Culturing Microalgae in Photobioreactors: Advanced Modeling and Experimentation

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Airlift Photobioreactors (PBR) for Microalgal/Cyanobacteria Cultures

Microalgal/Cyanobacteria are cultured in closed photobioreactors for:

- **High value products**
  - Health supplemental (i.e., Polyunsaturated Fatty Acids, Vitamins, Omega-3 Fatty Acids, …)
  - Biologically active substances (antiviral, antifungal)
  - Pigments (food color, fluorescent detection reagents, immunoassays)
  - Single Cell Protein (human, livestock)
- **Renewable energy**
  - Methane, biodiesel, ethanol or hydrogen
- **Wastewater and animal wastes treatment**
- **CO_2 Fixation**
- **Etc.**

Advantages of airlift reactors:

- Desired mixing rate
- Fair volume based production
- High photosynthetic efficiency
- etc.

Photobioreactors (PBR) – Problem Description

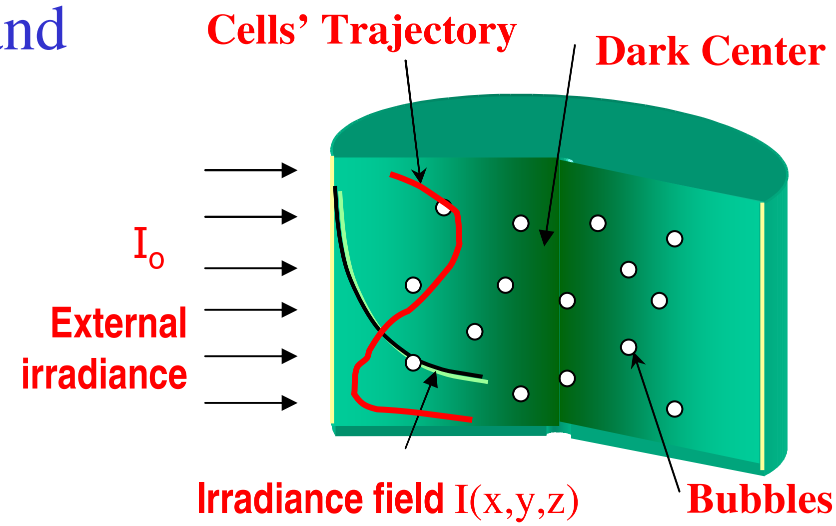
The major problem is light: its availability and its use efficiency

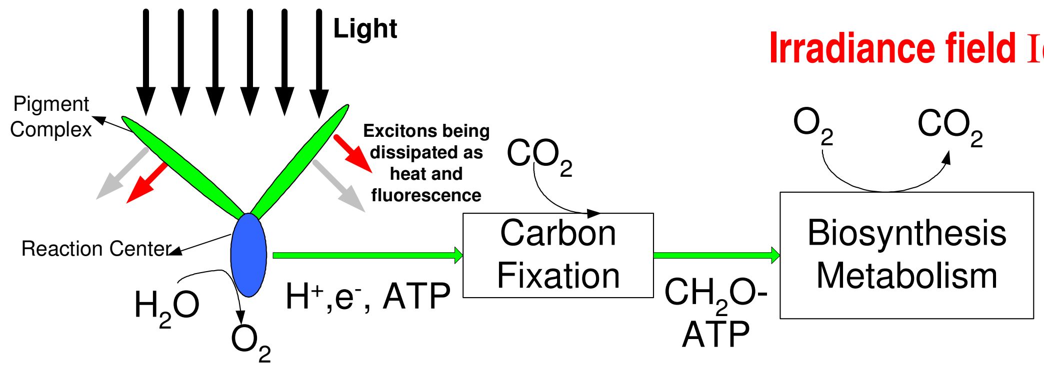
Photolimitation

+

Photoinhibition

light intensity gradient in a photobioreactor (PBR)





Cells' growth responds to the light history. Mixing, which induces the beneficial flashlight effects, can significantly enhance productivity

Hydrodynamics Affect:

- Cells' Movements → Light accessibility to the cells
- Liquid and Gas flow field → Cells' movements, light history
- Shear Stress → High shear stress damages the cells
- Mass Transfer → Access to the nutrient and remove O_2
- Concentration Distribution → Light intensity distribution inside the reactor

In-depth knowledge of hydrodynamics/flow pattern in the bioreactors is the key for design and scale-up. Advanced diagnostic techniques to characterize the local phenomena of the hydrodynamics are required

However, the current modeling approach relies on static growth rate using the light availability on volume-averaged base (I^v_{av})

Example: Molina Grima et al., 1997

$$\mu = \frac{\mu_{max} I_{av}^n}{I_k^n + I_{av}^n} - m \qquad \begin{cases} n = n_2 + n_3 / I_0 \\ I_k = I_k' + \left(\frac{I_0}{K_I}\right)^{n_1} \end{cases}$$

Objectives

- To advance the understanding of the hydrodynamics role in culturing microalgae and in photobioreactor performance
- To develop a fundamental modeling approach for the growth of microaglae in photobioreactors for proper performance evaluation, design, and scale-up

These can be achieved by:

- Using advanced measurement techniques (CARPT and CT) to investigate in details the hydrodynamics in an draft tube column reactor
- Analyzing and characterizing the interactions between hydrodynamics and photosynthesis
- Developing and evaluating a new modeling approach that integrates the first principles of photosynthesis, hydrodynamics, and irradiance distributions in the reactor
- Assess CFD modeling to obtain the needed hydrodynamics information for PBR analysis – a more accessible method for in-depth flow dynamic information

A New Approach for PBR Analysis and Modeling

Experimental Techniques: CARPT and CT- → Verification → **CFD Simulation?**

Local multiphase flow dynamics:
- **Microorganism cells' movements (*x(t), y(t), z(t)*)**
- **Liquid flow dynamics (Velocity profile, Turbulent intensity, Shear Stresses, Macro-mixing, etc.)**
- **Local phase distributions**

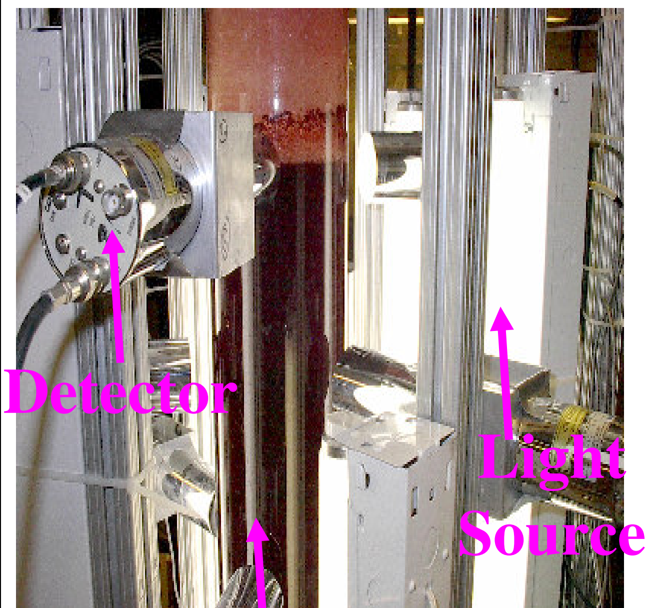
Modeling Irradiance Distribution, I (x, y, z)

- **Calculation of the temporal irradiance patterns, I(t)**
- **Characterization of the interactions between hydrodynamics and Photosynthesis**

Dynamic Photosynthetic Rate Model → **Fundamentally based modeling approach for PBR performance evaluation, design, scale-up, and process intensification** ← **Model Evaluation by Real Culturing Experiments**

CARPT Technique

Computer Automated Radioactive Particle Tracking (CARPT) – Simulating the cells/liquid elements' movement by a radioactive particle

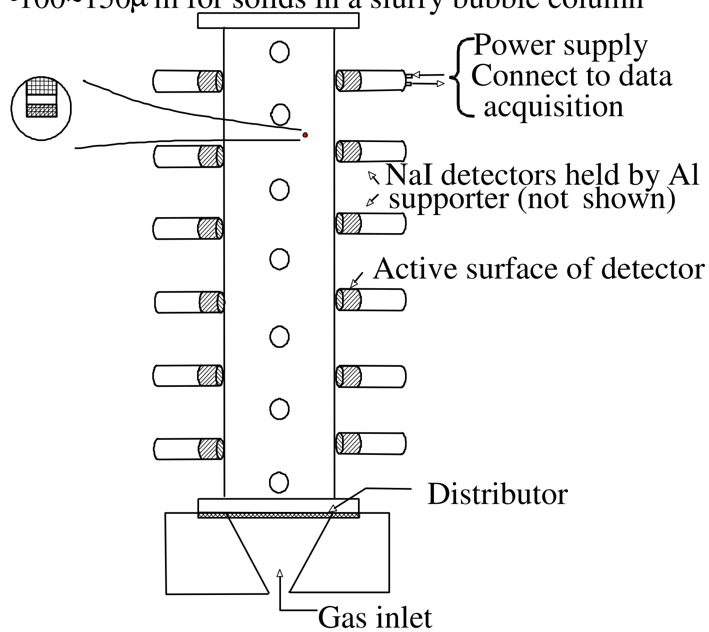


Reactor with algae inside

Radioactive Scandium

(Sc 46, 250μCi, emitting γrays)

- embedded in 0.8~2.3 mm polypropylene particle (neutrally buoyant with liquid)
- 100~150μ m for solids in a slurry bubble column



Example of Bubble column

Data Processing of Radiation Intensity Received by **N Detectors from a Single** Radioactive Sc-46 Particle

Intensity "I" for N detectors (Photon counts)

↓ Calibration curves "I vs. D (distance)"

Distance "D" from Particle to N detectors

↓ Weighted least square regression

Particle Position Px,y,z (t)

↓ Filtering noise due to statistical fluctuation of **γ rays** using Wavelet Analysis

Filtered Particle position Px,y,z(t), cells' movement

↓

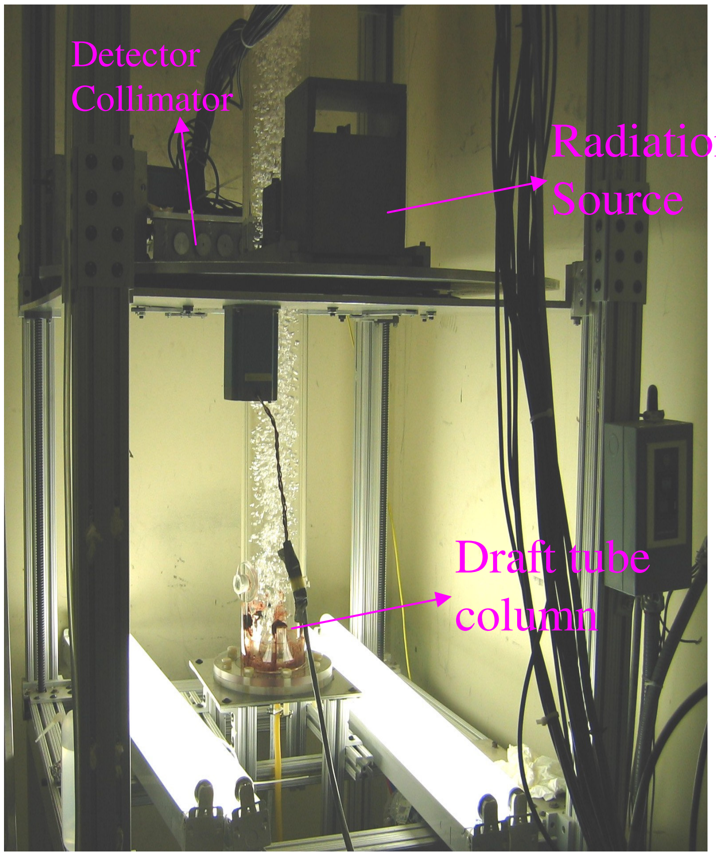
Instantaneous Lagrangian Velocities

↓

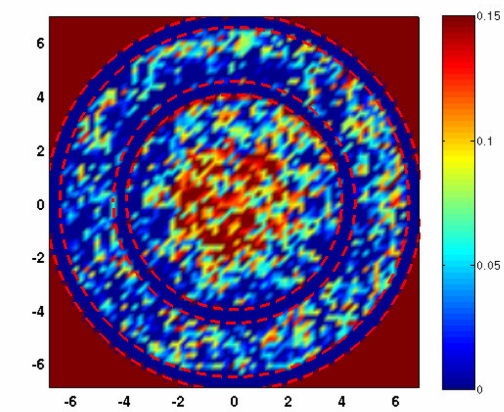
Time Averaged velocities & Turbulence Parameters

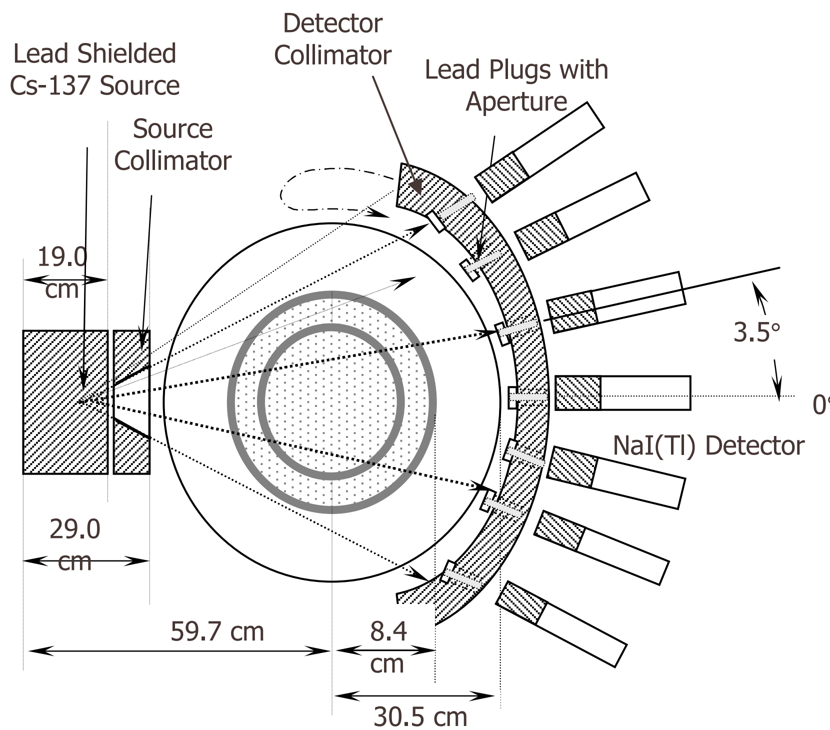
CT Technique

Computed Tomography (CT) – Seeing through the reactor for phase distributions



- Measurement of time-averaged cross-sectional phase holdup (volume fraction) distribution
- Estimation-Maximization (EM) algorithm used for image reconstruction





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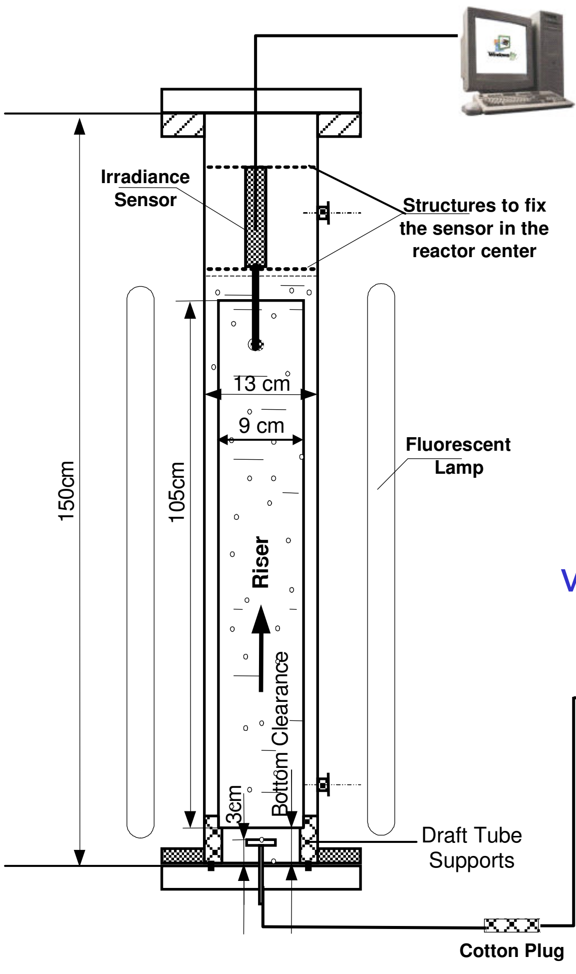
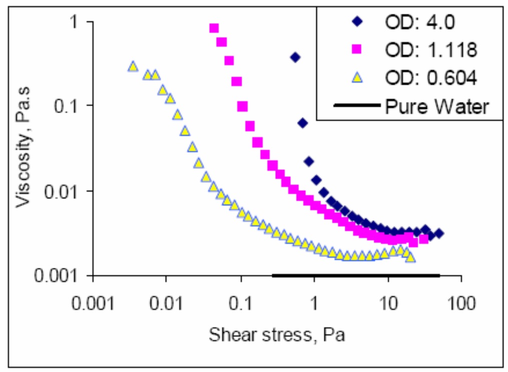
Reactor Conditions for CARPT &CT Experiments with/without Culturing Microalgae

Draft Tube Column





Profile of apparent viscosity versus shear stress at different biomass concentration

Experimental Procedure

- Initially OD<0.01 (12 hrs) and Ug = 0.3cm/s
- Turn on Four Lamps (275 $\mu E/m^2\ s$)
- Turn on All Lamps (1850 $\mu E/m^2\ s$) @ OD=1.0
- Ug=1cm/s

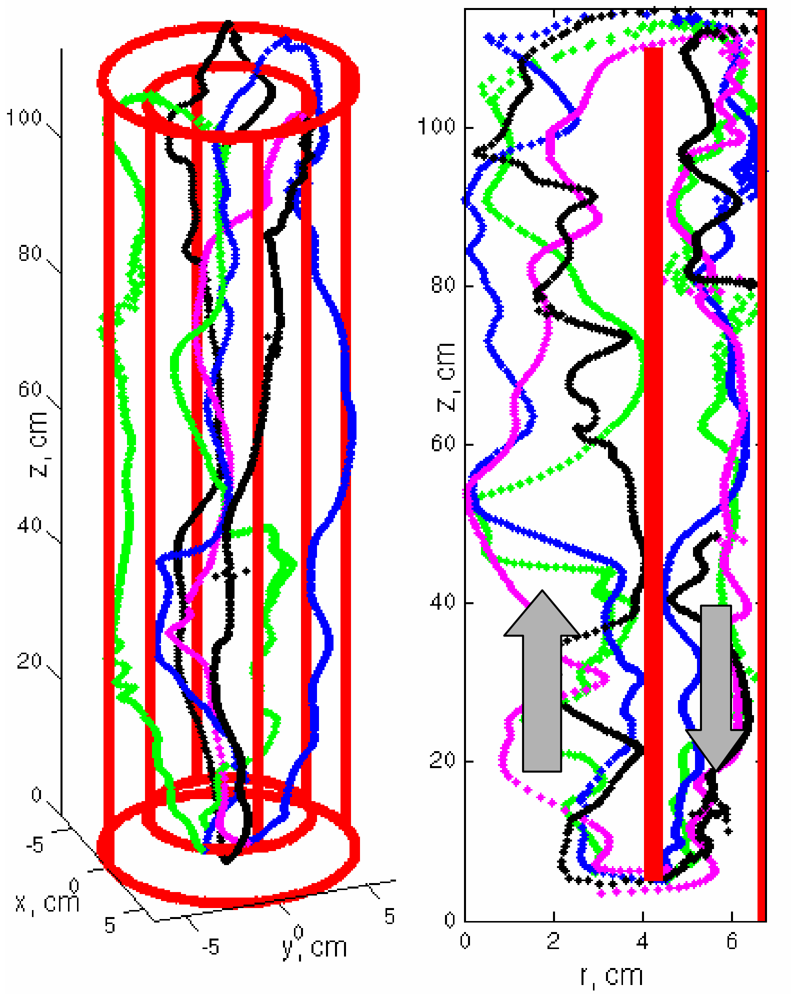
Biomass Concentration Analysis

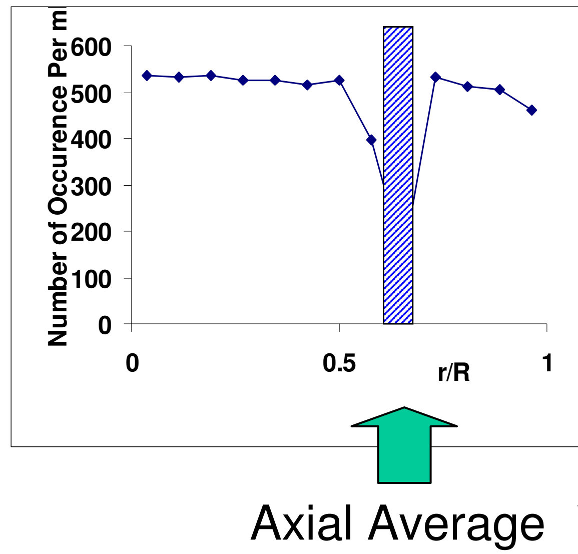
- Dry biomass weight, *g/L*
- Optical Density (OD) (Spectrometer)
- Cell No., Initial No.=10^6 *cell/ml*
- Chlorophyll a concentration, *mg/ml*

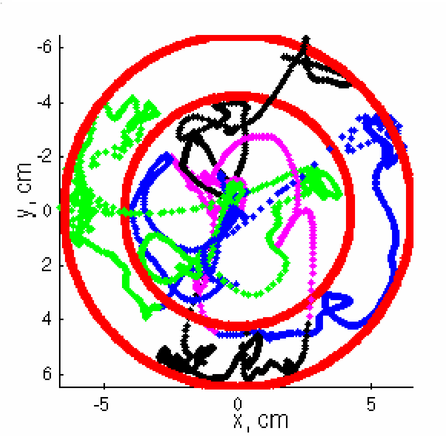
CARPT & CT Operating conditions with microalgae and air-water systems

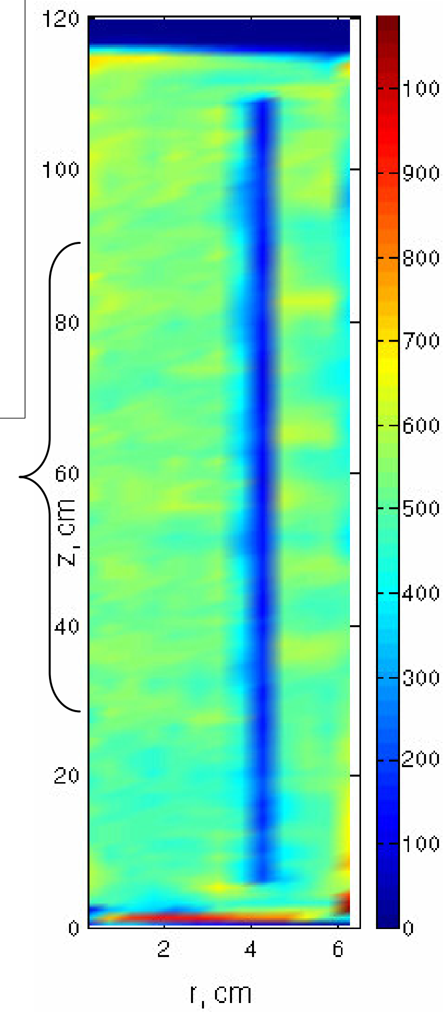
- Optical Density (OD) = 0.2 ~ 0.6
- Ambient condition
- Microalgae culturing / Air-water
- Top clearance: 3cm / 0, 3, 6 cm
- Bottom clearance: 5cm / 2, 5 cm
- Ug=0.3 and 1cm/s / 0.076, 0.3, 0.82, 1 and 5 cm/s

Particle Trajectories and Ergodicity





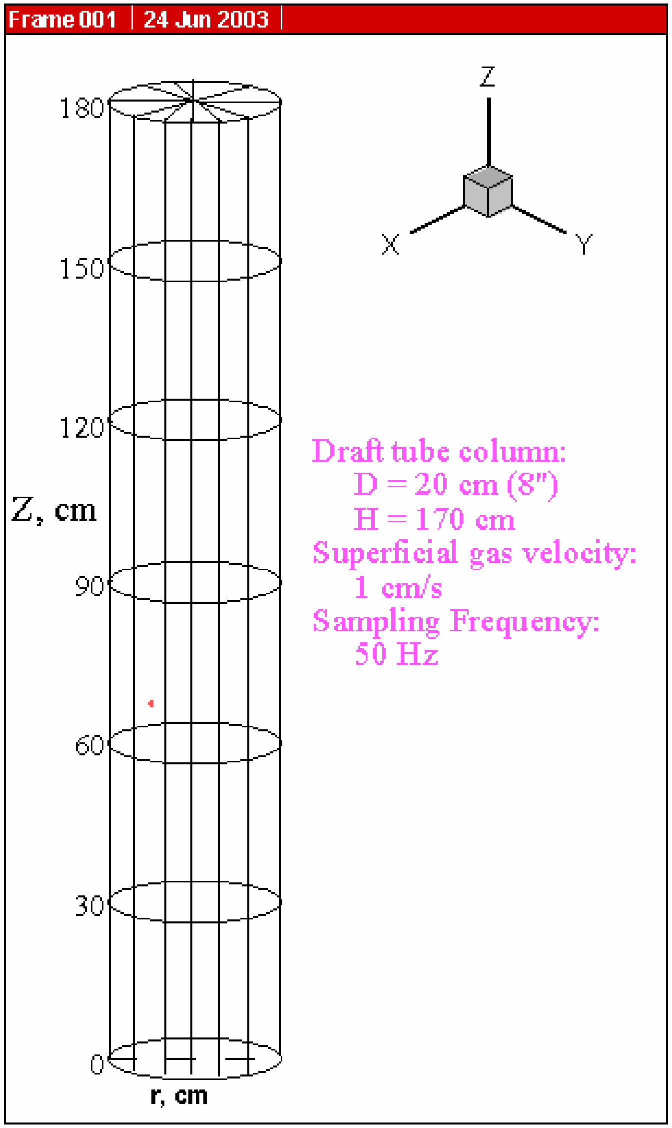




Typical Tracer Particle Trajectories

Number of Occurrence Per *ml*

Photobioreactor Analysis IV – Particle (Cell) Tracking



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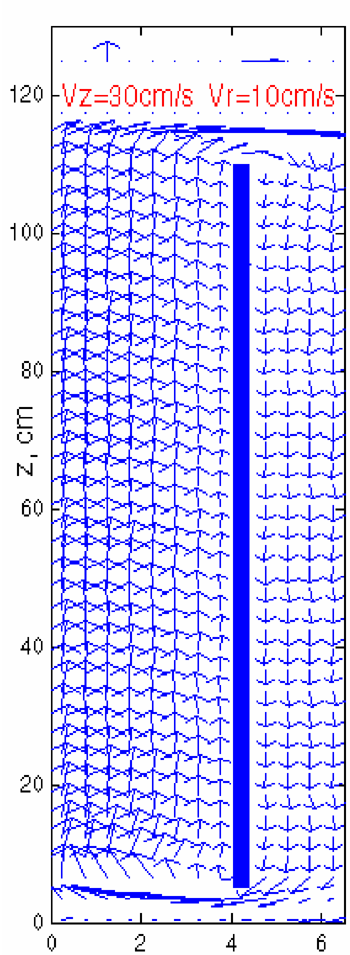
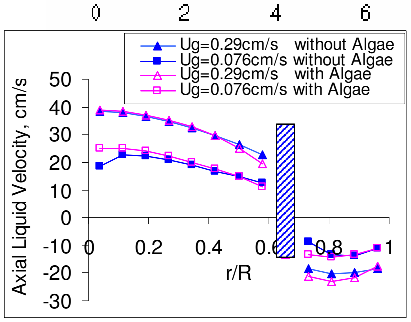
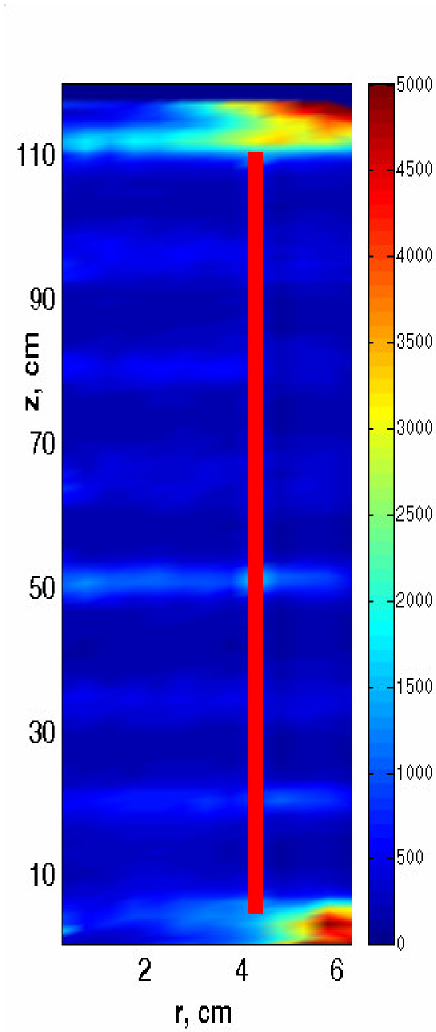
Multiphase Flow Field

Ug = 1 cm/s
Bottom Clearance: 5cm
Top Clearance: 3cm
Without Mocroalgae

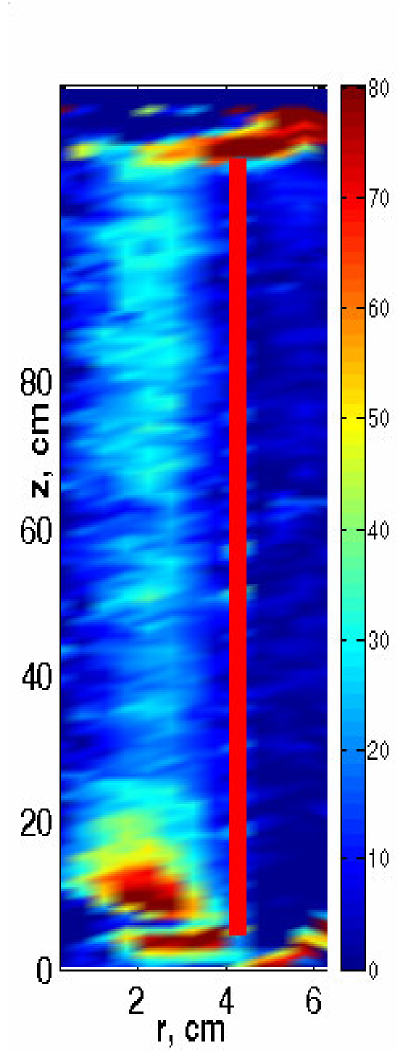




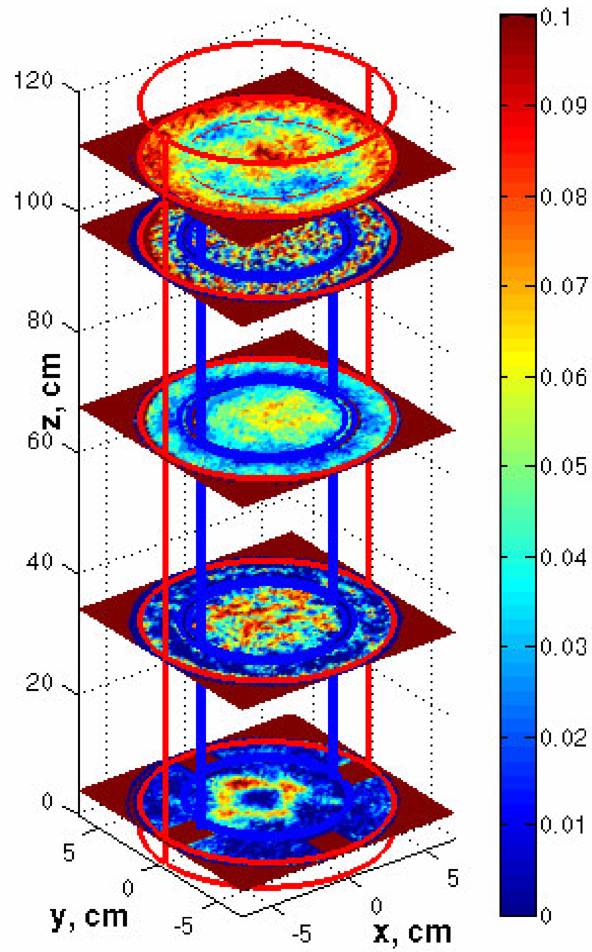
Axial liquid velocity



Visualization of the Turbulent Kinetic Energies (TKE)



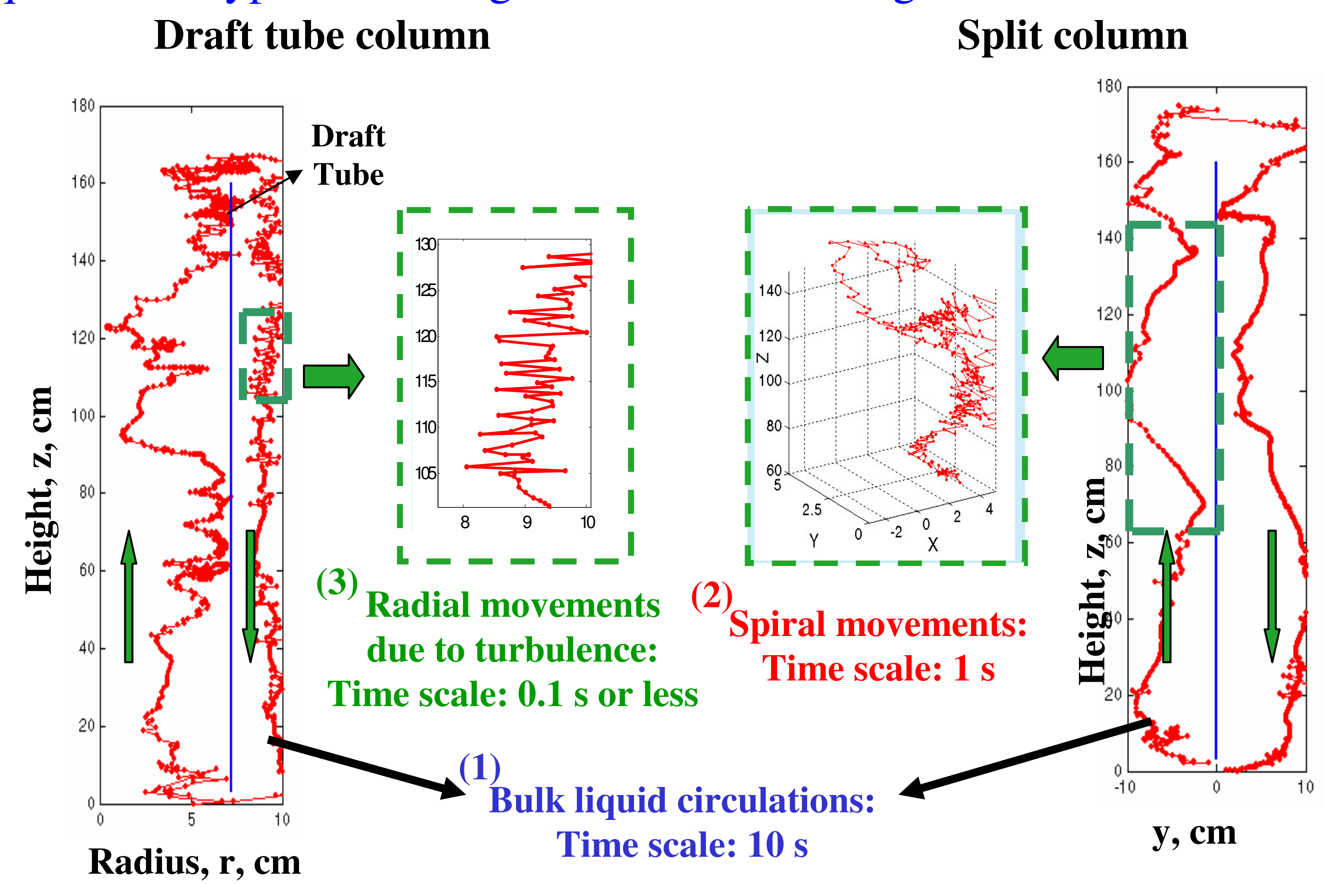
$$\tau_{rz} = \overline{u_r' u_z'}$$



Local gas holdup

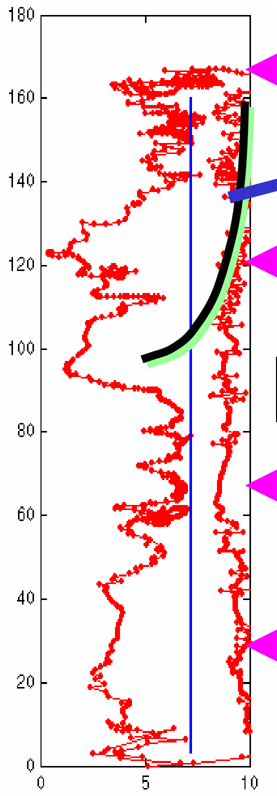
CARPT Results — Cell's trajectories

Three types of mixing mechanisms have been identified in airlift photobioreactors via CARPT technique. These types of mixing induce beneficial light fluctuations delivered to the cells.



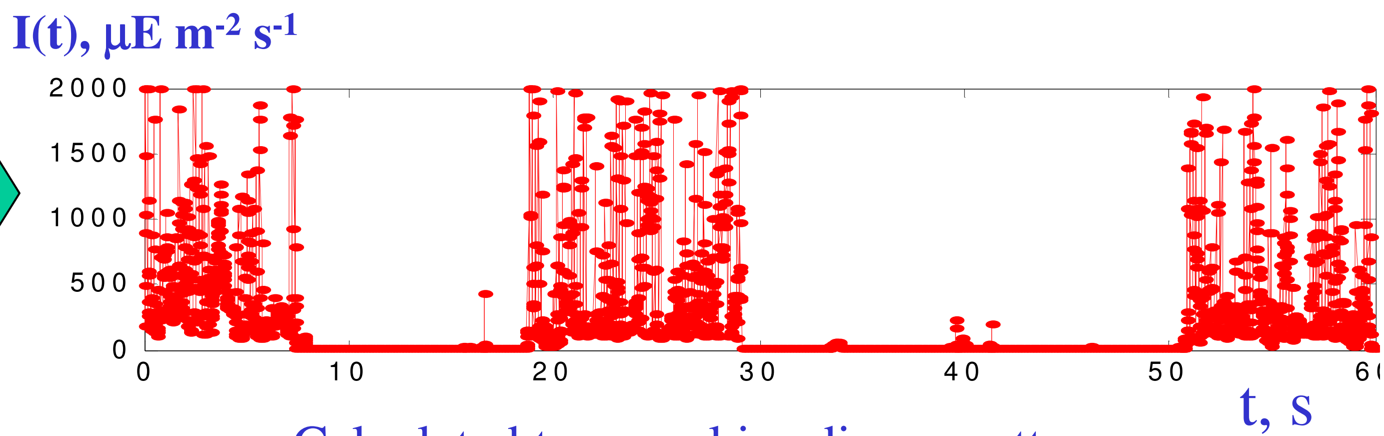
Time and length scales show overlapping and interaction between flow dynamics and photosynthesis.

Photobioreactor Analysis I – Light History



Lambert-Beer Law:

$$I = I_0 \cdot \exp[-(k_x \cdot x + k_w) \cdot d] \quad \text{(Evers, 1991)}$$



Calculated temporal irradiance pattern

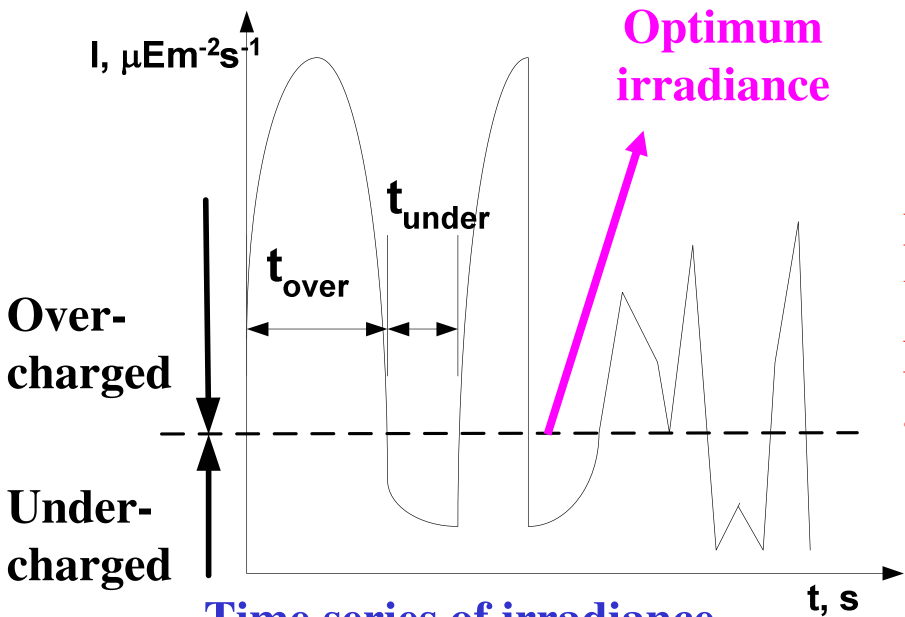
(**Calculation conditions:** I_0=2000$\mu E\ m^{-2} s^{-1}$, x = 80×10^6 *cells/ml*)

How to Characterize this process for reactor design, scale-up, and performance prediction ?

Photobioreactor Analysis I – Characterizing Light History

Characteristic Parameters

Over-/Under charged cycles in chaotic temporal irradiance pattern



Time series of irradiance experienced by the cells

Light Fluctuation Parameters:

- Time-averaged light intensity (Quantity of light transferred to the cells)

$$I_{av}^{t} = \frac{1}{T}\int_{0}^{T} I(t)dt$$

I^{t}_{av}=90 μE m^{-2} s^{-1}, I^{v}_{av}=164 irrespective of gas velocity and configuration)

For Ug=1cm/s, high irradiance (2000 μEm^{-2} s^{-1}) and cell concentration (80*10^{6} cells/ml)

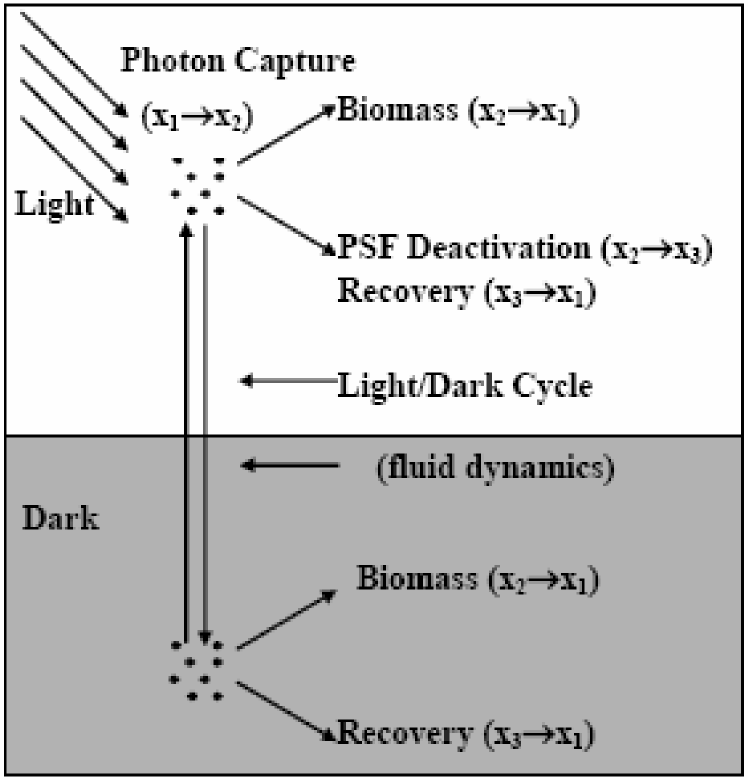
- Fluctuation Frequency:

  $f = 1 / (t_{over}+t_{under})$

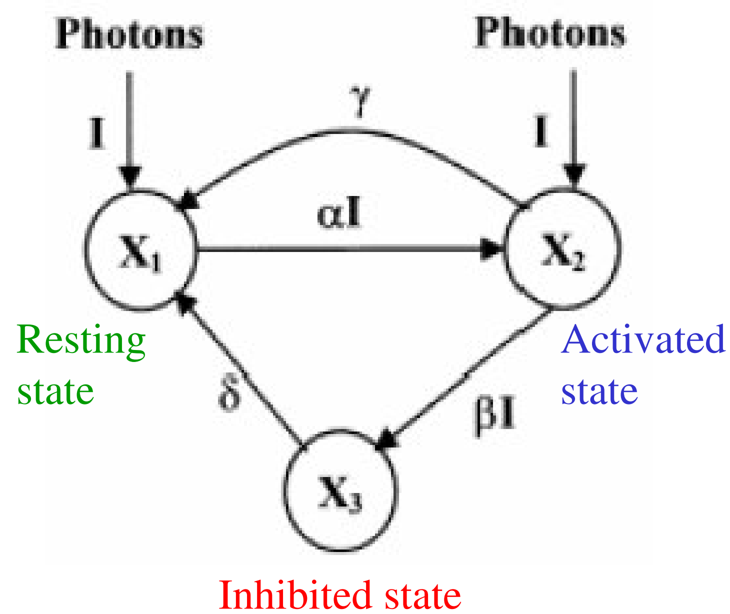
- Dimensionless relaxation time (fraction of over-charged time in a cycle):

  $\varphi = t_{over}/(t_{over}+t_{under})$

Dynamic growth model representation: Photosythetic factory (PSF) approach



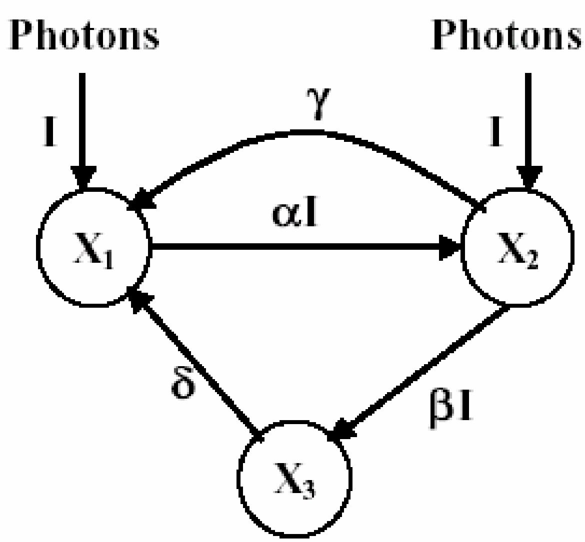
(a) Schematic representation of the interaction of photosynthetic kinetics and the fluid dynamics in the photobioreactor (from Wu and Merchuk, 2001).



(b) Structure of the three states model proposed by Eilers and Peeters (1988)

Photobioreactor Analysis II – Integrating Kinetics and Hydrodynamics

Luo & Al-Dahhan, *Biotech. & Bioeng.*, 85(4), 382, 2004



Kinetic model for photosynthesis (Eilers and Peeters, 1988)

Differential equations:

$$\frac{dx_1}{dt} = -\alpha I \cdot x_1 + \gamma \cdot x_2 + \delta \cdot x_3 \quad (1)$$

$$\frac{dx_2}{dt} = \alpha I \cdot x_1 - \gamma \cdot x_2 - \beta I \cdot x_2 \quad (2)$$

$$\frac{dx_3}{dt} = \beta I \cdot x_2 - \delta \cdot x_3 \quad (3)$$

$$x_1 + x_2 + x_3 = 1 \quad (4)$$

Growth rate:

$$\frac{1}{x}\frac{dx}{dt} = \mu = (k \cdot \gamma \cdot x_2 - Me) \quad (5)$$

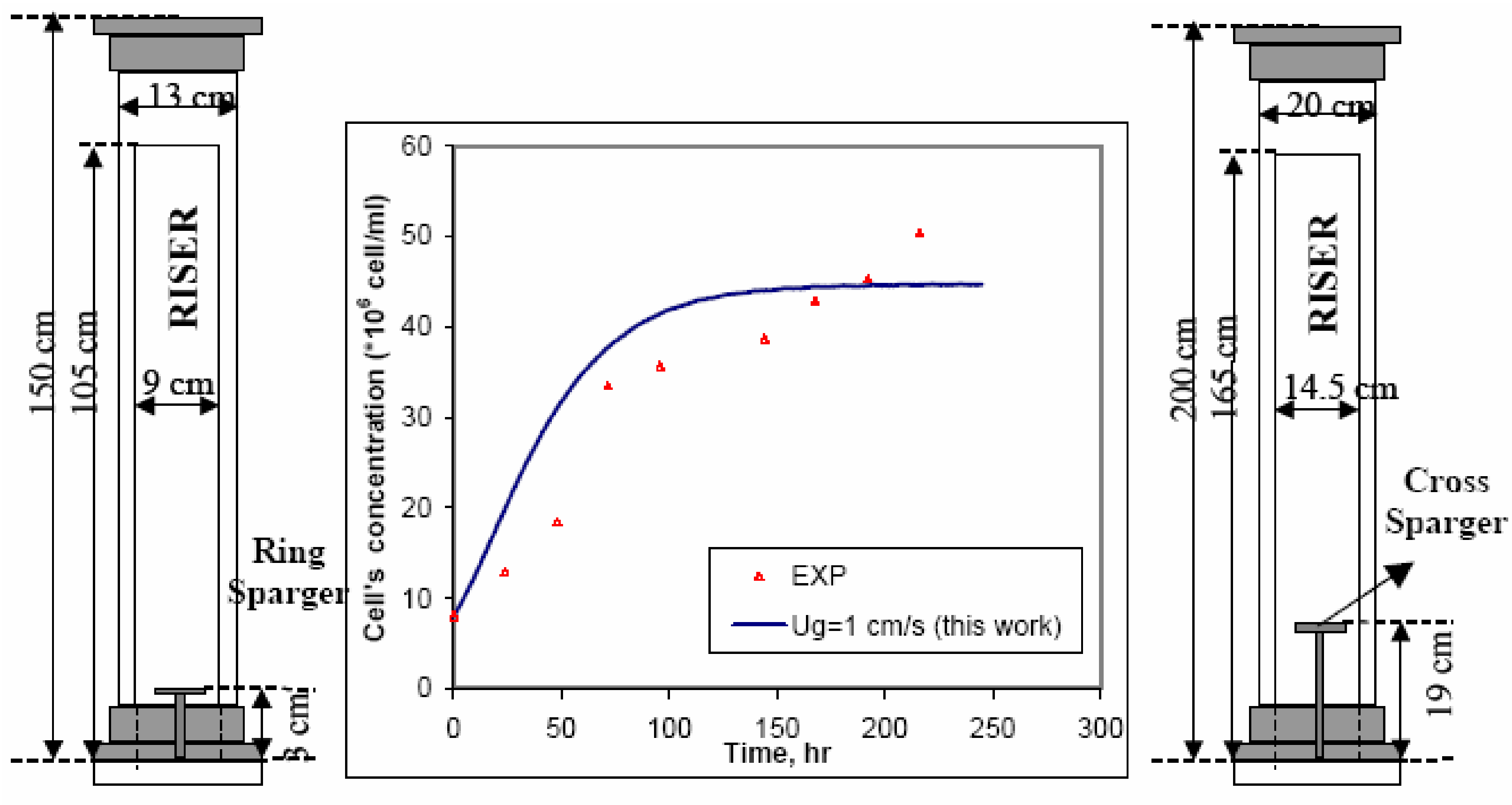
$$Me = \overline{Me} \cdot e^{k_m(\tau - \tau_c)} \quad (6)$$

Shear Stress (Wu and Merchuk, 2001)

Light History: $I = f\,(t, \textit{cell positions})$

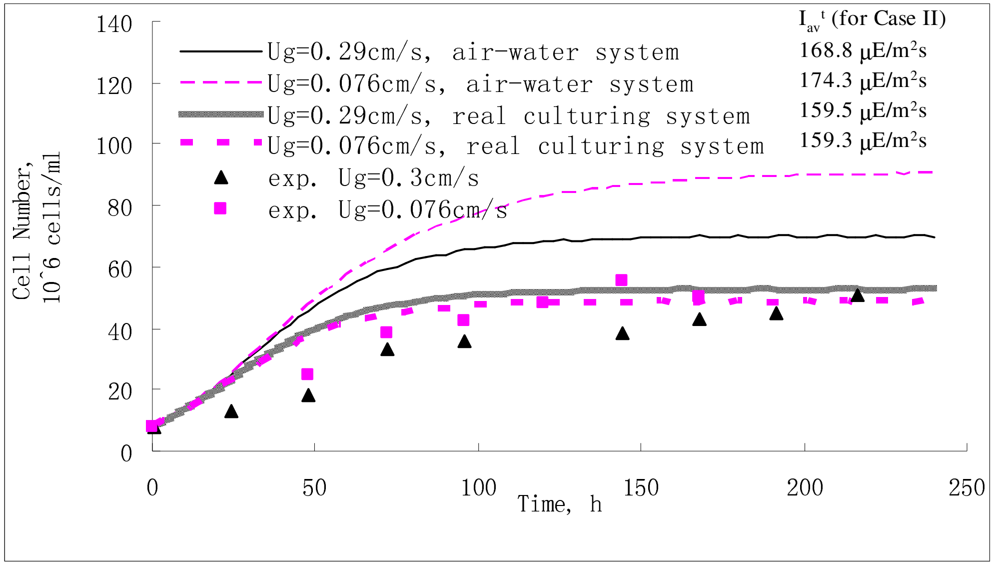
Initial conditions:

$x_1 = 1,\ x_2 = x_3 = 0,\ t = 0$



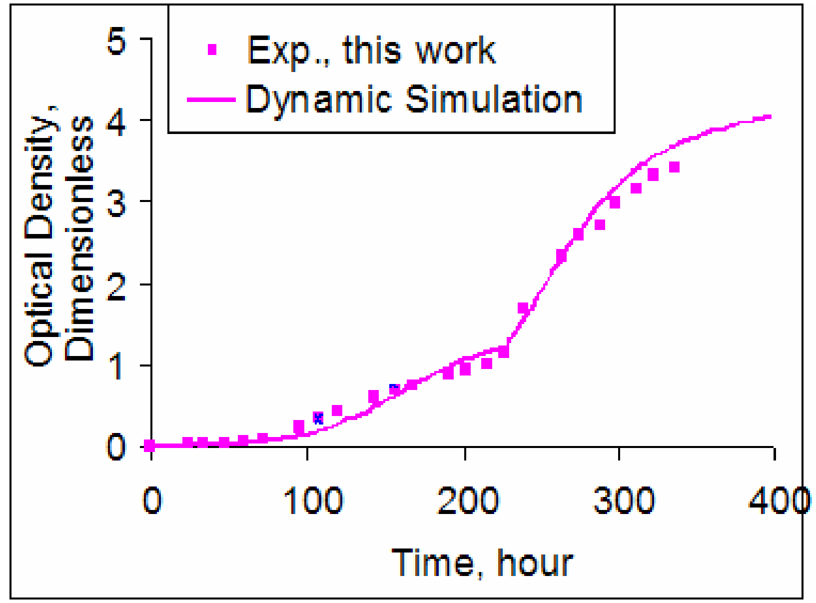
Simulation results by the dynamic model for the draft tube column (on the right) at Ug of 1 cm/s. The experimental data (Merchuk, et al., 2000) are based on the draft tube column on the left at the superficial gas velocity of 0.29 cm/s.

Model Predictions



Prediction of the dynamic model using CARPT data obtained in microalgae culturing system and in air-water system. The time-averaged light intensities were calculated by Case I (i.e., External Irradiance=250μE m^{-2} s^{-1}; Cell concentration=8×10^6 cells/ml).

The data are from Wu and Merchuk (2001).



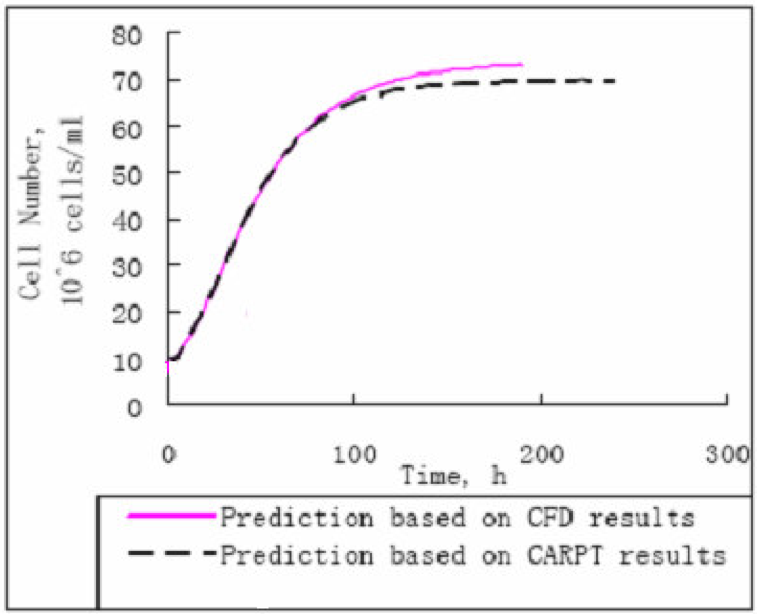
$$\frac{1}{x}\frac{dx}{dt} = \mu = (k \cdot \gamma \cdot x_2 - Me)$$

In the dynamic simulation, the values of k and Me are half of the values proposed by Wu and Merchuk (2001).

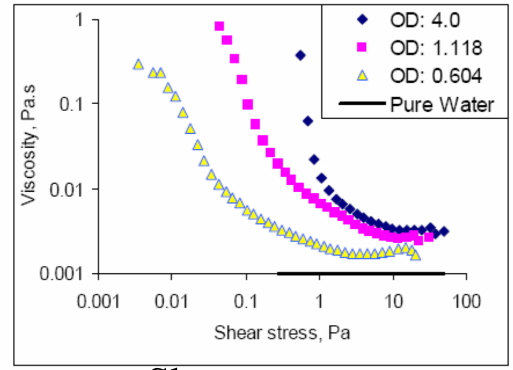
Can CFD provide the needed information for microalgae dynamic growth modeling ?

Air-water system

CFD/CARPT results after validating the closure

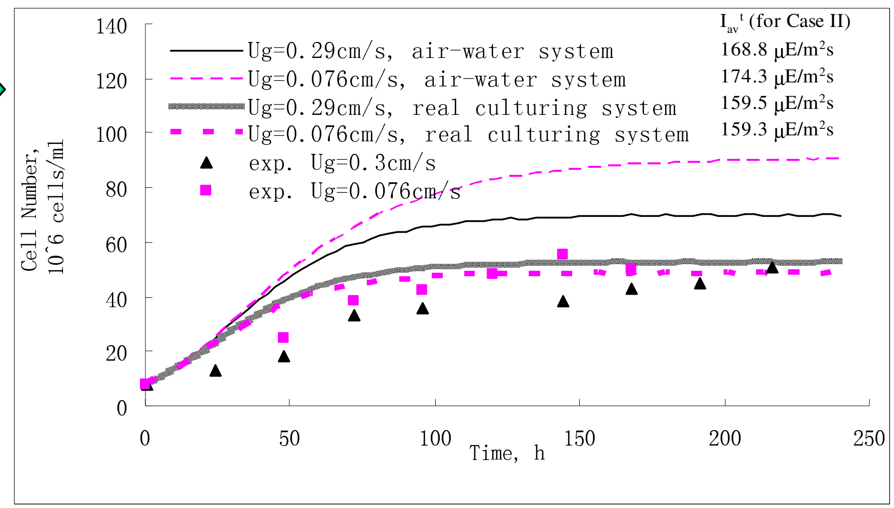


Apparent viscosity



Shear stress

CFD is **<u>not yet ready</u>** to be used under dynamic growth of microalgae



Summary

- ✓ Using CARPT and CT techniques, the local flow dynamics in a draft tube column reactor were studied, providing in-depth knowledge for PBR analysis, design, and scale-up.
- ✓ Three types of mixing mechanisms with different time scales were found in the airlift column reactors, which can introduce light fluctuations to the cells.
- ✓ The temporal irradiance patterns were calculated and further quantitatively characterized by three parameters: the time averaged irradiance, the frequency of the over-/under- charged cycles, and the dimensionless relaxation time.
- ✓ A new dynamic modeling approach was developed for culturing microalgae in PBR. This general approach integrates first principles of photosynthesis, hydrodynamics, and irradiance distribution within the reactor.
- ✓ The developed dynamic growth rate model predicted the trend and the reactor performances measured in this study and the performance measured by Merchuk et al. (2000).
- ✓ Work is needed to advance the CFD models and closures to properly simulate the hydrodynamics of photobioreactors under dynamic growth of microalgae.
- ✓ Upon such advancement, CFD would have the potential to be integrated along the newly developed approach to predict the microalgae culturing in photobioreactors.

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