration decreases in the beginning. When spatial scale increases more, OH-LIF intensity and NOx concentration increases conversely.
- Moderate reaction in lower oxygen concentration regions is predominant when the spatial scale increases, active reaction in higher fuel concentration regions might be predominant when the spatial scale increases more.

Summary

Gifu University
Department of Mechanical Engineering

We investigated the flame characteristics under the homogeneous and inhomogeneous oxygen concentrations.

- The inhomogeneous degree of oxygen concentration profiles were evaluated by unmixedness G and spatial scale λ of the fluctuation.
- The shape of flame was complicated in the inhomogeneous oxygen concentration profiles. It was caused by the locally differences of burning velocity.
- OH-LIF and NOx concentration decreases, when inhomogeneous degrees of oxygen concentration profiles increase, OH-LIF and NOx concentration increases conversely, when the inhomogeneous degrees increase more.
- Moderate reaction in lower oxygen concentration regions is predominant when the inhomogeneous degree increases, but the active reaction in higher fuel concentration regions might be predominant when the inhomogeneous degree increases more.