Visualizing dissolved oxygen concentration in groundwater flow with pressure sensitive paints (PSP)

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Introduction

Pressure sensitive paints (PSP) contain luminophores that fluoresce when excited with a specific wavelength of light. However, the higher energy state can be quenched in the presence of oxygen, reducing fluorescence intensity.

Using PSPs in underwater systems is a novel application that can be used to visualize the spatial heterogeneity of dissolved oxygen (DO) concentration in fluid flow. Through excitation with an LED, emission can be recorded with a charge-coupled device (CCD) camera with a low-pass filter to determine oxygen concentration (Fig. 1)

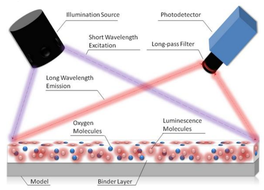

Figure 1: Experimental set-up for measuring PSP fluorescence (Credit: Ohio State University)

Purpose

Long term: To measure oxygen distributions in biofilms within sediment beds

Short term: To develop the experimental methodology for measuring oxygen concentration on the surface of a submerged PSP-coated plate by quantifying the intensity of emission

Procedure

Calibration Curve and Experiment

1. Submerge a horizontally mounted 2x2" PSP-coated thin aluminum plate in a water-filled tank
2. Measure the dissolved oxygen and illuminate the plate with an LED at a wavelength less than 530 nm
3. Record the fluorescence using a CCD camera
4. Decrease the DO level through incremental additions of sodium metabisulfite, a reducing agent, to the water
5. Repeat steps 3 and 4 until the DO level is near 0 mg/L to have a series of images of known oxygen concentrations

Image Analysis

6. Crop the images to an area most representative of the average intensity (no vignettes, minimal shadows) (Fig. 2)
7. Calculate the average intensity of each photo using MATLAB

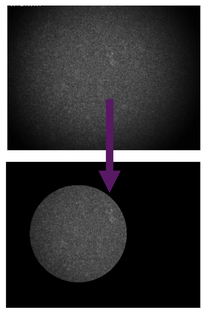

Figure 3: Cropping of photo to more representative area

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Results

Calibration curve: intensity vs. concentration

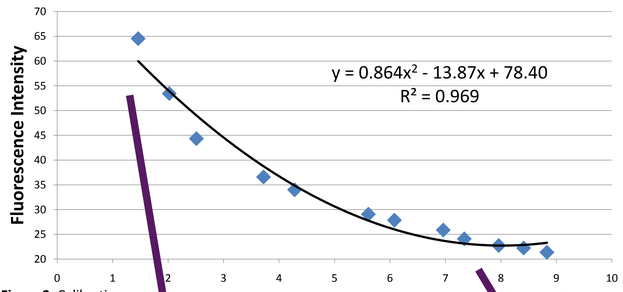

Figure 3: Calibration curve, intensity vs. concentration

Calibration Curve

The measured DO levels were matched to the average intensity values of the plate at that oxygen concentration. The values were then plotted to yield a second order polynomial. (Fig. 3)

As the concentration of oxygen increased, there was a lower intensity of emission, creating darker photos of pixel intensity (Fig. 4). This is also shown in the histograms– the mean intensity values decreased as the DO level increased (Fig. 5).

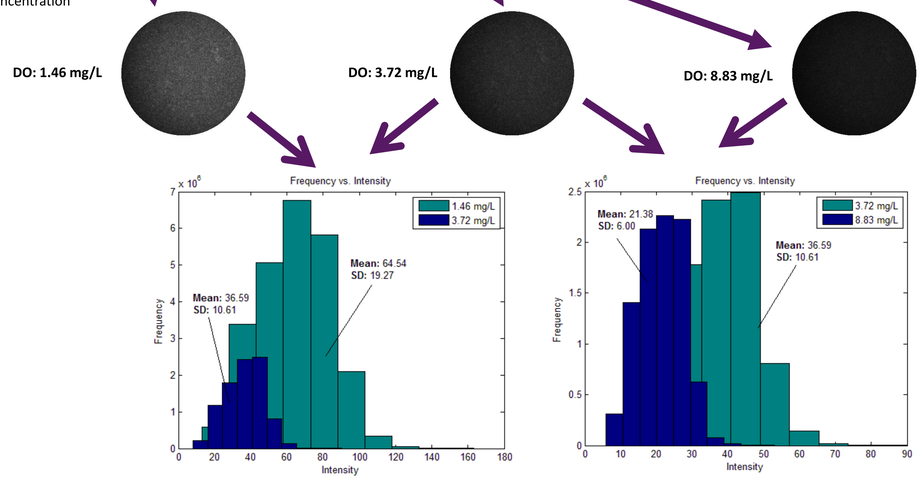

Figure 4: Cropped photos of PSP-coated plate at varying oxygen concentrations

Figure 5: Histograms of frequency vs. intensity at varying DO levels (1.46, 3.72, 8.83 mg/L)

Impingement of the PSP-coated plate with highly-oxygenated water

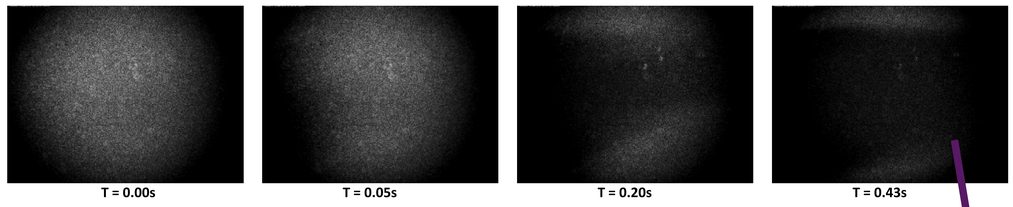

Figure 6: Frames from time lapse video showing surface impingement of oxygenated water

In three different trials, the plate was submerged in an oxygen-poor water environment (0.64 ± 0.27 mg/L). Oxygen-rich water (8.67 ± 0.11 mg/L) was pumped onto the surface of the plate at an oblique angle using a pipette.

In areas where the oxygen-rich water hit the surface of the plate, the recorded images showed reduced fluorescence. A time lapse series of photographs were taken to illustrate the fluid flow via reduced emission intensity (Fig. 6).

The best-fit line from Fig. 3 was used to approximate the oxygen concentration through using the recorded fluorescence intensity values to solve for the unknown concentration (Fig. 7).

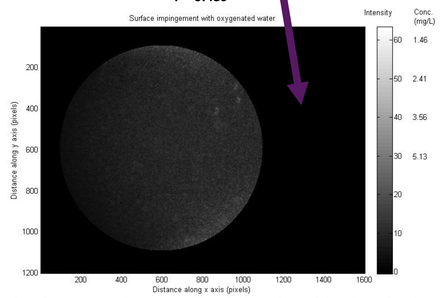

Figure 7: After the oxygen-rich water impinged the surface of the plate, the plate demonstrated decreased fluorescence compared to T=0. In this image, the affected region was cropped to the most representative area . The oxygen concentration at each point can be visualized using the color bar showing fluorescence intensity and oxygen concentration.

Pixel-by-Pixel Calibration Curve

To give a more accurate representation of the dissolved oxygen's spatial heterogeneity, this method was then improved to yield a calibration curve for each pixel. This takes into account differences in fluorescence that may stem from different paint thicknesses and lighting angle. Below are example calibration curves for three coordinates. Their differences illustrate how at different locations, there are different concentrations of DO.

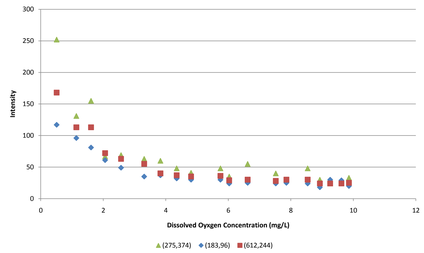

Figure 8: Calibration curve, intensity vs. concentration for three sample coordinates

Conclusion

In this experiment, it was found that the amount of dissolved oxygen could be related to emission intensity through exciting PSP molecules with an LED light and recording it with a CCD camera. The intensity decreased as a function of the oxygen concentration in the form of a second order polynomial.

Future Work

To better represent a groundwater system, a 2.5 flume of moving water will be used instead of a flat plate (Fig. 9).

Figure 9: Laboratory flume filled with PVC balls to model groundwater flow

PVC spheres will be painted with PSP to model sediment. Similar to before, calibration curves will determine unknown DO concentrations (Fig. 10). Later tests will add further complexity by adding biofilm to the system.

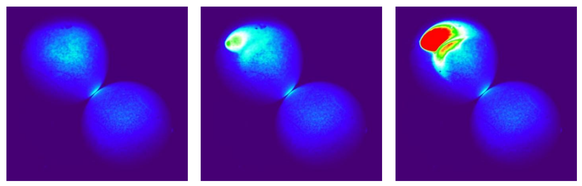

Figure 10: Time series images of oxygen-poor water impingement onto 1-in diameter PVC PSP-coated spheres in oxygen-rich water

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