Modeling Algae Growth in an Open-Channel Raceway

SCOTT C. JAMES and VARUN BORIAH

ABSTRACT

Cost-effective implementation of microalgae as a solar-to-chemical energy conversion platform requires extensive system optimization; computer modeling can bring this to bear. This work uses modified versions of the U.S. Environmental Protection Agency’s (EPA’s) Environmental Fluid Dynamics Code (EFDC) in conjunction with the U.S. Army Corp of Engineers’ water-quality code (CE-QUAL) to simulate hydrodynamics coupled to growth kinetics of algae (*Phaeodactylum tricornutum*) in open-channel raceways. The model allows the flexibility to manipulate a host of variables associated with raceway-design, algal-growth, water-quality, hydrodynamic, and atmospheric conditions. The model provides realistic results wherein growth rates follow the diurnal fluctuation of solar irradiation and temperature. The greatest benefit that numerical simulation of the flow system offers is the ability to design the raceway before construction, saving considerable cost and time. Moreover, experiment operators can evaluate the impacts of various changes to system conditions (e.g., depth, temperature, flow speeds) without risking the algal biomass under study.

Key words: CE-QUAL, EFDC, modeling algae growth, raceway.

1. INTRODUCTION

Plants, including algae, use photosynthesis to convert solar energy into organic forms of energy, especially liquid fuels. Plants use energy from the sun to combine water and CO$_2$ to yield biomass and chemical energy. While the mechanism of photosynthesis in microalgae is similar to that of higher plants, microalgae are generally more efficient converters of solar energy because of their simple cellular structure. In addition, because the cells grow in aqueous suspensions, they have more efficient access to water and nutrients. For these reasons, microalgae are capable of extremely rapid growth and some strains can double their biomass within 24 hours (Dempster and Sommerfeld, 1998).

Producing renewable energy (i.e., liquid transportation fuels) with low carbon emissions leads to lower global CO$_2$ emissions. When biomass-derived biofuels are oxidized, CO$_2$ is released, just as it is from fossil fuels; however, if new biomass is grown, then CO$_2$ can be recycled from the atmosphere through photosynthesis and the process repeated. Producing 100 kg of algal biomass fixes approximately 183 kg of CO$_2$. If no externally produced energy is used for biomass cultivation, harvesting, and conversion, then there would be no net emission of CO$_2$ in a full biomass fuel cycle resulting in a carbon-neutral process (Chisti, 2007).

Microalgae as a source of biomass for liquid fuels production have a number of advantages. Many strains are quite rich in oil content, ranging from 20% to 50% by dry biomass weight (Metting and Pyne, 1986; Spolaore et al., 2006). Waste-water discharge may be used to fertilize the growth medium or as a source of
nutrients for algal growth. Moreover, fossil-fueled power plant, CO₂-rich flue gas can be bubbled directly into an open-channel raceway as a source or inorganic carbon while helping to mitigate CO₂ emissions (Ben-Amotz, 2007; Sawayama et al., 1995; Yun et al., 1997). Displacement of food crops by biofuel algal “farms” should be minimal because microalgae may be grown in seawater or saline groundwater using non-arable land, as well as in hot, arid environments.

All of these factors combine to indicate that microalgae have the potential to be a viable feedstock for biofuels including biodiesel, green diesel, and aviation fuel. Biorefining technology and processes developed through DARPA’s Biofuels Program under BAA06-43 are currently capable of producing renewable aviation fuel (JP-8) from various biofuels feedstock that can include algae. The distinct benefit of bio-oil based aviation fuel and green diesel over biodiesel is that the former have a higher energy density, better cold flow performance, and are typically compatible with current petroleum based hydrocarbon fuel infrastructure. Due to the their high oil content, microalgae have the potential of serving as the raw material required to produce a large portion of the 140 billion gallons of gasoline-type biofuels and the 40–60 billion gallons of biodiesel necessary to replace all transport fuels consumed in the United States (Chisti, 2007).

1.1. Motivation for modeling

Current cost for production of micro-algal biomass range of $8–15/kg for ash-free organic dry biomass (Lee, 2001). For algal biomass to be cost competitive with petroleum-derived fuel stocks, the cost of production needs to be reduced to about $0.25/kg of ash-free organic dry biomass (Pedroni et al., 2001). In addition to lowering production costs, there remains considerable room for improvement in overall productivity of microalgae systems. For example, water loss and make-up, salt management, and thermal management remain outstanding system issues, especially in hot, arid environments (although these issues may be partially addressed by covering the raceways with green houses; at the expense of higher capital costs). Issues of productivity from species control to neutral lipid (oil) yield and harvesting are clearly themes central to biomass production. There is an urgent need to research how to isolate, select, improve, and maintain the algal strains required for large-scale, low-cost microalgae cultivation. Algal-species dominance and grazer control (and other biological invasions) are also troublesome aspects during scale-up. Moreover, the biomass concentration must be monitored and harvest times must be optimized to prevent excessive build-up of algae that increases the opacity of the water and creates optically dark zones. There is also a need to optimize the trade-off between biomass growth and neutral lipid production. Neutral lipid build-up can be triggered by imposing various stress factors on the algae. This leads to a slower growing or even contracting overall biomass but an increase in oil production.

1.2. Raceway ponds

Raceway ponds for microalgae cultivation have been in use since the 1950s. Considerable experience exists on the operation and engineering of raceway ponds and facilities. Currently, 440,000-m² (44-hectares, or 108.7-acres) of ponds are in use globally (Spolaore et al., 2006). Production of microalgal biomass for biofuel has been evaluated in studies of open-channel raceways sponsored by the U.S. Department of Energy (Sheehan et al., 1998). Despite their lower specific yield, open-channel raceways generally cost less to build, operate, and maintain than closed photo-bioreactors. These same growth-kinetics modeling subroutines used in raceways could easily be incorporated into a computation fluid dynamics internal flow model of a photobioreactor, hence this model could easily be migrated to simulate these systems.

A raceway pond is a closed-loop recirculation channel that is typically 0.1–0.3 m deep. The raceway is constructed of concrete or compacted earth and may be plastic lined to mitigate seepage losses. A paddlewheel is generally used to recirculate the biomass and the growth media (nutrients and water). Mixing is achieved through a combination of the effects of the paddlewheel and the interaction of the flowing water with the bottom and sides of the raceway. The flow rates and the depth of the raceway affect the distribution of nutrients, and these factors should be regulated to maintain algal suspension and mixing. Often, the culture is fed ahead of the paddlewheel and is harvested behind the paddlewheel upon completion of the circulation loop. CO₂ can be bubbled through the system to improve aeration and mixing, increase CO₂ consumption, and enhance algal biomass growth.

Although raceways are currently used for lower-cost biomass production, a number of operational parameters are candidates for analysis and optimization, including temperature, incident radiation, effects of covering raceways with greenhouses, nutrient availability, depth flow characteristics, geometry and channel dimensions, and predation.
2. METHODS

This work outlines a modeling platform that, from a systems-level standpoint, can be used to optimize algal growth in open-channel raceways. This effort is a qualitative exercise; system- and algae-specific parameters must be incorporated to obtain quantitative results applicable to a specific algae species and system. A detailed account of algae growth in open-channel raceways is provided by Terry and Raymond (1985).

2.1. EFDC and CE-QUAL models

The Environmental Fluid Dynamics Code (EFDC) (Hamrick, 1996), developed for the U.S. Environmental Protection Agency (EPA, 2000), is a fully three-dimensional hydrodynamic solver. The code solves the hydrostatic, free surface, Reynolds-averaged Navier-Stokes equations with turbulence closure similar to the models of Blumberg and Mellor (1987) and Johnson et al. (1993). The numerical solution techniques are the same as those of Blumberg and Mellor (1987) except for the solution of the free-surface, which is done using a preconditioned conjugate gradient (direct) solver rather than an alternating-direction-implicit method.

EFDC solves the three-dimensional, primitive-variable, vertically-hydrostatic, free-surface, turbulent-averaged equations of motions for a variable-density fluid. The model uses a stretched or sigma vertical coordinate and Cartesian or curvilinear-orthogonal horizontal coordinates. Dynamically coupled transport equations for turbulent kinetic energy, turbulence length scale, salinity, and temperature are also solved. The model is forced by boundary loadings, atmospheric conditions (e.g., temperature, pressure, wind shear, precipitation), and re-circulating boundary conditions. Thermal gains to the growth media are from wind-driven atmospheric convection and solar radiation absorption, while losses are through radiative heat transfer at night and any conductive exchange with the walls and bottom of the raceway.

The three-dimensional continuity equation in the stretched vertical and curvilinear-orthogonal horizontal coordinate system is as follows (Eq. 2.6 in Tetra Tech Inc., 2002):

\[ \frac{\partial}{\partial t} \left( m_x m_y H \right) + \frac{\partial}{\partial x} \left( m_y H u \right) + \frac{\partial}{\partial y} \left( m_x H v \right) + \frac{\partial}{\partial z} \left( m_x m_y w \right) = S_H, \]

where \( u \) and \( v \) are the horizontal velocity components in the dimensionless curvilinear-orthogonal horizontal coordinates, \( x \) and \( y \), respectively. The vertical velocity in the stretched vertical coordinate, \( z \), is \( w \). The scale factors of the horizontal coordinates are \( m_x \) and \( m_y \). The total water-column depth is \( H \). \( S_H \) represents volume sources and sinks including rainfall, evaporation, and any inflows and outflows.

Heat energy in the system is advectively and diffusively transported through the water column. There is convective heat transfer between the water surface and the atmosphere that is driven by the temperature difference and wind speed. Solar radiation (as mitigated by shade and/or cloud cover) is absorbed during the day and radiated away at night. Heat transfer between the water column and sides/bottom of the raceway is also allowed.

CE-QUAL was developed by the U.S. Army Corps of Engineers for a eutrophication study of Chesapeake Bay. This model, which operates fully in all three dimensions, initially had 23 independently activated scalar variables (Cerco and Cole, 1995) defined in Table 1, all of which are tracked in space and time (i.e., there is no averaging except within a single finite difference cell). Information required by CE-QUAL includes horizontal and vertical flows, cell volumes, cell dimensions, horizontal and vertical

<table>
<thead>
<tr>
<th>Table 1. Water-Quality Model State Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
</tr>
<tr>
<td>Salinity</td>
</tr>
<tr>
<td>Total active metal</td>
</tr>
<tr>
<td>Cyanobacteria</td>
</tr>
<tr>
<td>Diatoms</td>
</tr>
<tr>
<td>Green algae</td>
</tr>
<tr>
<td>Dissolved organic carbon</td>
</tr>
<tr>
<td>Labile particulate organic carbon</td>
</tr>
<tr>
<td>Refractory particulate organic carbon</td>
</tr>
<tr>
<td>Ammonium</td>
</tr>
<tr>
<td>Nitrate</td>
</tr>
<tr>
<td>Dissolved organic nitrogen</td>
</tr>
</tbody>
</table>

MODELING ALGAE GROWTH IN AN OPEN-CHANNEL RACEWAY 897
flow-face areas (curvilinear faces are approximated as their planar equivalents), and temperature distributions. The ability to monitor dissolved CO₂ concentrations including uptake by algae and exchange with the atmosphere (or added sources) was specifically added to the CE-QUAL model.

2.2. Algae growth

The governing equation for algal biomass growth is (Eq. 3.1 in Cerco and Cole, 1995):

\[
\frac{\partial}{\partial t} B = \left( P - B_M - P_R - w_s \right) B_t,
\]

(2)

where \( B \) is the algal biomass expressed as carbon equivalents (g C/m³), \( P \) is the production rate (1/day), \( B_M \) is the basal metabolism rate (1/day), \( P_R \) is the predation rate (1/day), and \( w_s \) is the settling velocity (m/day). The biomass production rate is determined by the availability of nutrients, the intensity of light, and the ambient temperature. The effect of each is multiplicative (Eq. 3.2 in Cerco and Cole, 1995),

\[
P = P_M f(N) g(I) h(T),
\]

(3)

where \( P_M \) is the production under optimal conditions (1/day), \( f(N) \) is the effect of non-optimal nutrient concentration (0 ≤ \( f(N) \) ≤ 1), \( g(I) \) is the effect of non-optimal illumination (0 ≤ \( g(I) \) ≤ 1), and \( h(T) \) is the effect of non-optimal temperature (0 ≤ \( h(T) \) ≤ 1). In the present analysis, nutrients are assumed to be in excess (i.e., \( f(N) = 1 \)), a reasonable assumption for a system wherein algae are cultured and nutrients can be monitored and added as needed. All of these functions are spatially dependent, and their values vary from cell to cell according to local nutrient concentrations, incident solar radiation, and temperature.

We collaborated with experimental biologists to improve upon the default values of the model parameters provided in CE-QUAL. The ideal growth parameters and growth rates for each species of algae vary significantly. As an illustrative example of the model’s capabilities, we chose to work with the widely documented diatom *Phaeodactylum tricornutum* (Bohlin).

2.3. Effect of varying light

The formulation of the correction due to non-optimal illumination is derived from Steele’s equation (DiToro, 1971)

\[
f(I) = \frac{I}{I_o} e^{1 - \frac{I}{I_o}},
\]

(4)

where \( I \) is the instantaneous illumination rate (W/m²) and \( I_o \) is the optimal illumination rate (W/m²). Algal production increases as a function of light intensity until an optimal intensity is reached, and beyond that optimal value, production varies in accordance with the type of light source. That is, algal growth curves under condition of continuous light and intermittent light (typically 14 hours of light, 10 hours of dark) are unique and species dependent (Nelson et al., 1979). Subject to intermittent light, growth rates approach a constant value, which is a function of the intermittency of the light, as the light intensity increases. On the other hand, under conditions of continuous light, the algal growth rate reaches a peak at the optimal light intensity and declines thereafter, but at a slower rate than under intermittent illumination. This decline may be attributed to the absence of an adequate recovery period for the light absorbing antenna apparatus of the photosynthetic process of algal cells. The equations adopted in the code assume a growth curve similar to that of algae growth under conditions of continuous light. The effect of intermittent light is accounted for through a correction factor termed “fractional day-length” (0 ≤ FD ≤ 1). Because the growth curves for algae cultured under intermittent and continuous light are quite different, the formulation adopted serves as an approximation. Further, the equation couples the effects of light intensity and biomass concentration on the growth rate through self-shading with depth penetration. Figure 1 compares empirical data from Geider et al. (1985) with the model’s equation for the effect of sub-optimal illumination when the algae concentration is approximately constant, and this serves as a justification for use of Eq. (4).

2.4. Effect of temperature

A second growth limiting parameter is temperature. Algal growth rate increases with temperature up to an optimal and decreases with further increases (Cossins and Bowler, 1987). It remains widely debated
whether the relationship between the growth rate and temperature is exponential or linear, with no conclusive evidence in support of either model (Montagnes and Lessard, 1999; Raven, 1988). CE-QUAL assumes an exponential variation for limitation due to non-optimal temperature $f(T)$ (Eq. 3.13 in Cerco and Cole, 1995):

$$h(T) = e^{-K(T - T_{\text{opt}})^2},$$

where $T$ is the local water temperature, $T_{\text{opt}}$ is the temperature for optimal growth, and $K$ is an empirical constant. Although two independent values of $K$ may be used to model $h(T)$ for temperatures above and below the optimal temperature, a single value of $K$ is adopted for this example to reduce the number of variables. Here, the values of $K$ and $T_{\text{opt}}$ are chosen to match the growth rate data presented by Montagnes and Franklin (2001) (Fig. 2). Because the data available are restricted to the temperature between 8°C and 25°C, extrapolating the curve to other temperatures serves as an approximation.

FIG. 1. Effect of sub-optimal illumination on algae growth rate. The model’s approximation, (4), is compared to experimental data from Geider et al. (1985). The graph plotted is for a case of constant biomass concentration. The functional behavior is assumed to hold at other biomass concentrations.

FIG. 2. Effect of temperature on the growth rate of $P. \text{tricornutum}$. The growth curve parameters are fit to data from Montagnes and Franklin (2001) and D. Franklin (unpublished data). The experimental data presented are obtained under a 14:10 light/dark (L:D) cycle at 50 μmol photons/m²-s. The method adopted in the code assumes that the effects of nonoptimal light and temperature on growth are independent.
Photosynthesis (as a result, growth rate at non-optimal temperatures) is affected by the intensity of illumination (Thompson, 1999). The model assumes that the effects of illumination and temperature on growth rates are independent. If more complex relationships are justified, they could easily be incorporated.

2.5. Effect of varying CO$_2$ concentration

An additional water-quality state variable representing the dissolved CO$_2$ concentration in the fluid was introduced. Figure 3 represents the interaction of inorganic carbon with the atmosphere and the food chain. Due to the small equilibrium constant for the hydration of CO$_2$, the proportion of carbonic acid is negligible. Therefore the processes of hydration and dissociation are conventionally treated as a single reaction (Chapra, 1997):

\[
H_2CO_3^* = HCO_3^- + H^+,
\]

where $[H_2CO_3^*] = [CO_2] + [H_2CO_3] \approx [CO_2]$. The concentration of $H_2CO_3^*$ is evaluated at each time step taking into consideration changes as a result of heterogeneous reactions such as re-aeration, photosynthesis, respiration, point-source loads, atmospheric forcing, and reactions involving organic carbon. Organic carbon consists of particulate organic carbon and dissolved organic carbon. One fraction of the particulate organic carbon undergoes dissolution to dissolved organic carbon, a second fraction settles to the bed and the remaining fraction is suspended in the fluid as a result of mixing. In this model, it is assumed that no particulate carbon is recycled from the raceway bottom to the water column. The dissolved organic carbon is respired or denitrified at a first-order rate into inorganic carbon. Heterogeneous reactions such as calcium carbonate dissolution and precipitation are not considered in the analysis. The saturation concentration of $H_2CO_3^*$ is computed as a function of temperature (Edmond and Gieskes, 1970).

Thermal management and the methods by which it is accomplished is a major consideration in whether a system will have favorable energy balance and affordability. Incorporation of the total heat content of the system as an output of the model facilitates study of additional cost and benefits of heating the system during winter or cooling the raceway during summer. For example, growth rates under conditions of restricted temperature fluctuation may be evaluated.

2.6. Model construction

A curvilinear orthogonal grid (Fig. 4) was developed to model a 43-m-long, 3-m-wide, closed-circuit algal raceway with a surface area of 129 m$^2$ (0.032 acre) and a volume of 38 m$^3$ (10,039 gallons). The 1860-cell grid comprises 15 $x$-coordinate cells and 124 $y$-coordinate cells. Four sigma ($z$-coordinate) levels were used. Grid independence was confirmed by comparing these results to those obtained from a grid with 10 sigma levels (water layers). The time step was 0.05 s to ensure model stability as stipulated by the

---

FIG. 3. Representation of the inorganic carbon cycle and its relationship with the food chain. The inorganic carbon species are carbonate (CO$_3^{2-}$), bicarbonate (HCO$_3^-$), and carbon dioxide/carbonic acid (H$_2$CO$_3^*$). Reactions with the food chain include photosynthesis (P) and respiration (R) (Chapra, 1997).
Courant-Friedrichs-Lewy (CFL) criterion. The CFL criterion is a condition for the convergence of an explicit time-marching solution to a hyperbolic partial differential equation. The model’s time step must be less than the advective flow time across the smallest cell to avoid inaccurate results. A withdrawal/return boundary condition was applied at the entrance and exit of the raceway. This ensures that the fluid, nutrients, and algae leaving the raceway through the last cell reenters the raceway through the first cell of the grid to replicate the operation of a paddlewheel. Although the model determines the algae concentration in units of grams of carbon per cubic meter, we use the Redfield ratio to obtain the algae concentration in units of grams biomass per cubic meter (Redfield, 1934).

The initial flow rate was assumed to be constant across the cross-sectional flow area and was set to 6.25 L/s. The initial algae concentration was 0.6 g/m³. The water in the algae raceway is initially saturated with CO₂. External sources of nitrogen, phosphorus, and silica are required for algae growth and are assumed in excess, although nutrient deficiency may be required to trigger lipid production. The channel roughness was chosen to mimic a plastic-lined channel; the log-law roughness height was specified to be 0.002 m. Atmospheric data from Palm Springs, California, during January and July, 2005 were used to model atmospheric conditions at potential algae farm sites (NCDC, 2005; NSRDB, 1961–1990.)
1991–2005). Hourly observations of temperature (wet/dry bulb), wind velocity, incident radiation, cloud cover, evaporation, precipitation, relative humidity, and atmospheric pressure are incorporated. The model accounts for salinity accumulation due to evaporation or dilution due to precipitation. The initial water temperature was 25°C. In the effort to optimize the growth rate, system parameters such as the raceway depth and the flow velocity could be varied.

3. RESULTS

When the model is properly configured, quasi-steady flow is quickly achieved (i.e., a velocity profile due to the friction between the fluid and the raceway walls/bottom is attained as driven by wind shear forces at the water surface and the specified flow from the paddlewheel). The model provides spatial and temporal data not only on the algal concentration in the raceway and the total biomass, but also for related variables such as temperature, dissolved CO₂, and residual nitrogen, phosphorus, and silica. Figure 5 shows the calculated algae concentrations plotted as functions of time for both January and July growth periods (left y axis). Temperature variations during the same months are also plotted (right y axis).

During the month of January, the atmospheric temperature varied between 9°C and 26°C, driving the growth media temperature along a similar trend. Thermal gains/losses in the pond are due to direct absorption of solar radiation, convective heat transfer from the atmosphere, short-wave radiation to the atmosphere at night, and conductive exchanges with the walls/bottom of the raceway. Because the temperature oscillated about the optimal growth temperature of *P. tricornutum* (~20°C), algae growth was rapid. During the daylight hours, indicated by an increase in the growth media temperature, the algae concentration increased. In the absence of daylight, the algal concentration decreases marginally due to consumption of organic carbon in the absence of photosynthesis due to algal respiration. The model is able to closely capture atmospheric phenomena as illustrated between days 6 and 8, when temperatures hovered around 9°C. During those days, extensive cloud cover resulted in decreased solar radiation and atmospheric temperature. Because the resultant growth media temperature and illumination levels were well below optimal, there was no significant increase in the algae concentration. Despite the adverse atmospheric conditions for a fraction of the growth period, the modeled algae concentration quadrupled in a matter of 10 days.

High atmospheric temperatures during July were well in excess of the optimal growth temperature and consequently algal growth rate significantly decreased. The algal concentration doubled over a period of 10 days. As the growth media temperature increases beyond optimal, growth rate slows. Decreases in algae concentration during the night, as explained above, are again observed.

An interesting phenomenon is observed in the model results at the 180° bend of the raceway. Due to drag force interaction between the culture fluid and the walls and bottom of the channel, a helical flow pattern is

![FIG. 5. Comparing algae growth and water temperature during January and July 2005. The model accurately reflects the effect of atmospheric conditions on algae growth rates and water temperature.](image)
established. This helical flow pattern is beneficial to algae growth because it results in multiple decreasing amplitude inversions of the water column, bringing water with low algae concentrations from the raceway bed to the surface euphotic zone, shortening average dark cycle times.

Variation of the concentration of dissolved O₂ and dissolved CO₂ in the growth media follow the trend of the diurnal changes in temperature and contributions from biomass are secondary. These results are supported by the fact that the system is well mixed due to the helical flow patterns at the 180° bends of the raceway and the effect of the paddlewheel (results not shown). CO₂-limited growth may occur under optimal growth conditions and external CO₂ sources may be needed to maximize biomass growth. This model could help identify the trade-off between the costs of providing additional CO₂ for improved algae yield.

Figure 6 illustrates the effect of water-column depth on the algae concentrations and the water temperature. As the water column depth increases, diurnal fluctuations in the temperature are less pronounced. At 10 cm, the water temperature closely follows the atmospheric temperature. At 60 cm, the water temperature follows the trend of the atmospheric temperature, but the variance is considerably less. The larger water body serves as a heat “buffer,” moderating the temperature. As a result, the water remains closer to the optimal algal growth temperature and growth is improved. A practical upper limit for the depth of the water column exists due to the attenuation of light in water as exacerbated by nutrient and algae concentrations. Results indicate that the water-column height may be varied in response to the atmospheric temperature to maximize algae yield.

Increasing the flow rate above 6.25 L/s does not improve the algae growth rate (Figure 7). At a flow rate of 6.25 L/s, the algae growth rate is relatively independent of the flow rate because the growing media is

---

**FIG. 6.** Effect of water-column depth on algae growth and water temperature. As the depth increases, the water body serves as a heat “buffer,” moderating the water temperature fluctuation.

**FIG. 7.** Increasing the flow rate from 6.25 to 62.5 L/s does not have a significant impact on the growth rate. Some minimum flow rate above 0.625 L/s must be maintained to ensure complete mixing in the system.
well mixed. When the flow rate is decreased by an order of magnitude to 0.625 L/s, the growth rate is impacted due to incomplete mixing of the growing media at such a slow flow rate. The model is capable of optimizing the flow rate for a given raceway configuration and thus minimizing power requirements for the paddlewheel.

The benefit of controlling atmospheric temperature (e.g., holding it constant within a greenhouse at 20°C) or by physically heating or cooling the water column is quantified in terms of the growth rate. Figure 8 compares the growth rates with and without atmospheric temperature regulation. Figure 9 illustrates the power requirements to maintain the water temperature within the range of 20 ± 2°C. The model is capable of assisting in decision making based on the economic feasibility of artificial temperature regulation and whether the corresponding increase in algae growth rate justifies the increased operating cost.

4. CONCLUSION

These results are illustrative of the broad range of data that may be obtained and analyzed from a model of a raceway pond. We have shown that extant environmental codes such as EFDC coupled with water-quality codes such as CE-QUAL can be used to model algae growth in raceway channels. This technique affords the opportunity to avoid lengthy, expensive experimental trials that currently constitute the bulk of scientific research in the rapidly emerging area of algal culture for biofuels production. The greatest benefit that numerical simulation of the flow system offers is the ability to design the raceway and set operational ranges of parameters before construction, thus avoiding the all-too-often used trial-and-error method.
Modeling should be used to optimize system parameters to improve efficiency. These could include new raceway designs, ideal flow rates, raceway depths (perhaps varied as a function of algae concentrations), and optimal harvest times. Correlation of variable flow rate and channel depth to solar energy conversion efficiency could also yield interesting results. The impact of climate change on growth rates and biomass productivity could also be used to determine long-term feasibility of a project. Moreover, experiment operators can evaluate the impacts of various system conditions (e.g., depth, harvest frequency, flow speeds) without having to risk the algal biomass under study. The savings in cost and time could be enormous.

Most experimental data available are sourced from small-scale tests. This model could be used to determine the feasibility and potential benefits of scaling up. Further, simulations may be run to quantify the benefits of integrating algae culture ponds with waste treatment plants and fossil-fuel-based power plants, among other possibilities.

ACKNOWLEDGMENTS

We are grateful to the Enabling & Predictive Simulation Research Institute, Sandia National Laboratories, and Bob Carling for financial support. We would also like to thank Ron Pate and Dominick Mendola for helpful comments on the early manuscript. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy’s National Nuclear Security Administration (under contract DE-AC04-94AL85000). This work was supported in part by the Laboratory Directed Research and Development program at Sandia National Laboratories.

DISCLOSURE STATEMENT

No conflicting financial interests exist.

REFERENCES


Address correspondence to:

*Dr. Scott C. James*

Sandia National Laboratories

*Thermal/Fluid Science & Engineering*

P.O. Box 969

Livermore, CA 94551-0969

E-mail: scjames@sandia.gov