COMSOL CONFERENCE
2016 MUNICH

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Computational analysis of hydrodynamics and light distribution in algal photo-bioreactors

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13.10.2016

OUTLINE

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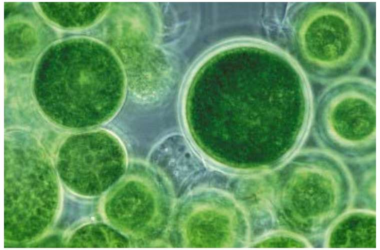
- Motivation
- System description
- Results
  - Hydrodynamics
  - Particle tracing
  - Light intensity
  - Different shapes of reactor
- Outlook

MOTIVATION

microalgae

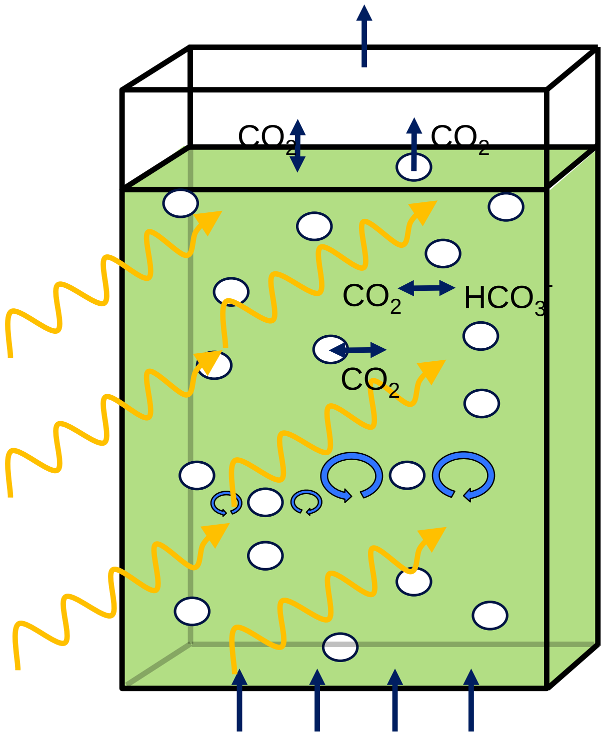


scale up

biofuel

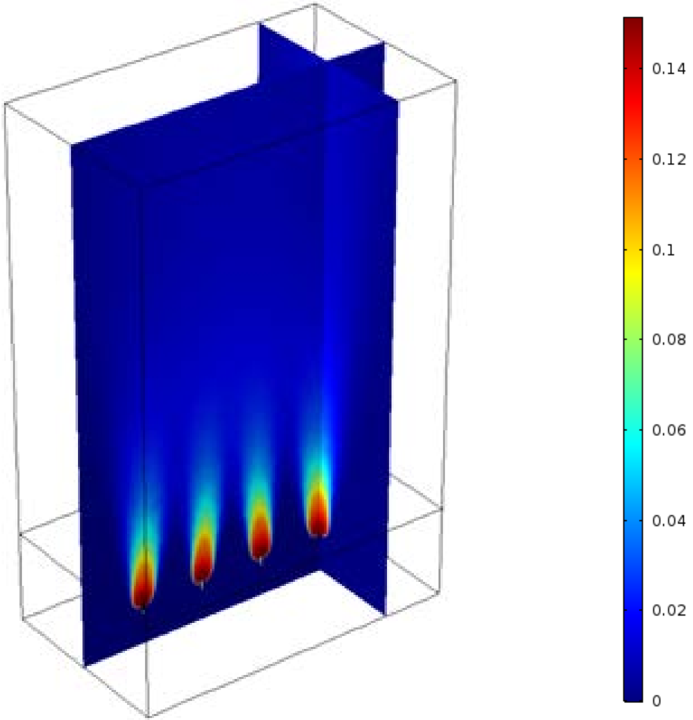
SYSTEM DESCRIPTION

- **Laboratory Photobioreactor (PBR)**
  Size is 10 x 6 x 21cm
- **Hydrodynamics**: The system is highly heterogeneous and requires the study of turbulence
- **Light Profile**: The distribution of light needs to be studied as light is scattered and absorbed by algae
- **Mass Transfer**: Amount of CO_2 transferred from gas to liquid is studied
- **Reactor Shapes**: Different shapes of the reactor are studied to minimize dead zones



HYDRODYNAMICS

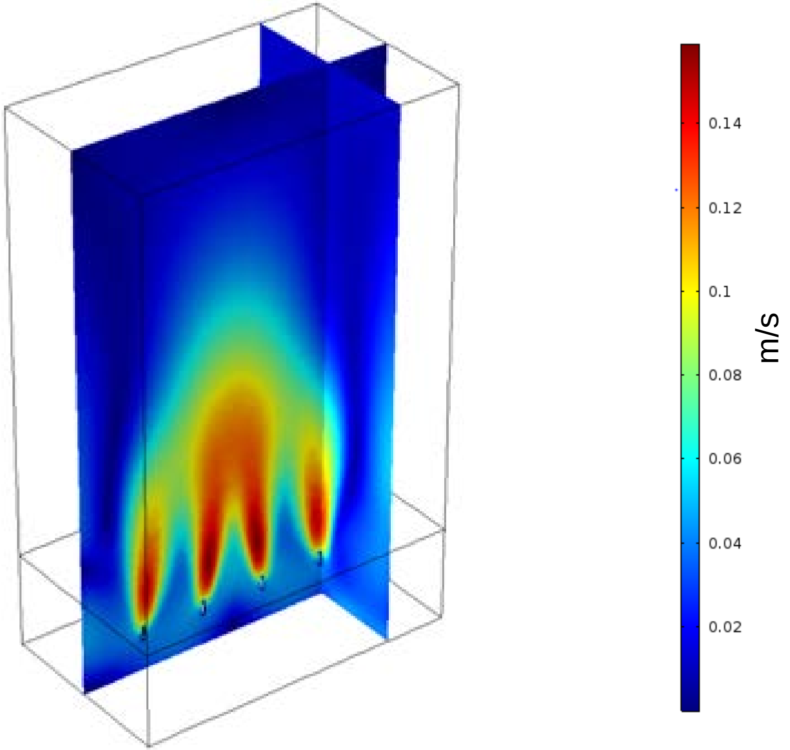
- Turbulent Bubbly Flow module was used to solve the Navier–Stokes equations
- *k-ε* model was implemented to include the effect of turbulence
- Inlet pipe was removed to speed up the simulations
- Bubble diameter is assumed constant



Gas phase volume fraction profile along 2 perpendicular planes

HYDRODYNAMICS

- Time dependent simulations were performed and their results used as input for stationary simulations
- 1st order discretization was implemented for both velocity and pressure
- Direct solvers were used to solve the discretized equations



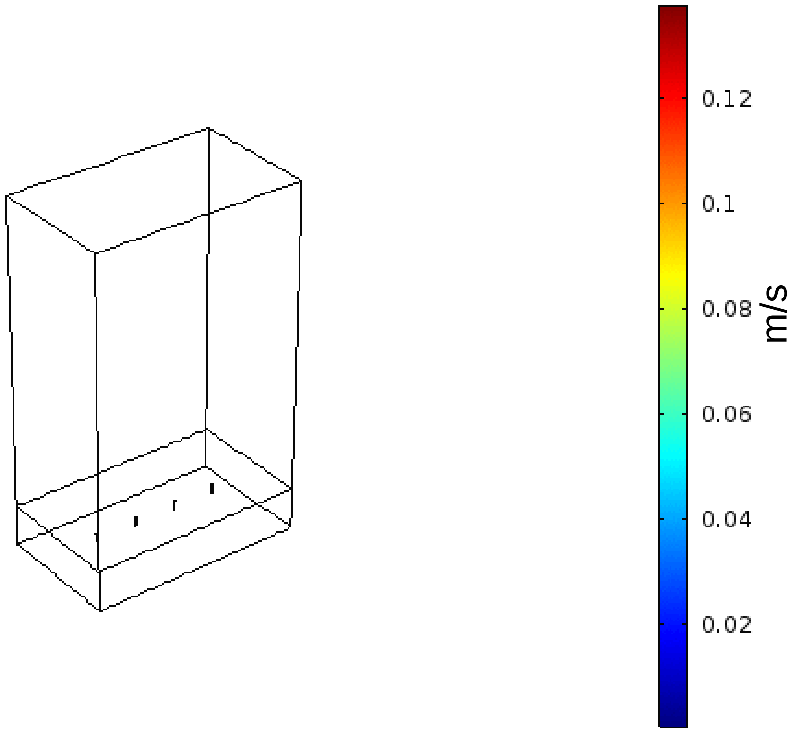
Liquid phase velocity profile along 2 perpendicular planes

PARTICLE TRACING

- Using the liquid phase velocity data from the hydrodynamic simulations, the paths of algae cells were traced using COMSOL's Particle Tracing Module

- Drag force is the only force affecting the movement of the algae cells

- A random turbulent dispersion was added to the velocity from the hydrodynamic data to account for the randomness because of turbulence



LIGHT INTENSITY SIMULATION

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Radiative Transfer Equation:

$$\frac{\partial I(s,\lambda)}{\partial s} = -\kappa I(s,\lambda) - \sigma I(s,\lambda) + \frac{\sigma}{4\pi}\int_{4\pi} I(\hat{s}',\lambda)\varphi(\hat{s},\hat{s}')d\boldsymbol{\Omega}$$

Absorption Out-Scattering In-Scattering

- Light intensity is homogeneously incident on one surface of the reactor
- Absorption and out-scattering reduce the intensity from direction *s*
- In-scattering term accounts for the light that is removed from other directions and is added to the current direction *s*

LIGHT INTENSITY SIMULATION

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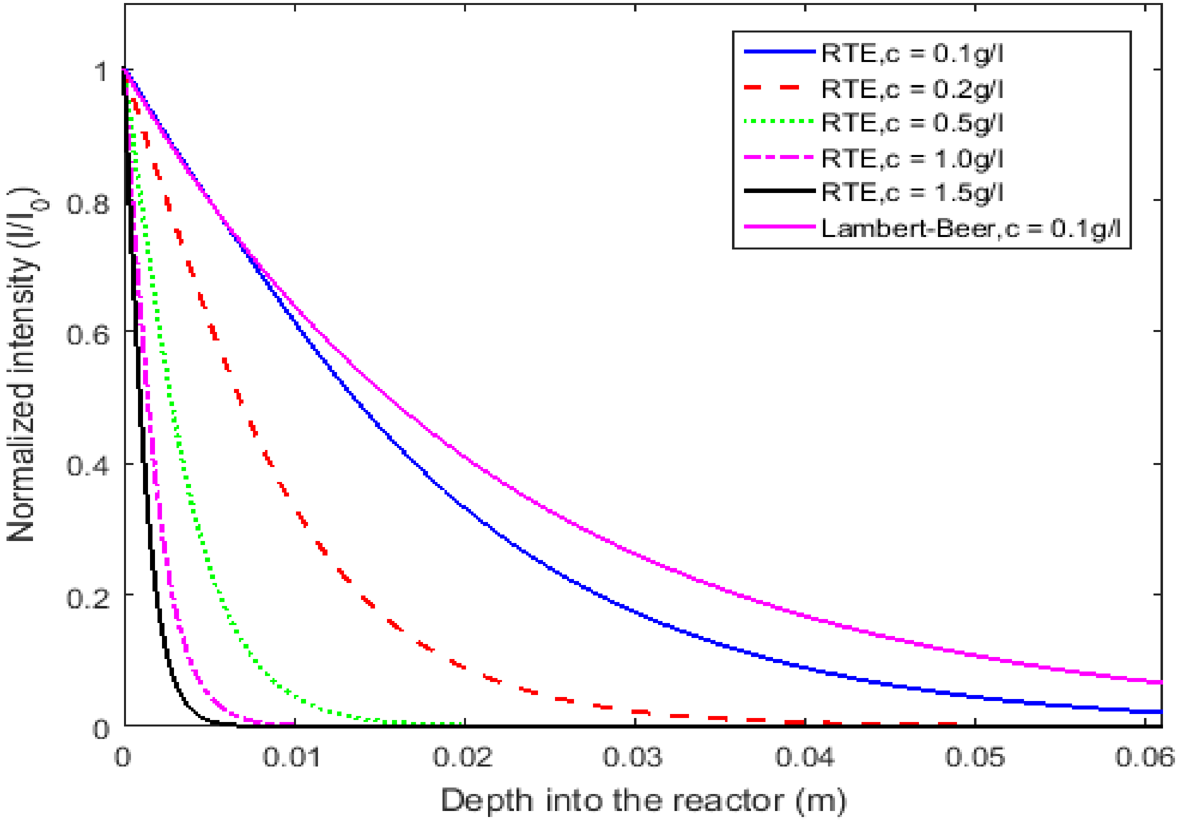
Radiative Transfer Equation:

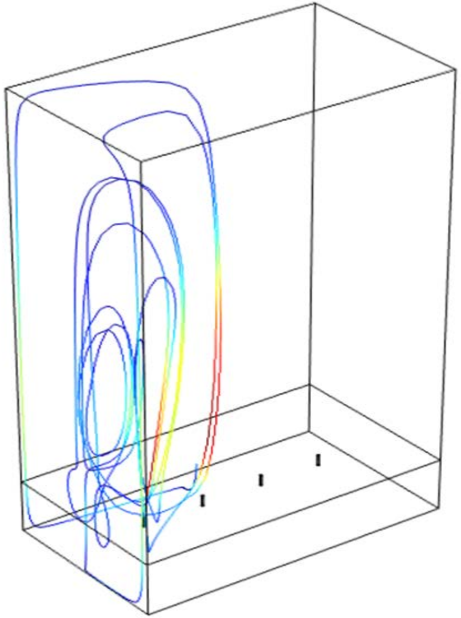
$$\frac{\partial I(s,\lambda)}{\partial s} = -\kappa I(s,\lambda) \quad - \sigma I(s,\lambda) \quad + \frac{\sigma}{4\pi}\int_{4\pi} I(\hat{s}',\lambda)\underbrace{\varphi(\hat{s},\hat{s}')}_{\text{phase function}} d\boldsymbol{\Omega}$$

- COMSOL's RTE solver (Heat Transfer Module) does not contain the phase function needed in this specific case
- A MATLAB code was written to calculate the intensity at each discretized points in the PBR.

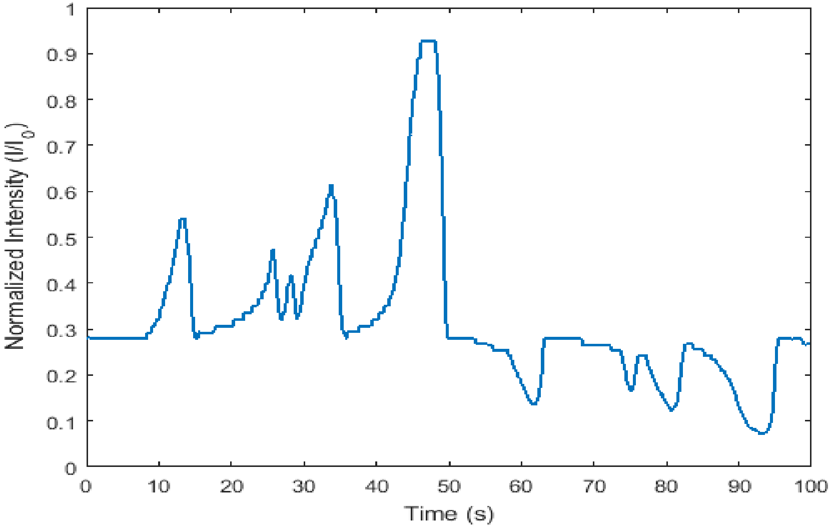
LIGHT INTENSITY SIMULATION



COMBINING LIGHT INTENSITY AND PARTICLE TRACING

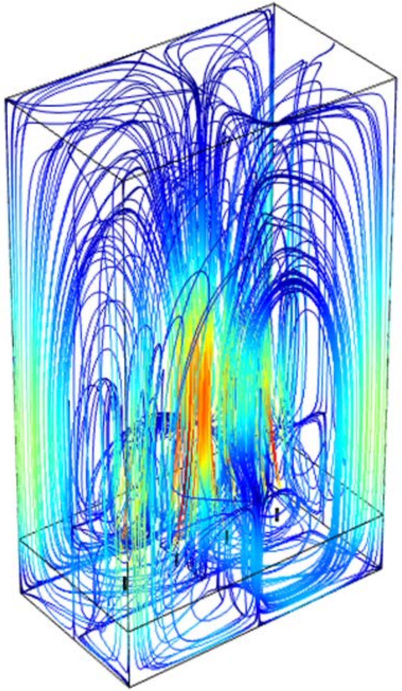


Path of a single algae cell from a given starting position

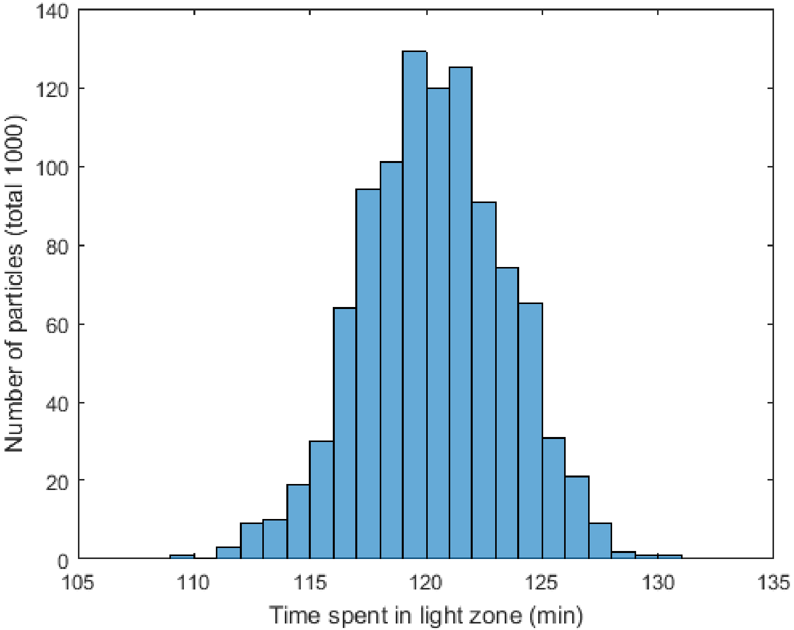


Normalized light intensity received by the algae cell over time

COMBINING LIGHT INTENSITY AND PARTICLE TRACING



Path for many algae cells from a given starting position



Time spent by algae cells in light zone ($I/I_0 > 0.1$) for total time 150 min and concentration 0.1 kg/m^3

DIFFERENT SHAPES OF REACTOR

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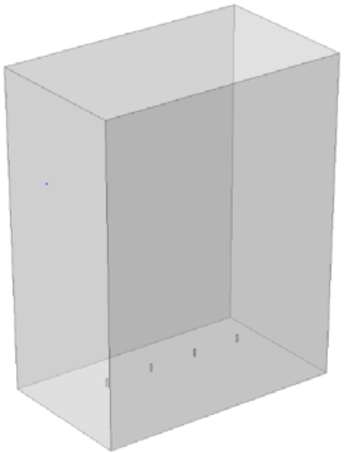
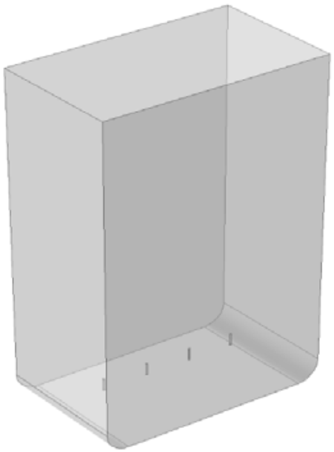


Actual shape of the PBR

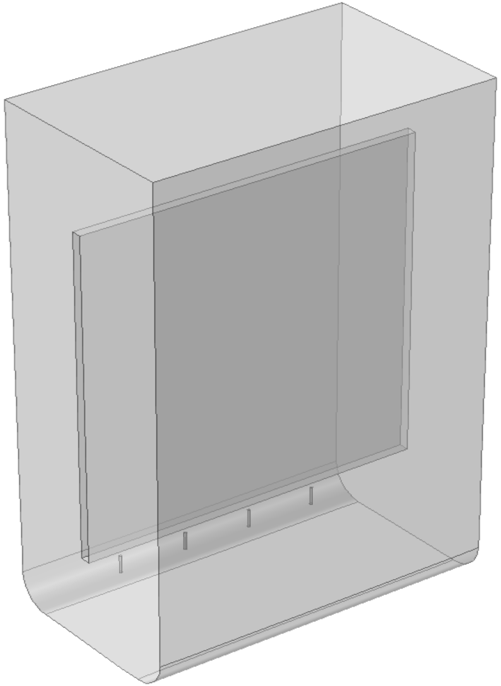


Corners smoothened

- Smoothened corners improve the liquid flow profile and mixing in the system

- This also reduces the possibility of dead zones mainly at the corners of the PBR

DIFFERENT SHAPES OF REACTOR



- Making it an Airlift reactor

- The plate divides the reactor into two regions
  - Riser
  - Downcomer

- The flow is highly turbulent in the riser region while laminar in the downcomer region

- Opens options to improve growth rate by combining the light exposure (light/dark cycles) and fluid flow patterns as the flow is more ordered than other designs

OUTLOOK

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- CFD and particle tracing results combined with the light intensity simulations provide a quantification of the instantaneous light experienced by the particles.
- As next step, mass transfer of CO_2 from the gas phase to the liquid phase will be calculated and combined with CFD and particle tracing.
- All these results will be combined with an algae growth model in order to optimize algae growth depending on reactor shape, gas input, illumination and algae concentration.

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Thank you for your attention!

APPENDIX

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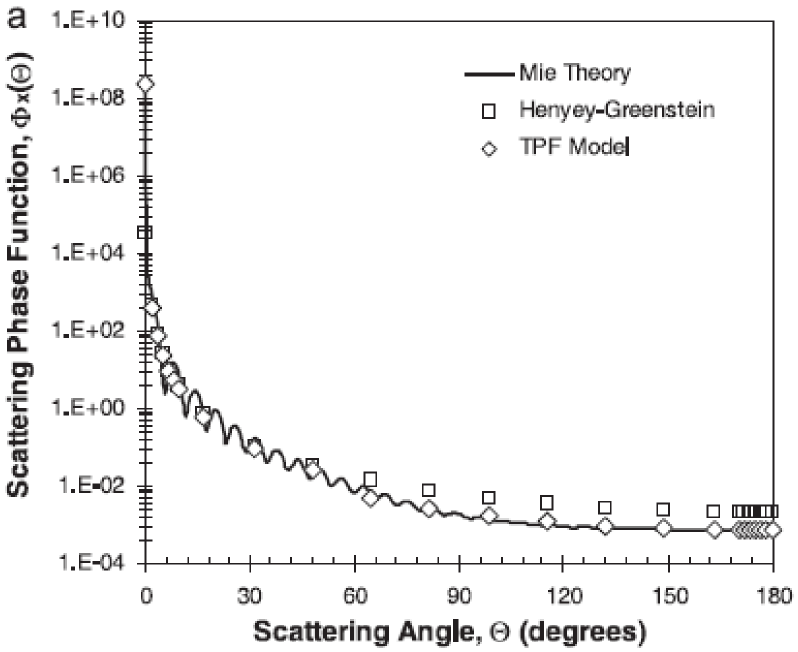

- The Henyey-Greenstein function is a good trade off between fast calculation and good approximation

$$\varphi(\hat{s},\hat{s}') = \frac{1-g^2}{(1+g^2-2g\cos\theta)^{1.5}}$$

where g is the asymmetric parameter (deciding whether the scattering is forward, backward or isotropic in nature and θ is the angle between incoming ($\hat{s}$) and outgoing ($\hat{s}'$) direction