Engineering Design of Algal Production Systems

NSF – CMMI Workshop
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Need Addressed

Design & Optimization of Microalgal Growth Systems for Biofuel Production

Demand for bio-oil @ $80/bbl is Insatiable!
- Must be Renewable & Sustainable
- Can be Carbon Neutral
- “Home Grown” Oil
Opportunity/Impact

50+ Companies are Pursuing Algae → Biofuels

- Large (ExxonMobil, Shell, etc) to Small (VC)

1st row: unknown, Solix, Valcent, Seambiotic, Cyanotech
2nd row: Greenfuels, Heliae, OriginOil, Algaelink, Earthrise
3rd row: ORNL

Why so many designs? Why does one work? Why might it not work?
Algal Biofuels Production Process

1. Select Proprietary Algae Strain
2. Grow in Photobioreactors
3. Grow in Open Ponds
4. Harvest Algae
5. Process Algae

- Algae Oils
- Proteins
- Carbohydrates
- Biomass

- Biofuels
- Other Products
- Animal Feed
- Electricity Generation
- Ethanol & Other Biofuels
- Solid Fuel
- Aquaculture Feed

ALDUO™
Challenges

- **Biology**
  - Genetics / Breeding
  - For Productivity
  - For Resistance

- **Low Cost Production Systems**
  - Oil @ $80/bbl = $0.50/kg

- **Harvesting and Conversion**
  - ~1g algae in 1L water
  - ~30% algal mass is lipids
  - → Need to process ~3000L culture to get 1L oil
Techno-Economic Modeling

- Economic and Macro Level Analysis
- Do the numbers add up?
- What are the key sensitivities?
- Does this make business sense?
- Often spreadsheet based

Typical Revenue by Product

<table>
<thead>
<tr>
<th>Product</th>
<th>Estimated Revenue from Downstream Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lipids (SVO)</td>
<td>$0.80/SL</td>
</tr>
<tr>
<td>Fuel</td>
<td></td>
</tr>
<tr>
<td>Speciality Chemicals</td>
<td>$2.00/SL</td>
</tr>
<tr>
<td>Nutraceuticals</td>
<td>$2.00/SL</td>
</tr>
<tr>
<td>Pharmaceuticals</td>
<td>$2.00/SL</td>
</tr>
<tr>
<td>Biomass</td>
<td></td>
</tr>
<tr>
<td>Methane</td>
<td>$10.00/SL</td>
</tr>
<tr>
<td>Livestock Feed</td>
<td>$1.00/kg</td>
</tr>
<tr>
<td>Fertilizer</td>
<td>$0.20/kg</td>
</tr>
<tr>
<td>Speciality Materials</td>
<td>$0.50/kg</td>
</tr>
<tr>
<td>Food Products</td>
<td>$3.00/SL</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Estimated Revenue from Ancillary Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Credits</td>
</tr>
<tr>
<td>Wastewater Treatment</td>
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</tbody>
</table>

Baseline Results per Hectare

<table>
<thead>
<tr>
<th>Product Yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Lignoc vet Harvest</td>
</tr>
<tr>
<td>Daily Biomass Harvest (after oil extraction)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Production Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of Producing Lipid (S/L)</td>
</tr>
<tr>
<td>Cost of Producing Biomass (S/kg)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Revenue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auxiliary Sources</td>
</tr>
<tr>
<td>Daily Revenues from Carbon Credits</td>
</tr>
<tr>
<td>Daily Revenues from Wastewater Treatment</td>
</tr>
<tr>
<td>Lipids (SVO)</td>
</tr>
<tr>
<td>Daily Revenues from Fuel</td>
</tr>
<tr>
<td>Daily Revenues from Speciality Chemicals</td>
</tr>
<tr>
<td>Daily Revenues from Nutraceuticals</td>
</tr>
<tr>
<td>Daily Revenues from Pharmaceuticals</td>
</tr>
<tr>
<td>Biomass</td>
</tr>
<tr>
<td>Daily Revenues from Methane</td>
</tr>
<tr>
<td>Daily Revenues from Livestock Feed</td>
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<tr>
<td>Daily Revenues from Food Products</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Annual Revenue</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4,353,800 $</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Annual Costs (Debt Service + Operating Costs)</th>
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</thead>
<tbody>
<tr>
<td>$4,179,412 $</td>
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</table>

<table>
<thead>
<tr>
<th>Annual Profit/Loss</th>
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</thead>
<tbody>
<tr>
<td>$174,347 $</td>
</tr>
<tr>
<td>6.00%</td>
</tr>
</tbody>
</table>

Pattarkine, V., and Eckelberry, R. “Algae Productivity Model (Alpha Release)” September 2009
System Level Modeling

- Mass and Energy Balance Analysis
- What are the key components/processes?
- Will this system work? Can it be controlled?
- 1-D or “lumped parameter” network analysis

Willson, B. “Large Scale Production of Microalgae for Biofuels” June 2009
Physics Based Modeling

- Process/Device Design & Optimization
- What is really happening inside the device?
- What are the key operating parameters?
- How can we make it better?
- Non-linear and coupled physical phenomena
- 3-D Computational Fluid Dynamics (CFD)

Combustion Industry

Aerospace Industry

Next: Algae Cultivation Industry!

Materials Processing Industry

CFDRC has 20+ years of experience developing and applying physics based modeling tools for many industries.

www.cfdrc.com
Example: Racetrack Modeling

Goals
• Investigate pond aspect ratio issues
• Corner recirculation / dead zones
• Determine pumping force

Inputs
• Geometry
• Desired bulk current velocity

Two designs with same area (~1.2 acre) and nominal current velocity = 4 cm/s but with 10x different aspect ratio

design #1 = 110 m x 44 m

design #2 = 1100 m x 4.4 m
Example: Racetrack Modeling

**Results**
- Velocity maps
- Pressure drop
- Pumping force

**Conclusions**
- High aspect ratio ponds have less recirculation and require less pumping force
- Should investigate turning vanes and flow straighteners

Note Scale Difference!

“Dead” Zone:
- ~50m²
- ~2m²

Pumping force:
- 49.9 N
- 26.2 N

110 m x 44 m design

1100 m x 4.4 m design
Example: Paddlewheel Modeling

Goals

• Determine paddlewheel torque input characteristics
• Investigate closed and open hub designs

Input Parameters

• Paddlewheel geometry and pond positioning
• Paddlewheel rotation speed (4 RPM)

hub radius = 15 cm
pond depth = 20 cm
bottom gap = 2 cm
Example: Paddlewheel Modeling

**Results**

- Transient pressure and velocity fields
- Time history of blade torques
- Free surface motion

**Conclusions**

- Closed hub acts like positive displacement pump and produces extreme torque spikes
- Modeling of alternate blade designs and pond positioning parameters could lead to smoother/lower torque solutions
Example: Novel Dewatering Method

Hydrodynamic Separation of Neutrally Buoyant Suspensions


APL 91, 033901 (2007)
J. Chroma 1162, #2 (2007)

Centrifugal separation: Force on particles move them radially with respect to the fluid

Hydrodynamic separation: Force on fluid particle transport neutrally buoyant suspensions to form band at stable location near side wall

Dean vortices sweep neutrally buoyant particles to stable equilibrium location

Transverse Flow Vectors


www.cfdrc.com

Energy & Materials Technologies
Example: Novel Dewatering Method

**Goals**

- **Determine optimal channel dimensions for lowest cost operation.**

  \[ \text{Cost} = f(\text{pressure drop, flow rate, residence time}) \]

**Results**

- **0.80 mm is best, 1.0mm is 4x more costly to operate**

![Channel Height Parametric Study](image-url)
Development of Full Physics Based Algae Growth Model

Graphic Source: Chisti, Y. “Algae Production: An Overview of Existing Options” Wind-Sea-Algae 2009, Copenhagen
**Research Project Underway**

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**Algae Growth Kinetics**

Each algae strain has its own growth kinetics formulation which is a function of light, nutrients, temperature, and other environmental factors.

**Function of Light:** A model for photosynthetic growth to explain three phenomena

(i) photoactivation, (ii) photoinhibition, and (iii) flashing light effect.

**Nutrients and Mass Transfer:** Photosynthetic process for algae growth to consume CO$_2$ and produce O$_2$.

**Shear Stress Effects:** The most extreme effect is cell disruption, but less dramatic responses, such as a decrease in growth rate or changes in metabolite synthesis, may take place before shear reaches lethal limits.

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Preliminary Results

Algae Concentration Growth With Diurnal Behavior

Photoactivation + Photoinhibition
There Are So Many Algae Growth System Designs!

Our Goal...
To develop the most accurate physics based modeling and simulation tools and techniques...
To help determine what works, what doesn’t, and why...

1st row: Seambiotic, Earthrise, Cyanotech,
2nd row: AlgaeLink, ORNL,
3rd row: unknown, Solix, Valcent,
4th row: Greenfuels, Arizona State Univ., OriginOil

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Summary

Algae Biomass Production Systems are “Fluidic” Systems

- Growth / Harvesting / Extraction / Refining can all be modeled
- Lend themselves to CFD based tools and techniques

Physics Based Modeling and Simulation are Valuable Tools

- Upfront design analysis
- Trend based parametric analysis
- Design optimization

Significant Benefits

- Lower technical and cost risks
- Try “what-if” scenarios
- Try and reject ideas faster to find winners earlier
Questions?

Thank you for your time and attention!

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Back-up Slides

About CFD Research Corporation

Simulation Process

Physics Capabilities
About CFD Research Corporation

Your Innovation Development Partner

Technology Development
- Innovative concepts & designs
- Prototype development & evaluation
- Expert analysis & optimization

High-fidelity Modeling & Simulation
- Physics based analysis tool development
- Applications to multi-scale phenomena

Serving Government & Industry Since 1987
- Staff of 100, 75% with advanced degrees
- Numerous national awards for technology development
- 45+ patents awarded or pending

CFDRC is a two-time (1996 & 2006) winner of Tibbetts award for successful commercialization of innovative technologies.

www.cfdrc.com
Simulation Process

Geometry Acquisition
- CAD system or build within the simulation tools

Solver Setup
- Define physics to be solved
- Define material properties
- Define boundary conditions

Mesh Generation
- Discretize region of interest for computations

Generate Solution
- Physics code solves the problem (usually on PC)

Post Process
- Interrogate results and collect data

CFDRC has 20+ years of experience developing and applying physics based modeling tools for many industries.
Physics Capabilities

CFDRC developed the CFD-ACE+ Multiphysics Software Suite
- Sold to ESI Group in 2004 who currently markets the product

CFDRC continues to develop on the CFD-ACE+ platform
- Actively working on adding algae specific capabilities

CFD-ACE+ Features:
- Rich Physics Modules
- Rich Feature Set
- Expert System GUI
- Customizable with User Subroutines
- Parallel Processing

Physics for the Algae Industry
- specialized development in progress
- e.g., light propagation / growth kinetics

CFDRC is focused on developing algae related physics models (e.g., light propagation / growth kinetics)