Numerical and experimental investigation of hydrodynamics and light transfer in open raceway ponds at various algal cell concentrations and medium depths

Hossein Amini^{a,*}, Abolhasan Hashemisohi^a, Lijun Wang^{b,**}, Abolghasem Shahbazi^b, Marwan Bikdash^a, Dukka KC^a, Wenqiao Yuan^c

^a*Computational Science and Engineering Department, NC A&T State University; 1601 E. Market St. Greensboro, NC 27411*

^b*Chemical, Biological and Bioengineering Department NC A&T State University 1601 E. Market Street Greensboro, NC 27411*

^c*Biological and Agricultural Engineering Department NC State University D.S Weaver Labs, Campus Box 7625, Raleigh, NC 27695*

Abstract

A spectral radiation-transport model was integrated with a three dimensional computational fluid dynamics model to simulate the hydrodynamics and light transfer in open raceway ponds (ORPs). The predicted three-dimensional velocity and light intensity agreed well with measured values collected on a lab-scale ORP. However, there was a slight difference in the predicted velocity profiles using two different types of boundaries for the paddlewheel, i.e., the moving zone boundary and inlet velocity boundary, with R^2 values between the predicted and measured velocities of 0.9947 and

*E-mail address: hossein.amini.che@gmail.com

**corresponding author; E-mail address: lwang@ncat.edu

0.9838, respectively. The R^2 value between the predicted and measured light intensity was 0.9939. Simulations were further conducted on a large-scale ORP with 100 m² surface area operated at total medium depths of 0.2 and 0.3 m, average cell concentration of 0.4 g/L, and inlet velocities of 0.1, 0.2 and 0.3 m/s from the paddlewheel. The increase of inlet flow velocity from 0.1 to 0.2 m/s resulted in a more uniform cell concentration profile. However, when the inlet velocity was further increased from 0.2 to 0.3 m/s, there was only a slight increase in the uniformity of the cell concentration. In addition, the simulation results showed that sedimentation of cells more likely occurred at the bottom of the ORP with a total medium depth of 0.2 m than at 0.3 m at the same inlet velocity. The increase of inlet velocity from the paddlewheel resulted in a uniformly distributed light intensity in the region near the medium surface (e.g., 0.05 m depth from the surface) owing to improved mixing. However, owing to a sudden drop in the light intensity after a few centimeters from the medium surface, the cell sedimentation that occurred at the bottom of the ORPs had negligible effects on the light penetration depth in the medium.

Keywords: Open raceway pond; microalgae; light intensity distribution; computational fluid dynamics; *Chlorella vulgaris*

1. Introduction

Microalgae have been considered as energy crops for biofuels since the 1970s [1, 2]. Open raceway ponds (ORPs) are considered as economical systems for large-scale cultivation of microalgae [3]. It is critical and challenging to achieve a uniform distribution of nutrients, CO_2 , light, and algal cells in an ORP for high productivity and energy efficiency [4]. The cultivation of microalgae in an ORP is a complicated hydrodynamic process in multiphase flow involving solid algal cells, CO_2 and O_2 gases, and liquid culture medium. Proper mixing during the multiphase flow in an ORP is the key to efficiently supply CO_2 , remove generated O_2 , evenly distribute nutrients, prevent cell sedimentation, and improve the accessibility of light for all cells [4–6].

Light is one of the important factors that affect the microalgae growth rate [7]. The density of algal culture affects both the local light intensity and light penetration depth [7]. In order to achieve optimal design and scale-up of an ORP, it is very important to understand the effects of design parameters and operating conditions on mixing and light distribution patterns in an ORP. The effects of different ORP geometries and designs on mixing and light intensity distribution have been studied experimentally [3, 5, 8]. The velocity distribution in an ORP can be used to determine the effectiveness of mixing

in ORP channels. However, it cannot fully predict the algal cell distribution that directly affects the light distribution in the ORP [4]. Therefore, it is important to study the algal cell flow patterns in an ORP and the effect of lighting characteristics such as light scattering and absorption coefficients on algal cells.

The simulation of radiative transport within a photobioreactor is computationally challenging owing to its spatial, directional, and wavelength dependencies resulting from the complex interactions of radiation with water, algae, and air. However, modern commercial computational fluid dynamics (CFD) tools enable us to make use of a wavelength dependent radiative transfer equation (RTE) in well-resolved complex geometries of algal culturing systems [9]. CFD models can be used to predict the multiphase flow patterns and light intensity distribution in an ORP [8, 10, 11]. In addition, they were used to evaluate the power consumption, dead zone volume, and shear stress under different velocities, channel length-to-width ratios, and culture depths [12–14]. Furthermore, CFD models were used to study cell trajectory and mixing efficiency in ORPs [3, 4]. It is also possible to apply CFD simulations to analyze the radiation characteristics of solids in suspension, and the effects of solid concentration and system geometry on the light

transfer pattern [7, 15, 16]. However, the mixing characteristics in those published CFD models were evaluated solely based on the fluid flow pattern in ORPs without consideration of real algal cells. Those models could not predict the dynamic algal distribution in ORPs, which affects light distribution and mixing.

The objective of this study was to develop a CFD model to simulate the hydrodynamics of multiphase flow and the resulting light intensity distribution in an ORP simultaneously with microalgal cells at various medium depths. The CFD model was further validated by the experimental data of velocity and light distribution collected from a lab-scale ORP.

2. Materials and experimental methods

2.1. Microalgae strain and culture medium

C. vulgaris (UTEX 2714) was purchased from the UTEX culture collection of algae at the University of Texas in Austin. The algal seed was cultivated using the autoclaved Bolds medium. The seed tubes were incubated in a shaker (AlgaeTron AG 130-ECO, Quibit systems Inc., Canada) at a temperature of 24°C and light intensity of 22 W/m² to prepare the pre-culture as recommended by the supplier.

57 The traditional Bold's medium was used to cultivate *C. vulgaris* in the
58 ORP. The Bold's medium was composed of 25 mg/L $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, 75 mg/L
59 $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, 250 mg/L NaNO_3 , 25 mg/L NaCl , 75 mg/L K_2HPO_4 , 175 mg/L
60 KH_2PO_4 , 8.82 mg/L $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$, 1.44 mg/L $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$, 0.71 mg/L MoO_3 ,
61 1.57 mg/L $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, 0.49 mg/L $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, 11.42 mg/L H_3BO_3 , 50.0
62 mg/L EDTA, 31.0 mg/L KOH, 4.98 mg/L $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ and 1.0 ml/L H_2SO_4 .

63 2.2. Cultivation of *C. vulgaris* in lab-scale ORP

64 Experiments were carried out in a lab-scale ORP in a greenhouse as shown
65 in Figure 1 to validate the CFD model. The ORP was constructed of fiber
66 glass, with dimensions of 1.4 m length $\times$ 0.5 m depth $\times$ 0.35 m width. The
67 paddle wheel was constructed of stainless steel, including five blades with a
68 length of 0.30 m and a width of 0.24 m. The paddle wheel was driven by
69 a two-phase motor with variable speed to control the rotational speed of
70 the impeller. The paddle wheel rotational speed was set at 10 rpm for all
71 experiments. The minimum gap between the tip of the blades and the pond
72 bottom was 0.01 m. Experiments were conducted under a medium depth of
73 0.2 m and a total medium volume of 140 L. Fluorescent light panels, each of
74 which includes eight fluorescent light bulbs with a total power of 97 W, were
75 installed directly above the paddle wheel of the ORP to achieve a constant

(a) Experimental ORP

(b) Locations for velocity measurement

(c) Locations for light intensity measurement

Figure 1: Lab-scale ORP in a greenhouse and the diagram of the locations for the measurement of velocity and light intensity

76 continuous light intensity of 22 W/m^2 on the surface of the pond.

77 A total of 140 L precultured *C. vulgaris* in Bolds medium at a cell con-
78 centration of 0.1 g/L was prepared and transferred into each ORP at the
79 beginning of the cultivation.

80 2.3. Velocity and light intensity measurements in ORP channels

81 The three-dimensional velocity distribution (v_x , v_y , and v_z) in the ORP
82 was measured at an acoustical sampling frequency of 25 Hz by an acoustic
83 Doppler velocimeter (ADV, NorTek, Vectrino, Norway). The lab-scale ORP
84 has two channels separated by a divider as shown in Figure 1. The pad-
85 dlewheel is located in one channel. The field velocity measurements were
86 carried out at 12 locations immediately after the bend of the other channel
87 with three different depths of 0.05, 0.1, and 0.15 m and four different dis-
88 tances of 0.05, 0.1, 0.15, and 0.2 m from the channel wall, as shown in Figure
89 1b.

90 Various concentrations of *C. vulgaris* at 0.1, 0.2, 0.3, and 0.4 g/L were
91 used in the ORP illuminated by the panels to measure the light distribution.
92 The photosynthetically active radiation (PAR) under the water surface was
93 measured at various depths (0-0.1 m) inside the ORP at the center of the
94 channel without the paddle wheel as shown in Figure 1c, using an under-

95 water light sensor (Li-cor LI-192 Underwater Quantum Sensor, Li-cor Inc.,
96 Nebraska, USA), connected to a data logger (LI1400, Li-cor Inc., Nebraska,
97 USA). This quantum sensor measures the PAR in the wavelength range of
98 400-700 nm from all angles in one hemisphere.

99 **3. Mathematical modeling of multiphase flow and light transfer**

100 *3.1. Eulerian multiphase CFD model*

101 An Eulerian multiphase model was developed to simulate the fluid dy-
102 namics of algal cells and culture medium. The two phases of algal cells
103 and culture medium were treated mathematically as fully interpenetrating
104 continua by introducing the concepts of solid-phase viscosity and solid-phase
105 pressure for algal cells [17]. The fluid of the culturing medium was considered
106 as the primary phase. The solid algal cells were considered as the secondary
107 phase to be dispersed in the first phase. A volumetric fraction, α , which
108 varies from 0 to 1, was assigned to each physical phase. Various volumetric
109 fractions were used in the model to represent different algal cell concentra-
110 tions. *C. vulgaris*, which has a spherical shape and single cell structure (d_p
111 = $3\mu\text{m}$ [18] and $\rho = 1125\text{ kg/m}^3$ calculated from wet cell mass and volume)
112 was used as the model algae in the culture medium.

113 The mass conservation equation for the phase, q , which is either for the
 114 algal cells or the culture medium, is given by

$$115 \quad \frac{\partial}{\partial t} (\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \vec{u}_q) = \sum_{p=1}^n (\dot{m}_{pq} - \dot{m}_{qp}) \quad (1)$$

116 where α_q is the volumetric fraction of the phase, ρ_q is the density of the phase
 117 q , $\vec{u}_q$ is the velocity vector of the phase q , and $\dot{m}_{pq}$ and $\dot{m}_{qp}$ are the inter-
 118 phase mass transfer between the p^{th} and q^{th} phase, respectively. The total
 119 volumetric fraction, which is the sum of all volumetric fractions, must be
 120 equal to unity, i.e., $\sum_{q=1}^n \alpha_q = 1$ in each computational cell. The momentum
 121 conservation equation for the phase, q , is given by

$$122 \quad \frac{\partial}{\partial t} (\alpha_q \rho_q \vec{u}_q) + \nabla \cdot (\alpha_q \rho_q \vec{u}_q \vec{u}_q) = -\alpha_q \nabla p_q + \nabla \cdot \vec{\bar{\tau}}_q$$

$$123 \quad + \alpha_q \rho_q \left(\vec{F}_{ex,q} + \vec{F}_{lift,q} + \vec{F}_{vm,q} \right)$$

$$124 \quad + \sum_{p=1}^n \left(\vec{R}_{pq} + \dot{m}_{pq} \vec{u}_{qp} - \dot{m}_{qp} \vec{u}_{qp} \right) \quad (2)$$

$$125$$

126 where $\vec{F}_{ex,q}$, $\vec{F}_{lift,q}$, and $\vec{F}_{vm,q}$ are the external body force, lift force, and
 127 virtual mass force, respectively. As the lift force is usually insignificant com-
 128 pared to the drag force, $\vec{F}_{lift,q}$ is assumed to be negligible [17]. $\vec{u}_{qp}$ and $\vec{u}_{pq}$

129 are the interphase velocities, and $\vec{R}_{pq}$ is the drag force between phases. $\bar{\bar{\tau}}_q$
 130 stands for the stress-strain tensor of the q^{th} phase that is defined as

$$131 \quad \bar{\bar{\tau}}_q = \alpha_q \mu_q (\nabla \vec{u}_q + \nabla \vec{u}_q^T) + \alpha_q \left(\lambda_q - \frac{2}{3} \mu_q \right) \nabla \cdot \vec{u}_q \bar{\bar{I}} \quad (3)$$

132 where μ_q and λ_q are the bulk viscosity and shear of the phase, q , respectively,
 133 and $\bar{\bar{I}}$ is the unit tensor.

134 3.1.1. Fluid-solid momentum exchange

135 The drag force acting on a single particle in a solid particle system can
 136 be expressed by the product of a liquid-solid momentum exchange coefficient
 137 K_{sl} and the relative (or slip) velocity between the liquid and solid phases
 138 [17].

$$139 \quad \vec{R}_{ls} = K_{ls} (\vec{u}_l - \vec{u}_s) \quad (4)$$

140 The fluid-solid exchange coefficient for a dilute solid-liquid system, such as a
 141 microalgal culture medium, can be written as [17]

$$142 \quad K_{sl} = \frac{3}{4} C_D \frac{\alpha_s \alpha_l \rho_l |\vec{u}_s - \vec{u}_g|}{d_s} \alpha_l^{-2.65} \quad (5)$$

143 where C_D is given by

$$144 \quad C_D = \frac{24}{\alpha_l Re_s} [1 + 0.15 (\alpha_l Re_s)^{0.687}] \quad (6)$$

145 3.1.2. Turbulence model

146 The RNG $k - \varepsilon$ turbulence model with a time-dependent solver was used
 147 to simulate the fluid flow in the coupled paddlewheel and raceway pond.
 148 The RNG $k - \varepsilon$ can achieve stable calculations even at a high Reynolds
 149 number. In addition, the $k - \varepsilon$ turbulence model generates solutions for
 150 complex geometries owing to the implementation of a wall function [4]. The
 151 governing equations of the turbulent kinetic energy, k , and dissipation rate,
 152 ε , are given by

$$153 \quad \rho \frac{\partial k}{\partial t} + \rho u_j \frac{\partial k}{\partial x_j} = \tau_{ij} \frac{\partial u_i}{\partial x_j} + \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] - \rho \varepsilon \quad (7)$$

154

$$155 \quad \rho \frac{\partial \varepsilon}{\partial t} + \rho u_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] \\ 156 \quad \quad \quad + C_{\varepsilon 1} \frac{\varepsilon}{k} \tau_{ij} \frac{\partial u_i}{\partial x_j} - C_{\varepsilon 2} \rho \frac{\varepsilon^2}{k} \quad (8) \\ 157$$

158 where σ_k and σ_ε are the turbulent Prandtl numbers for the kinetic energy
159 and dissipation rate, respectively, while $C_{\varepsilon 1}$ and $C_{\varepsilon 2}$ are the first and second
160 experimental model constants for dissipation rate, respectively. The values
161 assigned were $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$, $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.92$, and $C_\mu = 0.09$.

162 The turbulent viscosity defined by the $k - \varepsilon$ turbulence model is given by

$$163 \quad \mu_t = \frac{\rho C_\mu k^2}{\varepsilon} \quad (9)$$

164 3.2. Modeling of light transfer

165 3.2.1. Light transfer governing equation

166 Radiative intensity in an ORP depends on the spatial position and an-
167 gular direction. Radiation transfer into an absorbing, scattering, and non-
168 emitting medium, such as algal suspensions in a culture medium, is governed
169 by the RTE, which is derived from energy balance. In ANSYS Fluent, light
170 transfer in the culture medium can be modeled by the discrete ordinates
171 (DO) radiation model, which is based on the RTE [19]. The basic RTE at

172 position $\vec{r}$ and in the direction $\vec{s}$ can be written as

$$\begin{aligned}
173 \quad & \frac{dI(\vec{r}, \vec{s})}{ds} + (k + \sigma_s)I(\vec{r}, \vec{s}) \\
174 \quad & = kn^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r}, \vec{s}') \Phi(\vec{s} \cdot \vec{s}') d\Omega' \quad (10) \\
175
\end{aligned}$$

176 where $\vec{r}$ is the position vector, $\vec{s}$ is the direction vector, $\vec{s}'$ is the scattering
177 direction vector, s is the path length, k is the absorption coefficient, n is the
178 refractive index, σ_s is the scattering coefficient, σ is the Stefan-Boltzmann
179 constant ($5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$), I is the radiation intensity (which depends
180 on $\vec{r}$ and $\vec{s}$), T is the local temperature, Φ is the phase function, and Ω' is
181 the solid angle. The phase function $\Phi(\vec{s} \cdot \vec{s}')$ accounts for scattering from
182 direction $\vec{s}'$, to direction $\vec{s}$, and determines the fraction of in-scattering
183 radiation.

184 Several computational methods for solving equation (10) have been estab-
185 lished. However, only the DO finite volume and Monte Carlo (MC) methods
186 can be used to model non-gray radiation and semi-transparent walls [20].
187 The MC method is not often used in a CFD context owing to its high com-
188 putational cost, as it is difficult to couple MC radiation calculations with a
189 fluid dynamics solver. Consequently, the DO method was used to solve the

190 RTE in this study.

191 3.2.2. Medium optical properties

192 The absorption, scattering, and extinction coefficients in Equation (10)
193 are strongly dependent on the wavelength [19]. Under a single scattering
194 regime, the radiation characteristics of microorganisms are linearly depen-
195 dent on their concentration [19]. The specific scattering, absorption, and
196 extinction coefficients of *C. vulgaris* at 3.5 g/L were taken from literature
197 [21] and shown in Figure 2.

198 The average optical characteristics of *C. vulgaris* medium in the visible
199 light range (400-700 nm) were used to calculate the light intensity. The
200 optical characteristics of *C. vulgaris* at different local culture concentrations
201 can be determined by [21]

$$E_{ext,\lambda} = \frac{\beta_\lambda}{X} \quad , \quad A_{abs,\lambda} = \frac{k_\lambda}{X} \quad , \quad S_{scat,\lambda} = \frac{\sigma_\lambda}{X} \quad (11)$$

202 where $E_{ext,\lambda}$ is the specific spectral extinction coefficient; $A_{abs,\lambda}$ is the specific
203 spectral absorption coefficient; $S_{scat,\lambda}$ is the specific spectral scattering coef-
204 ficient; λ refers to the wavelength, β_λ is the spectral extinction coefficient,
205 and X is the cell concentration (kg/m³). To calculate the optical character-

Figure 2: Spectral specific absorption ($A_{abs,\lambda}$), scattering ($S_{scat,\lambda}$), and extinction ($E_{ext,\lambda}$) coefficients of *C. vulgaris* at a culture concentration of 3.5 g/L [21]

istics of *C. vulgaris* at a particular cell concentration, the values presented in Figure 2 should be divided by 3.5.

The scattering coefficient, σ_s , can be expressed as [19]

$$\sigma_{s,\lambda} = \beta_\lambda - k_\lambda \quad (12)$$

Figures 3a-3d show the specific optical characteristics of *C. vulgaris*, at various concentrations in the range of 0.1-0.4 g/L, which were calculated by Equations (11) and (12) using the data given in Figure 2. User defined functions (UDFs) were written in C programming language to determine the

Figure 3: Absorption (k_λ), scattering (σ_λ), and extinction (β_λ) coefficients for *C. vulgaris* [21] at the concentrations of (a) 0.1 g/L, (b) 0.2 g/L, (c) 0.3 g/L, and (d) 0.4 g/L

optical properties of *C. vulgaris* at various local cell concentrations. The UDFs were then hooked to the absorption and scattering coefficients tab on the material panel of the ANSYS Fluent CFD simulation platform for the algal cell phase.

3.3. Boundary conditions

The wall boundary condition was used for the side walls and bottom of the pond. A symmetry boundary condition was assigned for the top of the

220 system. There are two ways to define the boundary of the paddle wheel
221 in the CFD model: (1) moving zone and (2) velocity inlet. The inclusion
222 of the paddle wheel in the moving zone of a multiphase CFD model for
223 simulating a large-scale ORP is computationally intensive [4]. It is common
224 to simplify the model and reduce the computational time by using a constant
225 momentum source of inlet velocity generated by the paddle wheel in CFD
226 models [4, 10–12].

227 3.3.1. *Moving zone boundary of a paddle wheel*

228 For the simulation of the lab-scale ORP using the CFD model, the moving
229 paddle wheel was considered as a moving cylindrical zone that passes against
230 a cylindrical interface using the sliding mesh technique. The paddle wheel
231 blades were considered as wall boundary conditions circulating the water
232 in the channels. An interface boundary condition was used to connect the
233 moving zone with the multiphase-fluid zone in the ORP.

234 3.3.2. *Inlet velocity boundary of paddle wheel*

235 For the simulation of the large-scale ORP, the inlet velocity boundary
236 condition was used to account for the rotating paddlewheel. This simplifi-
237 cation can significantly reduce the computational time [8]. To validate this

238 simplification, simulations for the lab-scale ORP were conducted using both
239 boundary conditions for the paddle wheel which were used during the exper-
240 iments on the lab-scale ORP.

241 3.3.3. *Lighting boundary conditions*

242 The bottom and side walls of the ORP were considered to be opaque.
243 The top wall was considered as a semi-transparent wall. The top wall was
244 exposed to a radiation of 22 W/m^2 light intensity on the top of the fluid free
245 surface used in the lab-scale ORP during experiments.

246 3.4. *Computer simulation procedure*

247 All simulations were conducted using the ANSYS Fluent parallel mode
248 on a Dell Precision T7810 work station with 2 Intel Xeon CPUs and a total
249 number of 16 cores (E5- 2687W v3, 3.10GHz), 64 GB of RAM, and Windows
250 7 operating system.

251 3.4.1. *Lab-scale ORP modeling and experimental validation*

252 The predicted three-dimensional velocities (v_x, v_y , and v_z) and light in-
253 tensities were compared with those values measured at different locations of
254 the lab-scale ORP indicated in Figures 1b and 1c.

Figure 4: (a) Geometric design and (b) mesh generation of the CFD model

255 The three-dimensional geometric model was created in ANSYS work-
 256 bench 16.0 using DesignModeler as depicted in Figure 4a. As the paddle
 257 wheel was not entirely submerged, the computational domain at the paddle
 258 wheel location was extended up to 0.8m from the bottom of the ORP in
 259 order to encompass the impeller fully. Therefore, the ORP was divided into
 260 three domains: the moving zone of paddle wheel, multiphase culture medium
 261 zone, and air zone at the top of the culture medium.

262 The unstructured hexahedral mesh was created by the software ANSYS
 263 DesignMesh 16.0 (Figure 4b). The sliding mesh technique was used to ac-
 264 count for the paddle wheel rotation. This method represents the movement
 265 of the entire paddle wheel. The optimum mesh size was found to be 0.014 m,
 266 where the results did not significantly change by further decreasing the mesh

size. This mesh size led to 1.02×10^6 CFD cells. Time step sizes larger than 0.01 s resulted in divergence, whereas very small time step sizes were also computationally intense. Therefore, to prevent a diverging solution and save computational time, the time step size was set at 0.01 s.

To replace the moving zone boundary of the paddle wheel with the velocity inlet boundary condition, the linear velocity was calculated from the angular velocity of the rotating paddle wheel by

$$v = r\omega \quad (13)$$

where v is the linear velocity (m/s), r is the radius of the paddle wheel (m), and ω is the angular velocity of the rotating paddle wheel (rad/s).

3.4.2. Simulation of scaled-up ORPs

The model was used to study the effects of the inlet velocity from a rotating paddle wheel and channel depth on algal cell and light distribution in a large-scale ORP. The ORP had an area of 100 m^2 with an aspect ratio (AR) of channel length to width of 10, and two different medium depths of 0.2 and 0.3 m.

A case study was conducted to predict the light distribution in the chan-

284 nels of ORPs for the weather condition in North Carolina, USA. The solar
285 irradiance data provided by NREL, represents the light intensity on the sur-
286 face of the medium. The maximum solar irradiance of 330 W/m^2 in June
287 was used as the top radiation boundary condition of the CFD model.

288 3.4.3. *Determination of pseudo-steady-state condition*

289 As the fluid flow in an ORP is a transient phenomenon, simulations
290 started with zero velocity as the initial condition. However, a pseudo-steady-
291 state condition can be defined in which there are no significant changes in the
292 maximum velocity and the velocity profile when the simulation time further
293 increases. The simulation time required to achieve the pseudo-steady state
294 was defined as the minimum required mixing time. After the pseudo-steady
295 state was reached, the predicted three-dimensional velocities at each mea-
296 suring location for the next 20s simulation time at intervals of 0.25s were
297 exported to an excel file to calculate the average velocities in the x , y , and z
298 directions and were compared to the experimental data measured with the
299 ADV instrument.

300 4. Results and discussion

301 4.1. CFD code validation

302 Figure 5 shows the predicted velocity profile distribution in the lab-scale
303 ORP at a distance of 5 cm from the medium surface at various flow times.
304 When the rotational speed of the paddle wheel was 10 rpm, at which the in-
305 let velocity was 0.25 m/s, the maximum predicted velocities in the lab-scale
306 ORP were 0.43, 0.48, 0.86 and 0.82 m/s at simulation times of 5, 7.5, 10, and
307 15 s, respectively. Therefore, there was no significant change in the maximum
308 velocity when the simulation time was higher than 10 s. Figure 6 shows a
309 quantitative comparison between the experimental data and numerical re-
310 sults obtained using the moving zone and inlet velocity for the paddle wheel.
311 As observed from Figure 6, the three-dimensional fluid velocities in the x
312 and y directions (v_x and v_y) predicted by the CFD model agreed well with
313 experimental values. The slight differences observed for some points might
314 be caused by nonstationary vortexes during the experiments.

315 Figure 7 shows the overall comparison between the predicted and mea-
316 sured velocities. The predicted velocities for the simulations using the moving
317 zone boundary for the paddle wheel were determined as the average values
318 obtained for 20 s additional flow time at intervals of 0.25 s after the simula-

Figure 5: Predicted velocity profile distribution at a distance of 5 cm from the medium surface in the lab-scale ORP, at various flow times of (a) 5 s, (b) 7.5 s, (c) 10 s, and (d) 15 s

319 tion reached the pseudo-steady state. The R^2 value between the measured
 320 and predicted velocities by the CFD model with moving zone boundary for
 321 the paddle wheel was 0.9947. The velocities for the simulations using the
 322 inlet velocity for the paddle wheel were determined by the CFD model at a
 323 steady-state condition. The R^2 value between the measured and predicted
 324 velocities by the CFD model with the velocity inlet boundary for the pad-
 325 dle wheel was 0.9838. The simulation without considering the paddle wheel

Figure 6: Comparison of the predicted and measured three-dimensional velocities at various depths, with various distances from the outer wall of the open pond's channel

Figure 7: Statistical comparison of velocities obtained by experimental measurements, and CFD simulations with two types of boundary conditions for the paddle wheel

326 eliminated the effects of wave formation near the paddle wheel area. It can
 327 be observed from Figure 7 that there is a slight difference in the predicted
 328 velocity profiles using the two different types of boundaries for the paddle
 329 wheel. To reduce the computational time, the paddle wheel geometry was
 330 replaced with velocity inlet and outflow boundary conditions for simulating
 331 large-scale ORPs, as the simulation of the paddle wheel was not the focus of
 332 this study. Three different velocities, i.e., 0.1, 0.2, and 0.3 m/s were consid-

Figure 8: Contours of the predicted light intensity distribution in the lab-scale ORP channel containing the *C. vulgaris* culture medium with a dry algal concentration of 0.1 g/L

333 ered in this study. However, the simulation of paddle wheel design should be
 334 considered for the energy consumption analysis and the design of a paddle
 335 wheel.

336 4.1.1. Light intensity validation

337 Figure 8 shows the contour plot of the computed total radiative flux in the
 338 lab-scale ORP channel containing *C. vulgaris* culture medium at an initial
 339 cell concentration of 0.1 g/L. The predicted light intensity was higher in the
 340 regions far from the side walls and in the middle of the ORP channel. The
 341 low light intensity in the regions near the side walls, middle wall, and paddle
 342 wheel, was caused by the shielding of irradiation from the light panels at the
 343 top.

Figure 9 shows the comparison between the measured and predicted total

Figure 9: Comparison of experimental (symbols) and predicted (dash dotted lines) light distribution (400-700 nm) at various depths of the lab-scale ORP and concentrations of 0.1 g/L, 0.2 g/L, 0.3 g/L, and 0.4 g/L

344

345 radiative flux on a plane located in the middle of the lab-scale ORP channel

346 at various depths ranging from 0.01 to 0.10 m at various algal biomass con-

347 centrations of 0.1, 0.2, 0.3, and 0.4 g/L. The predicted light intensity profiles

348 were in good agreement with the measured profiles. The CFD model slightly

349 overestimated the light intensity compared to the measured light intensity,

350 which might be caused by shading effects during measurements. Figure 10

Figure 10: Statistical comparison of light intensities obtained by experimental measurements and CFD simulations at four different culture medium concentrations

351 shows the overall comparison between the predicted and measured light in-
 352 tensities. The R^2 value between the measured light intensities and predicted
 353 values by the CFD model was 0.9939. It can be observed from Figure 9 that
 354 the light intensity significantly decreased with increase of algal cell concentra-
 355 tion. The measured light intensity at the depth of 0.05 m from the medium
 356 surface decreased from 8.7 to 0.5 W/m² when the algal cell concentration
 357 increased from 0.1 to 0.4 g/L.

358 4.2. Effects of inlet velocity from paddle wheel and medium depth on mixing

359 4.2.1. Effects of paddle wheel velocity

360 The effects of inlet velocity and medium depth were studied on algal cell
361 mixing in an ORP with 100 m² footprint area and an algal cell concentration
362 of 0.4 g/L. Figure 11 shows the velocity contours at the depth of 0.05 m from
363 the medium surface for both medium depths of 0.2 and 0.3 m. At the same
364 inlet velocity, there is a slight difference in the velocity profiles at different
365 medium depths as shown in Figures 11a vs. 11b, 11c vs. 11d, and 11e vs.
366 11f. At the depth of 0.05 m from the medium surface, the maximum velocity
367 was 0.25 m/s for the total medium depth of 0.2 m, compared to 0.24 m/s for
368 the medium depth of 0.3 m when the inlet velocity from the paddle wheel
369 was 0.1 m/s. When the inlet velocity was increased to 0.2 and 0.3 m/s, the
370 maximum velocities increased to 0.46 and 0.69 m/s at 0.2 m depth compared
371 to 0.45 and 0.68 m/s at 0.3 m medium depth, respectively. Although it was
372 reported that the increase of the medium depth decreased the head loss
373 per unit volume of the medium [22], the medium depth had no significant
374 influence on the velocity distribution at the same distance from the channel
375 free surface. The maximum velocities obtained for the inlet flow velocities
376 of 0.1, 0.2, and 0.3 m/s at the depth of 0.05 m from the medium surface

Figure 11: Contour plots of predicted velocity distribution at a depth of 0.05 m for the 100 m² ORP operated at various inlet velocities and medium depths with an algal cell concentration of 0.4 g/L

377 were 0.25, 0.45, and 0.7 m/s, respectively, for both medium depths of 0.2 and
378 0.3 m.

379 The regions where the fluid velocity is lower than 0.1 m/s were character-
380 ized as dead zones in the literature [8], where cells tend to settle. As observed
381 from Figure 11, the dead zones mostly occur after the first bend, where the
382 majority of head losses are located as well [8]. Although the increase of the
383 inlet flow velocity from 0.2 to 0.3 m/s, increased the maximum velocity from
384 0.45 to 0.7 m/s for both total medium depths of 0.2 and 0.3 m, it did not
385 significantly decrease the dead zone size. Hukan et al. [8] reported as well
386 that the increase of the paddle wheel rotational speed from 12 to 20 rpm
387 (corresponding to a an average fluid velocity of 0.27 to 0.43 m/s) had little
388 effect on dead zone volumes.

389 According to the literature [22], a velocity of 0.05 m/s is sufficient to
390 maintain the suspension of algal culture in a raceway culture. However, such
391 a low velocity is difficult to maintain in a large pond because of frictional
392 losses in the channel and corners. Figure 12 shows the cell concentration dis-
393 tribution in the ORP with medium depths of 0.2 and 0.3 m and an average
394 cell concentration of 0.4 g/L at various inlet velocities. These values were
395 calculated by dividing the volume of a zone with a specific cell concentration

(a) medium depth of 0.2 m

(b) medium depth of 0.3 m

Figure 12: Cell concentration distribution in the 100 m² ORP operated at various inlet velocities and microalgae medium depths of 0.2 m and 0.3 m and average cell concentration of 0.4 g/L

by the total volume of the medium. The values for the zones with cell concentrations higher than 0.45 g/L and lower than 0.34 g/L were not reported because they were negligible. As observed from Figures 12a and 12b, the increase of the inlet flow velocity from 0.1 to 0.3 m/s increased the volume of the regions with average cell concentrations of approximately 0.4 g/L, resulting in a more uniform cell concentration profile. The increase of the inlet velocity from 0.1 to 0.2 m/s increased the volumes of the region with a cell concentration between 0.39 and 0.41 g/L from 68.6% to 87.45% for the total medium depth of 0.2 m and from 79.9% to 98.2% for the total medium depth of 0.3 m. However, when the inlet velocity was further increased from 0.2 to 0.3 m/s, there was only a slight increase in the volume of the region with a cell concentration between 0.39 and 0.41 g/L, which was increased to 92.8% and 98.8% for the 0.2 and 0.3 m medium depths, respectively. When the inlet velocity increased from 0.1 to 0.3 m/s, the volume of the regions with a cell concentration of more than 0.41 g/L decreased from 15.5% to 9% for the medium depth of 0.2 m, and from 10.4% to 1% for the medium depth of 0.3 m. The volume of the regions with a concentration of less than 0.39 g/L decreased from 12.6% to 1.1% for the medium depth of 0.2 m, and from 8.6% to 0.4% for the medium depth of 0.3 m. However, the energy consumption

415 by the paddle wheel increased as well with the increase of the inlet velocity.

416 4.2.2. *Effects of medium depth*

417 Figure 13 shows the effects of microalgal medium depth on the cell distri-
418 bution along the ORP channels. By comparing the cell distribution contours
419 for depths of 0.2 and 0.3 m, it can be observed that the sedimentation of cells
420 more likely occurs at the bottom of the ORP with a total medium depth
421 of 0.2 m; than at 0.3 m medium depth at the same inlet velocity. As ob-
422 served from Figure 13, an increase in the medium depth from 0.2 to 0.3 m
423 decreased the volume of the region with a cell concentration above 0.41 g/L
424 from 15.5% to 10.4%, 8.4% to 1.56%, and 6.5% to 1% for velocities of 0.1,
425 0.2, and 0.3 m/s, respectively. An increase in the medium depth from 0.2 to
426 0.3 m decreased the volume of the region with a cell concentration lower than
427 0.39 g/L from 12.6% to 1.1%, 3.1% to 1.1%, and 1.2% to 0.4% for velocities
428 of 0.1, 0.2, and 0.3 m/s, respectively. However, increasing the medium depth
429 decreased the light penetration into the microalgal medium resulting in a
430 lower specific growth rate.

(a) 0.1 m/s inlet velocity

(b) 0.2 m/s inlet velocity

(c) 0.3 m/s inlet velocity

Figure 13: Effects of the total medium depth on cell concentration distribution in ORP at various inlet velocities

4.3. Effects of local biomass concentration on light distribution profile

The variation of local cell concentrations results in different optical characteristics in *C. vulgaris* culture medium. Figure 14 shows the local light intensity contours at the depth of 0.05 m for the ORPs with 0.2 and 0.3 m medium depths. There was a large variation of cell concentration in the ORP, which resulted in a large variation of local optical characteristics and light intensity along the channels. For the surface irradiance of 330 W/m^2 , the maximum light intensity at the depth of 0.05 m did not change significantly when the inlet velocity increased from 0.1 to 0.3 m/s. However, it can be observed from the contour plots that the increase of the flow velocity resulted in more uniform light intensity distribution along the channels because of the more uniform cell distribution. The maximum light intensity of 165 W/m^2 at the depth of 0.05 m occurs after the first bend, where the local velocity was low, and thus the cell concentration was low as well. The increase of the inlet velocity from 0.1 to 0.3 m/s resulted in a more uniform light intensity profile at the upper layers owing to improved mixing. The average light intensities at the depth of 0.05 m were 135, 150, and 148 W/m^2 for the ORP with a medium depth of 0.3 m for the inlet velocities of 0.1, 0.2, and 0.3 m/s, respectively. For the medium depth of 0.2 m, the average light intensities at the

Figure 14: Predicted light intensity contours at depth of 0.05 m and various flow velocities for ORPs with 0.2 and 0.3 m medium depths

depth of 0.05 m were 143, 148, and 155 W/m² at inlet velocities of 0.1, 0.2, and 0.3 m/s, respectively. Therefore, the increase of inlet velocity increased the uniformity of light intensity at a specific depth; it did not significantly change the average light intensity in the ORP.

Figure 15: Predicted light penetration into the channel depth for ORPs with 0.2 and 0.3 m medium depths operated at 0.2 m/s paddlewheel velocity, 0.4 g/L average cell concentration, and 330 W/m² surface irradiance

453

Figure 15 shows the light intensity distribution along the channel depth at the middle of the channel across the channel width for ponds with 0.2 and 0.3 m medium depths, at the typical paddle wheel velocity of 0.2 m/s and 0.4 g/L average cell concentration. The light intensity drastically dropped after a few centimeters from the surface of the channel. The maximum light intensity at the depth of 0.05 m decreased to 45% of the surface irradiance for 0.2 m medium depth and 41% for the 0.3 m medium depth. Therefore,

460

461 although at some areas of the channel optical parameters were higher because
462 of the cell sedimentation, the light absorption by microalgal cells did not
463 change because of the low light penetration into the medium. However, the
464 cell sedimentation prevented the cells from receiving sufficient light energy,
465 which resulted in lower biomass production rate.

466 5. Conclusions

467 An integrated three-dimensional CFD and spectral radiation model was
468 developed to simulate the hydrodynamics and light transfer in ORPs with
469 different algal cell concentrations and medium depths. The predicted three-
470 dimensional velocity and light intensity agreed well with the measured values
471 collected on a lab-scale ORP. There was a slight difference in the predicted
472 velocity profiles using two different types of boundaries, i.e., the moving zone
473 boundary and inlet velocity boundary for the paddle wheel, with R^2 values
474 between the predicted and measured velocities of 0.9947 and 0.9838, respec-
475 tively. The R^2 value between the predicted and measured light intensity
476 was 0.9939. Simulations showed that the increase of the paddle wheel ve-
477 locity of a 100 m² ORP increased the volume of the regions with an average
478 cell concentration of approximately 0.4 g/L, resulting in a more uniform cell

479 concentration profile. The increase of the inlet velocity from 0.1 to 0.2 m/s
480 increased the volumes of the region with a cell concentration between 0.39
481 and 0.41 g/L from 68.8% to 87.45% and from 79.9% to 98.2% for the to-
482 tal medium depths of 0.2 and 0.3 m, respectively. However, when the inlet
483 velocity was further increased from 0.2 to 0.3 m/s, there was only a slight
484 increase in the volume of the region with a cell concentration between 0.39
485 and 0.41 g/L, which was increased to 92.8% and 98.8% for the 0.2 and 0.3 m
486 medium depths, respectively. In addition, the simulation results showed that
487 the sedimentation of cells more likely occurred at the bottom of the ORP
488 with a total medium depth of 0.2 m than at 0.3 m medium depth at the same
489 inlet velocity. The increase of the inlet velocity from the paddle wheel re-
490 sulted in a uniformly distributed light intensity in the region near the medium
491 surface. However, as the light intensity dropped sharply after a few centime-
492 ters from the surface of the medium, the sedimentation that occurred at the
493 bottom of the ORPs had negligible effects on the light penetration depth in
494 the medium.

495 **Acknowledgments**

496 A contribution of North Carolina Agricultural and Technical State Uni-
497 versity, supported by funds fully provided by U.S. Department of Agriculture
498 (USDA NIFA awards: 2013-38821-21141 and NC.X-294-5-15-130-1). Men-
499 tion of a trade name, proprietary products, or company name is for presenta-
500 tion clarity and does not imply endorsement by the authors or the university.

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