COMSOL CONFERENCE 2016 MUNICH

JÜLICH FORSCHUNGSZENTRUM

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

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OUTLINE

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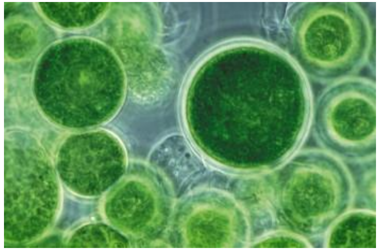
- Motivation
- System description
- Results
  - Hydrodynamics
  - Particle tracing
  - Light intensity
  - Different shapes of reactor
- Outlook

MOTIVATION

microalgae



scale up

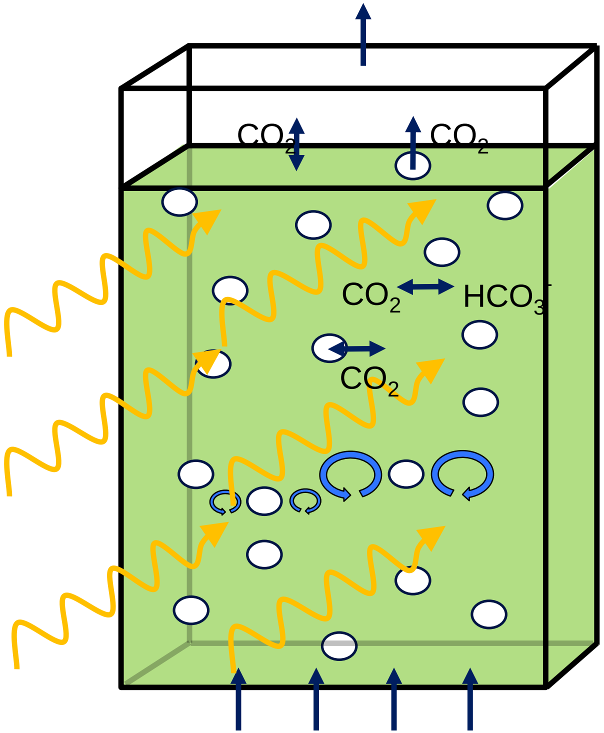
biofuel

cosmetics

pharmaceutical

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



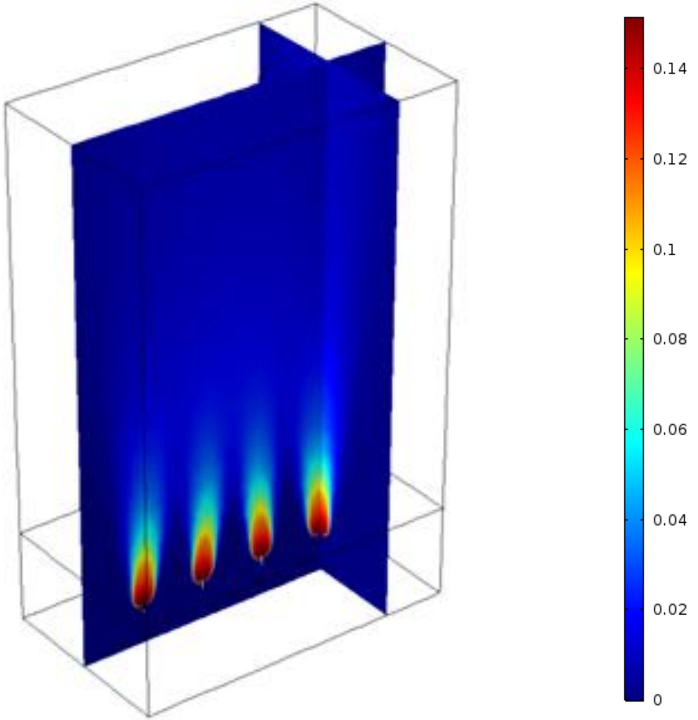
HYDRODYNAMICS

- 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



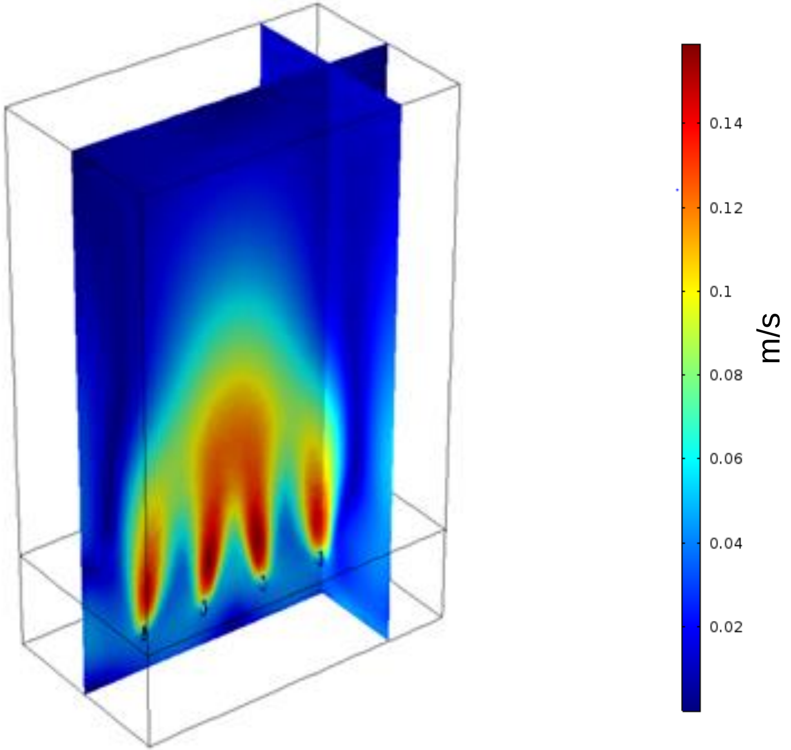
Gas phase volume fraction profile along 2 perpendicular planes

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

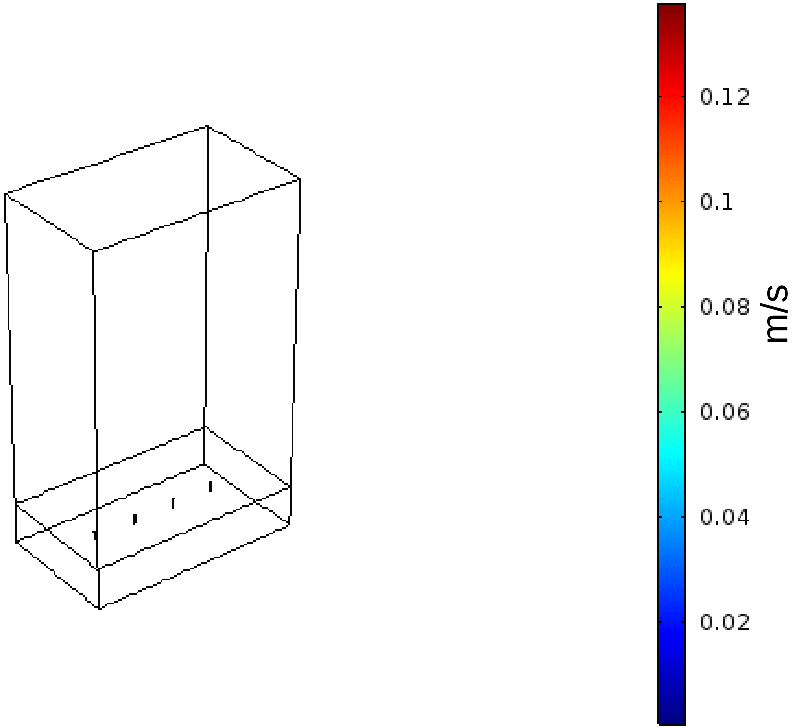
- Direct solvers were used to solve the discretized equations



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

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

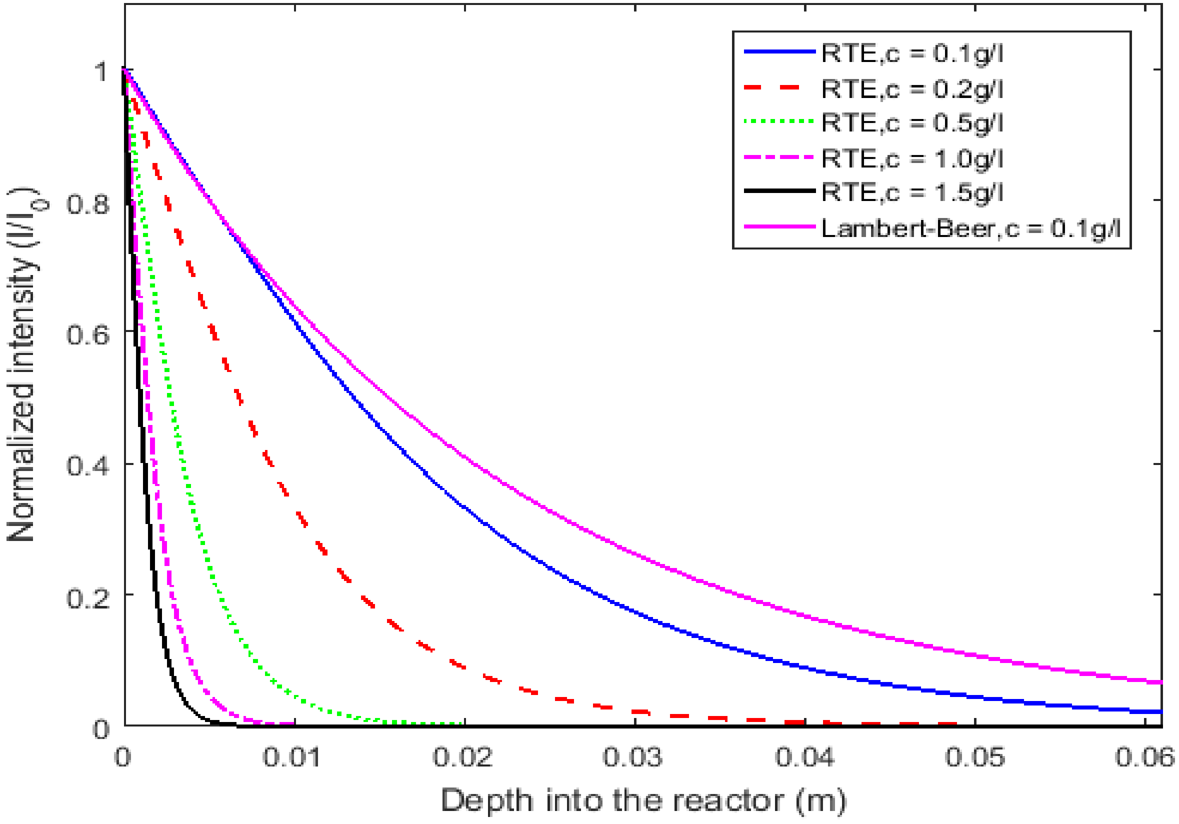
Radiative Transfer Equation:

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

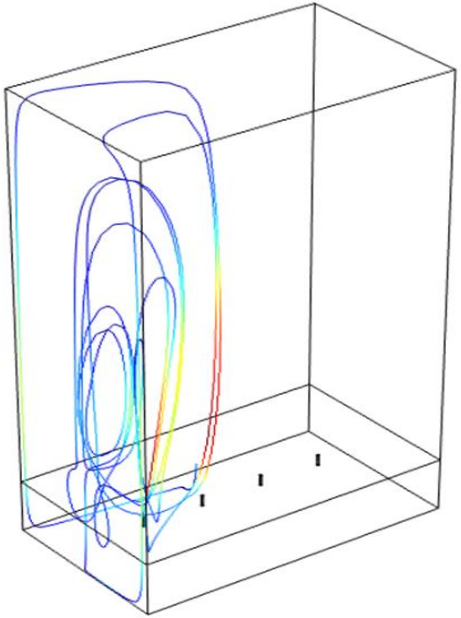
- COMSOL's RTE solver (Heat Transfer Module) does not contain the phase function needed in this specific case

- A MATLAB code was written to calculate the intensity at each discretized points in the PBR.

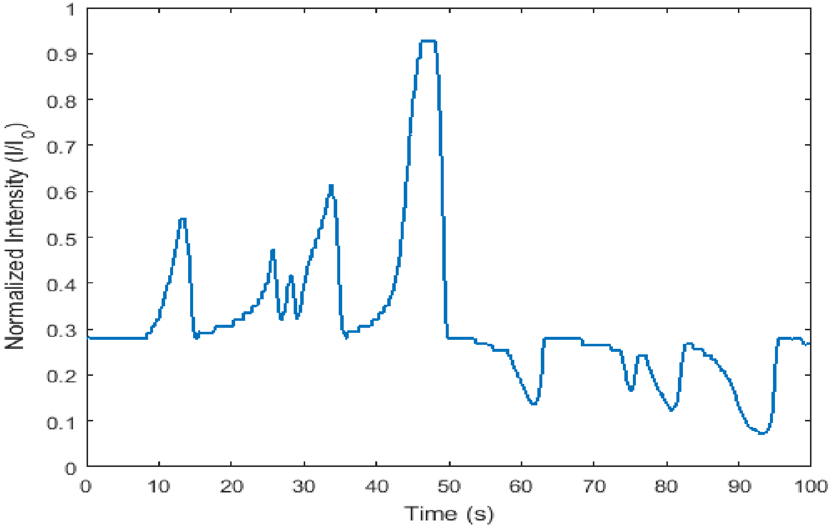
LIGHT INTENSITY SIMULATION



COMBINING LIGHT INTENSITY AND PARTICLE TRACING

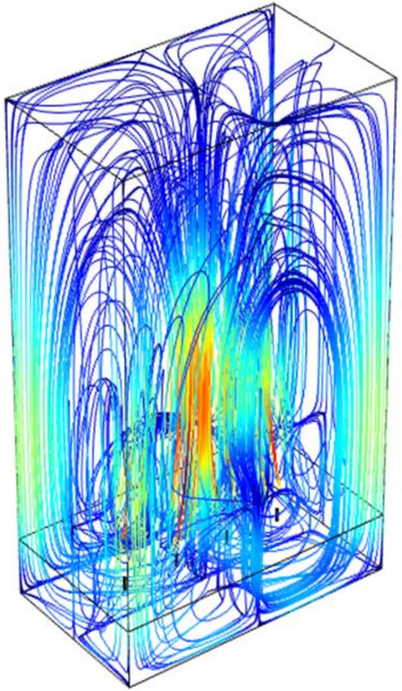


Path of a single algae cell from a given starting position

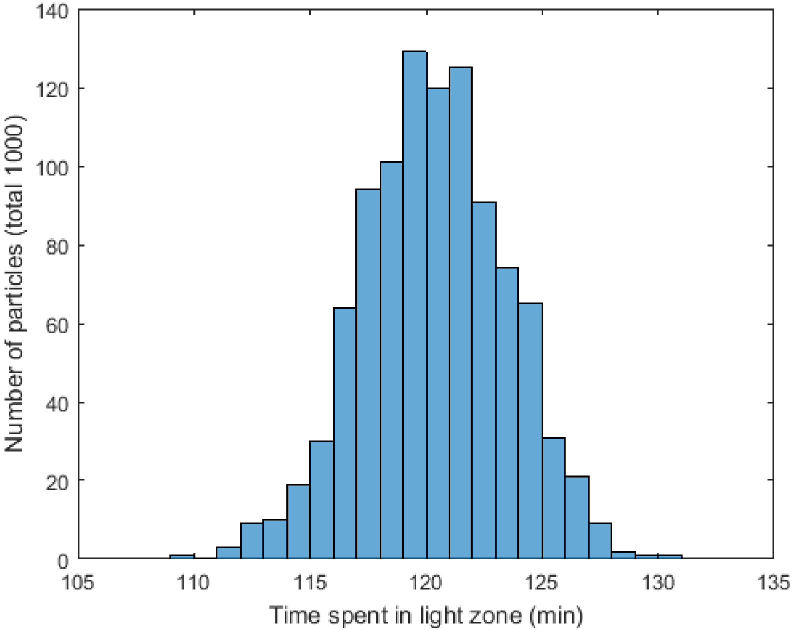


Normalized light intensity received by the algae cell over time

COMBINING LIGHT INTENSITY AND PARTICLE TRACING

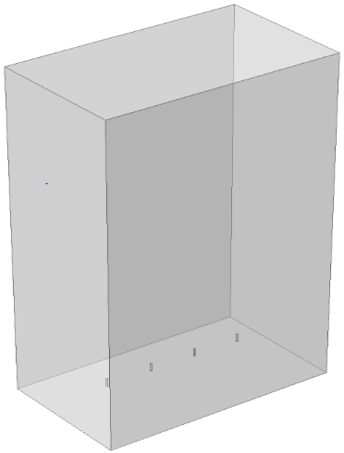


Path for many algae cells from a given starting position

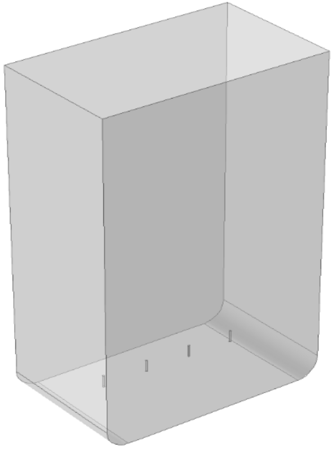


Time spent by algae cells in light zone ($I/I_0 > 0.1$) for total time 150 min and concentration 0.1 kg/m^3

DIFFERENT SHAPES OF REACTOR



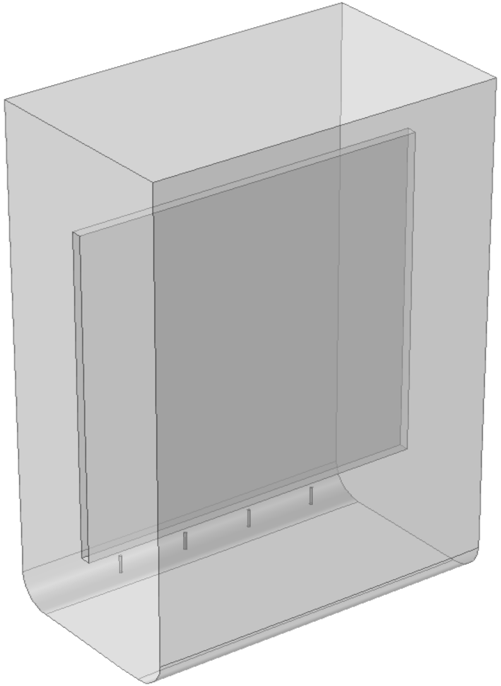
Actual shape of the PBR



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

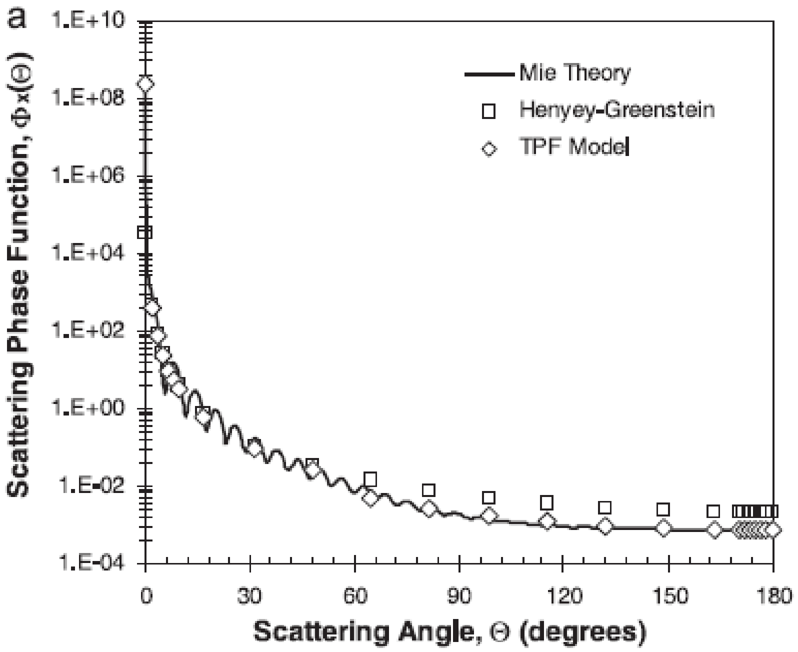
- Hydrodynamics and particle tracing results combined with the light intensity simulations provide a quantification of the instantaneous light experienced by the particles.

- As next step, mass transfer of CO_2 from the gas phase to the liquid phase will be calculated and combined with hydrodynamics 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.

Thank you for your attention!

APPENDIX



- 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