Karlsruhe Institute of Technology

Institute of Environmental Sciences (iES)
University of Koblenz-Landau

# Measurement of surface-cooling induced gas-transfer using luminescence oxygen imaging technique


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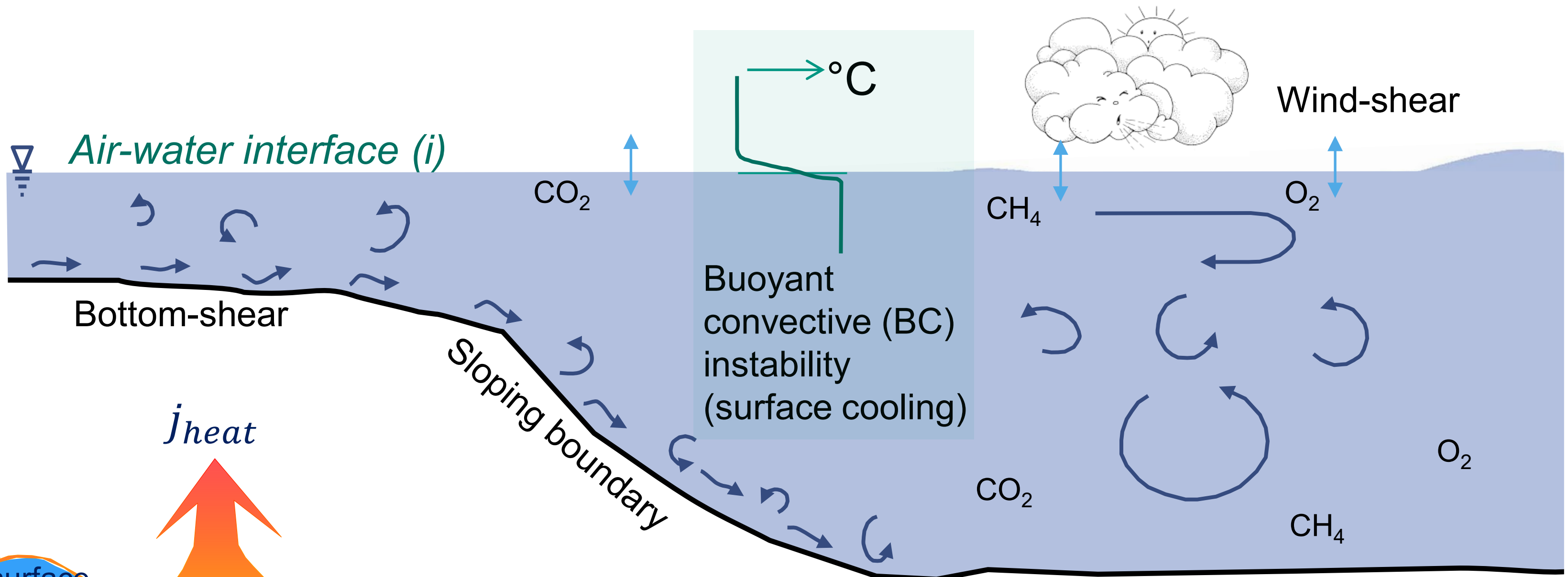
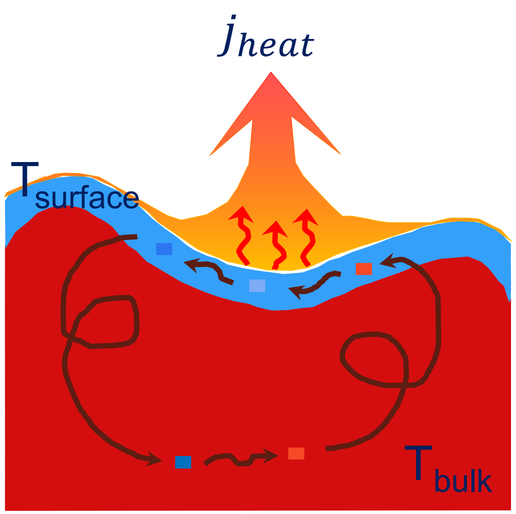
# Surface cooling induced gas transfer

$$\langle j \rangle = -\left[ D \frac{\partial \langle C \rangle}{\partial z} - \overline{w'C'} \right]$$

$$\langle j \rangle = k_L (C_i - \langle C_b \rangle)$$

$$k_L = f(wind\ speed)$$




$$k_L \cong u_* F S_c{}^n$$

$$k_L \cong \frac{D}{\delta_c}$$

$$\frac{k_h}{k_L} = \left( \frac{Sc}{Pr} \right)^n$$

**Imaging technique** as an important tool to study fundamental mechanisms of transport processes

# $O_2$ imaging applications in flowing waters

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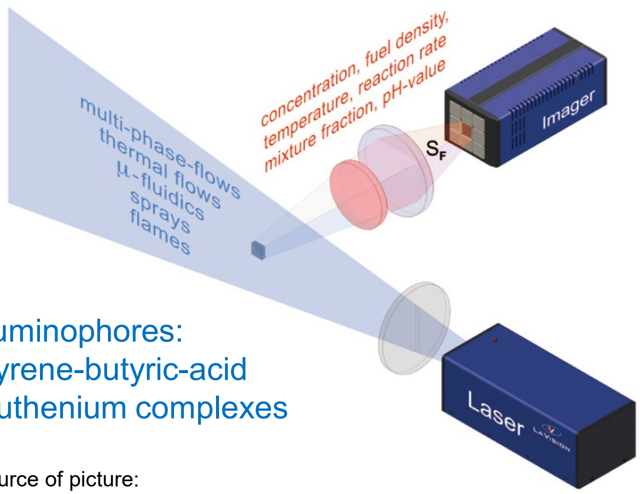
LIF apps. review in Crimaldi, J.P. (2008) and Rüttinger, et al. (2018)

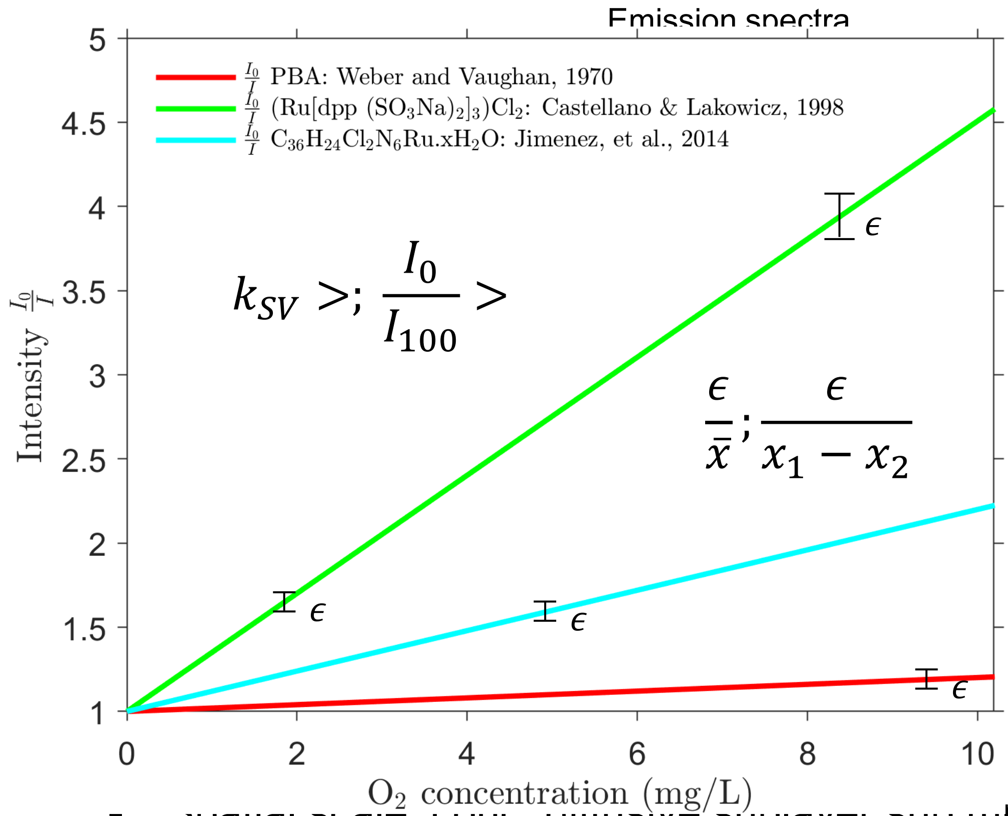
Applications: planar- (water surface) and curved-interface (bubble)

## Laser-induced Fluorescence (LIF)




Luminophores:
Pyrene-butyric-acid
Ruthenium complexes

Source of picture:
https://www.smart-piv.com/en/techniques/lif-plif/




- Spatial scale: conc. diffusive sublayer sub mm
- Time scale: ms - s

## $O_2$ quenching principle

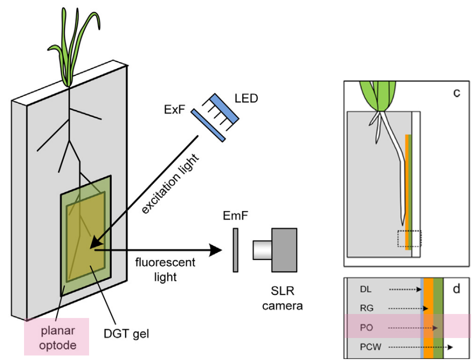
$$\frac{I_0}{I} = \frac{\tau_0}{\tau} = 1 + k_{SV}\ [O_2]$$

$k_{SV}$: Stern-Volmer constant

$I_0,\ \tau_0$: intensity, lifetime in the absence of $O_2$

# Luminescence $O_2$ imaging system

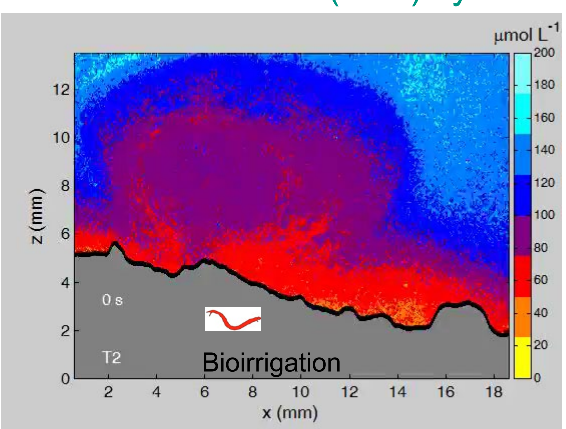
Planar optode
Optical $O_2$ sensor nano-(macro)particles




Luminophores:
Platinum/palladium-porphyrin complexes

Picture source: Santner, J., et al. 2015
Review: Moßhammer, et al., 2019

## Lifetime-based LIF (τLIF) system

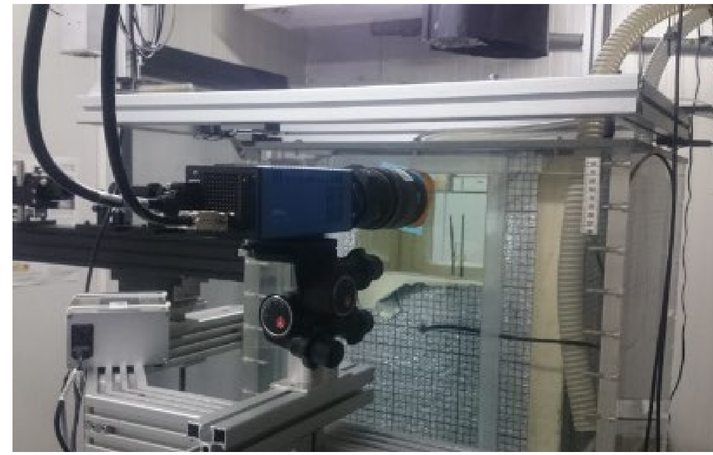



## Further development

4W 450 nm laser

11 μm/pixel

FOV: 13.2 × 17.6 mm



Integration time: 62.6 ms (160 ms)

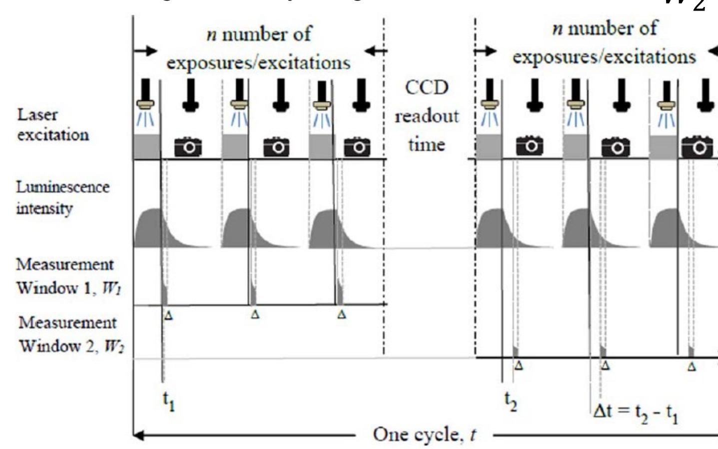
$$\tau = \frac{t_2 - t_1}{\ln \frac{W_1}{W_2}}$$

PtOEP + MY

Seeding conc.: 0.2% v/v

$O_2$ sensitivity: 5-7%

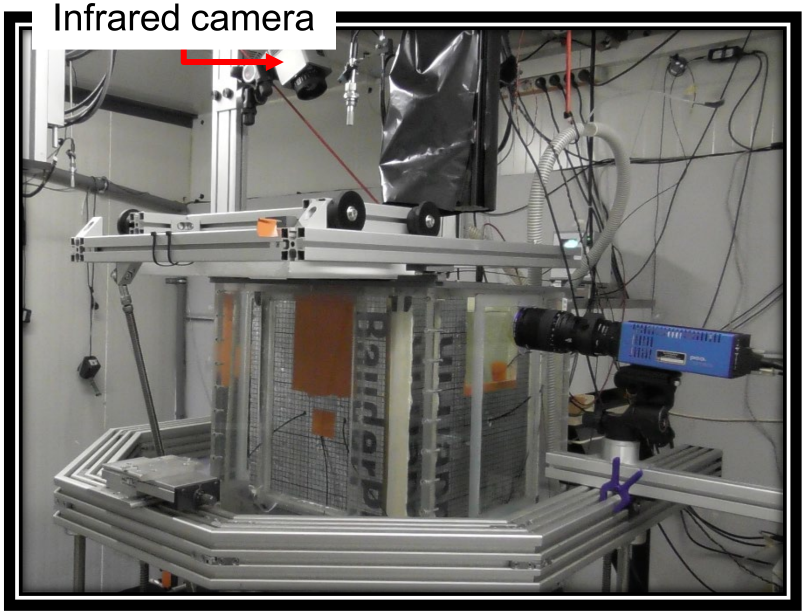
Integration time of single intensity image



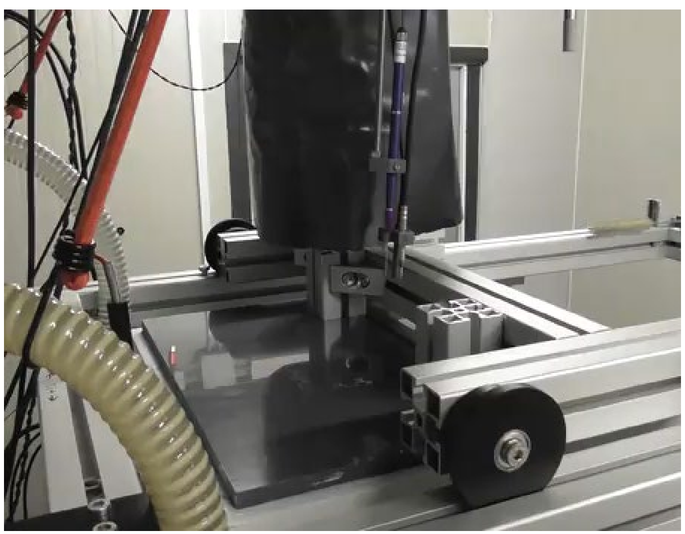

Integration time of single lifetime image

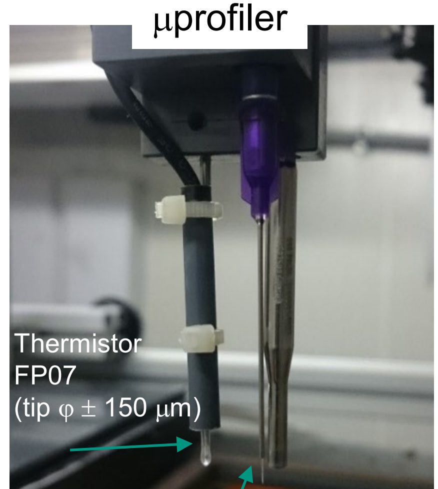
PtOEP: platinum(II)-octaetylporphyrin
MY: macrolex yellow → antenna dye

# Climate chamber facility

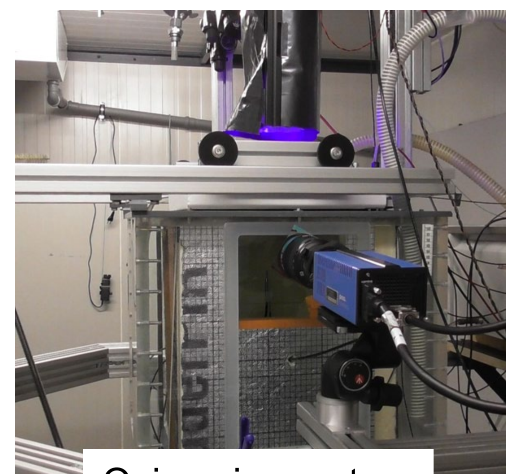



| Typical operation | | in nature |
|---|---|---|
| $T_{water}$ | 20…35°C (± 0.2) | …15 - 20°C… |
| $T_{air}$ | 5…20°C (± 0.5) | …+5°C - 25+°C |
| $\Delta T_{bulk}$ $(T_w - T_a)$ | 5…20°C | …+13°C… |
| *Ra* | $5 \ldots 27 \times 10^9$ | $10^{11}$ (lake) |
| *Sc* | 370…500 | 500 ($O_2$ 20°C) |
| *Pr* | 5…7 | 7 (water) |
| Heat flux | 70…350 $Wm^{-2}$ | -400…+400 $Wm^{-2}$ |






Fiber-optic $O_2$ sensor (tip φ ± 50 μm)



# $O_2$ imaging system validation and uncertainty

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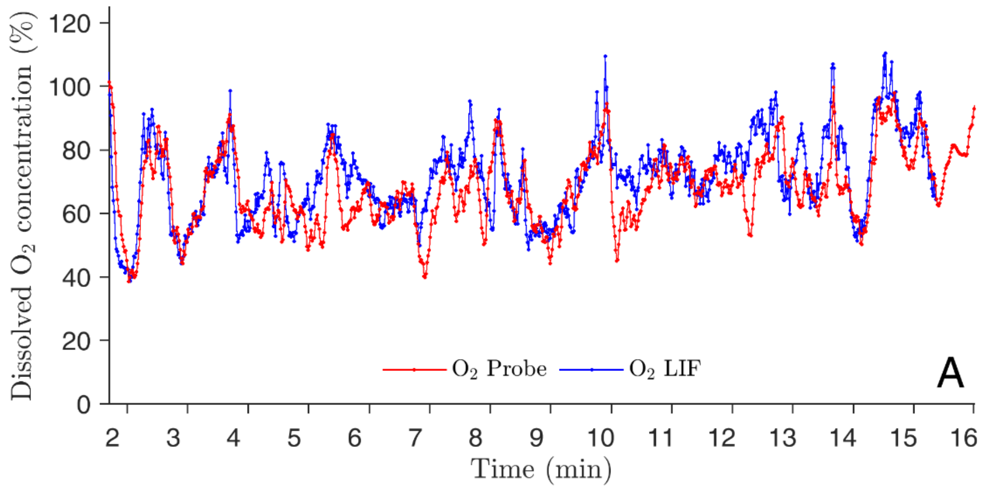
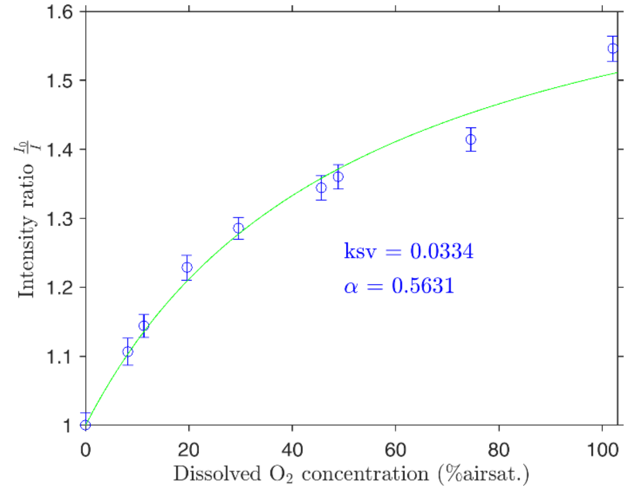
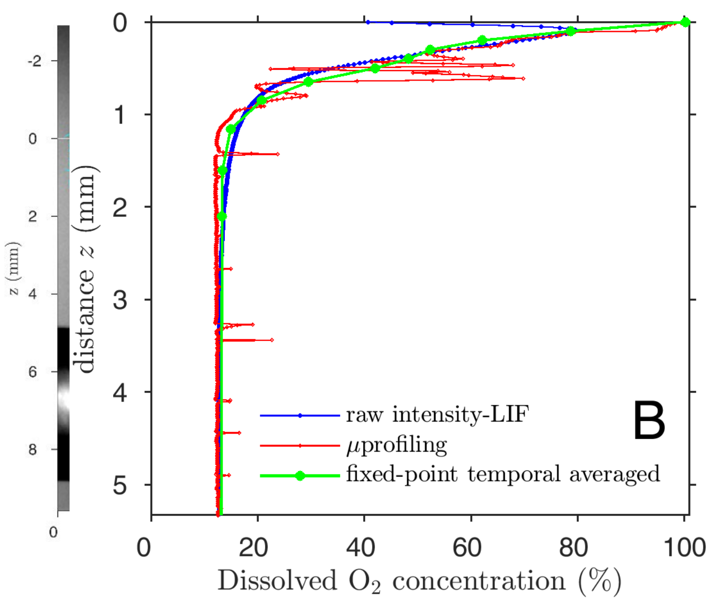


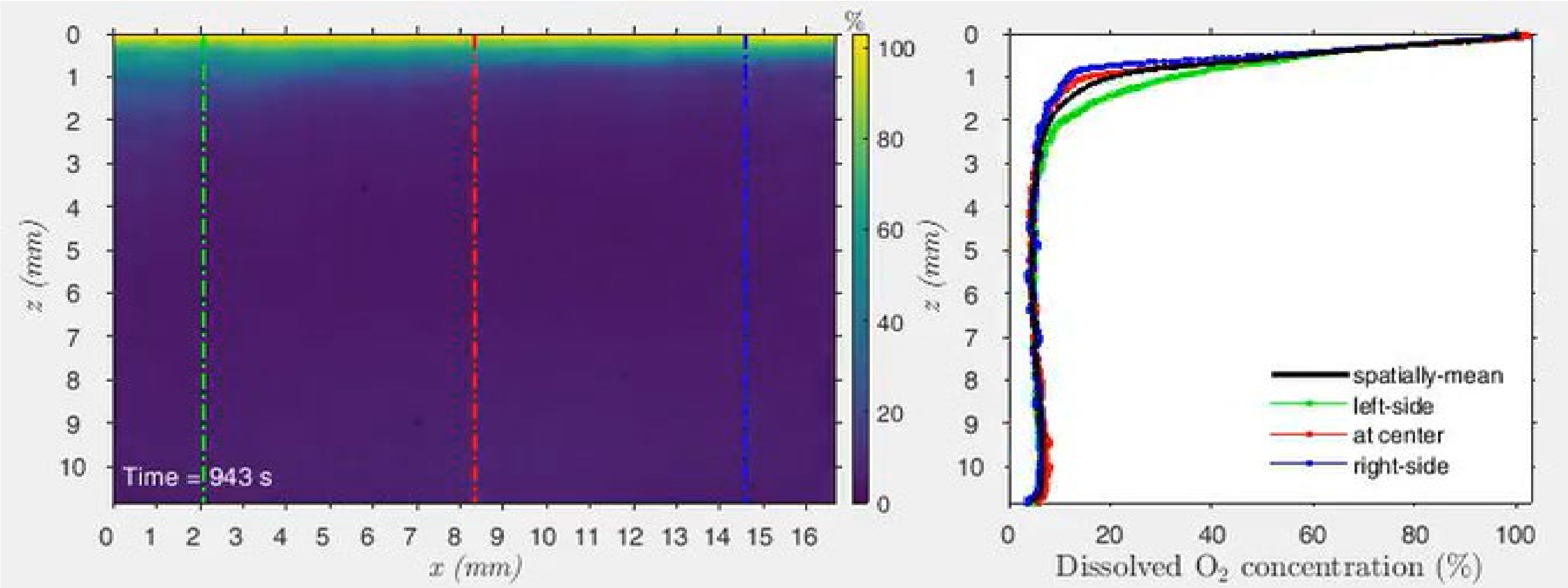




- Insitu calibration curve measurement
- Modified Stern-Volmer relationship
- $O_2$ sensitivity: 5-7%
- A good agreement with the point-wise $O_2$ sensor
- Optical distortion near interface <100 $\mu$m


IfH

# $O_2$ concentration dynamics



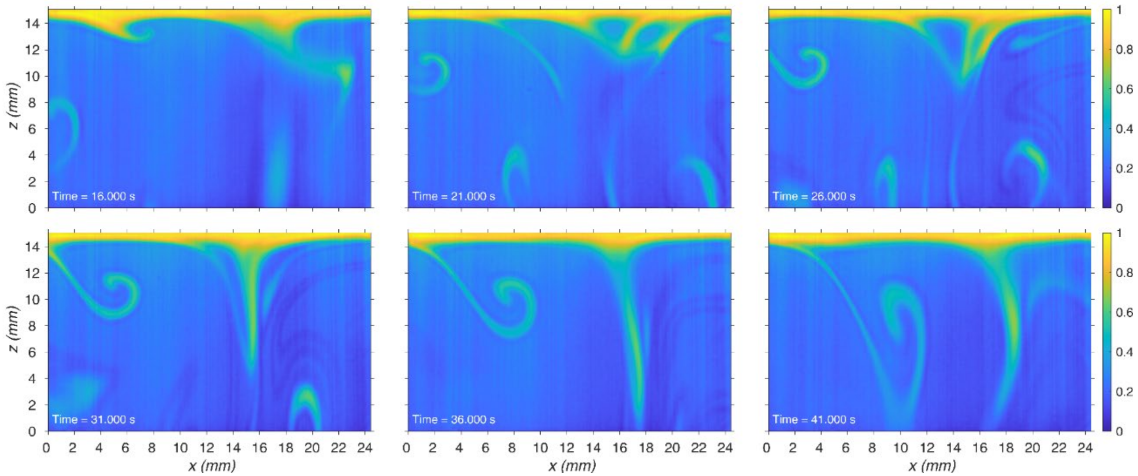

Experimental setup

$T_w = 22°C$, $T_a = 5°C$

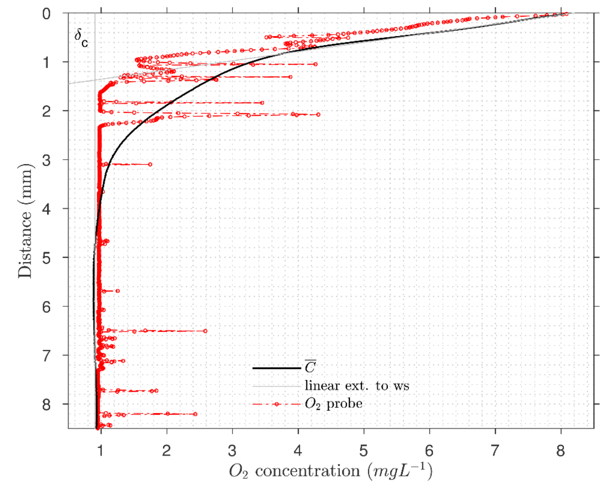
$Ra = 1.32 \times 10^{10}$,

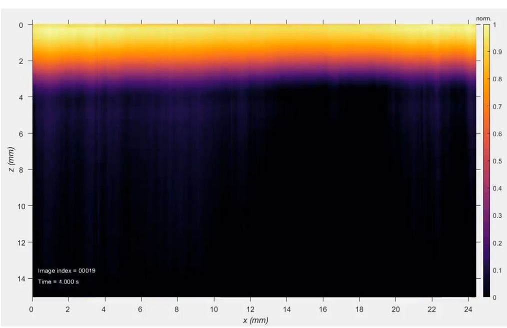
$Sc = 480$, $Pr = 6.6$

# Estimation of characteristic scales




Mean profile and gas flux $\langle \boldsymbol{j} \rangle$




Example velocity scale = ~1 mm/s

$$B = -\frac{g\alpha}{\rho C_p} q = -2.43 \times 10^{-8}\ \mathrm{m^2 s^{-3}}$$

$$w_* = (Bh)^{1/3} = 2.7\ \mathrm{mm\ s^{-1}}$$

$$k_L = \frac{D}{\delta_c}$$

$$k_L = 1.76 \times 10^{-4}\ \mathrm{cm/s}$$

Bulk measurement

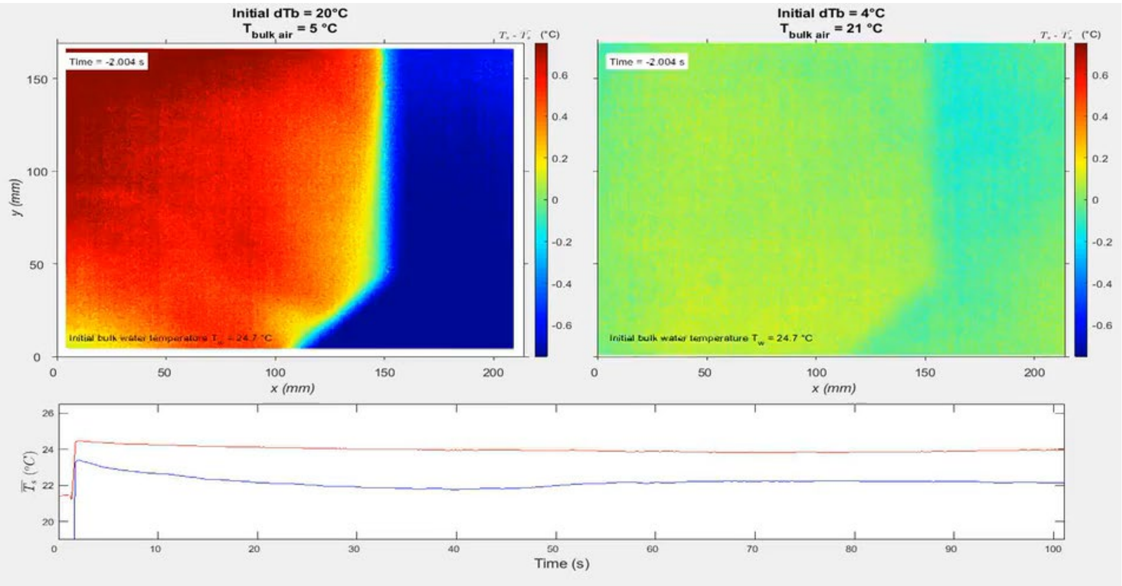
$$\left(\frac{k_L}{d}\right) t = ln\left(\frac{C_i - C_b}{C_i - C_{b\_init}}\right)$$

$$k_L = 2.56 \times 10^{-4}\ \mathrm{cm/s}$$

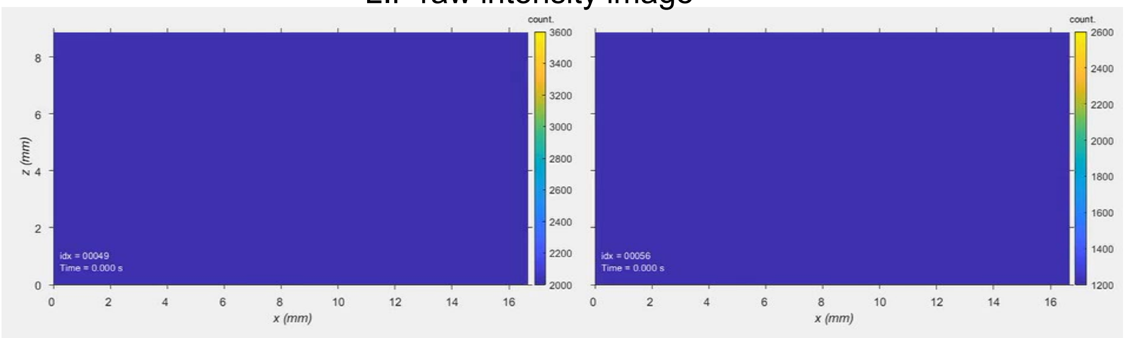
# $O_2$ conc. and surface temperature dynamics

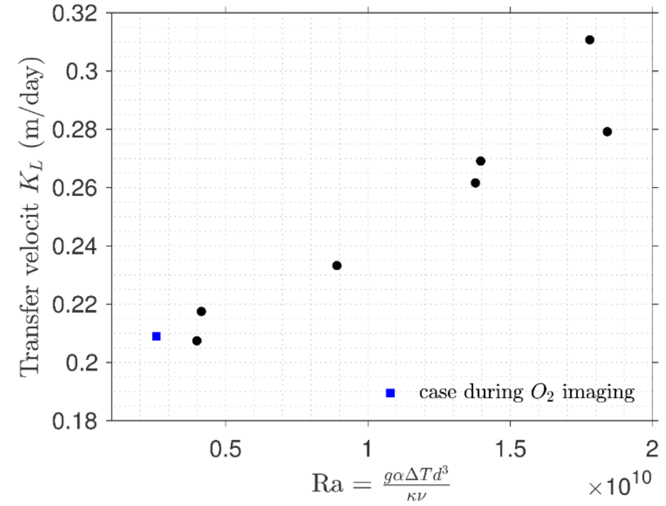
High heat flux | Low heat flux

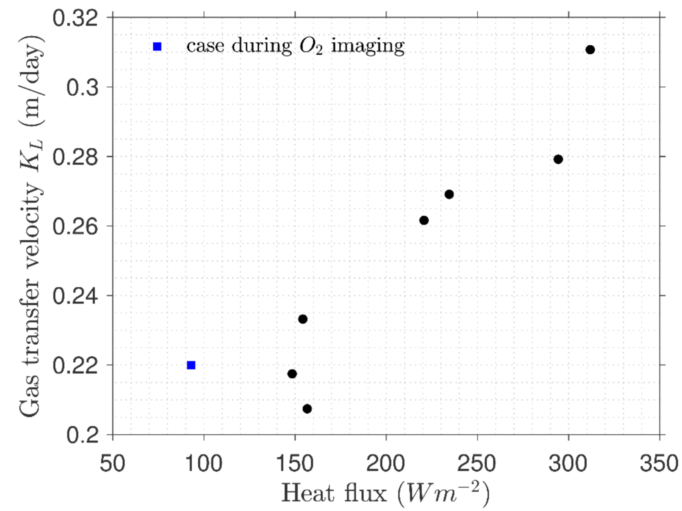
Surface temperature using infrared camera




LIF raw intensity image



# Summary

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- The current measurement setup allowed visualization of oxygen transfer dynamics
- The development of convection cells in the water surface was also observed
- Quantitative results obtained from the measurements are in good agreement with benchmark data
- Positive correlation of heat flux and gas transfer velocity

**Remarks:**

$O_2$ quantification based on lifetime method (requiring two intensity images separated by time $\Delta t$) was limited by CCD read-out time. To increase time resolution, one way would be by using two cameras simultaneously.

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## THANK YOU VERY MUCH

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