LECTURE 22: Laser Induced Fluorescence (LIF) Technique Part - 01

Dr. Hui HU

Martin C. Jischke Professor and Director

Advanced Flow Diagnostics and Experimental Aerodynamics Laboratory

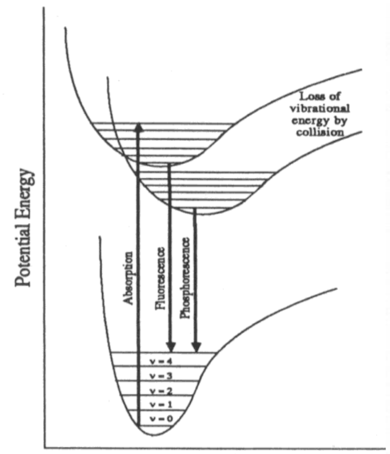
Department of Aerospace Engineering, Iowa State University
2251 Howe Hall, Ames, IA 50011-2271
Email: huhui@iastate.edu

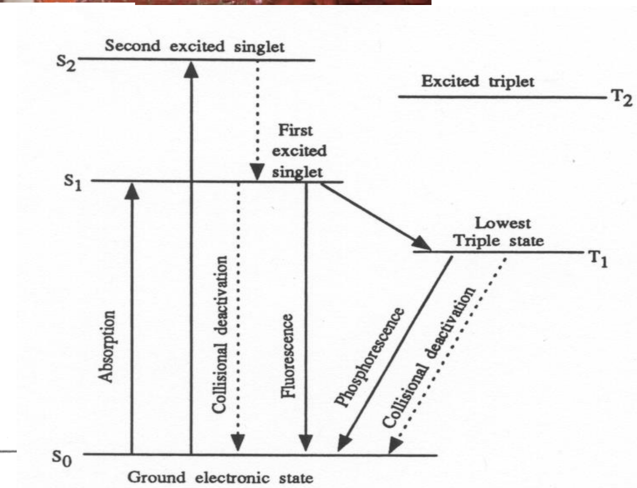
❑ Laser Induced Fluorescence (LIF) and Phosphorescence

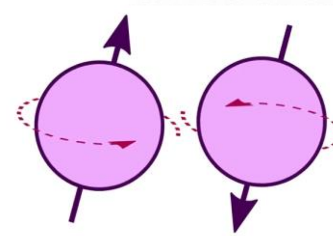
- *Laser-induced fluorescence (LIF) is the optical emission from molecules that have been excited to higher energy levels by absorption of electromagnetic radiation.*

- *Laser-induced fluorescence (LIF) technique is widely used for thermal fluids studies for qualitative flow visualization and quantitative flow variable measurements*

- *Flow variables can be measured based on LIF technique:*
  - *Species concentration/mole fraction (e.g., Na, OH, NO, O2, CH, CO, acetone)*
  - *Temperature*
  - *Velocity*
  - *Pressure*







- https://www.youtube.com/watch?v=CcN8NnGGPhs

Laser Induced Fluorescence (LIF) and Phosphorescence

- *Fluorescent tracers / molecules:*
- *Absorption spectrum*
  - *The wavelength of the laser for excitation.*
- *Emission spectrum:*
  - *Determine the working wavelength of camera for image.*
- *Stokes shift:*
  - *Differences between the absorption peak and emission peak.*

Absorption spectrum

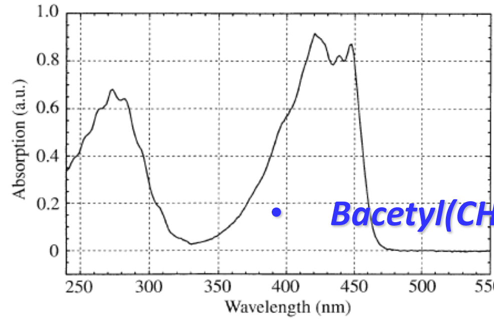


Fig. 1. Absorption spectrum for biacetyl

Emission spectrum

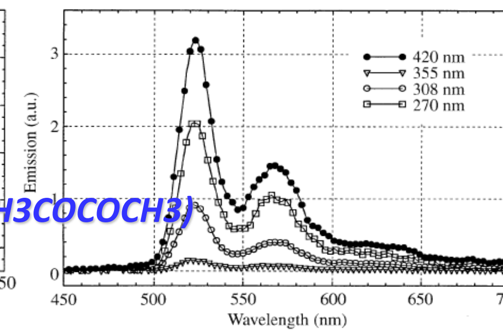
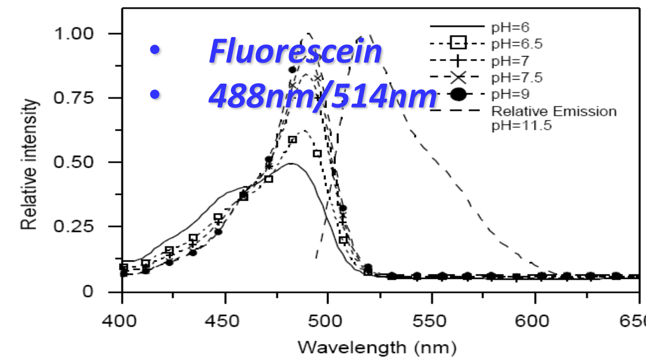
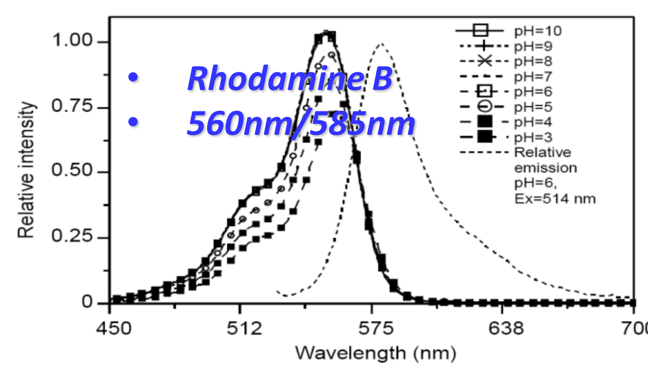


Fig. 2. Phosphorescence emission spectra for biacetyl for four different excitation wavelengths

- *Bacetyl(CH3COCOCH3)*



- *Fluorescein*
- *488nm/514nm*

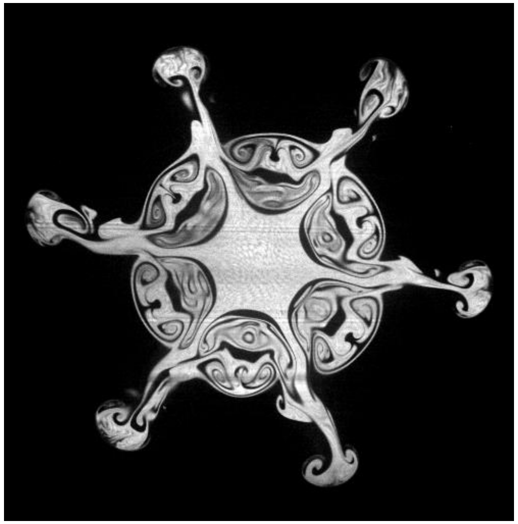


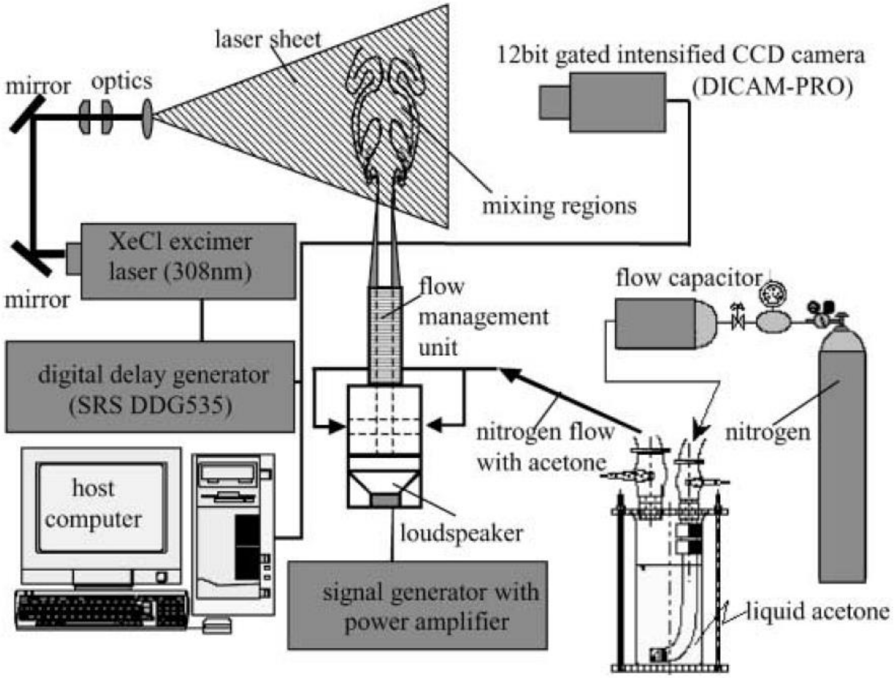
- *Rhodamine B*
- *560nm/585nm*

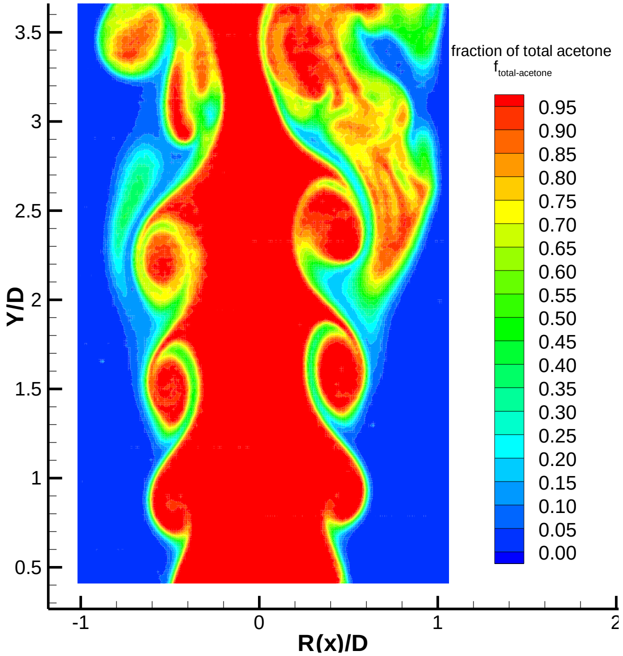
LIF Vs. PLIF

- ***Planar Laser Induced Fluorescence (PLIF) is the 2-D version of the LIF technique.***

- ***In PLIF, laser light, typically from a pulsed laser for high peak power, is shaped into a thin sheet and passed through the regions of interest to excite fluorescent tracers premixed in the fluid flow. Fluorescence images are acquired to provide useful information, either qualitatively or quantitatively, about a fluid property of interest.***







Fundamentals of LIF technique

- *According to quantum theory, for diluted solution and unsaturated excitation, the decay of photoluminescence emission (fluorescence and phosphorescence) intensity (I_{em}) can be expressed as:*

$$I_{em} = A I_i C \varepsilon \Phi$$

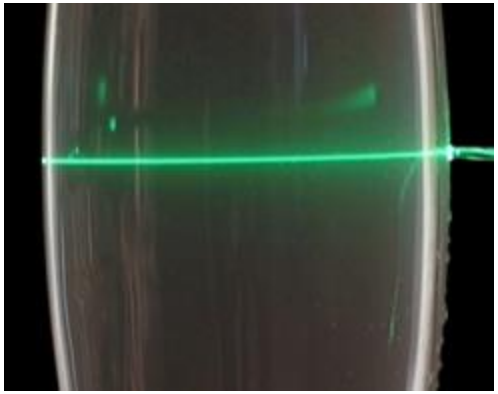
A : a parameter representing the detection collection efficiency

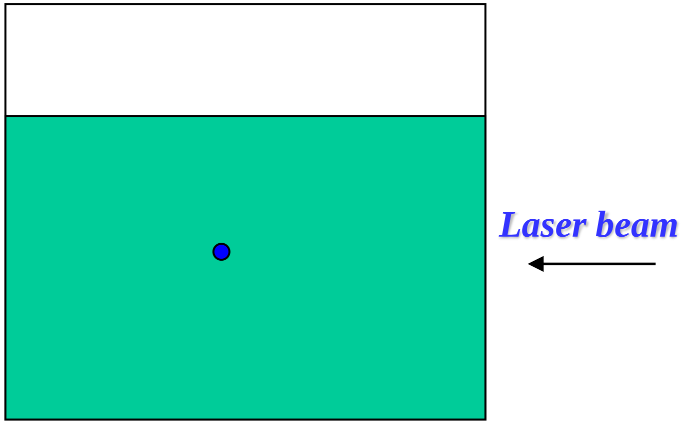
I_i: the local incident laser intensity

C : concentration of Fluorescescent dye

ε: the absorption coefficient, temperature-dependant

Φ: Fluorescence quantum yield, temperature-dependant

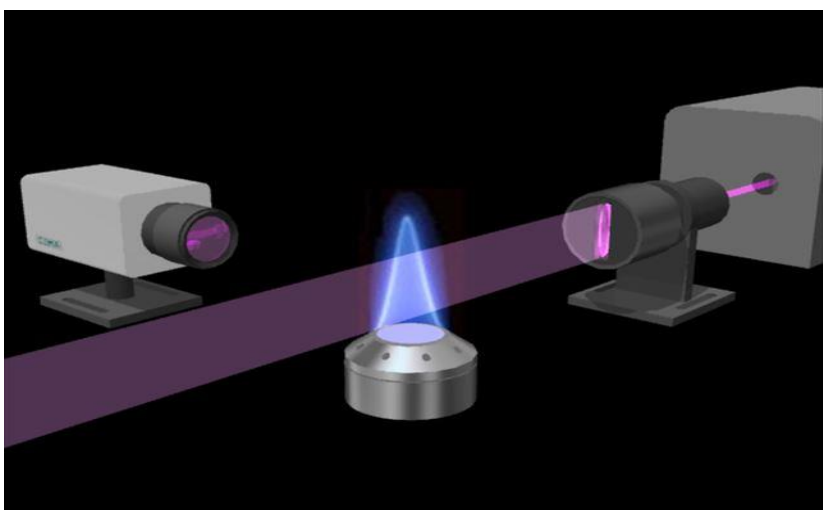




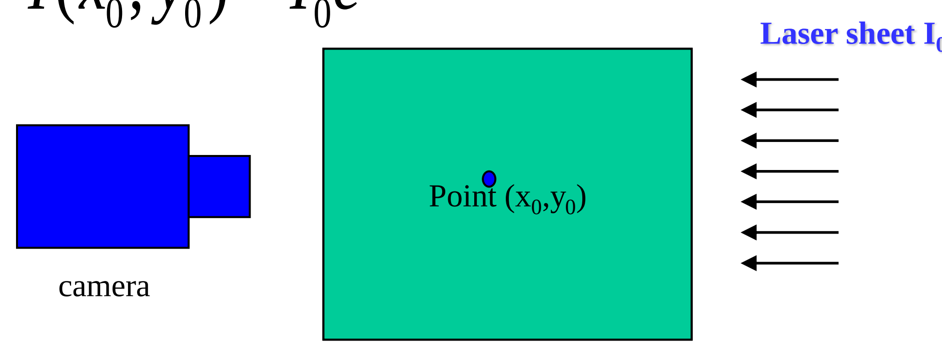
PLIF - intensity at point (x_0, y_0)

$$H_f(x_0, y_0) = I(x_0, y_0) A \Phi \varepsilon(T) L C(x_0, y_0)$$

$H_f(x_0, y_0)$:	*measured fluorescence intensity*
A:	*the fraction of the fluorescence light collected by camera.*
Φ :	*quantum efficiency,*
L:	*the length of the sampling volume along the path of excitation beam*
ε:	*molar absorption coefficient*
$C(x_0, y_0)$:	*the molar concentration of the fluorescent dye.*
$I(x_0, y_0)$:	*the intensity of excitation light beam at the point (x_0, y_0)*



$$I(x_0, y_0) = I_0 e^{-\varepsilon l c}$$



PLIF for Concentration field measurements

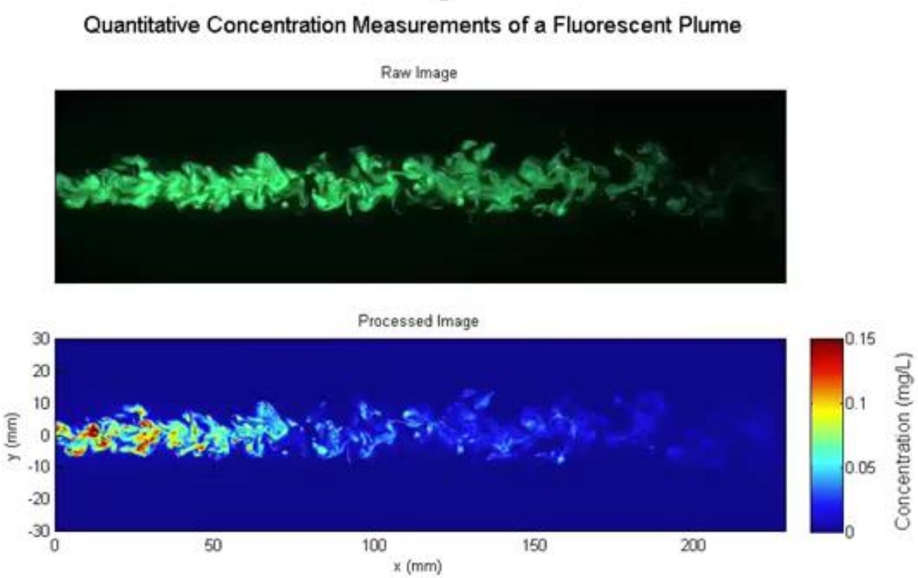
$$H_f(x_0, y_0) = I(x_0, y_0)\, A\, \Phi(T)\, \varepsilon(T)\, C(x_0, y_0)$$

$\Phi(T)$ and $\varepsilon(T)$ are constant for constant temperature condition

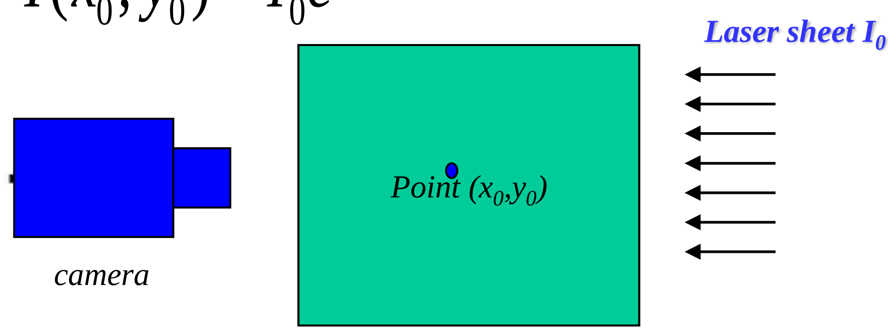
$$\Rightarrow H_f(x_0, y_0) \propto I(x_0, y_0) C(x_0, y_0)$$

$I(x_0, y_0)$ can be preditermined through calibration.

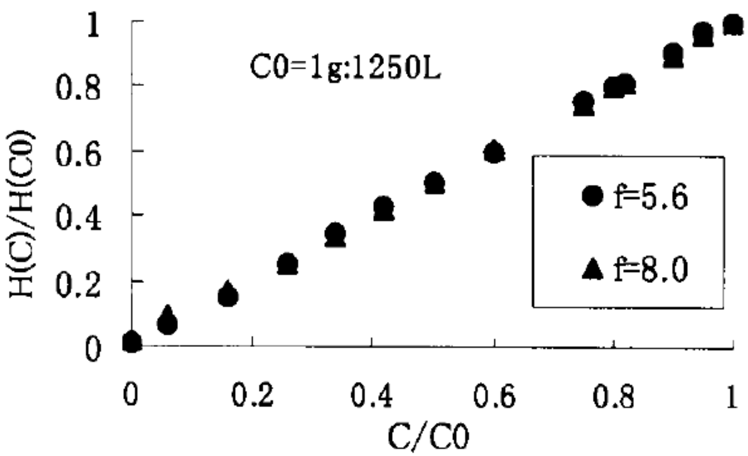
$$\Rightarrow H_f(x_0, y_0) \propto C(x_0, y_0)$$



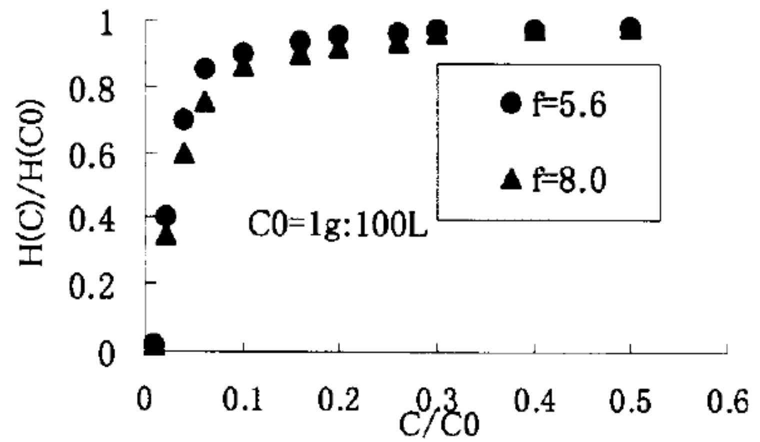
$$I(x_0, y_0) = I_0 e^{-\varepsilon l c}$$



Calibration for Fluid Concentration Measurement

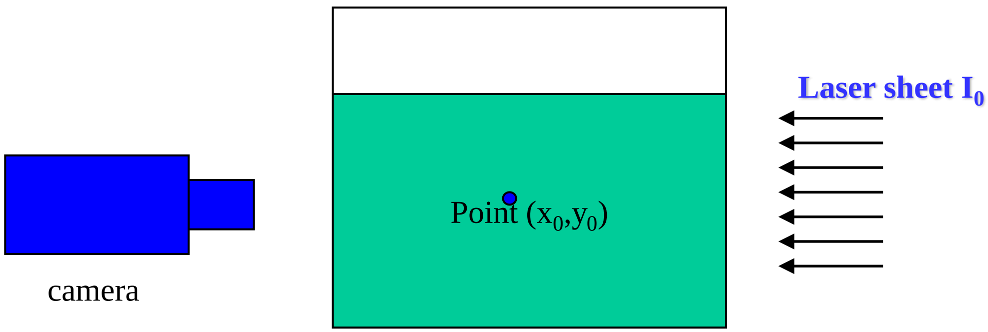


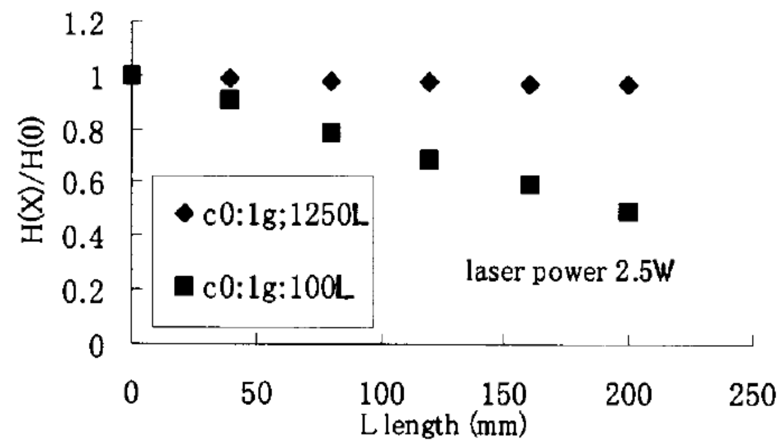
A. at low concentration



B. at high concentration (f is the aperture of the CCD camera)

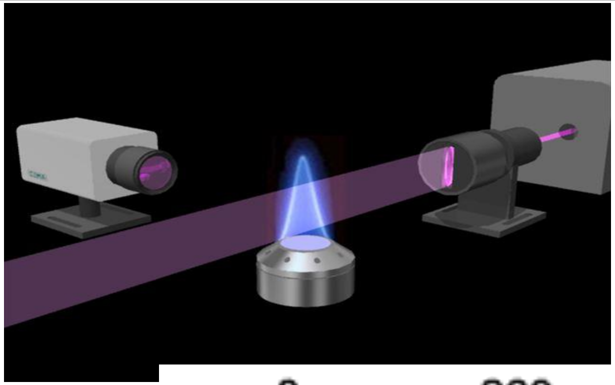
$$H_f(x_0, y_0) = I(x_0, y_0) A \Phi \varepsilon(T) L C(x_0, y_0)$$



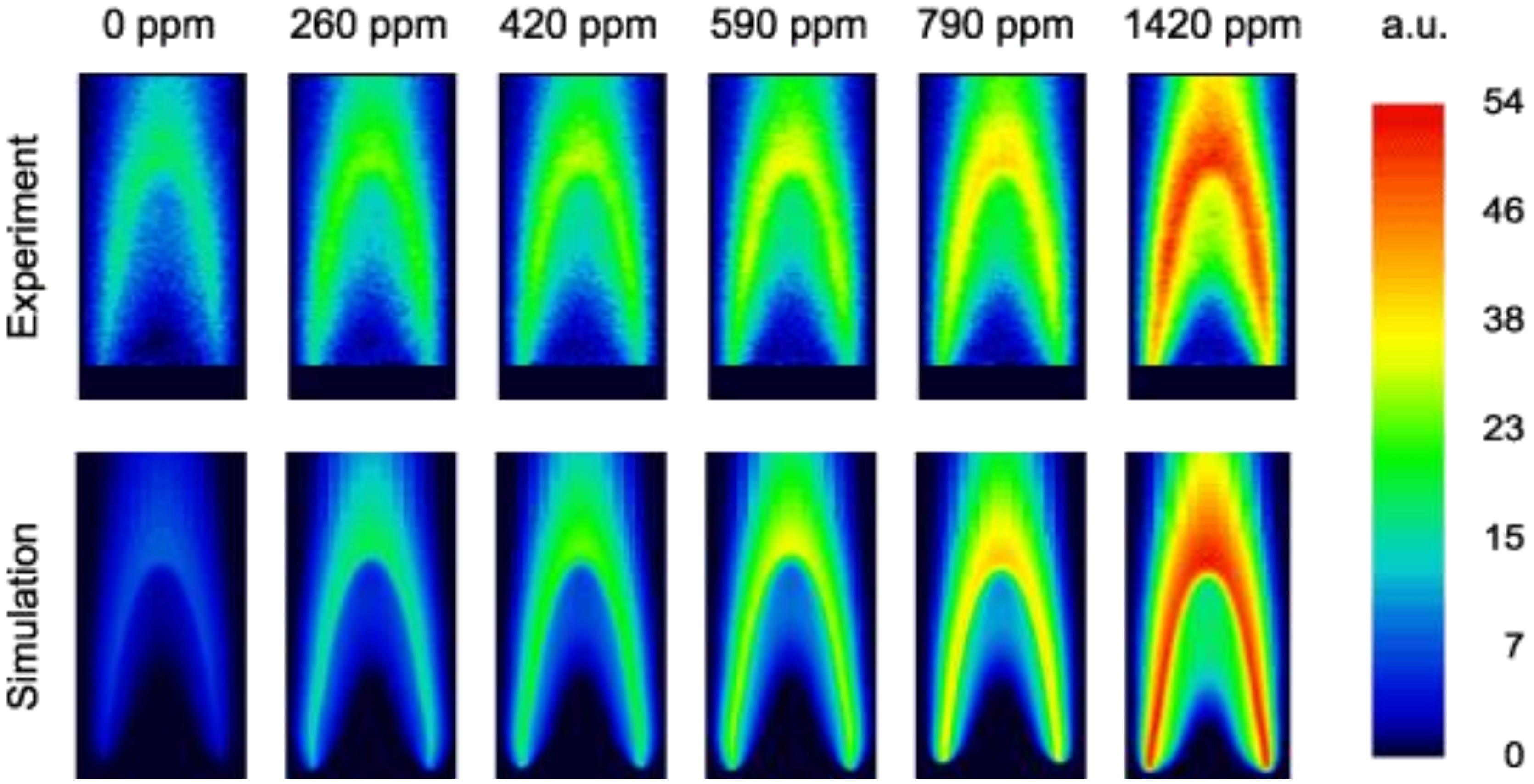


b. Light attenuation performance of the disodium

PLIF for Species Concentration Measurements

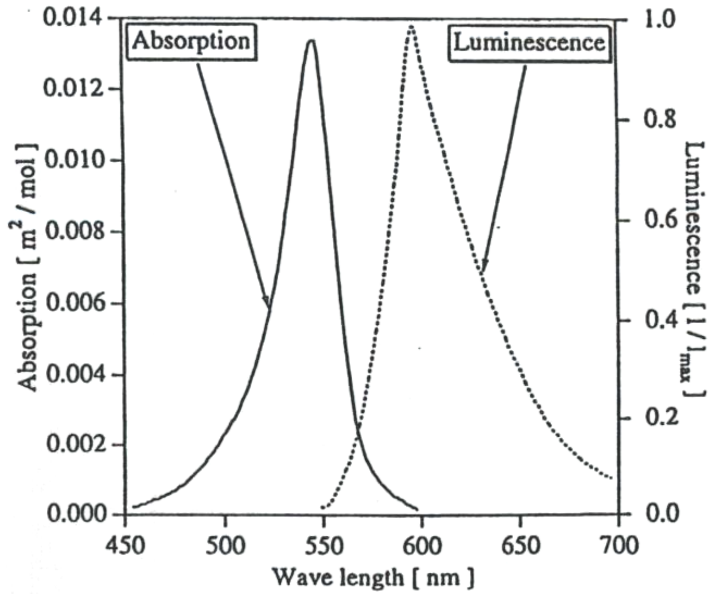


- *NO-molecule excitation LIF images obtained (top) from measurement and (bottom) by synthetically processing the results of the flame simulation*



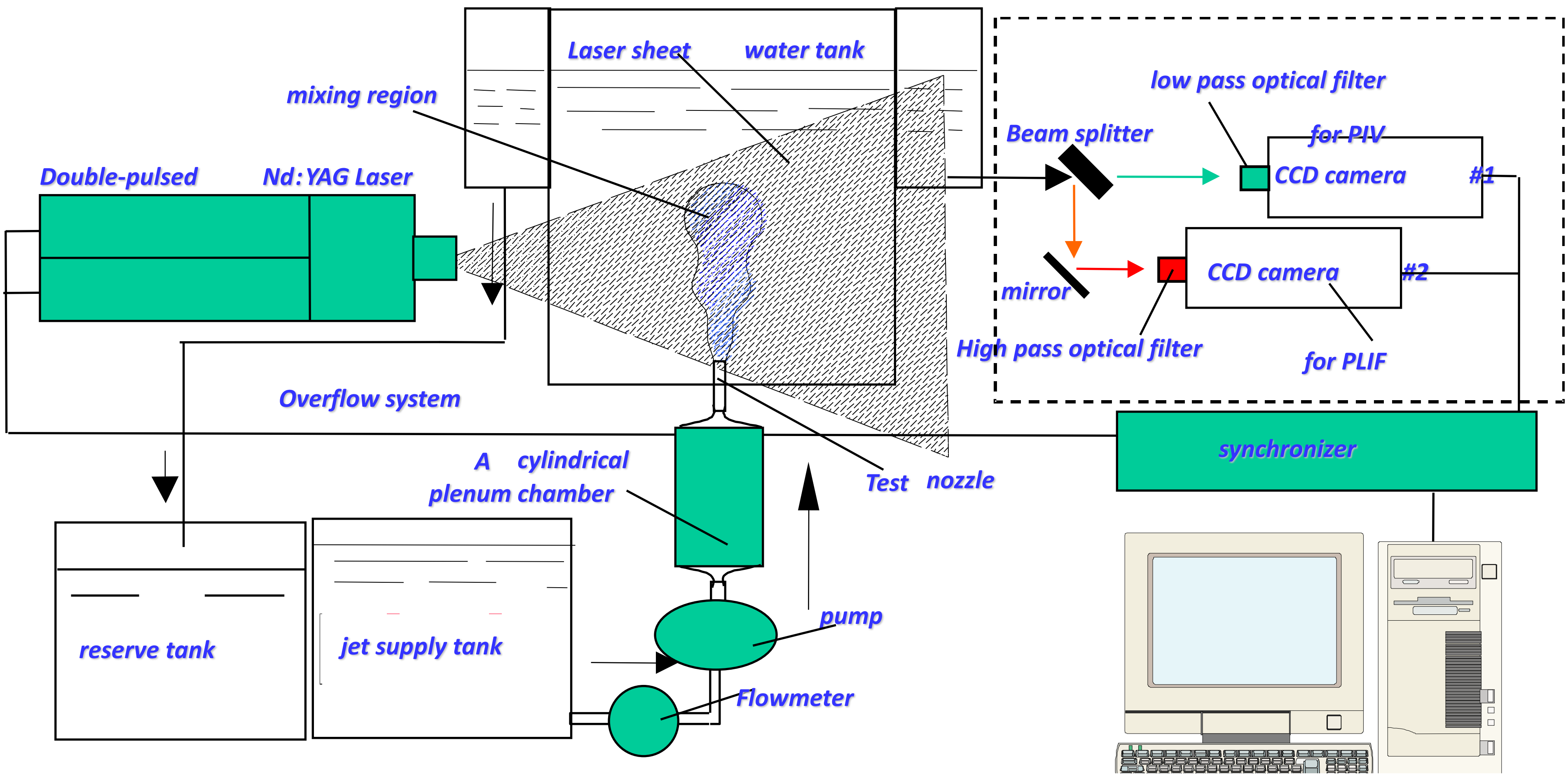
❑ PIV-PLIF COMBINED SYSTEM

- *Nd-YAG pulsed laser*
  - *wave length 532 nm*
  - *power is 200 mJ/pulse,*
  - *5ns illumination*
  - *10 Hz double-pulsed illumination.*
  - *the time delay between two pulses is 3 ms for the present study*
- *CCD camera*
  - *high-resolution correlation CCD cameras (TSI PIVCAM10-30, 1K by 1K resolution).*
- *PIV tracer*
  - *hollow glass particles d=8-12µm*
- *PLIF dye*
  - *Rhodamine B*



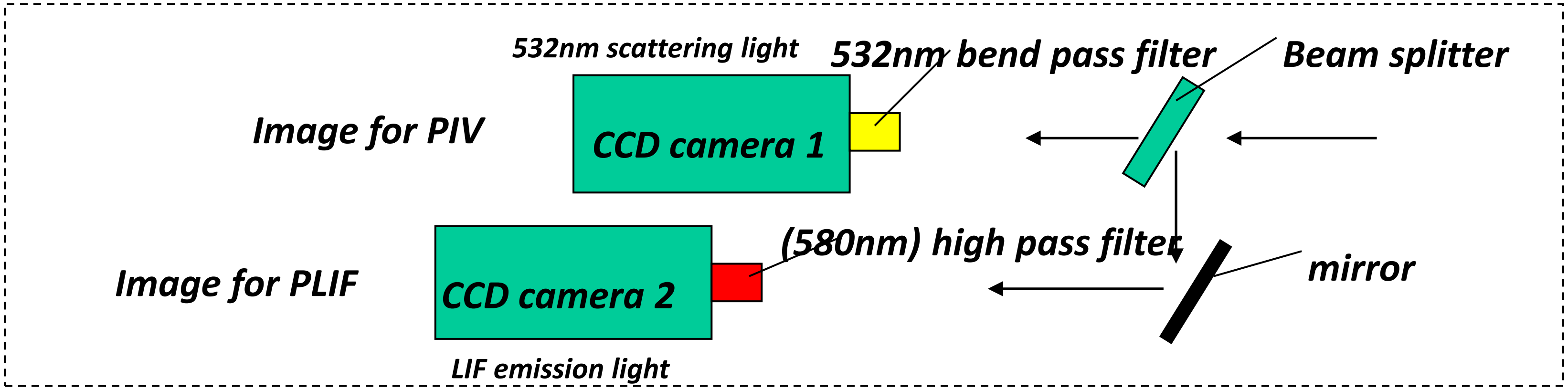
Absorption and emission spectrum of Rhodamine B

❑ Experimental Set-up



- <u>Hu H</u>, **Saga T, Kobayashi T, Taniguchi N,** "Analysis of a Turbulent Jet Mixing Flow by Using a PIV-PLIF Combined System", *Journal of Visualization,* Vol.7, No.1, pp33-42, 2004

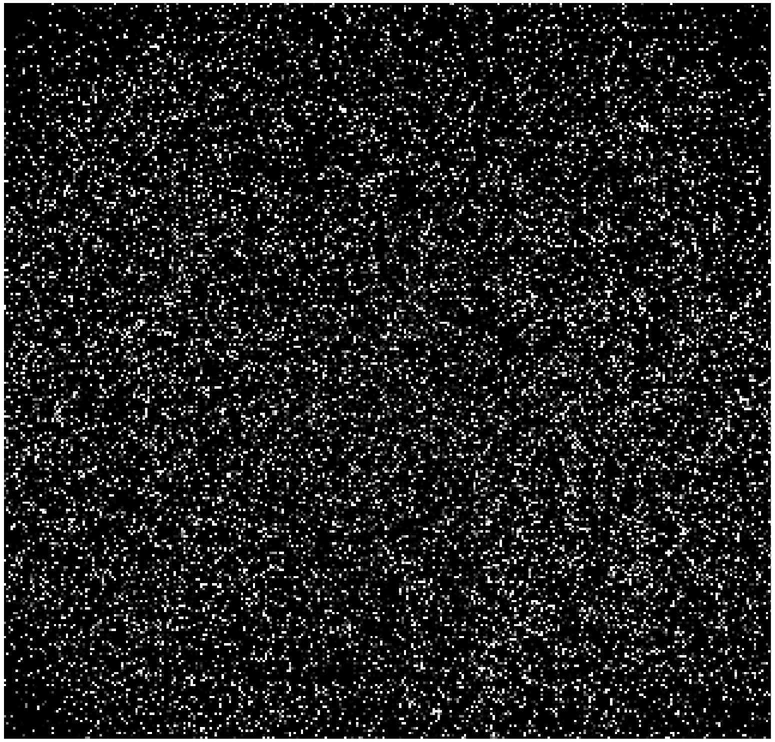
❑ Simultaneous PIV-PLIF Image Recording System



- **<u>Hu H</u>, Saga T, Kobayashi T, Taniguchi N,** "Analysis of a Turbulent Jet Mixing Flow by Using a PIV-PLIF Combined System", *Journal of Visualization,* Vol.7, No.1, pp33-42, 2004

❑ Simultaneously Acquired PIV-PLIF Images

Original images from the PIV-PLIF system

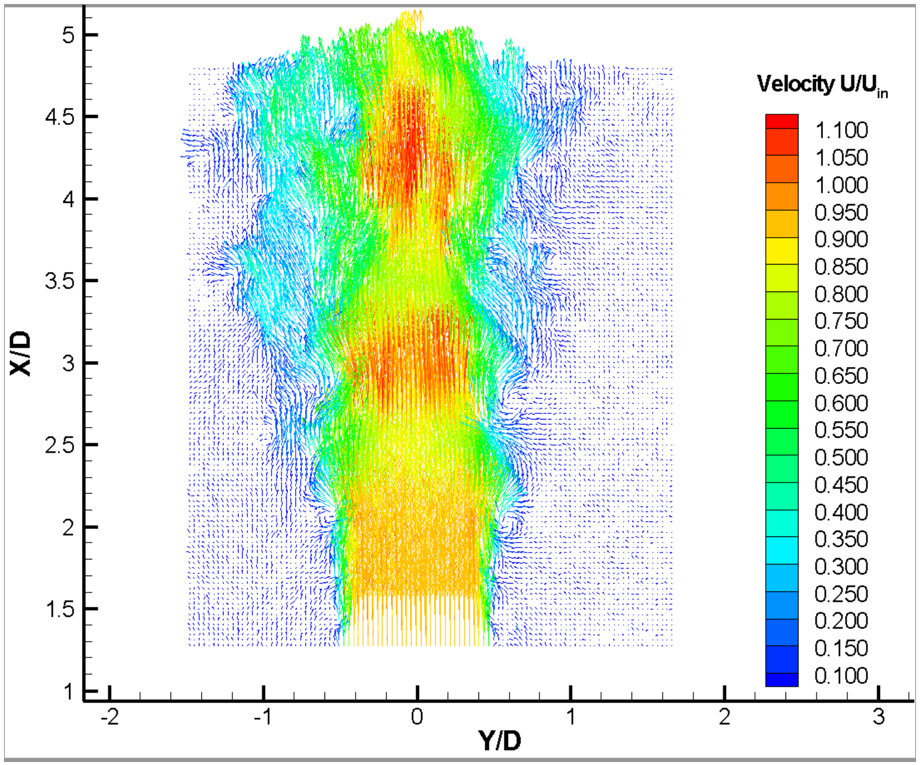


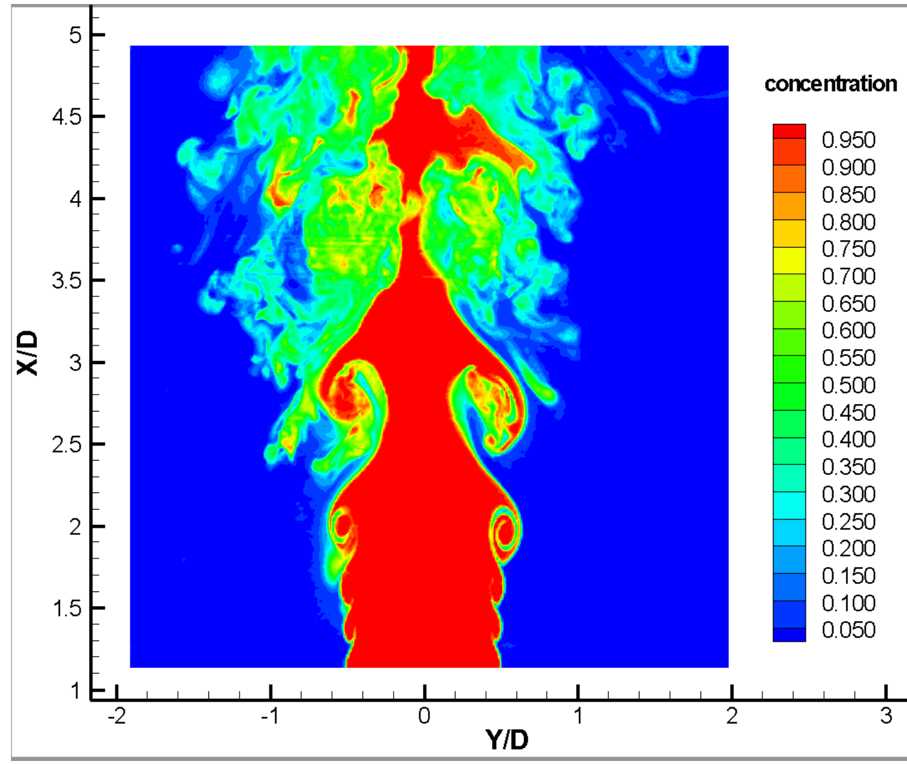
PIV image

PLIF image

- **<u>Hu H</u>, Saga T, Kobayashi T, Taniguchi N,** "Analysis of a Turbulent Jet Mixing Flow by Using a PIV-PLIF Combined System", *Journal of Visualization,* Vol.7, No.1, pp33-42, 2004

❑ Instantaneous PIV and PLIF Measurement Results





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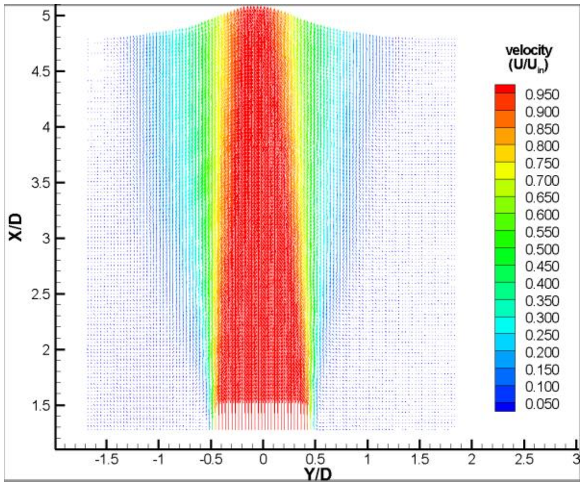
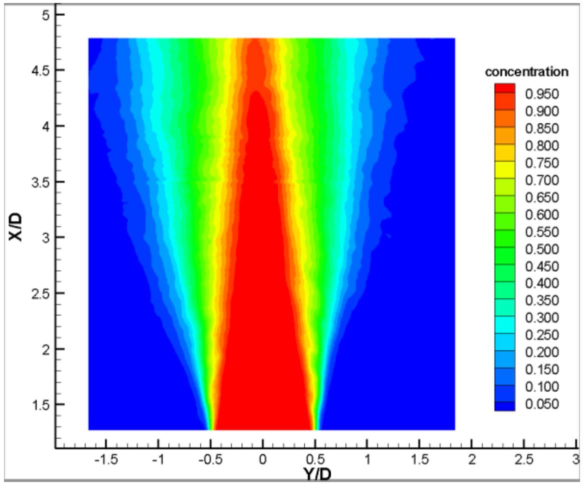
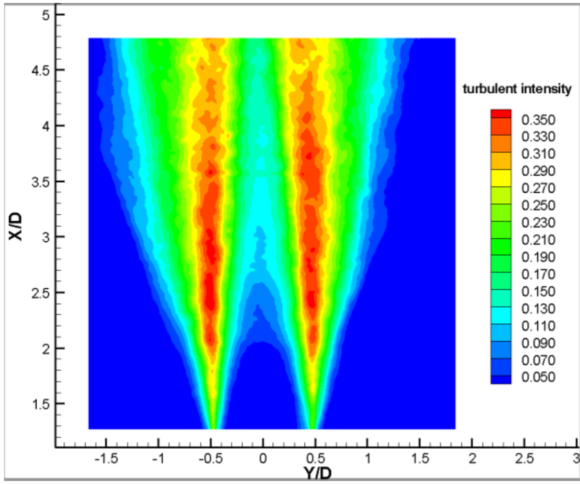
❑ Measurement Results of the PIV-PLIF Combined System



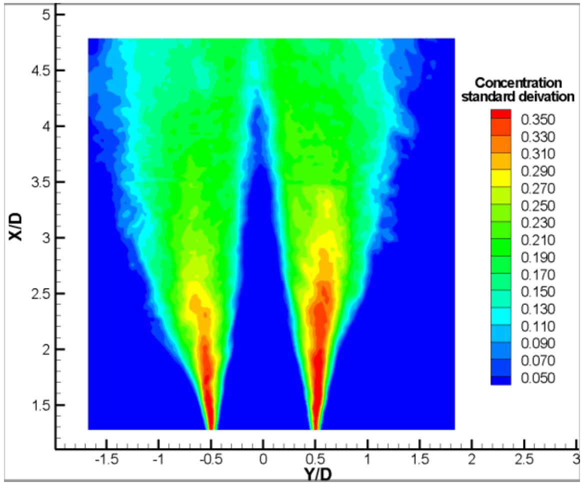
mean velocity distribution



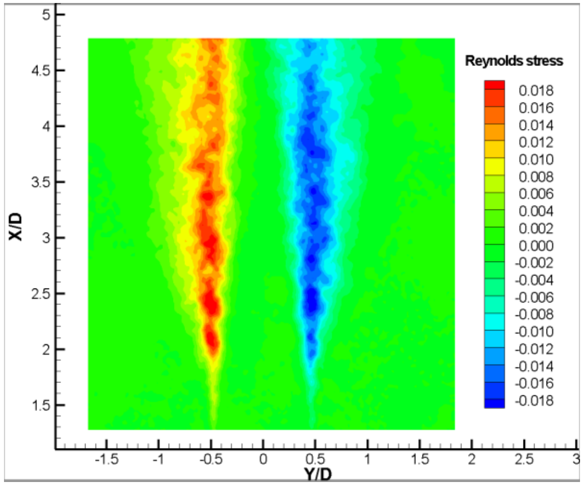
mean concetration distribution



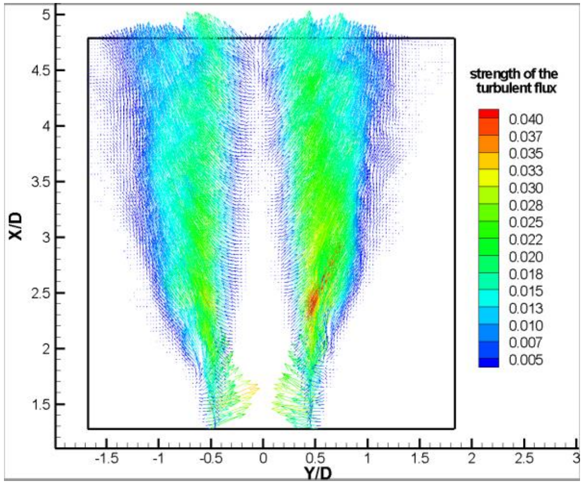
$$\frac{\sqrt{\overline{u'u'}+\overline{v'v'}}}{U_{in}}$$



$$\frac{\sqrt{\overline{\xi'\xi'}}}{\xi_o}$$

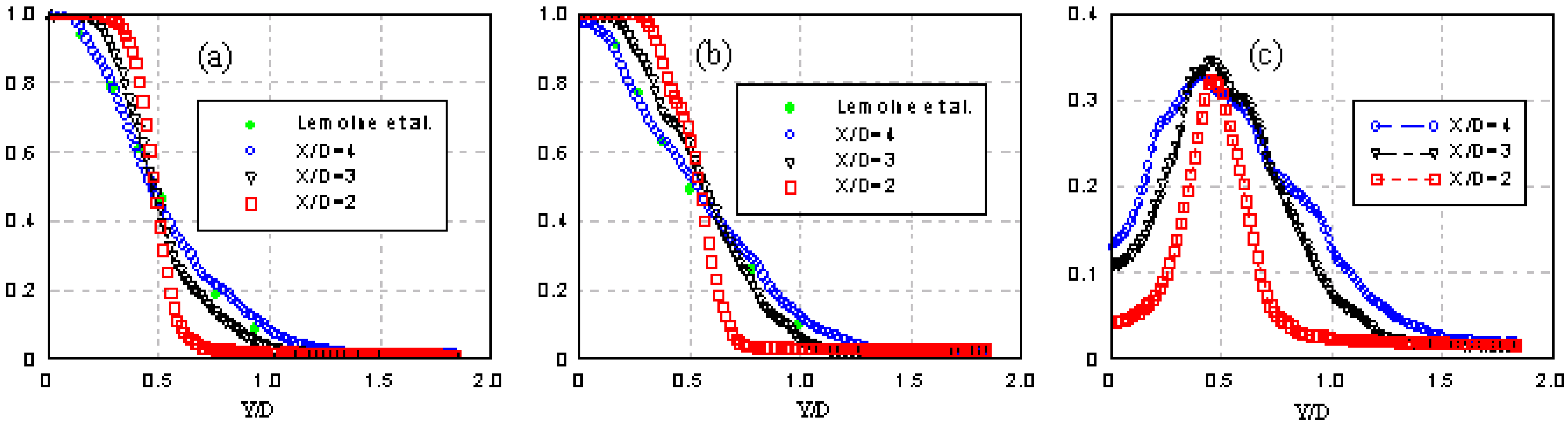


$$\frac{-\overline{u'v'}}{U_{in}}$$

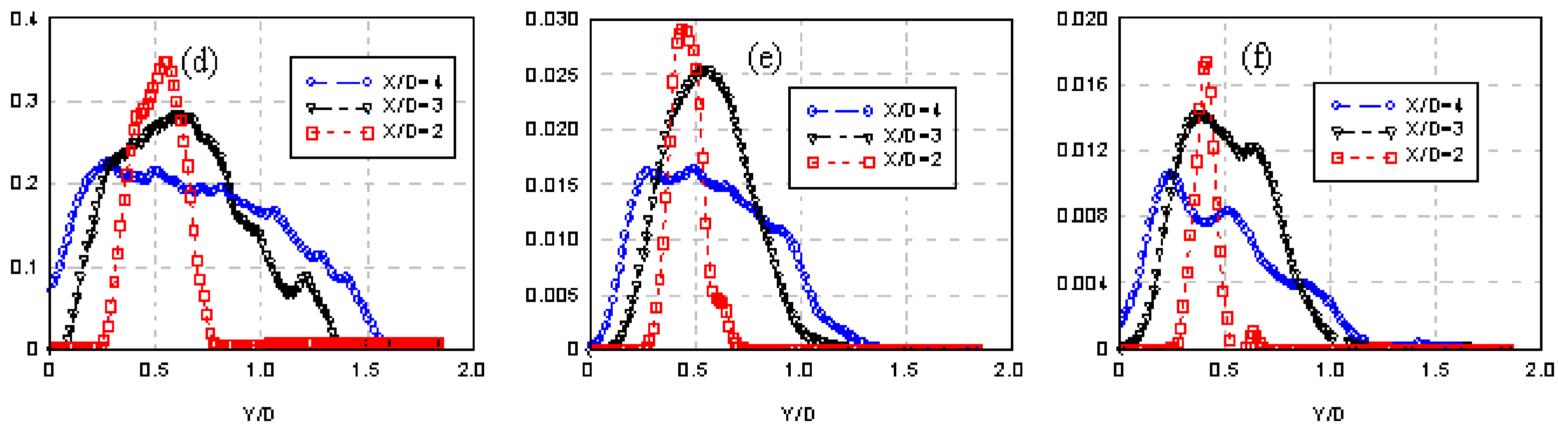


$$\frac{\overline{u'\xi'}}{U_{in}\xi_0},\frac{\overline{v'\xi'}}{U_{in}\xi_0}$$

❑ Measurement Results of the PIV-PLIF Combined System



a. Ensemble-averaged velocity (U/U_{in}) b.Ensemble-averaged concentration (ξ/ξ_0) c.Turbulent intensity ($T = \frac{\sqrt{\overline{u'u'}+\overline{v'v'}}}{U_{in}}$)



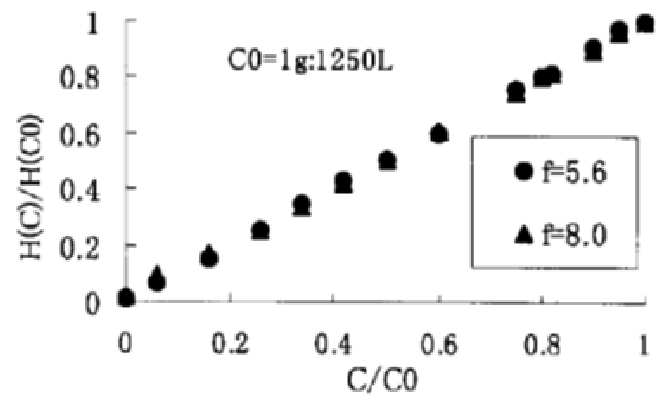
d. Concentration standard deviation ($\frac{\sqrt{\overline{\xi'\xi'}}}{\xi_0}$) e. Axial turbulent flux ($\frac{\overline{u'\xi'}}{U_{in}\xi_0}$) f. Radial turbulent flux ($\frac{\overline{v'\xi'}}{U_{in}\xi_0}$)

- **Hu H, Saga T, Kobayashi T, Taniguchi N,** "Analysis of a Turbulent Jet Mixing Flow by Using a PIV-PLIF Combined System", *Journal of Visualization,* Vol.7, No.1, pp33-42, 2004

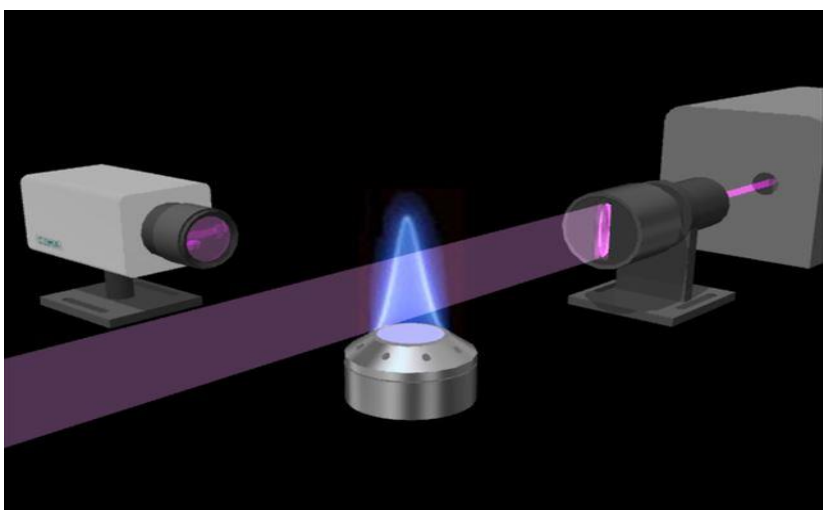
PLIF - intensity at point (x_0,y_0)

$$H_f(x_0,y_0)=I(x_0,y_0)A\Phi\varepsilon(T)LC(x_0,y_0)$$

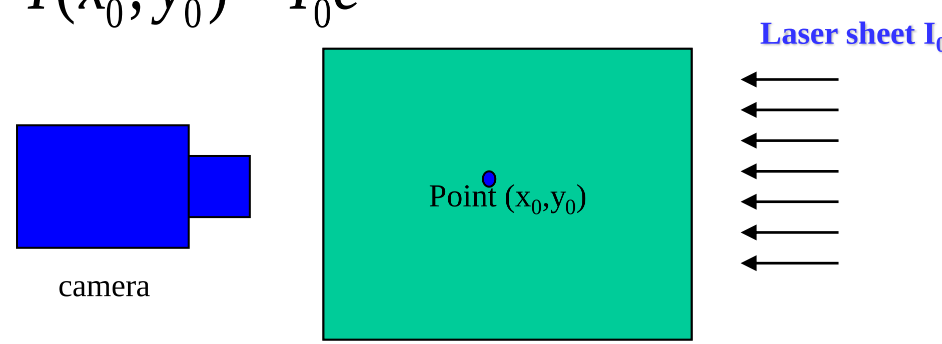
$H_f(x_0,y_0)$:	*measured fluorescence intensity*
A:	*the fraction of the fluorescence light collected by camera.*
Φ :	*quantum efficiency,*
L:	*the length along the path of excitation beam*
ε:	*molar absorption coefficient*
$C(x_0,y_0)$:	*the molar concentration of the fluorescent dye.*
$I(x_0,y_0)$:	*the intensity of excitation light beam at the point (x_0,y_0)*



A. at low concentration



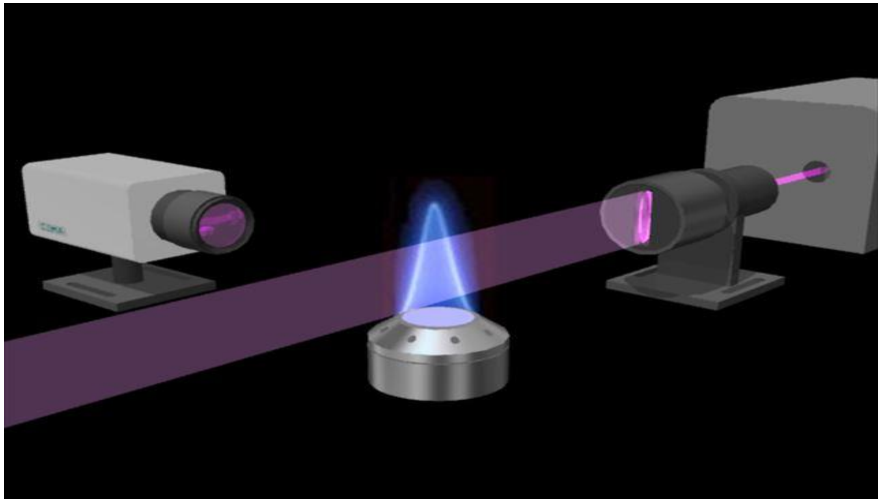
$$I(x_0,y_0)=I_0e^{-\varepsilon lc}$$

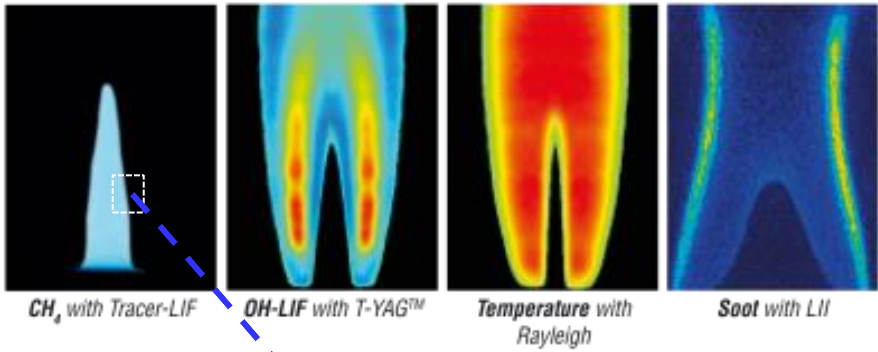


❑ PLIF for Fluid Mixing Characterization

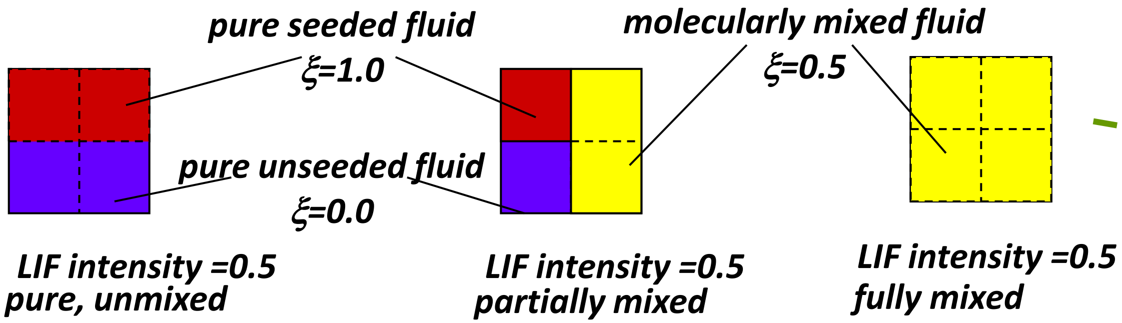
- *Instantaneous, quantitative, planar measurement of molecular mixing is of significant potential interest in numerous applications of importance.*

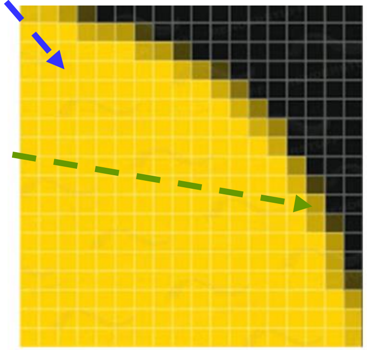
- *Laser Induced Fluorescence (LIF) intensity is linearly proportional to the concentration of dye within a small sampling volume regardless of the fluid mixing state. Therefore, conventional LIF technique tends to overpredict the amount of molecularly mixed fluid.*





  - ***Sub-pixel stirring in LIF-based measurements***





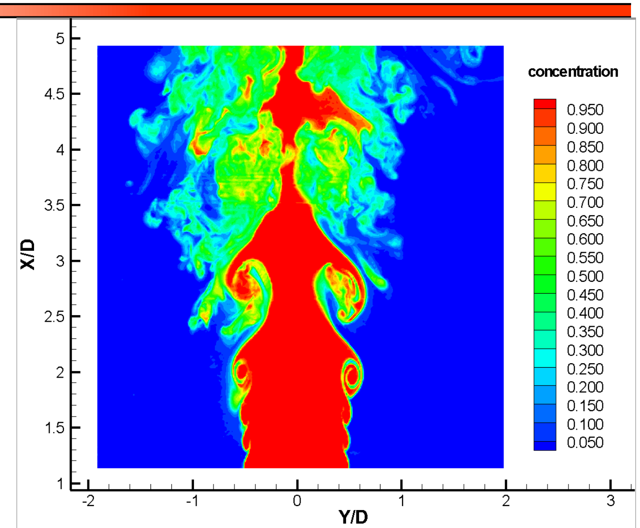
Resolution-free estimation of the extent of molecular mixing

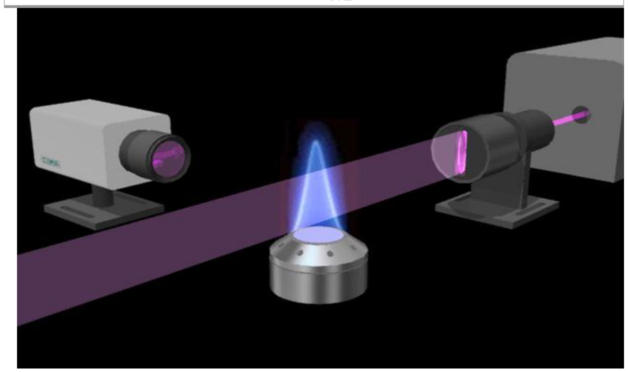
– ***Chemical Reaction technique*** ***(Breidenthal 1981)***

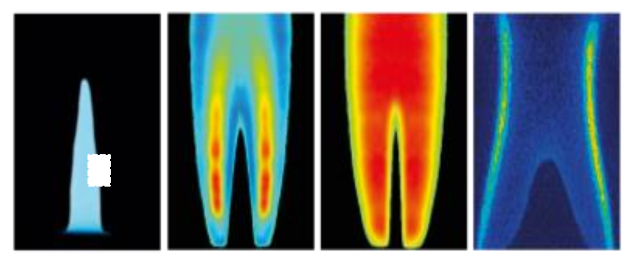
- *utilizes a fast-chemical reaction. Heat release of the chemical reaction may influence the mixing process of two streams.*

– ***Cold chemistry method***

- ***Quenching of Nitric Oxide (NO) LIF*** ***(Clemens & Paul, 1995)***
  - *Resolution free measurement of pure (unmixed) fluid; No information of the mixing state in a particular volume; The mixing state can not be determined instantaneously.*
- ***Sensitized phosphorescence technique*** ***(Yip et al., 1994)***
  - *Sensitized phosphorescence phenomena; two tracers; high noise level.*
- ***Dual-tracer LIF technique*** ***(King et al. 1997, 1999)***
  - *Simultaneous imaging of the LIF signals of two tracers, such as acetone and NO; complex experimental set up; two tracers, two excitation laser sources, two cameras for image recording .*



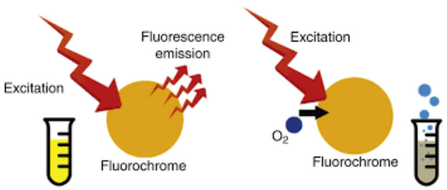


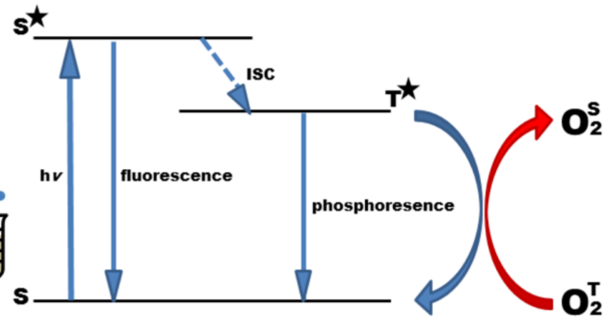


CH_4 with Tracer-LIF | OH-LIF with T-YAG™ | Temperature with Rayleigh | Soot with LII

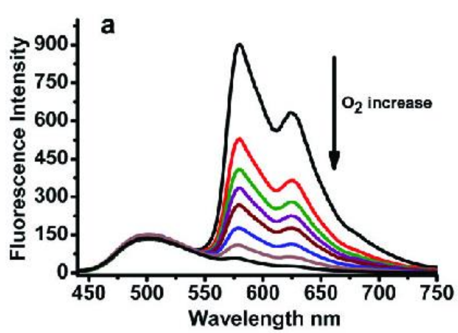
Oxygen quenching of acetone phosphorescence

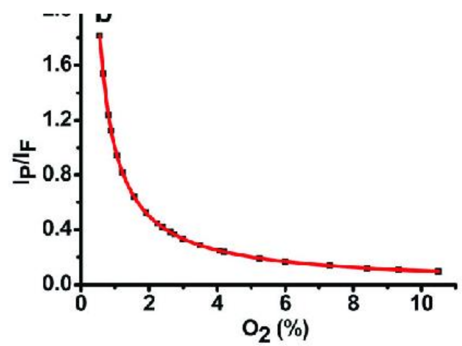
Oxygen quenching

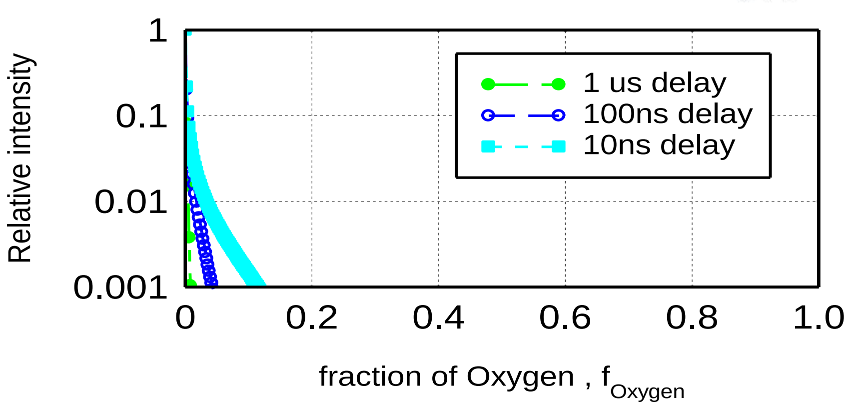




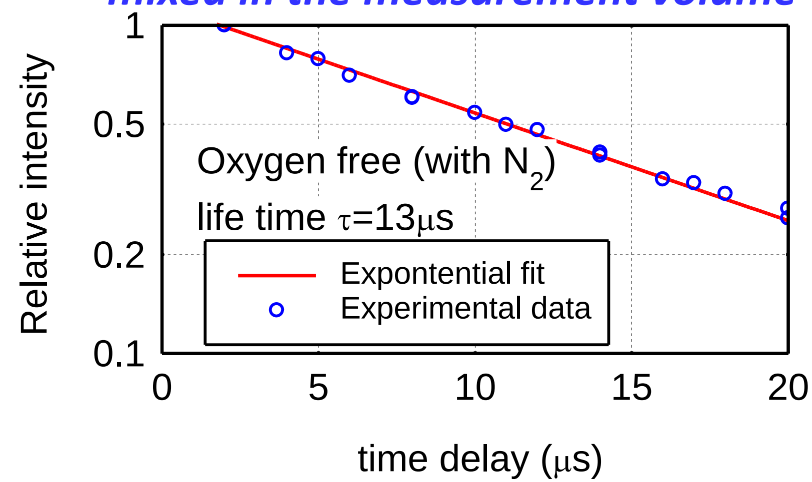
$$\frac{\tau_0}{\tau} = 1 + K_{SV} Q \qquad \text{or} \qquad \frac{\tau_0}{\tau_{O_2}} = \frac{I_0}{I_{O_2}} = 1 + K_{SV} P_{O_2}$$

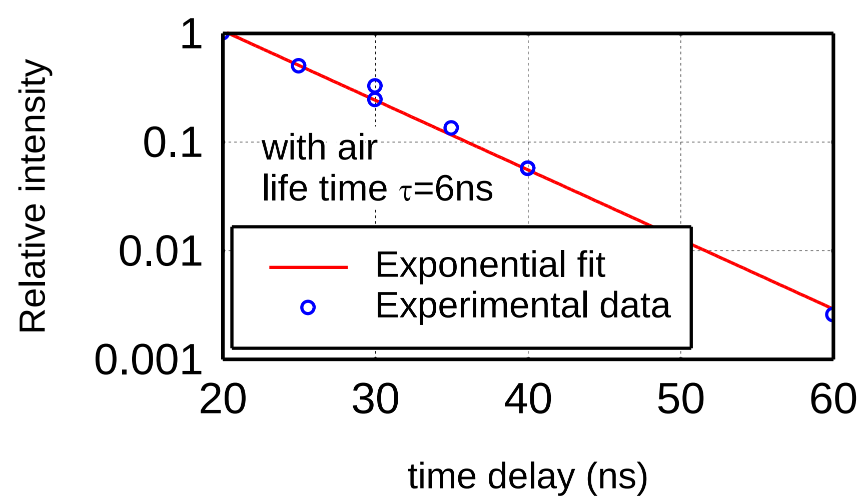






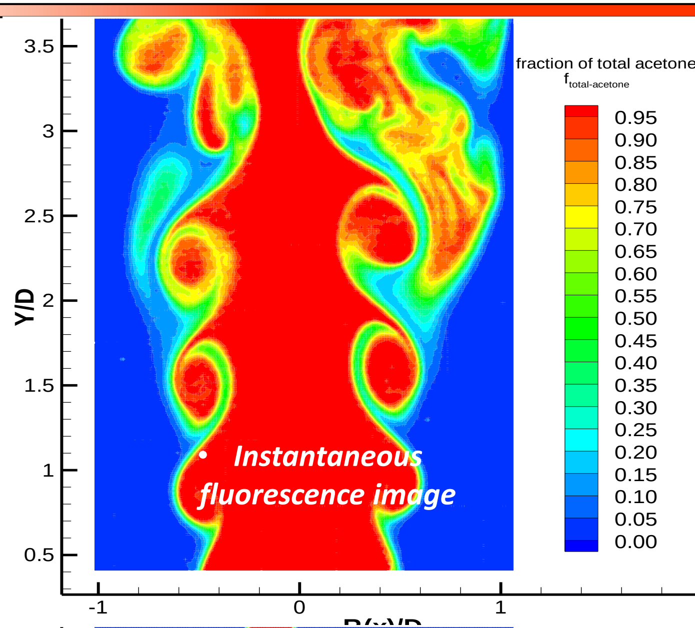
- *The phosphorescence intensity of acetone decreases three orders after 1μs when 1.0% of oxygen is mixed in the measurement volume*

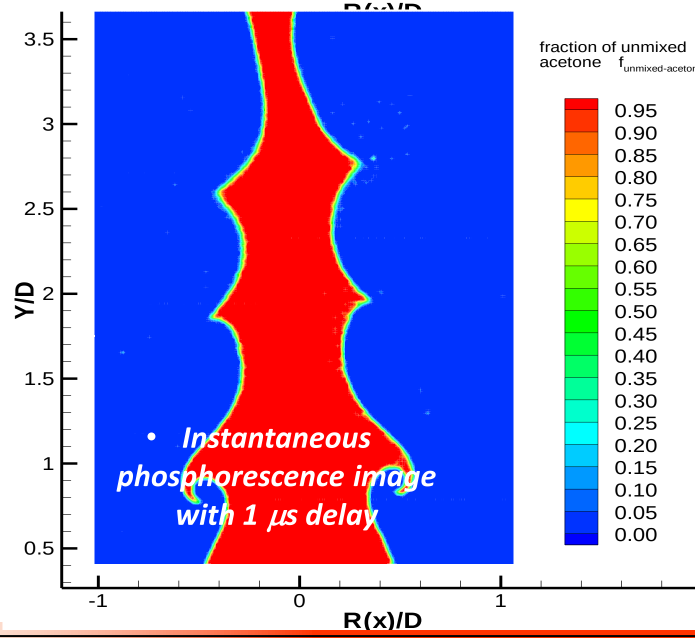




❑ The present method

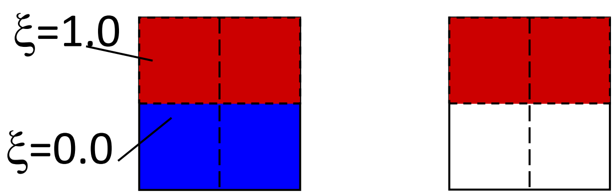
- A unique ***single-tracer, single-laser excitation and dual-frame detection technique*** *will be described in the present study.*
- *It utilizes the extraordinary difference of oxygen quenching behaviors between the laser-induced **fluorescence** signal and laser-induced **phosphorescence** signal of the same tracer (such as acetone or biacetyl).*
- ***Fluorescence signal*** *of the tracer, which is almost **not quenched** by oxygen in air, is used to represent the behavior of passive scalar. This is the same as conventional LIF technique)*
- ***Phosphorescence signal*** *of the same tracer, which is **greatly quenched** by the oxygen in air, displays mixing-state-dependant behavior.*
- *By **combining the information** from both fluorescence and phosphorescence signals, the instantaneous, quantitative planar measurements of molecularly mixed fluid fraction in the gaseous flow can be achieved.*





Mixing state within a pixel

Case A. Pure, unmixed

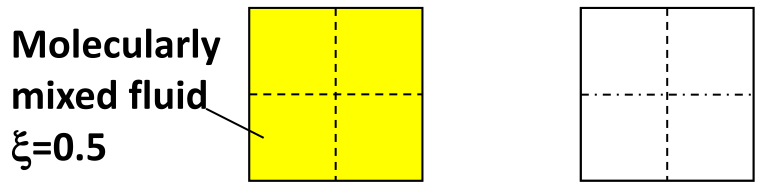


Fluorescence = 0.5 **Phosphorescence = 0.5**

$$f_{total-tracer} = 0.5;\ f_{unmixed-tracer} = 0.5$$

$$f_{mixed-tracer} = 0.0;\ \eta_{mixed} = 0.0\%$$

Case B. fully unmixed

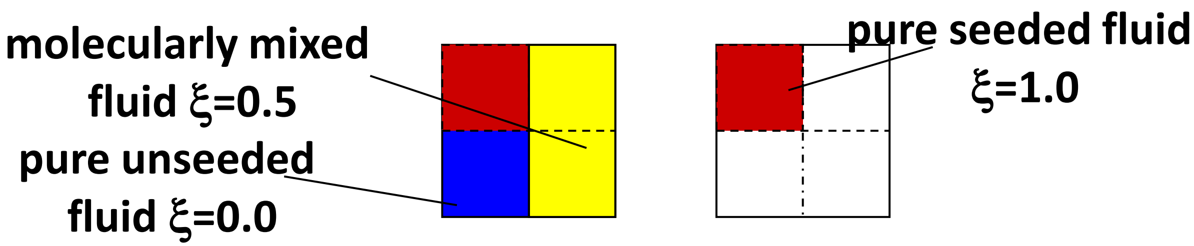


Fluorescence = 0.5 **Phosphorescence = 0.0**

$$f_{total-tracer} = 0.5;\ f_{unmixed-tracer} = 0.0$$

$$f_{mixed-tracer} = 0.5;\ \eta_{mixed} = 100.0\%$$

Case C. partially unmixed (Sub-resolution stirring)



Fluorescence = 0.5 **Phosphorescence = 0.25**

$$f_{total-tracer} = 0.5,\ f_{unmixed-tracer} = 0.25$$

$$f_{mixed-tracer} = 0.25,\ \eta_{mixed} = 50.0\%$$

Fluorescence and phosphorescence signal processing

- ***Fluorescence signal* is linearly proportional to the *total fraction of tracer* (acetone or biacetyl) in a fluid flow *regardless of the fluid mixing state*.**

$$f_{total-tracer} = \frac{I_{Fluo}}{(I_{Fluo})_0}$$

- ***Phosphorescence signal* is linearly proportional to the *unmixed fraction of tracer*.**

$$f_{unmixed-tracer} = \frac{I_{phos}}{(I_{phos})_0}$$

- ***Molecularly mixed fraction*:**

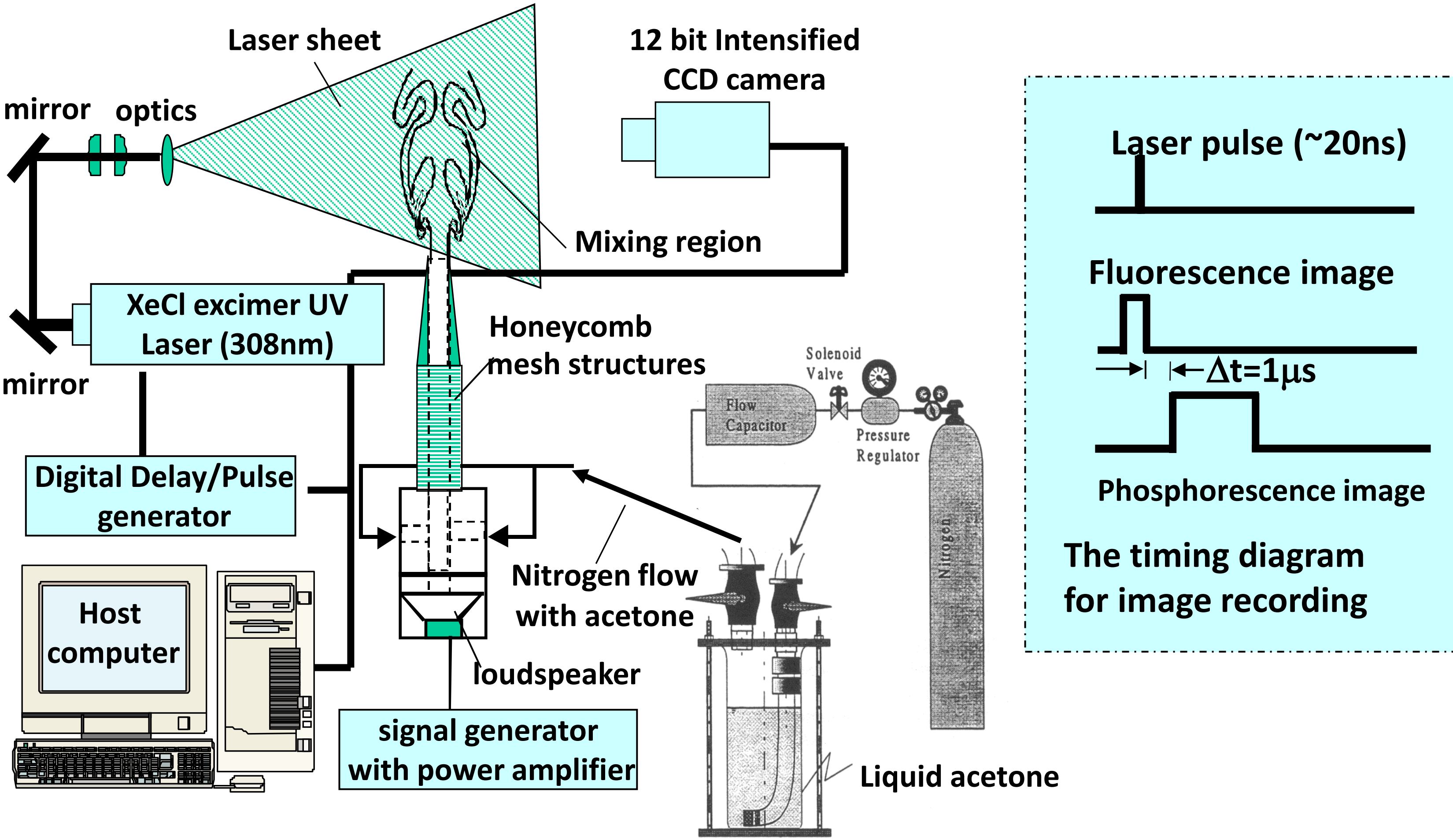
$$f_{mixed-tracer} = f_{total-tracer} - f_{unmixed-tracer}$$

- ***Mixing efficiency*: defined as the ratio of molecularly mixed seeded-tracer (acetone or biacetyl) to the total the tracer within each pixel.**

$$\eta_{mixed} = \frac{f_{mixed-tracer}}{f_{total-tracer}}$$

- **Hu H, Koochesfahani MM,** "A Novel Method for Instantaneous, Quantitative Measurement of Molecular Mixing in Gaseous Flows". *Experiments in Fluids*, Vol. 33, No. 1, pp202-209, 2002

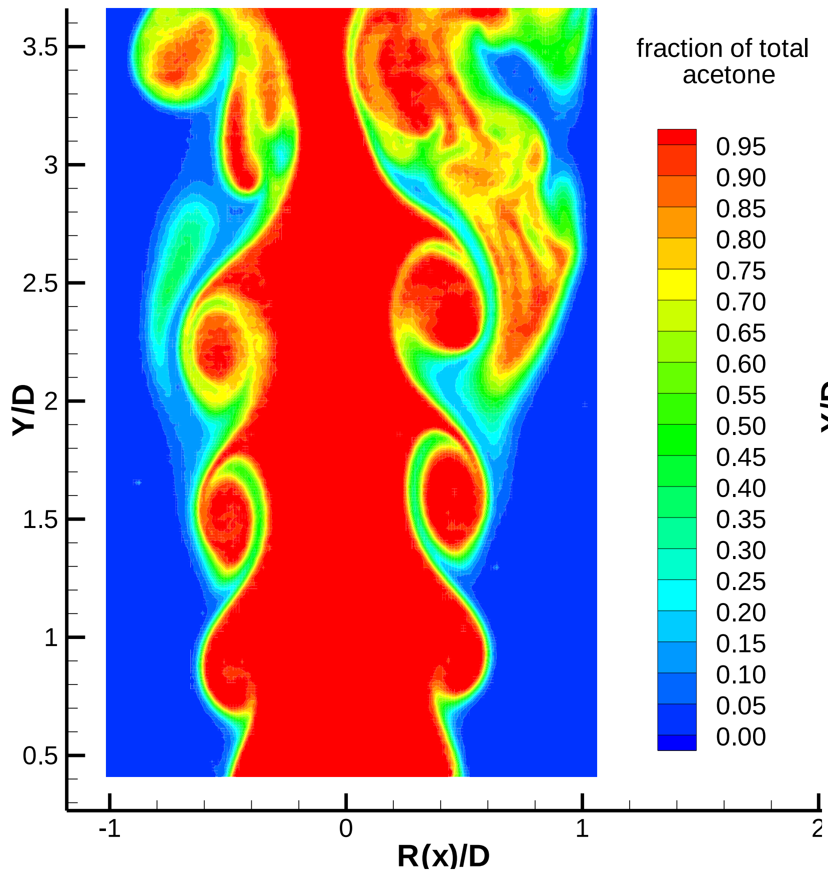
Experiment Set-up

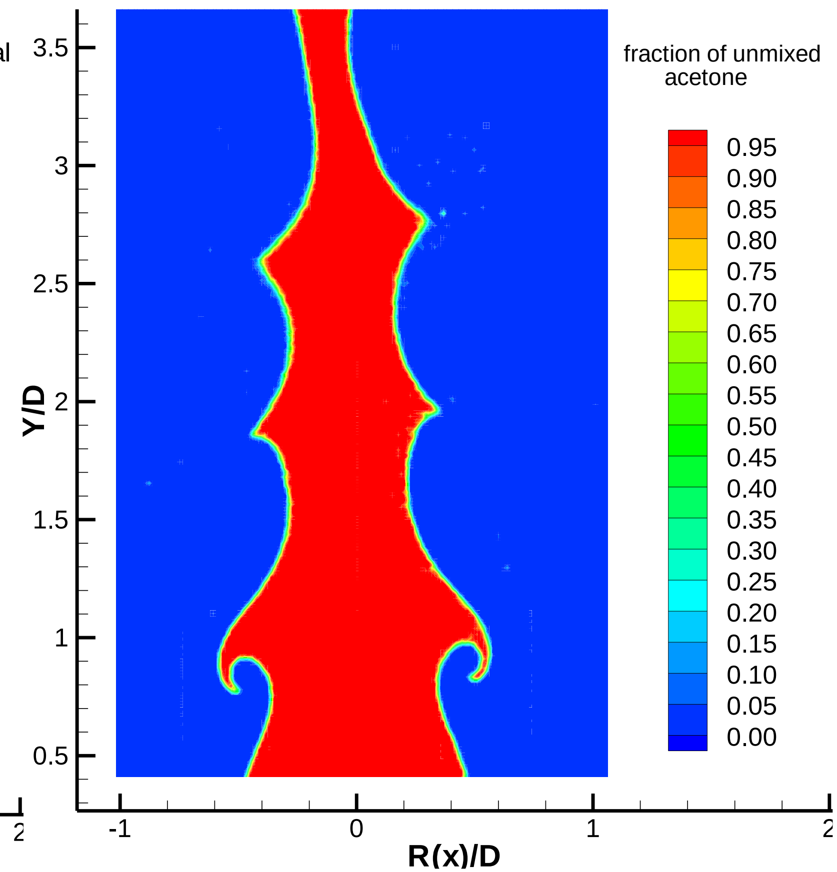


- *U_0=4.0m/s ,D=25mm, Re=DU_0/ν=6,500, excitation frequency f=80Hz*
- *UV laser (200mJ/pulse, wavelength 308nm)*
- *12 bit intensified CCD camera (1280 pixel by 1024 pixel)*

- **Hu H, Koochesfahani MM,** "A Novel Method for Instantaneous, Quantitative Measurement of Molecular Mixing in Gaseous Flows". *Experiments in Fluids*, Vol. 33, No. 1, pp202-209, 2002

Measurement results and Discussions





Instantaneous fluorescence image $f_{total\text{–}acetone}$

Instantaneous phosphorescence image with 1 μs delay $f_{unmixed\text{–}acetone}$

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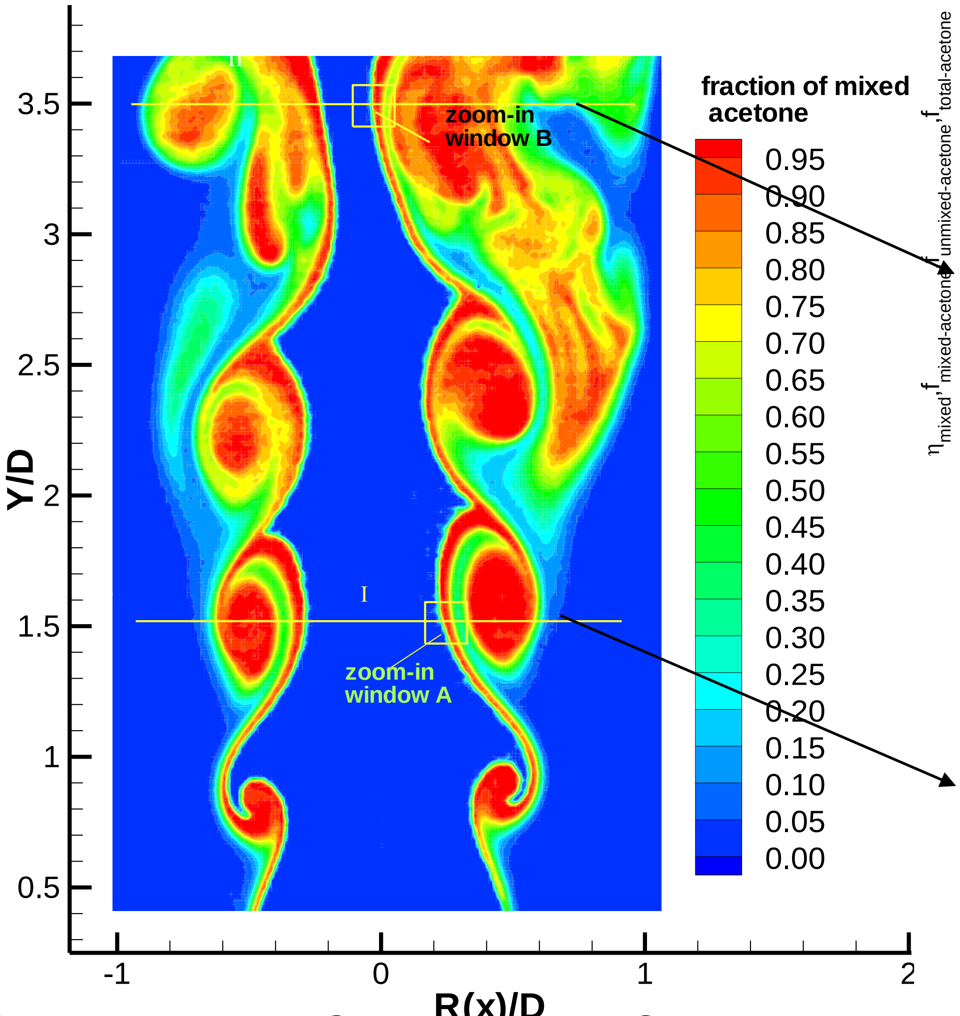
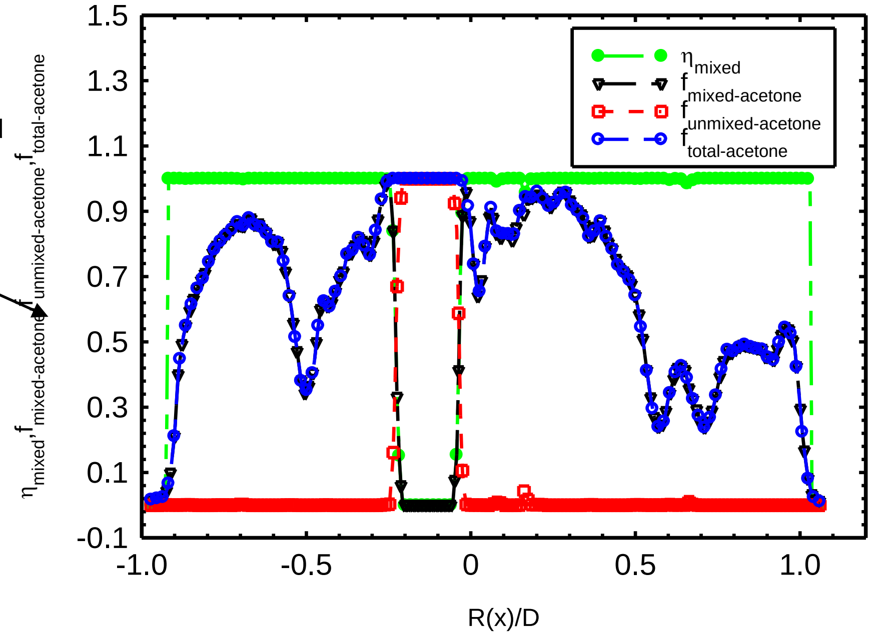
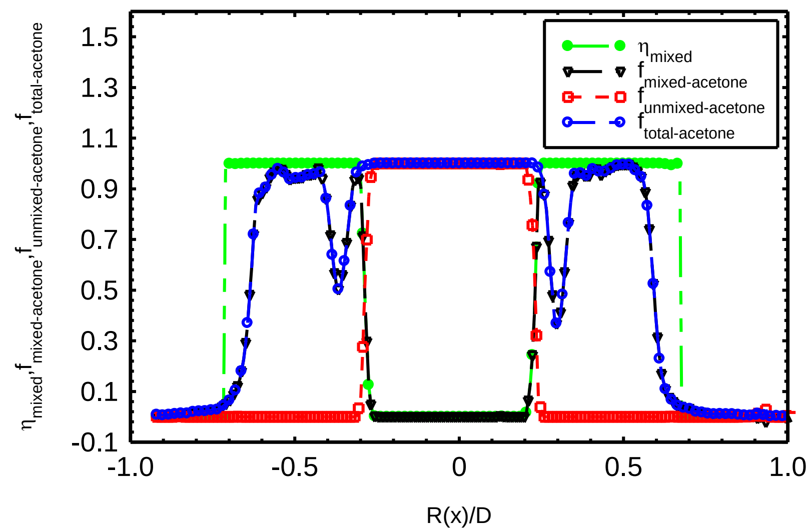
Measurement results and discussions

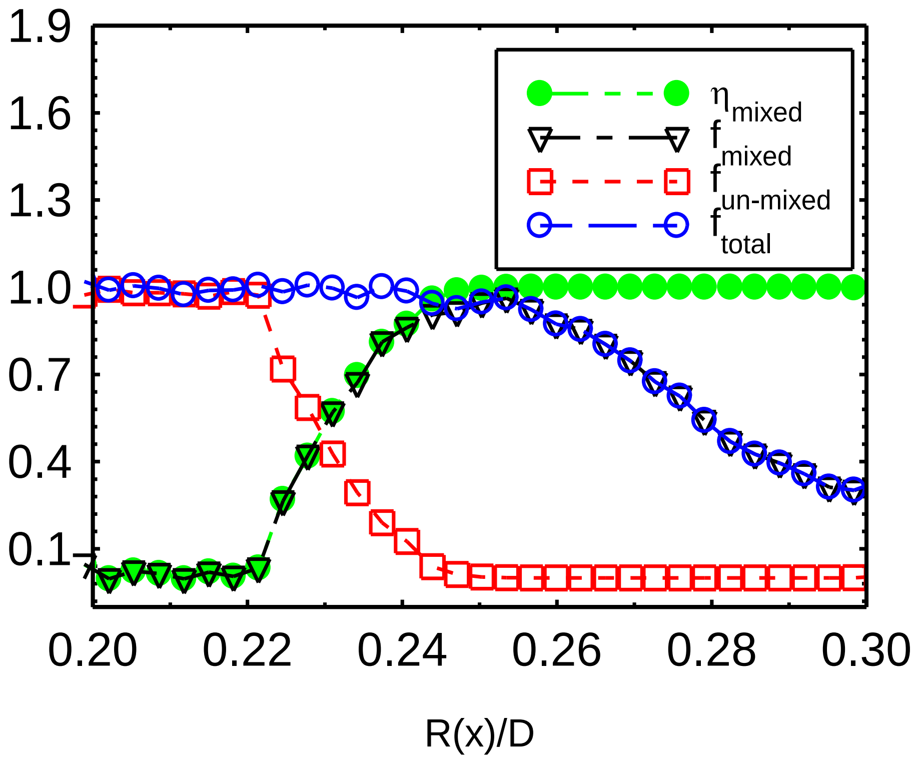




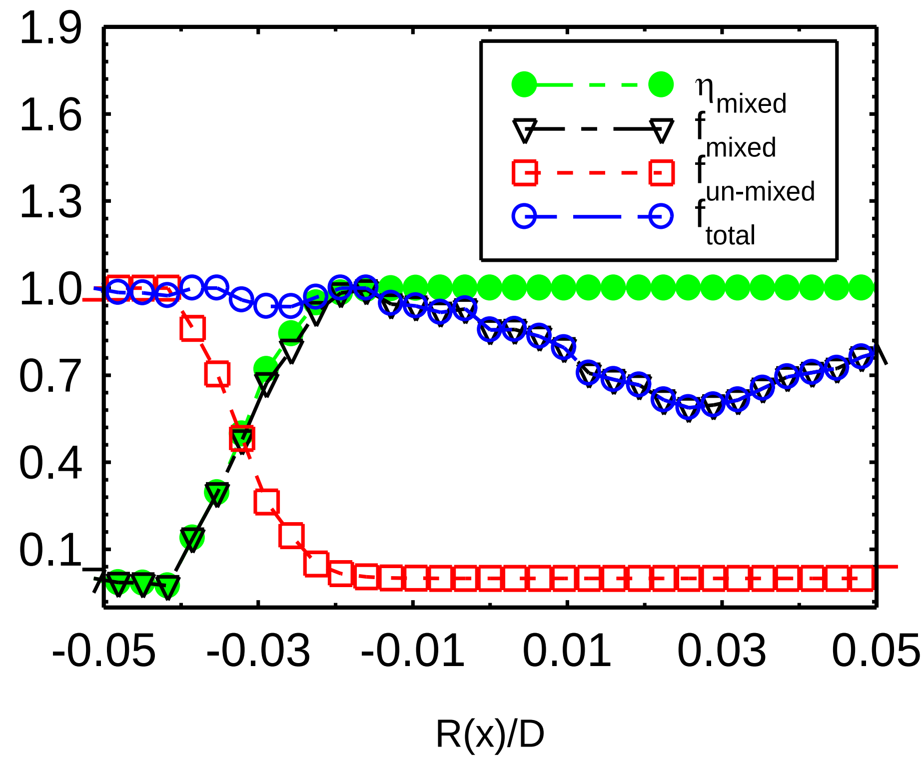


$$f_{mixed-acetone} = f_{total-acetone} - f_{unmixed-acetone}$$

Determination of Sub-resolution stirring



a. Zoom-in window A



b. Zoom-in window B

$f_{total-acetone}$, $f_{unmixed-acetone}$, $f_{mixed-acetone}$ and η_{mixed} profiles

- **<u>Hu H</u>, Koochesfahani MM**, "A Novel Method for Instantaneous, Quantitative Measurement of Molecular Mixing in Gaseous Flows". *Experiments in Fluids*, Vol. 33, No. 1, pp202-209, 2002

Conclusions

- ***A unique technique for conducting instantaneous, quantitative, planar measurement of the molecular mixing state in gaseous flows has been developed.***
  - *The technique utilizes the extraordinary difference of the oxygen quenching characteristics between laser-induced fluorescence and laser-induced phosphorescence of the same seeded tracers (acetone or biacetyl). The fluorescence, which is almost not quenched by oxygen in air, is used to represent the behavior of passive scalar in a gaseous flow. While, phosphorescence signal, which is greatly quenched by oxygen, displays mixing-state-dependant behavior.*

- ***This is a one-tracer, one-excitation-source and dual-frame technique.***
  - *Compared with previous dual-tracer, dual-excitation and dual-camera techniques, it can save the investment of various expensive laser systems, avoid complex optical arrangement and exclude the troublesome coordinate mapping procedures.*

- ***The technique was applied to conduct measurements in an excited gaseous jet.***
  - *The results demonstrated the capability of the present technique for obtaining instantaneous, quantitative measurement of molecularly mixed fluid fraction, while at the same time, quantitatively visualizing large-scale mixing structures in gaseous flows.*