LECTURE 23: Laser Induced Fluorescence (LIF) Technique Part - 02

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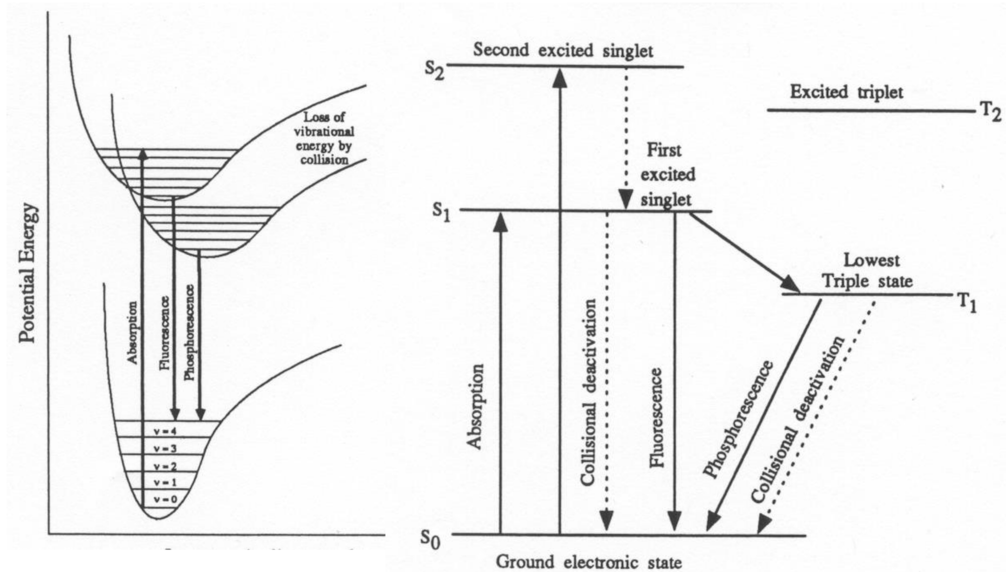
❑ Laser Induced Fluorescence (LIF) and Phosphorescence

- *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*

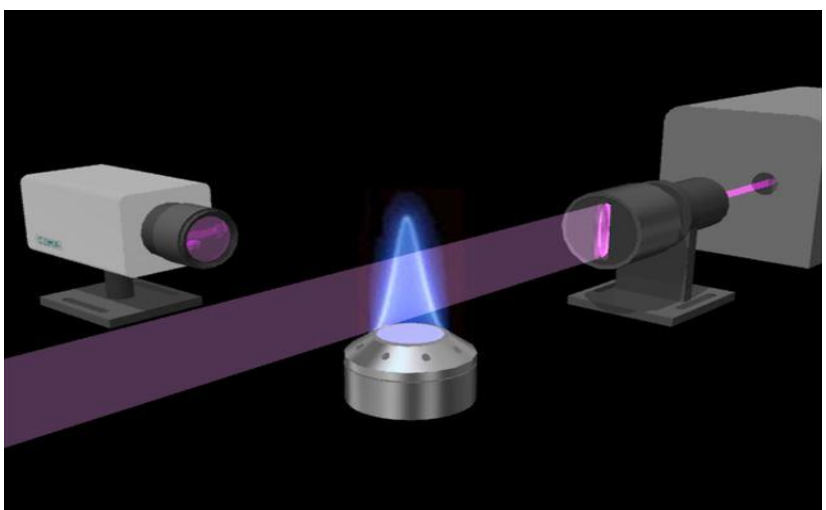
- *Flow variables can be measured based on LIF technique:*
  - *Species concentration/mole fraction (e.g., Na, OH, NO, O2, CH, CO, acetone)*
  - *Temperature*
  - *Velocity*
  - *Pressure*



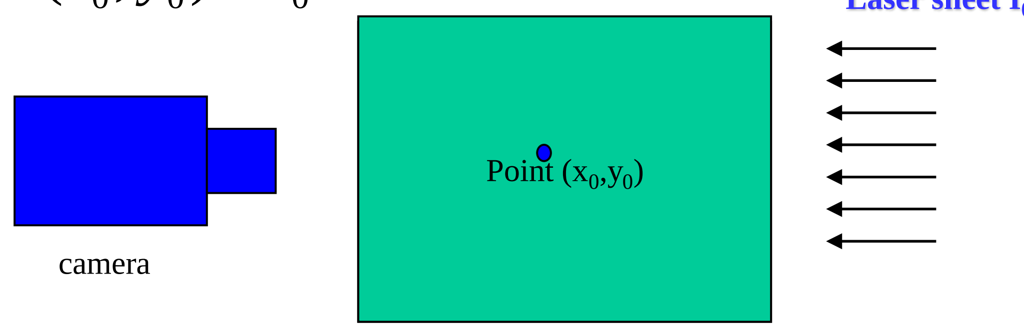
❑ PLIF - intensity at point (x_0,y_0)

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

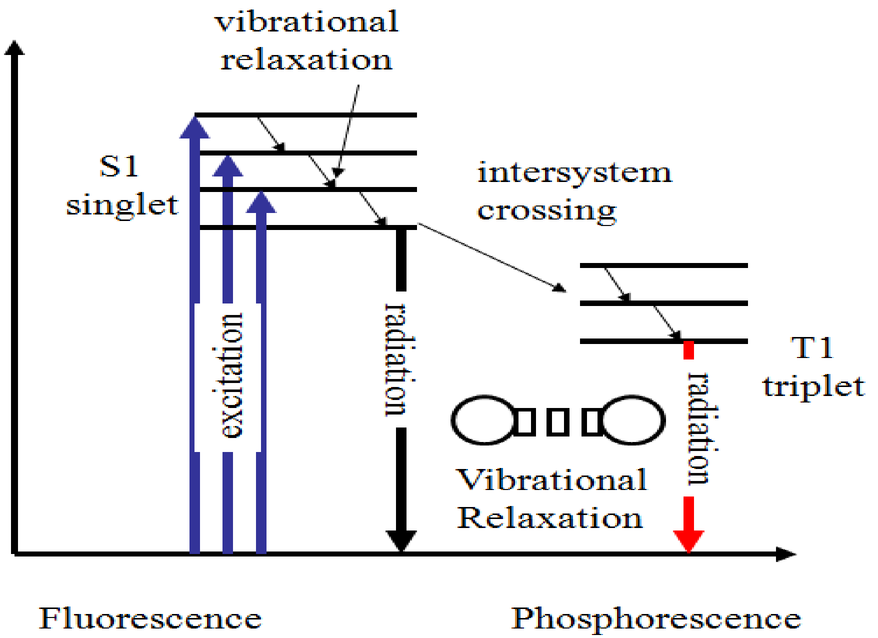
$H_f(x_0,y_0)$:	*measured fluorescence intensity*
A:	*the fraction of the fluorescence light collected by camera.*
Φ :	*quantum efficiency,*
L:	*the length of the sampling volume along the path of excitation beam*
ε:	*molar absorption coefficient*
$C(x_0,y_0)$:	*the molar concentration of the fluorescent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

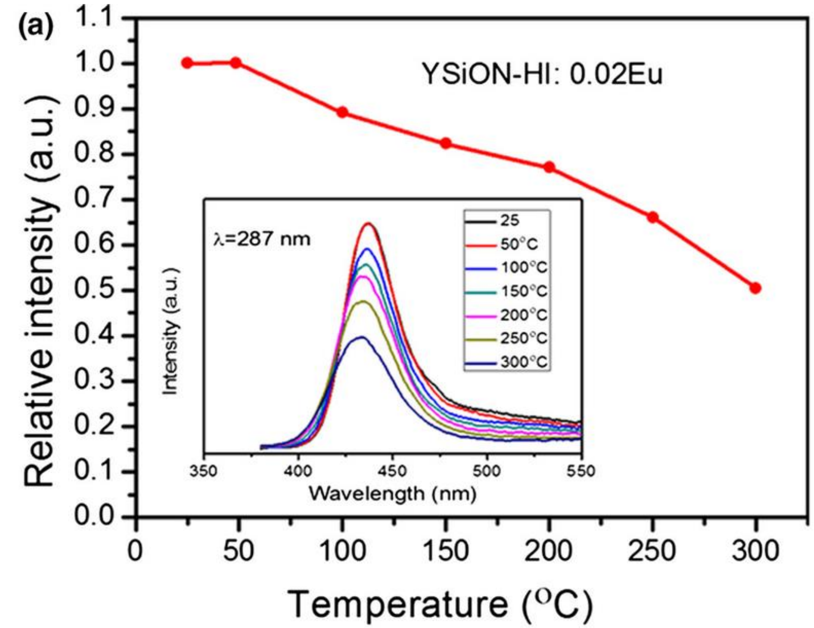


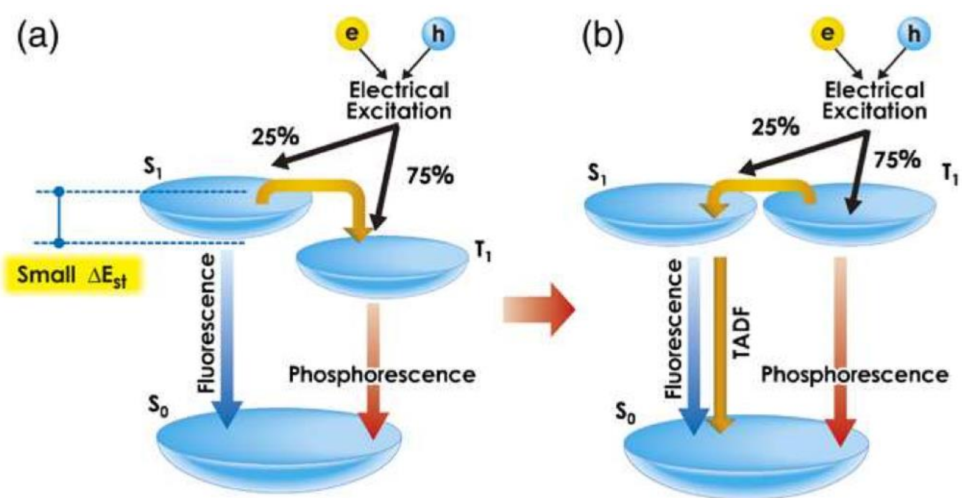
$$I(x_0,y_0)=I_0e^{-\varepsilon lc}$$



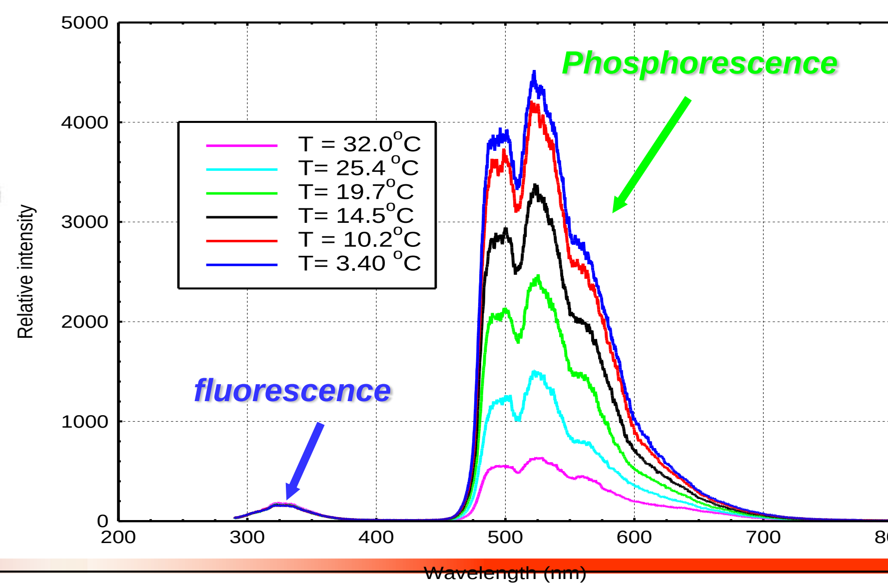
Thermal Quenching of Photoluminescence







Spectraphotometer Output vs Wavelength



PLIF for Temperature Field Measurements

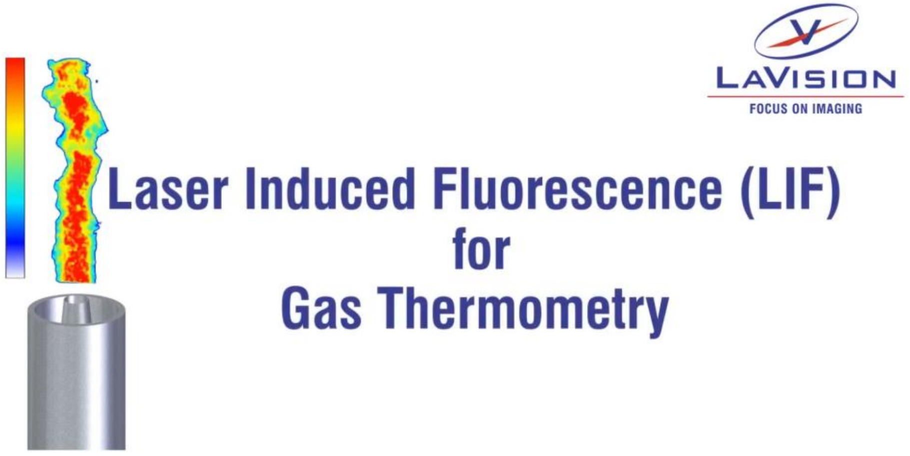
$$H_f(x_0,y_0) = I(x_0,y_0)\, A\, \Phi(T)\, \varepsilon(T)\, C(x_0,y_0)$$

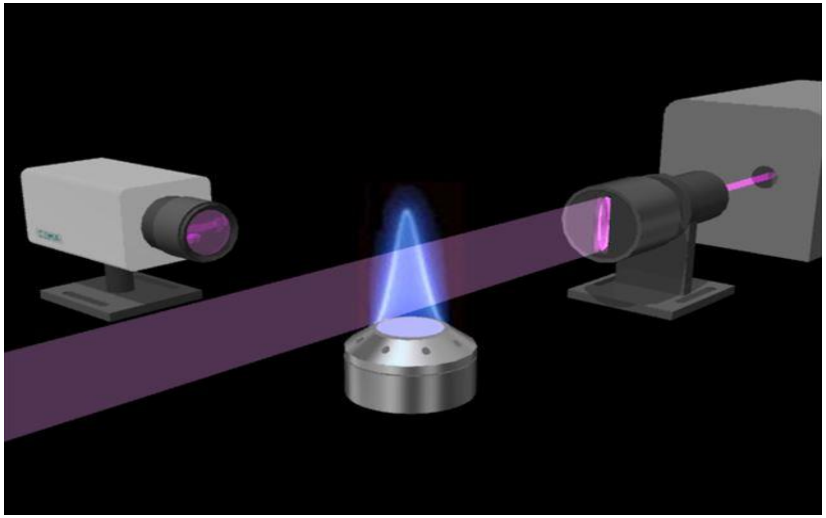
$I(x_0,y_0)$ can be predetermined through calibration
concentration $C(x_0,y_0)$ is kept as constant

$$\Rightarrow H_f(x_0,y_0) \propto \Phi(T)\, \varepsilon(T)$$

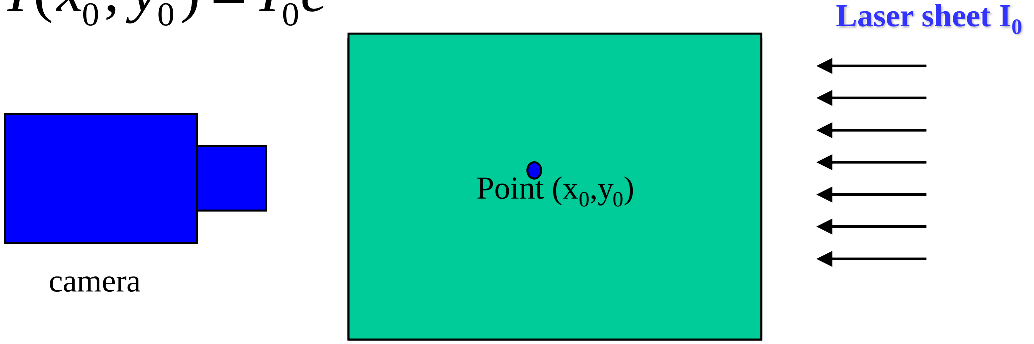
$$\Rightarrow H_f(x_0,y_0) \propto H_f(T)$$

$\Rightarrow H_f(T)$ can be predetermined through a calibration experiment.

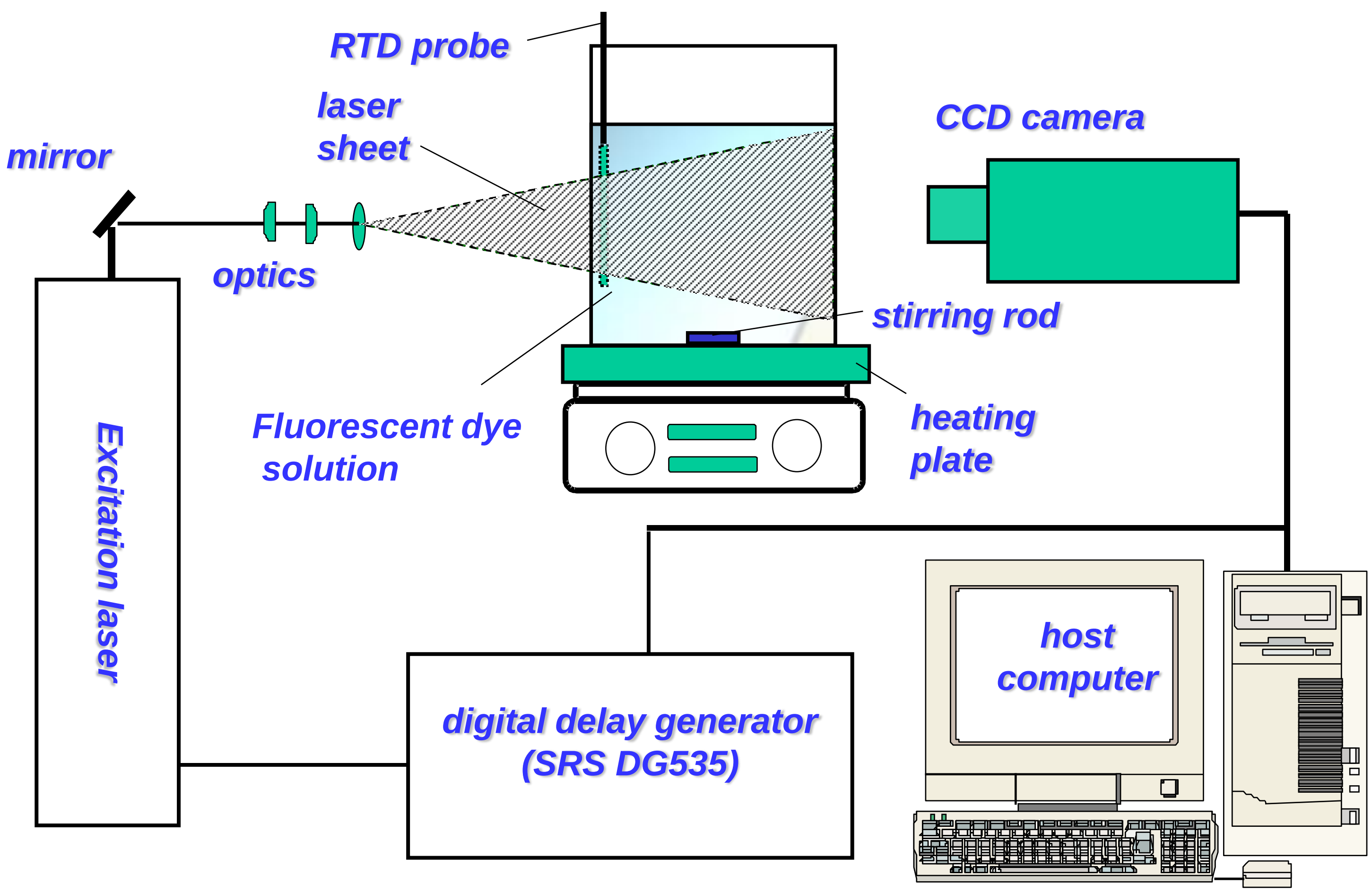




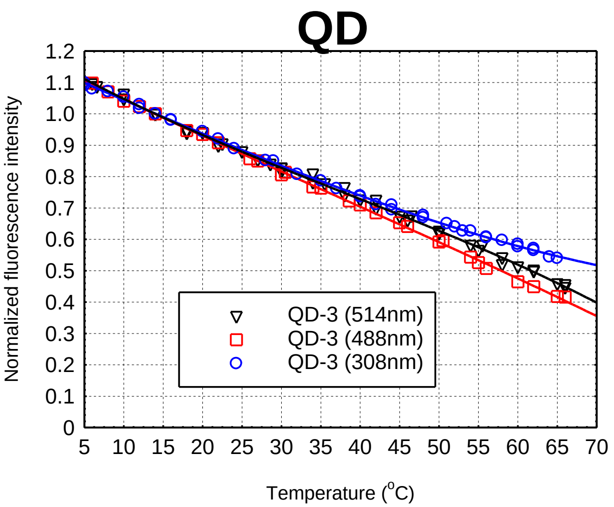
$$I(x_0,y_0) = I_0 e^{-\varepsilon l c}$$

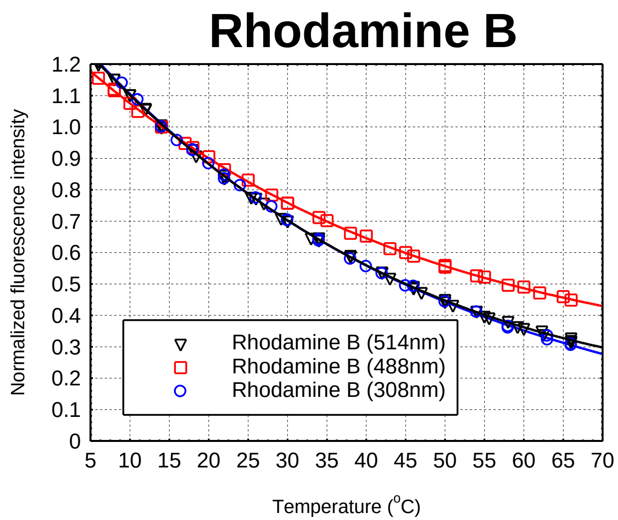


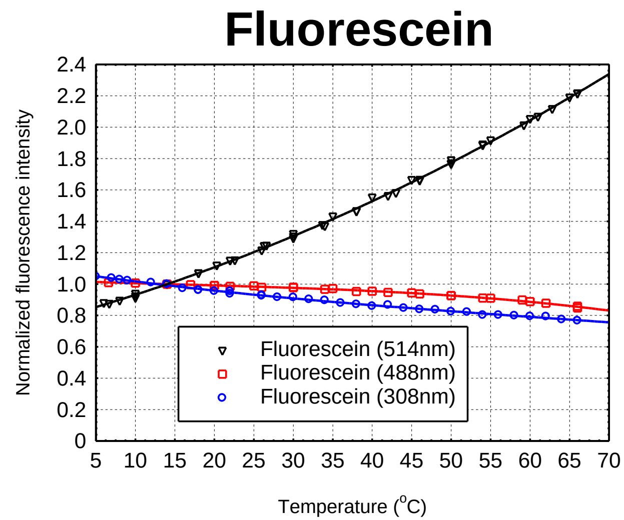
Temperature Calibration Experiments



Temperature Sensitive of QD, Fluorescein and Rhodamine B







	308nm Excimer laser	488nm Argon-ion laser	514nm Argon-ion laser
QD-3	-0.94% per °C (5°C ~ 65°C)	-1.14% per °C (5°C ~ 65°C)	-1.05% per °C (5°C ~ 65°C)
Rhodamine B	-1.57% per °C (5°C ~ 65°C)	-1.20% per °C (5°C ~ 65°C) Kim & Khim (2001) -1.35 % per° C (15°C ~ 40°C)	-1.52% per °C (5°C ~ 65°C) Coppeta & Roger(1998) -1.54 % per° C (20°C ~ 60°C)
Fluorescein	-0.45% per °C (5°C ~ 65°C)	-0.25% per °C (5°C ~ 65°C) Coppeta & Roger(1998) -0.16 % per° C (20°C ~ 60°C)	+2.25% per °C (5°C ~ 65°C) Coppeta & Roger(1998) +2.43 % per° C (20°C ~ 60°C)

More Fluorescent Dyes

Dye	Peak Abs/Em	pH-Dependent Absorption	Temperature Dependent Absorption	Temperature Dependent Emission
Fluorescien	488/514	5–8	Yes	2.43% per °C, Ex=514 −0.16% per °C Ex=488
HPTS	455/520	6–9	Yes	1.21% per °C, Ex=488 High Uncertainty
Lucifer Yellow	400/560	None over pH range 3–10	Not tested	Not tested
Rhodamine B	560/585	Below 6	Yes	−1.54% per °C, Ex=514
Sulforhodamine	585/607	None over pH range 3–10	Minimal	0.22% per °C Ex=514
Kiton Red	565/592	None over pH range 3–10	Yes	−1.55% per °C, Ex=514
Phloxine B	540/564	None over pH range 4–9	Yes	0.53% per °C Ex=514
LDS 698	435/687	Below 6	Yes	−1.27% per °C Ex=488
1–4 DHPN	Acidic 366/453 Basic 402/483	6–9	Yes	−1.1% per °C, Excitation Black light see Fig. 8

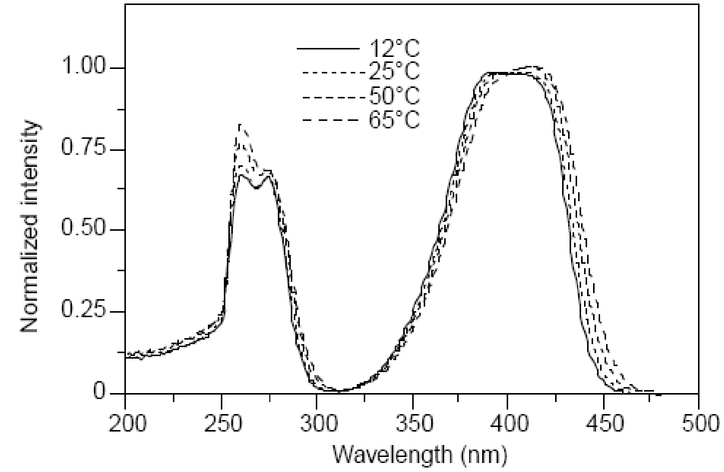
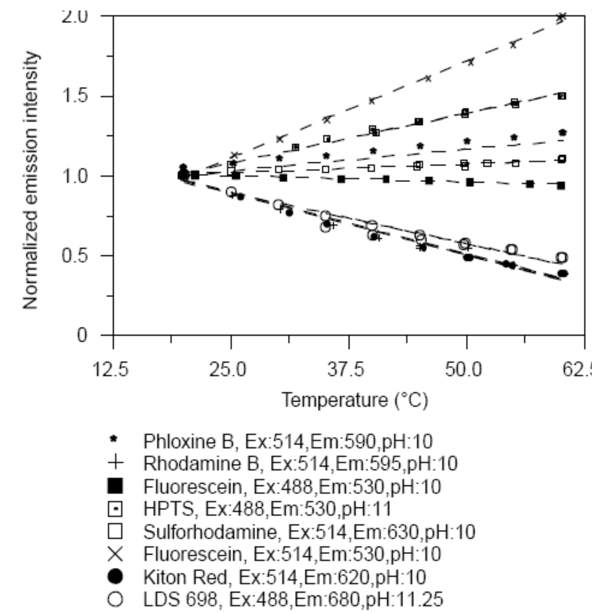
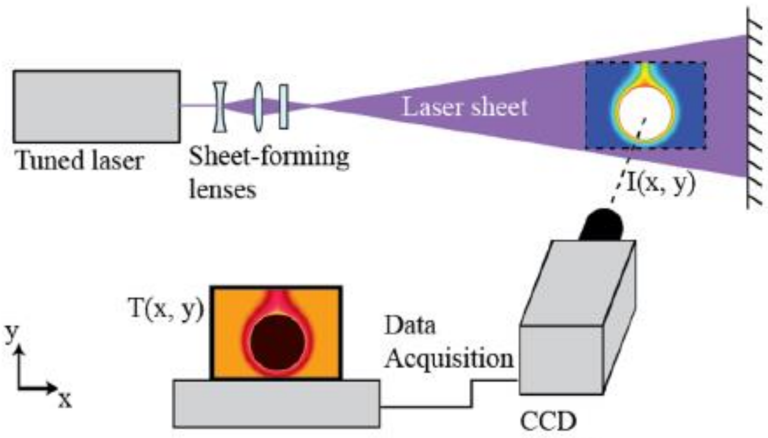
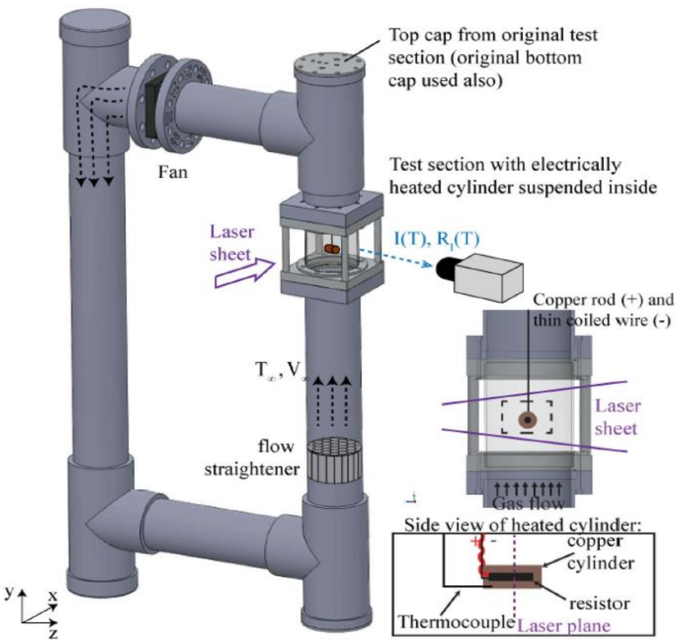


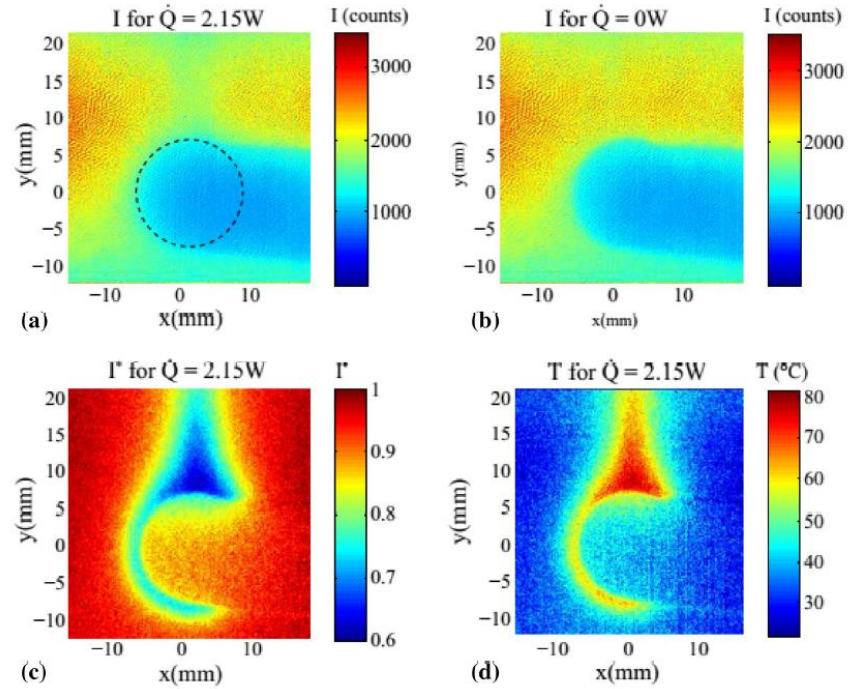
Fig. 10. 1,4-DHPN's relative absorption versus wavelength as a function of temperature

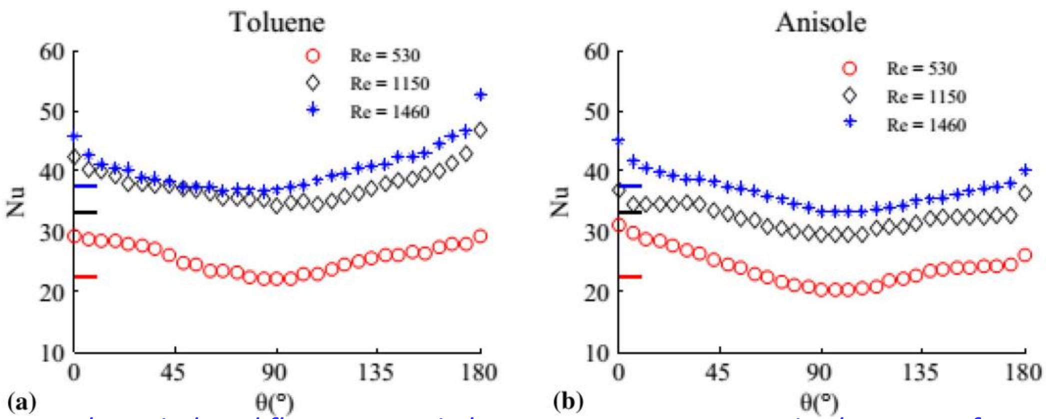


Quantification of Heat Transfer around a Heated Cylinder



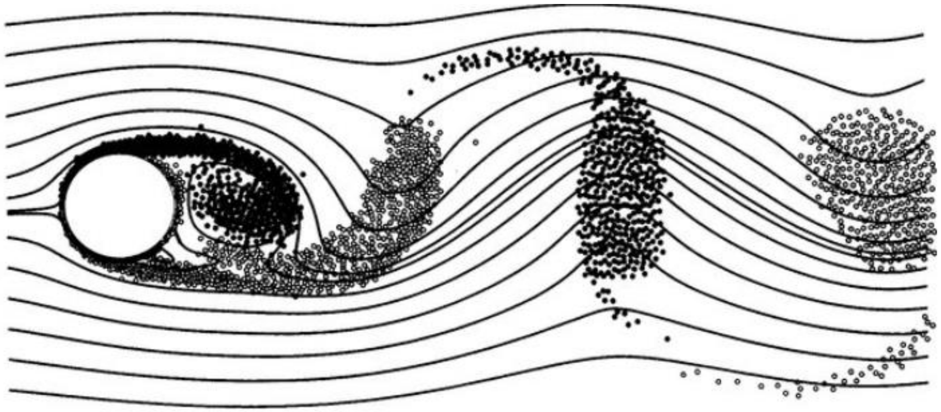


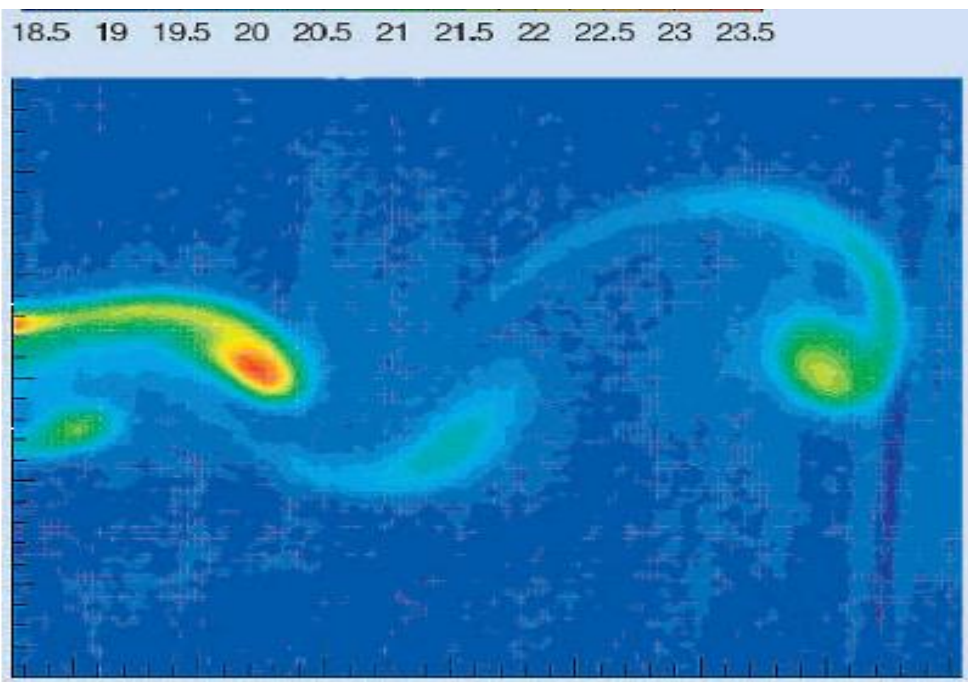




- *Fanning, E., Donnelly, T., Lunney, J.G. et al. Application of gaseous laser-induced fluorescence in low-temperature convective heat transfer research. Exp Fluids **61,** 123 (2020). https://doi.org/10.1007/s00348-020-02959-x*

Quantification of Heat Transfer around a Heated Cylinder





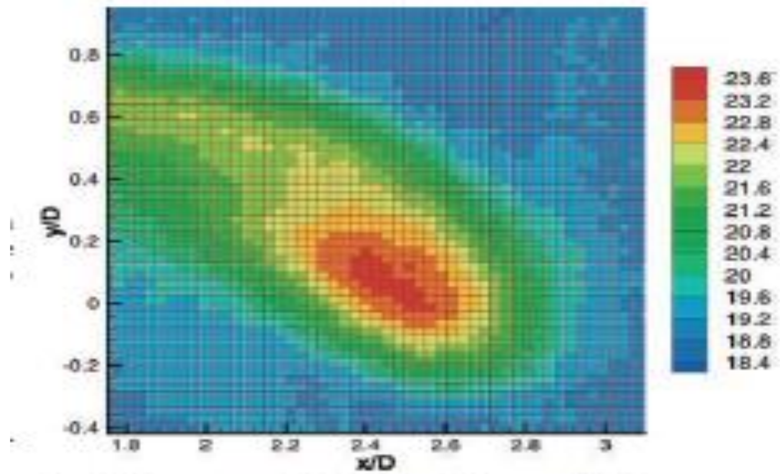


Fig. 10. Temperature distribution in the warm blob

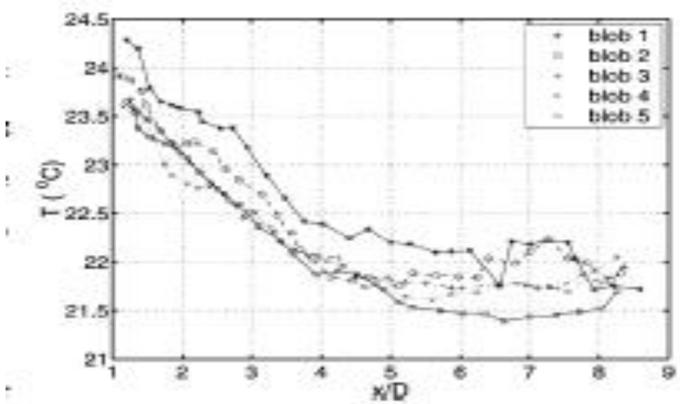
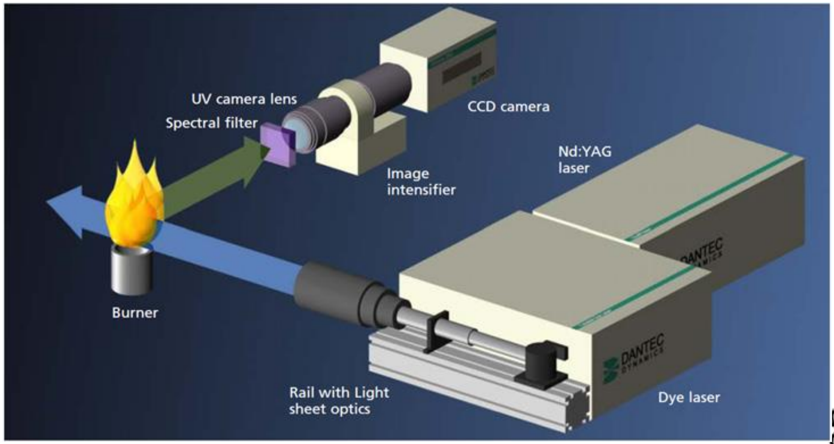
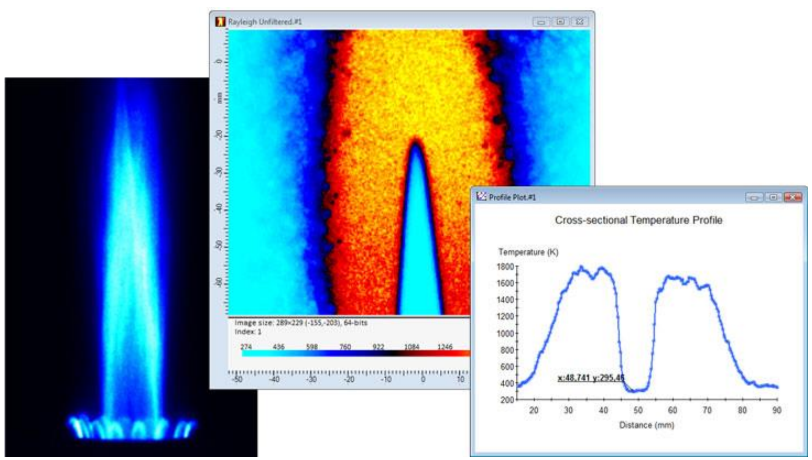


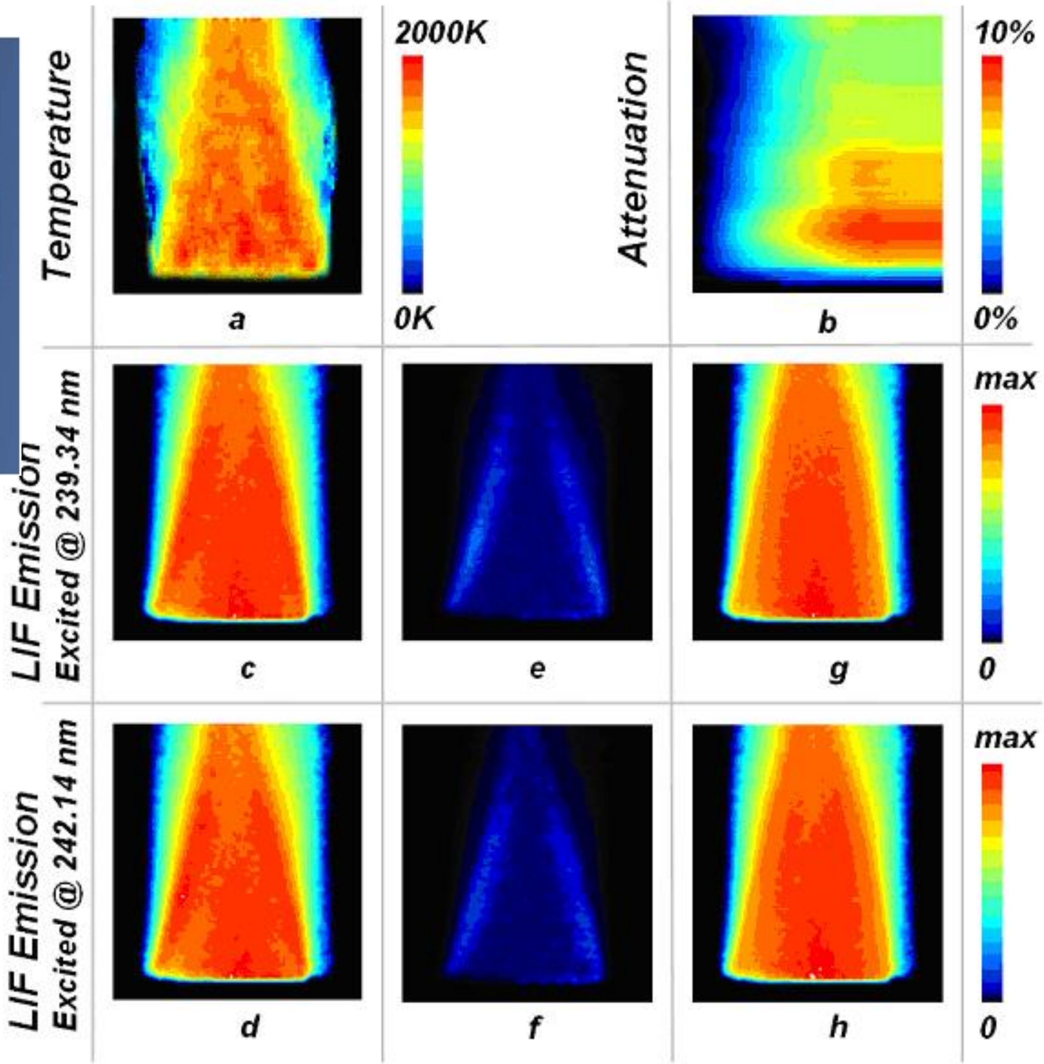
Fig. 11. The maximum temperature in the warm blob as function of the downstream position

- *Seuntiëns, H. J.; Kieft, R. N.; Rindt, C. C. M.; van Steenhoven, A. A., "2D temperature measurements in the wake of a heated cylinder using LIF", Experiments in Fluids, Volume 31, Issue 5, pp. 588-595 (2001).*

PLIF Measurements of Temperature Distributions of A Flame

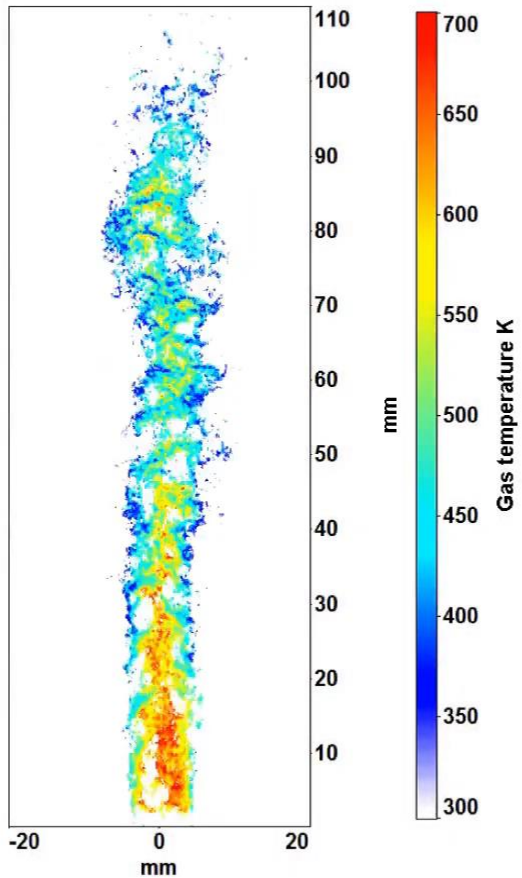






- *Results of imaging analysis of CO_2 UV-PLIF*

❑ PLIF-PIV combined System for Simultaneous Measurements of Flow Velocity and Temperature Distributions



LAVISION
FOCUS ON IMAGING

Phosphor Thermometry / Thermographic PIV

❑ Dual-Color LIF technique

- *LIF-based thermometry with two fluorescent dyes.*

$$H_{f1}(x_0, y_0) = I_i(x_0, y_0)\, A_1\, \Phi_1(T)\, \varepsilon_1(T)\, C_1$$

$$H_{f2}(x_0, y_0) = I_i(x_0, y_0)\, A_2\, \Phi_2(T)\, \varepsilon_2(T)\, C_2$$

$$\frac{H_{f1}(x_0, y_0)}{H_{f2}(x_0, y_0)} = \frac{I_i(x_0, y_0)\, A_1\, \Phi_1(T)\, \varepsilon_1(T)\, C_1}{I_i(x_0, y_0)\, A_2\, \Phi_2(T)\, \varepsilon_2(T)\, C_2} = \frac{A_1\, \Phi_1(T)\, \varepsilon_1(T)\, C}{A_2\, \Phi_2(T)\, \varepsilon_2(T)\, C}$$

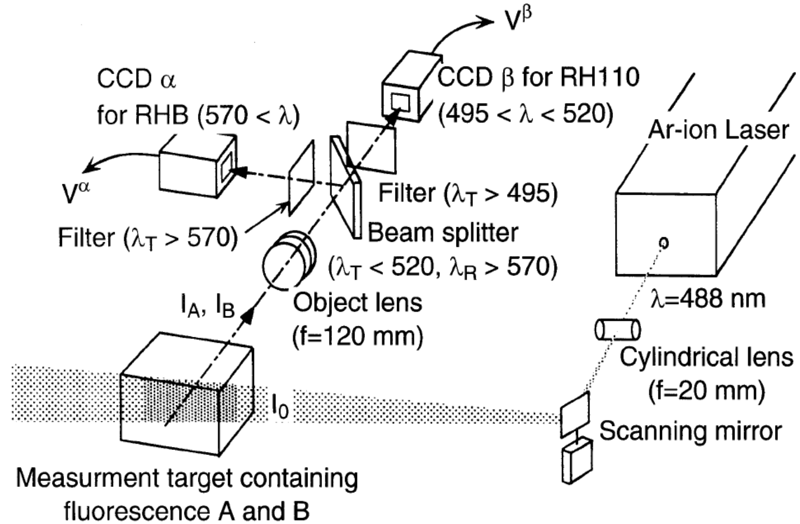


Fig. 1. Arrangement of the optical components

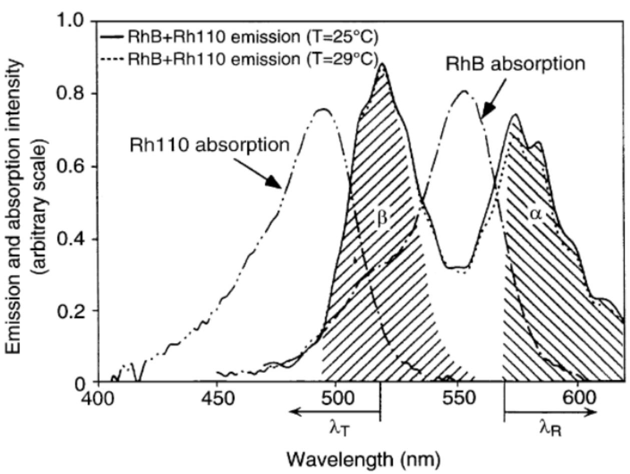


Fig. 2. Emission and absorption spectra of a mixture of RhB and Rh110 (C_{RhB} = 2.0 mg l^{-1}, C_{Rh110} = 0.2 mg l^{-1})

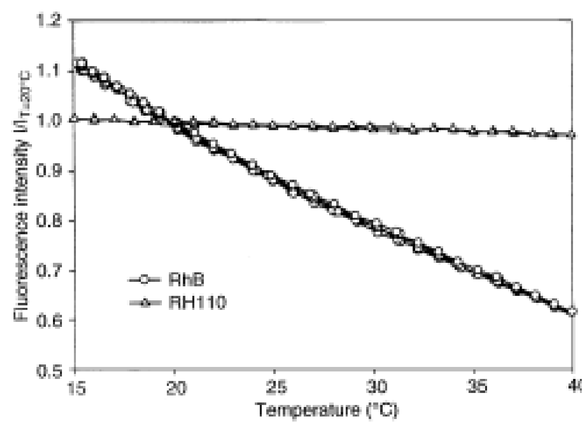


Fig. 3. Variation of the fluorescence intensity against temperature

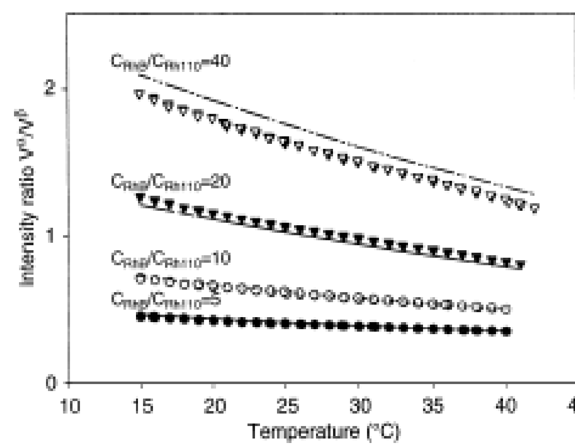


Fig. 7. Variation of the ratio between two CCD camera's output against temperature

- *Sakakibara K. and Adrian R, Whole field measurement of temperature in water using two-color laser induced fluorescence, Experiments in Fluids 26(1999)7–15.*

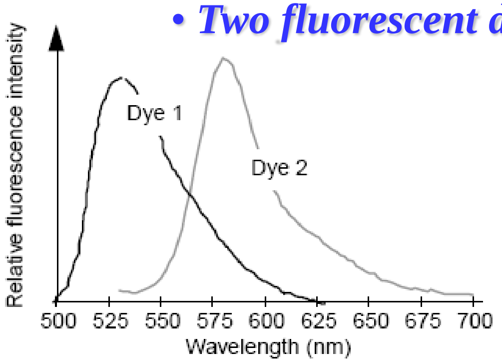
❑ Dual-Color LIF technique

$$H_{f_1}(x_0, y_0) = I_i(x_0, y_0)\, A_1\, \Phi_1(T)\, \varepsilon_1(T)\, C_1$$

$$H_{f_2}(x_0, y_0) = I_i(x_0, y_0)\, A_2\, \Phi_2(T)\, \varepsilon_2(T)\, C_2$$

$$\frac{H_{f_1}(x_0, y_0)}{H_{f_2}(x_0, y_0)} = \frac{I_i(x_0, y_0)\, A_1\, \Phi_1(T)\, \varepsilon_1(T)\, C_1}{I_i(x_0, y_0)\, A_2\, \Phi_2(T)\, \varepsilon_2(T)\, C_2} = \frac{A_1\, \Phi_1(T)\, \varepsilon_1(T)\, C}{A_2\, \Phi_2(T)\, \varepsilon_2(T)\, C}$$

- *Two fluorescent dyes*



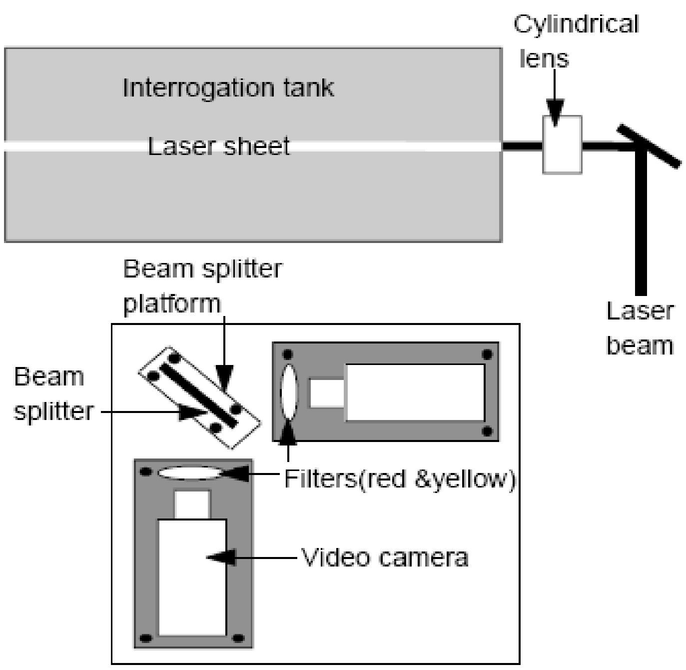


Fig. 1. Top view of experimental set up

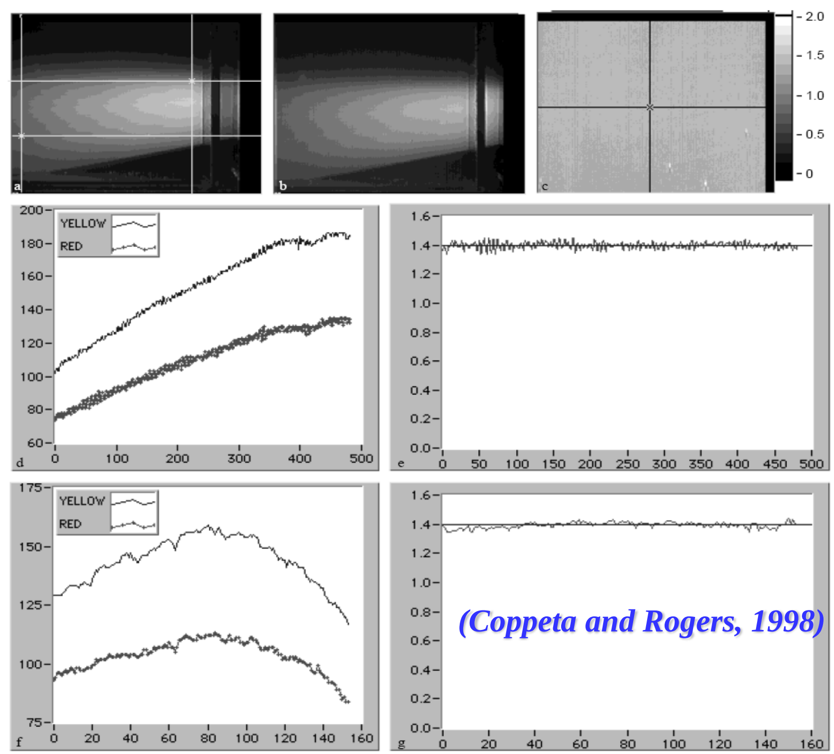


Fig. 2. a Yellow fluorescence intensity image; b red fluorescence intensity image; c ratio "image", d pixel intensity versus position for a horizontal cross section of each image; e ratio of horizontal cross section intensity values; f pixel intensity versus position for a vertical cross section of each image; g ratio of vertical cross section intensity values

❑ Results of the Dual-color LIF technique

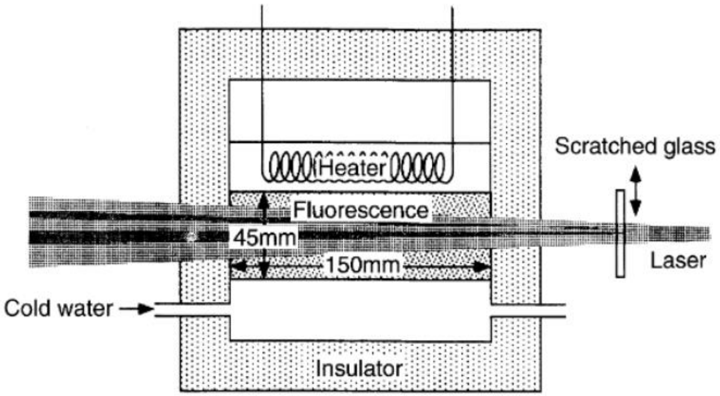


Fig. 10. Experimental apparatus for the stable thermally stratified layer

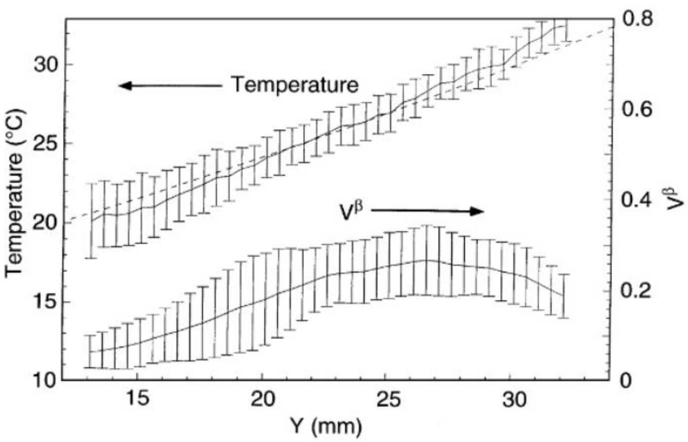


Fig. 11. Temperature profile of the stable thermally stratified layer. Laser light intensity is proportional to V^β

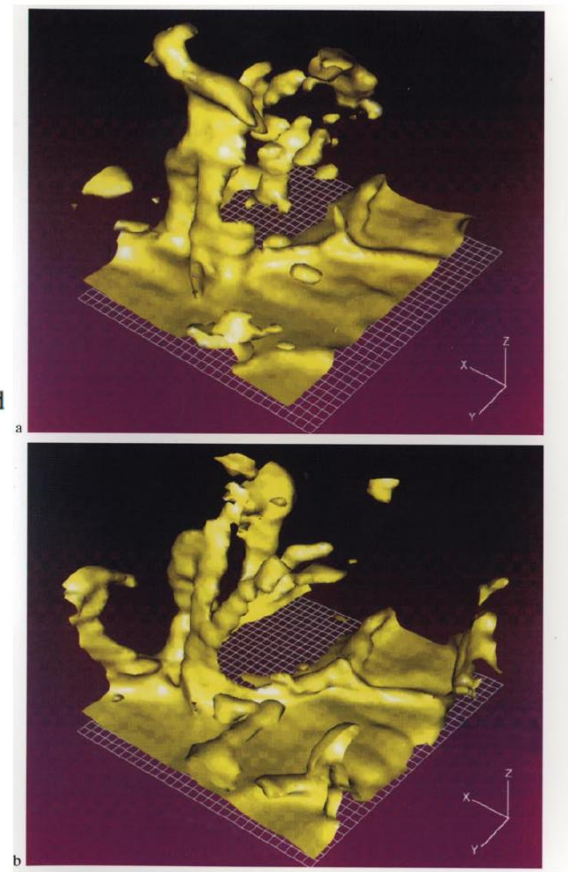


Fig. 13.

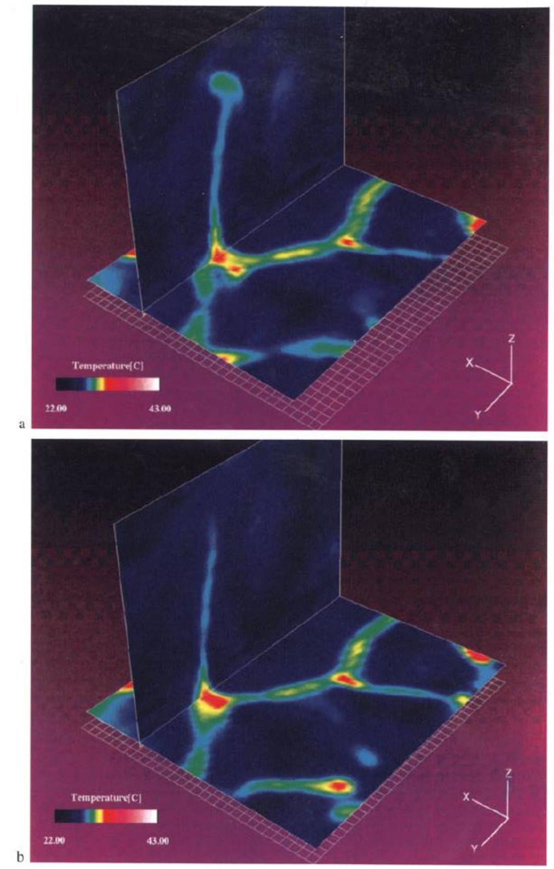
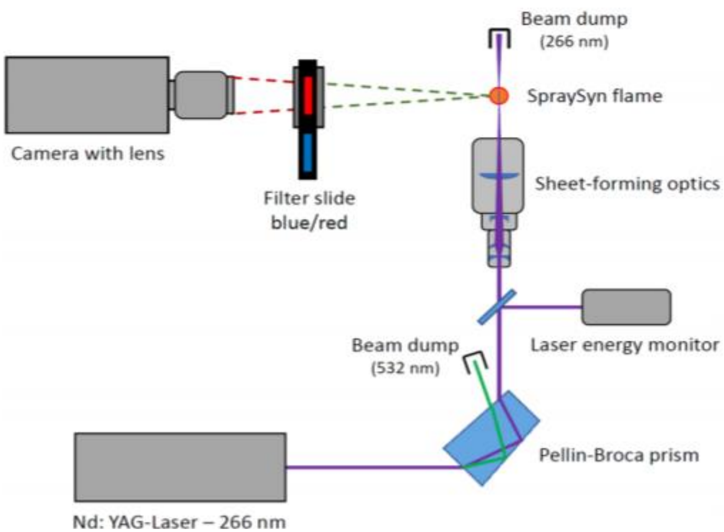
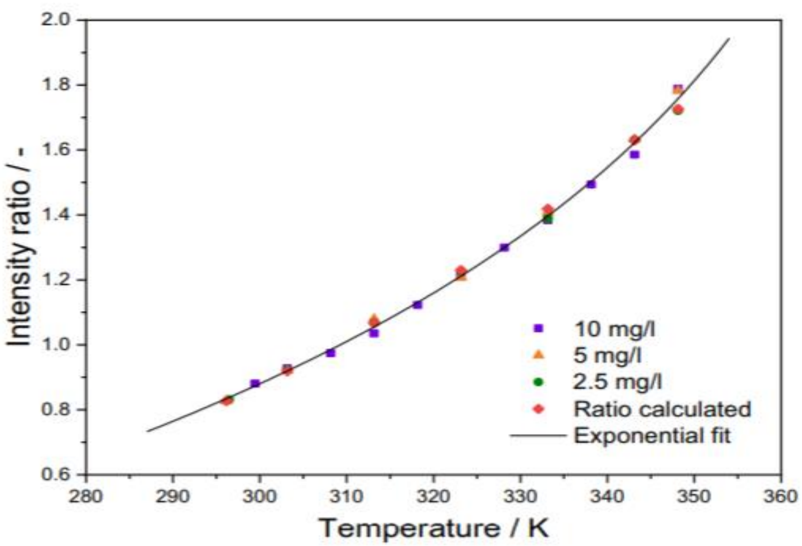


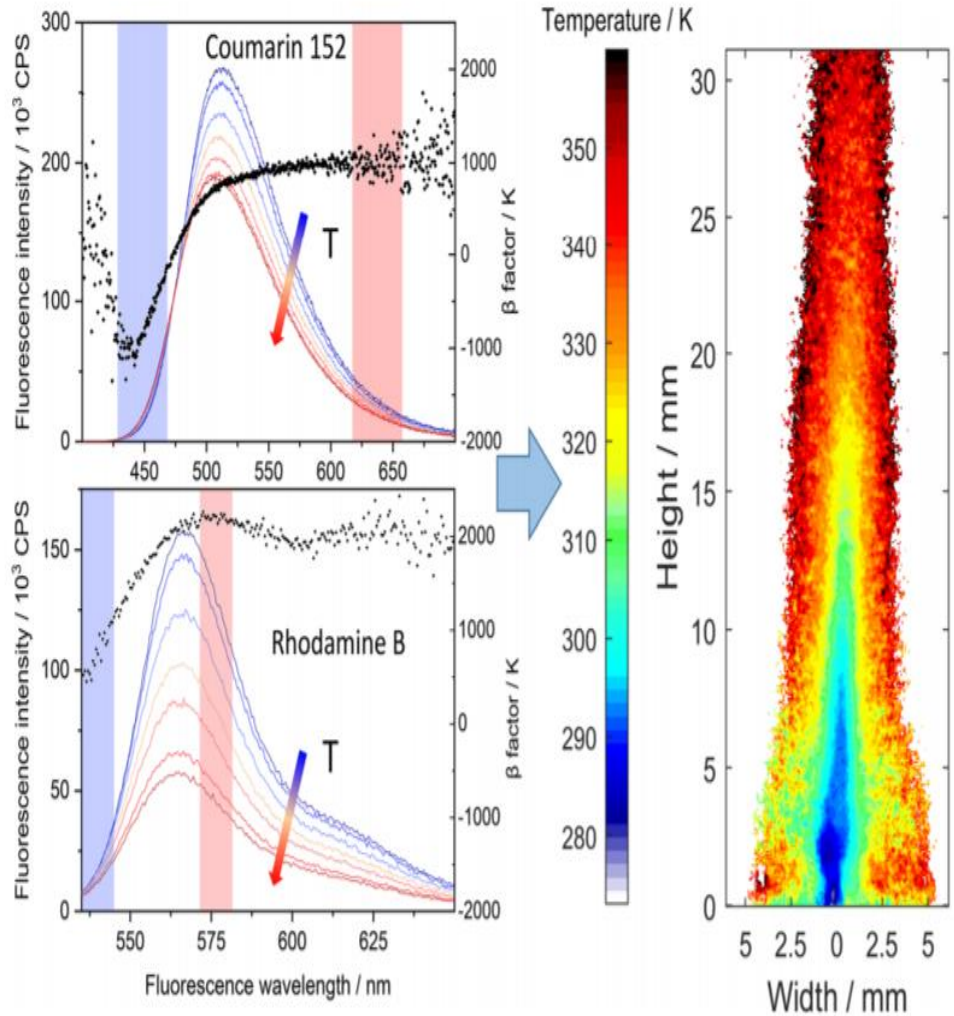
Fig. 14.

- *Sakakibara K. and Adrian R, Whole field measurement of temperature in water using two-color laser induced fluorescence, Experiments in Fluids 26(1999)7–15.*

❑ Dual-Color LIF technique



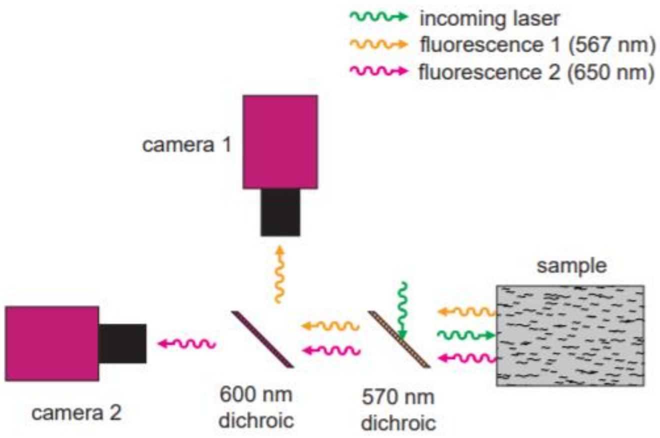




- *Prenting, M.M., Bin Dzulfida, M.I., Dreier, T. et al. Characterization of tracers for two-color laser-induced fluorescence liquid-phase temperature imaging in sprays. Exp Fluids **61,** 77 (2020).*

❑ Dual-Color LIF technique

- *Advantage:*
  - *Ratio-metric method*
  - *Do not need to calibrate the uniformity of the laser intensity distribution*



- *Disadvantage:*
  - *Spectrum conflict between two fluorescent dyes*
  - *Photobleaching rate differences of the two dyes*
  - *Low temperature sensitivity*

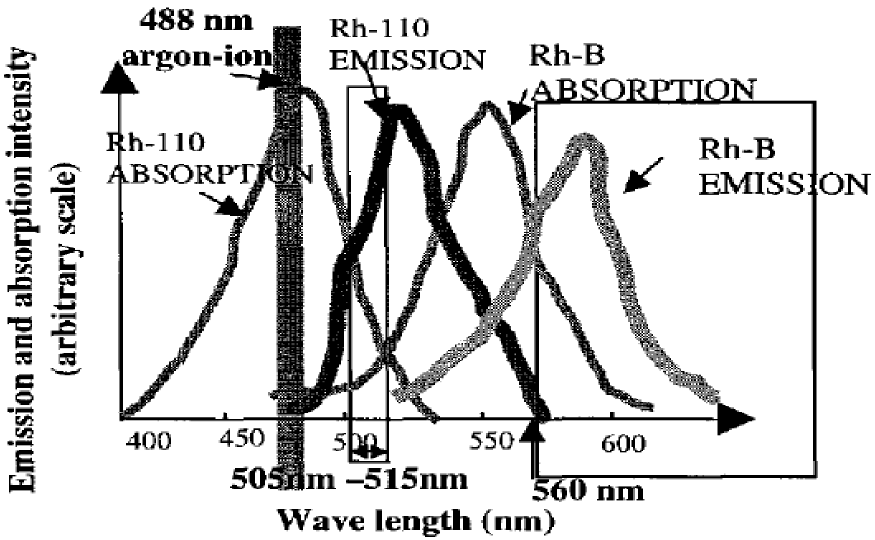


Fig. 2 Absorption and fluorescence spectra of Rhodmine-110 and Rhodamine-B

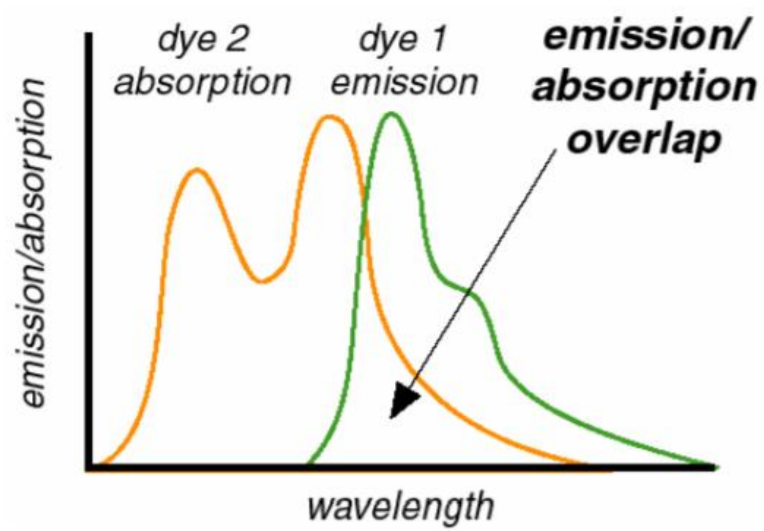
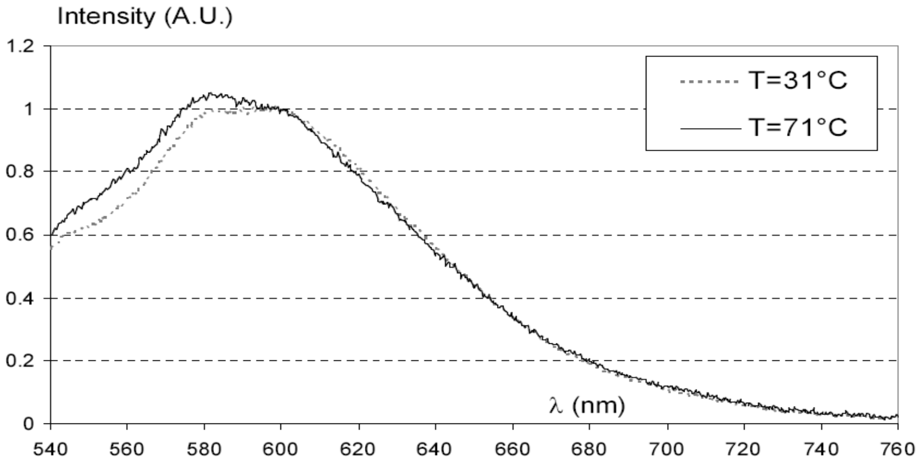


Figure 5: Reabsorption schematic

❑ Dual-Emission-Band LIF technique

- ***Single dye; Two emission band method***



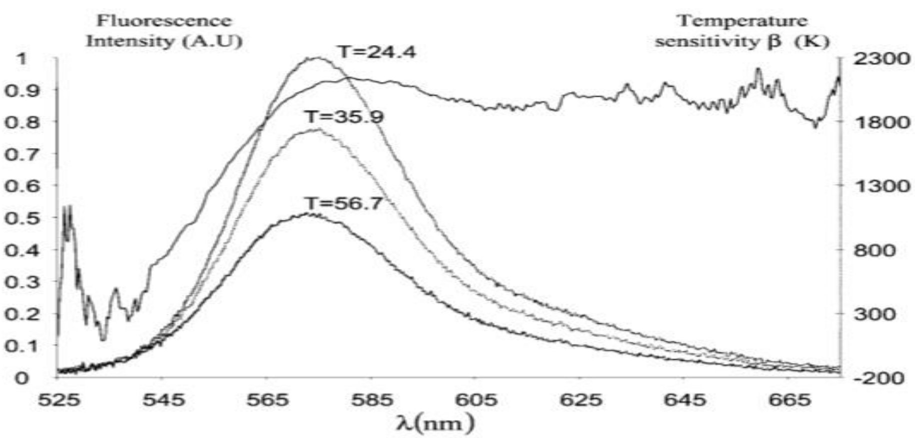
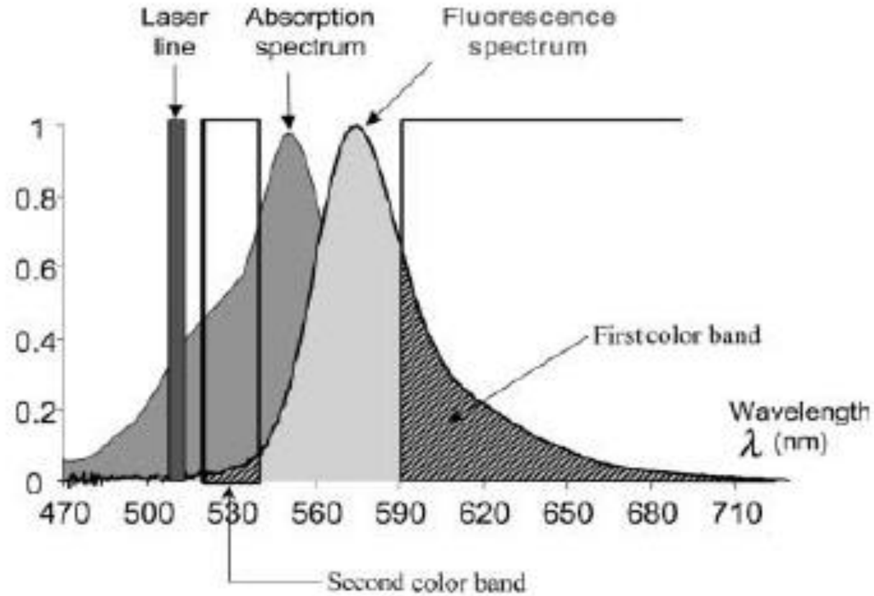
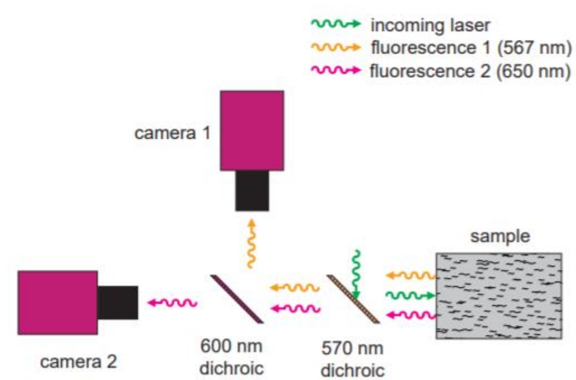


Fig. 1. Evolution of the rhodamine B fluorescence spectrum as a function of the temperature and distribution of the temperature sensitivity coefficient β as a function of the wavelength

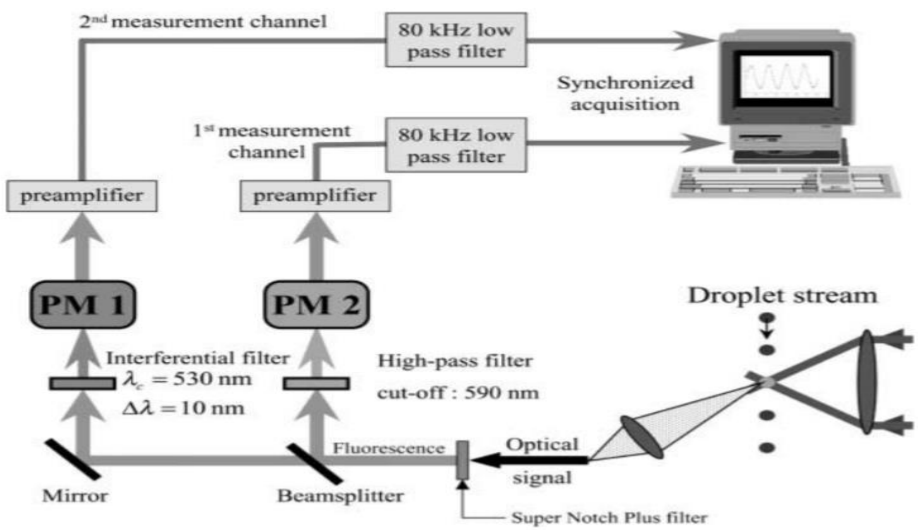


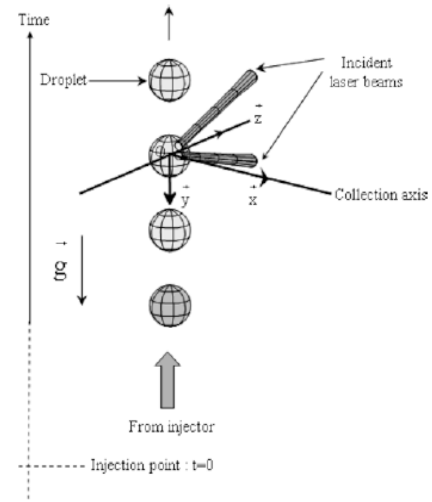
ig. 2. Sketch of the two selected spectral bands

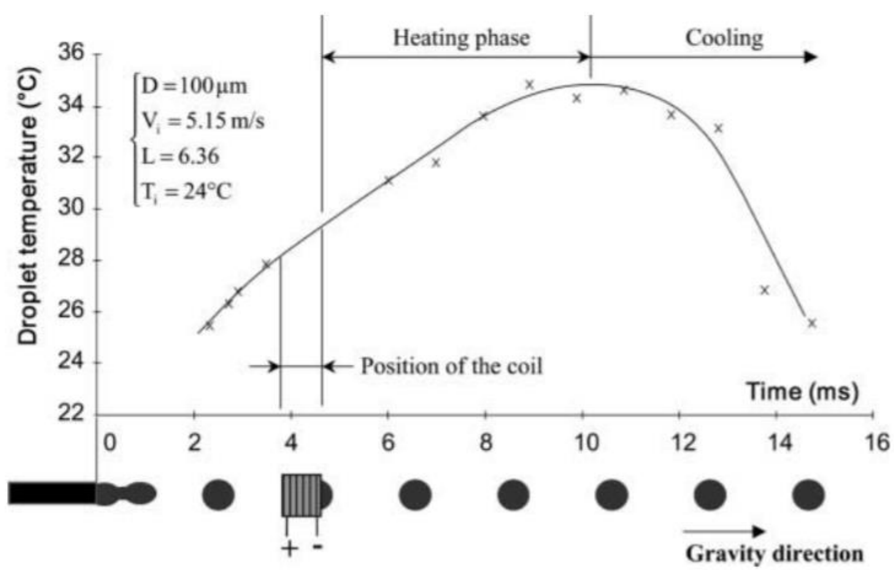


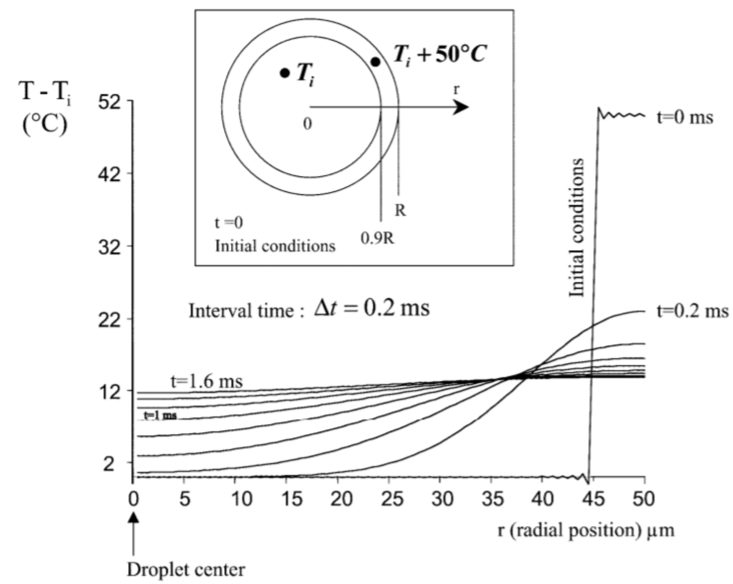
- *Lavieille, P., Lemoine, F., Lavergne, G. et al. Evaporating and combusting droplet temperature measurements using two-color laser-induced fluorescence. Experiments in Fluids **31,** 45–55 (2001).*

❑ Dual-Emission-Band LIF technique









- *Lavieille, P., Lemoine, F., Lavergne, G. et al. Evaporating and combusting droplet temperature measurements using two-color laser-induced fluorescence. Experiments in Fluids **31,** 45–55 (2001).*

❑ Dual-Emission-Band LIF technique

- *Advantage: single dye*
- *Disadvantage: Single level is weak;*

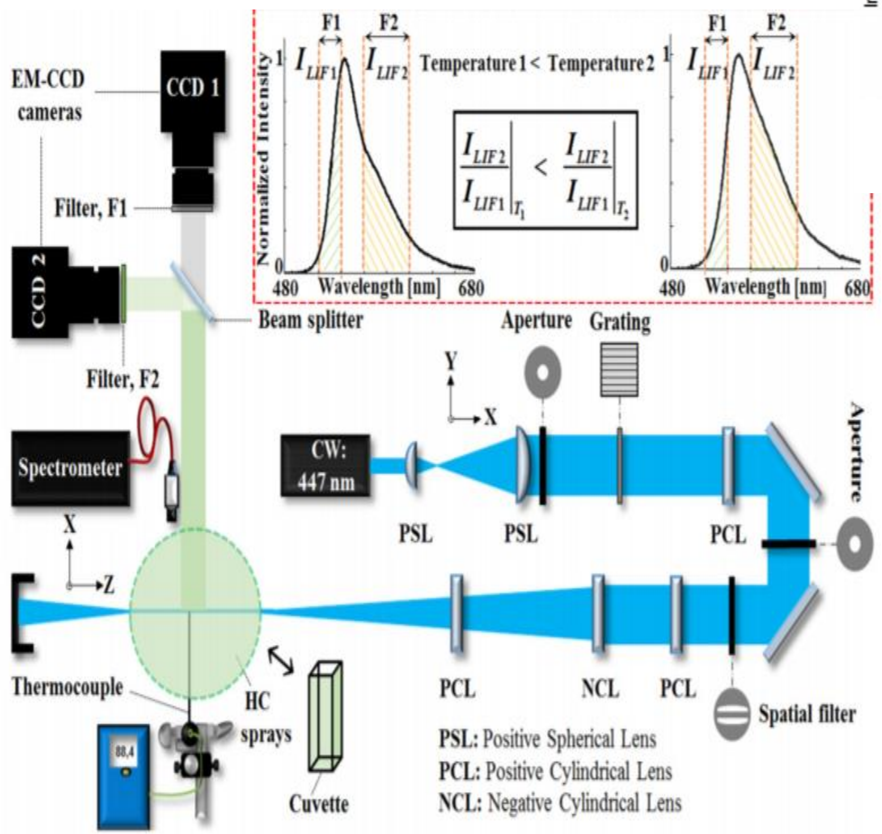


Fig. 5. Experimental setup of SLIPI two-color LIF ratio thermometry including all optical components. The dashed box (red) on the top right is an illustration of two-color LIF ratio thermometry principle.

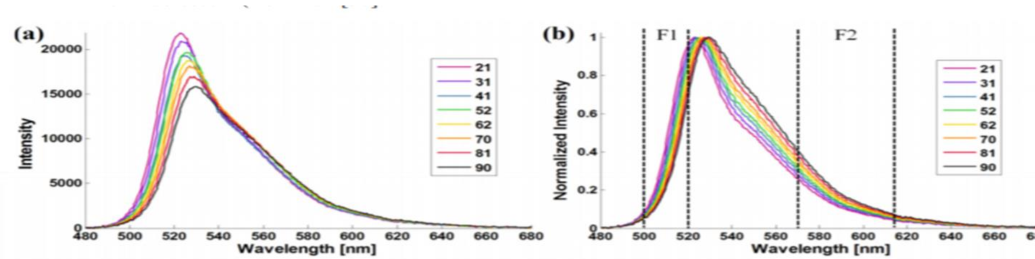


Fig. 3. Non-normalized in (a) and normalized in (b) LIF emission spectra of the Fluorescein dye at 447 nm excitation and for a temperature ranging between 21°C and 90°C: A change in LIF emission intensity and spectral shift are apparent. The spectral range of two selected optical filters (F1, F2), used for the LIF ratio (see section 3.2) is also indicated in (b).

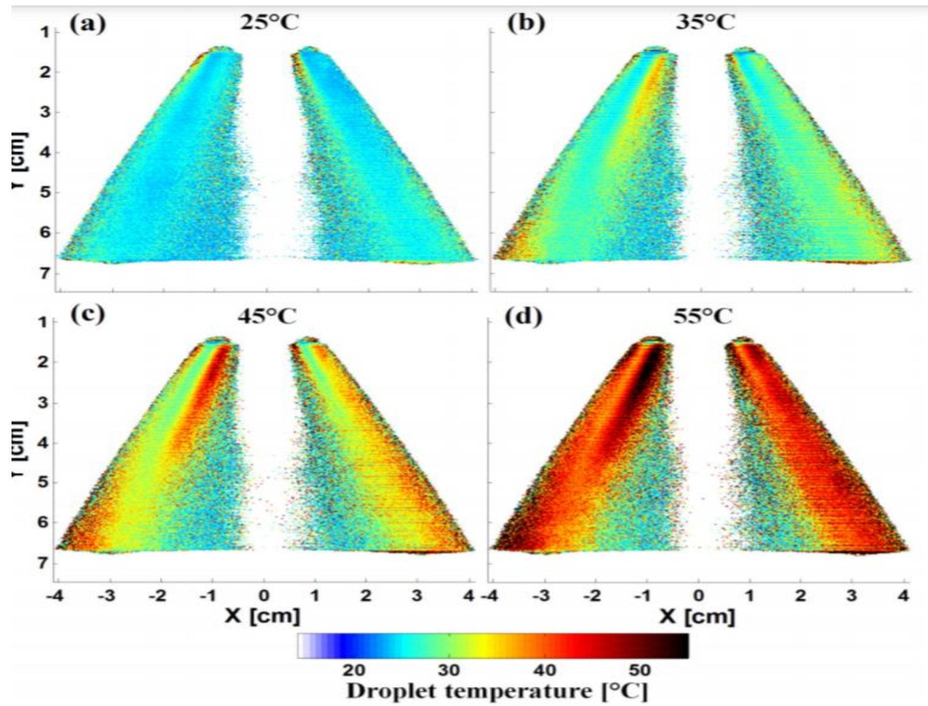


Fig. 13. Two-dimensional map of droplet temperature in a hollow-cone water spray at reference temperature varying between 25°C to 55°C. The spray cools down in its hollow region while the liquid located nearer to the nozzle orifice is hotter.

- *Yogeshwar Nath Mishra, Fahed Abou Nada, Stephanie Polster, Elias Kristensson, and Edouard Berrocal, "Thermometry in aqueous solutions and sprays using two-color LIF and structured illumination",Optics Express Vol. 24, Issue 5, pp. 4949-4963 (2016)*