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Application of computational fluid dynamics (CFD) on the raceway design for the cultivation of microalgae: a review

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Abstract

Microalgae are a potential solution to supersede fossil fuels and produce renewable energy. The major obstacle to the commercialization of microalgae-based biofuels is the high production cost, including nutritional requirements, photobioreactor design, and downstream processes. As for the photobioreactor design, open ponds have been adopted by major commercial plants for their economic advantages. Raceway is a popular type among open ponds. Nevertheless, the fluid dynamics of the raceway operation is quite complex. Software simulation based on Computational Fluid Dynamics is an upcoming strategy for optimizing raceway design. The optimization intends to affect light penetration, particle distribution, mass transfer, and biological kinetics. This review discusses how this strategy can be helpful to design a highly productive raceway pond-based microalgal culture system.

Keywords Raceway · CFD · Light penetration · Particle distribution · Biological kinetics

Introduction

The evolving concern about global warming and has motivated scientists worldwide to search for alternative energy sources to replace fossil fuels [1]. Microalgae—a group of photosynthetic autotrophic microorganisms—are a renewable biofuel feedstock. Their advantages include high growth rate, simple structure, and high oil content (up to 80% by weight) [2]. Microalgae have a wide range of applications, including pharmaceuticals, cosmetics, bioremediation, aquaculture feed, bioplastic production, pigments, nutraceutical (nutritional ingredients), and nutritional supplements for humans and animals [3, 4].

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In spite of the mentioned benefits, extremely high production costs hinder the commercialization of microalgae [5]. Among the available cultivation systems, open raceway ponds are economic and effective for large-scale cultivation. To enhance the microalgal biomass productivity, it is extremely important to optimize the design parameters and the operating conditions of an open raceway system. Computational fluid dynamics (CFD) is used for modeling of an open raceway system. The aim of this review is to collect the applications of CFD optimizing microalgae cultivation in open systems.

Open cultivation systems for microalgae

The most common open systems include unstirred shallow ponds, stirred circular ponds, and paddlewheel stirred raceway ponds [6]. Open cultivation systems have lower production costs than closed systems or photobioreactors. They are relatively convenient to maintain and easy to scale up [7]. Nevertheless, open systems suffer from many limitations like water loss by evaporation, poor light utilization, diffusion of CO_2 into the atmosphere, high land requirement, and contamination [8]. Due to the inefficiency of the stirring mechanism, biomass productivity is relatively low as compared to closed photosynthesis bioreactor [9].

Circular ponds

Circular ponds are frequently utilized in Southeast Asia for the culture of *Chlorella* sp. and for wastewater treatment [7, 10]. Generally, the diameter of a commercialized circular pond is 30–50 m, and the depth is 0.3–0.7 m. A pivot agitator is facilitated in the center. The design of circular ponds is limited to 10 ha because of the low efficiency of mixing provided by the rotating pivot arm. A lot of companies in Taiwan and Japan use circular ponds for the cultivation of *chlorella* sp. to generate β-carotene [10]. That study demonstrated that the combination of a hydrofoil impeller with the down-flow operation system can increase the biomass concentration of *Chlorella pyrenoidosa* by 65.2–88.8% compared with using a grid plate (with double arms and a four-pitched-blade turbine) in a circular pond [11]. The cultivation of *Oscillatoria* in circular ponds using diluted wastewater resulted in biomass yield of 15 g m^{-2} day^{-1}, along with 80% of ammonia removal and 50% of total organic carbon extraction [12].

Unstirred ponds

An unstirred pond is the most economical among the available commercial culture methods. It is used for several microalgae species, such as *Dunaliella salina* [12]. In Australia, unstirred ponds are utilized for the cultivation of *Dunaliella salina* for β-carotene production. Lee stated that natural lakes in Southeast Asia contribute more than 30 tons/year of dried microalgal biomass [10]. Nevertheless, the application of unstirred ponds is restricted to the kinds of microalgae that aggregate even under poor conditions. These species have to overcome contaminants like protozoa that influence the culture medium [13]. The application of herbicides/pesticides is some ways to control biological contamination in such cultivations of unstirred ponds [14]. It was reported that an industry in Whyalla, South Australia, generates 7 to 10 tons/year of β-carotene in 460 ha of open ponds and 6 tons/year of β-carotene in 250 ha of unstirred pond areas in Hutt Lagoon, Western Australia [15].

Raceway ponds

Since 1950, raceway ponds have been used for microalgae cultivation. They are either built as single units or as a group of joint units. The depth of raceway ponds is normally limited to 15–40 cm to avoid photosynthetic limitations. The raceway channels are either constructed from concrete or compacted earth or lined with plastic. To avoid the sedimentation of the microalgal culture, the water is continuously driven by paddlewheel, pump, and airlift for the agitation and circulation of the mixture. Raceway systems depend on the mixing efficiency, which optimally exposes microalgal cells to sunlight and CO_2. A current velocity of 10–20 cm s^{-1} is satisfactory to prevent deposition and settling. Poor mixing hinders the oxygen removal during photosynthesis. If the mixing velocity is greater than or equal to 30 cm s^{-1}, the energy cost will be too high [12]. Studies that reported successful microalgal cultivation in raceway systems are sampled in Table 1.

The Cyanotech Corporation in the USA has the largest number of raceway units (> 60), each of which is around 2.9 m^2 in area. They claim to reach a cell concentration of

Table 1 Mass cultivation of microalgae in raceway

Strain	Design of raceway	Focus of study	References
Spirulina platensis	0.7 m in length, 0.075 in depth, 0.2 m width	The cultivation of *Spirulina platensis* in open raceway	[10]
Botryococcus braunii	1.13 m in length, 0.3 in depth, 0.6 in width	The cultivation of green alga *Botryococcus braunii* in open raceway	[11]
Chlorella sp.	1.5 m in length, 0.7 m in depth, 1 m in width	The cultivation of *Chlorella* sp in open raceway	[12]
Graesiella sp.	20 m in length, 0.2 m in depth, 12 m in width	Effective cultivation of a novel oleaginous microalga *Graesiella* sp. WBG-1	[13]
Scenedesmus sp.	1.13 m in length, 0.2 m in depth, 0.9 in width	Influence of water depth on *Scenedesmus* sp. Production	[14]
Isochrysis galbana	1.4 m in length, 0.3 m in depth, 0.4 in width	Raceway pond design for *Isochrysis galbana* culture for biodiesel	[15]
Nannochloropsis salina	3.66 m in length, 0.65 m in depth, 1.31 m in width	Effect of outdoor conditions on *Nannochloropsis salina* cultivation	[16]
Phaeodactylum. tricornutum and Isochrysis galbana	300 m in length, 0.3 in depth, 1 m in width	A dynamic optimization model for designing open-channel raceway ponds for algal biomass	[17]
Chlorella vulgaris	7.5 m in length, 2.5 m in width	Unveiling algal cultivation using raceway ponds for biodiesel production	[18]

1 gr dry weight per liter, and a productivity of 10–25 gr dry weight per m^2 per day [10]. The productivity of biomass in a raceway system is typically 60–100 mg dry weight per liter per day [16].

In general, open raceway systems have lower construction and maintenance costs than other closed systems [17]. The assistance of the paddlewheel not only helps expose the cells of microalgae to sunlight and CO_2 but also avoid microalgae sedimentation yielding a higher biomass of microalgae [18].

The application of CFD software to raceway design

Introduction to CFD software

Computational fluid dynamics is a powerful tool to analyze fluid flow, heat and mass transfer, chemical reactions, and related phenomena [19, 20]. There are physical and chemical indicators in the CFD software that can be used to develop process system models. CFD can also simulate liquid and gas flows in the turbulent and laminar regimes, even in the multiphase flows and the interaction between fluids and solid structures [20].

CFD has applications in aeronautics, automotive, building HVAC (heating, ventilation, and air conditioning), petrochemicals, energy/power generation, process engineering, oil and gas, product design, optimization, and turbomachinery, among many others. The advantages and limitations related to CFD are collected in Table 2.

Most CFD software packages perform three principal tasks as follows.

Pre-processing stage This step involves the learning and characterization of a problem, geometric illustration, building a fit grid, adding chemical and physical characteristics of phenomenon, and estimating materials balance and boundary conditions.

Solving stage This software resolves the equations by adjusting the meshing and estimating the model input until the most optimum convergence is reached. In general, the numerical analytical method will be adopted to get the optimum values.

Post-processing stage The software helps visualize fluid properties, track particle transportation, and study variables at each point in the regime. ANSYS CFD-Post, EnSight, FieldView, ParaView, and Tecplot 360 are among the most popular post-processing software, especially in those complicated flow patterns [19], water loss and make-up, the management of salt (especially for the culture of marine), and the management of thermal transfer [21].

CFD software can analyze the cultivation of microalgae in a photobioreactor. We can use software simulation to optimize a two-phase turbulent flow for increasing the growth rate. This kind of simulations using a raceway system was carried out in some studies [21–23]. The authors optimized the paddlewheel velocity, the medium depth, the design of construction, and the great operating conditions. Good modeling of the drag coefficients and the momentum exchange among the phases of liquid and gas are also necessary [24]. Besides, CFD software helps to simulate the process of atmosphere, land, and water management, the management of safety and disaster, and even renewable energy and fertilizer production [25].

CFD modeling of raceway system

In a raceway, there are three reference zones: the paddlewheel movement zone, the multiphase culture medium zone, and the air zone at the top of the culture medium. To run a CFD software simulation, the configuration needs to provide the geometric design of the raceway (e.g., in ANSYS Design Modeler) along with the setting of mesh generation [26]. The selection of the tetrahedral mesh (e.g., in ANSYS Design Mesh). The sliding mesh method can be used to arrange the dynamic and the statistic areas [11].

The sliding-mesh method is utilized to tune in the whole movement of the paddlewheel. If the paddlewheel is not fully submerged, the domain of computation can be extended to entirely cover the impeller [27]. The optimal mesh size was

Table 2 Advantages and limitations of CFD application

Advantages	Limitations
The physical boundary of system can be considered in disconnection type	The deviations of simulation results from the real data might be significant for the simple flow pattern and for the undermined boundary flow
The simulation can provide the calculated data at some specific location points within the system that cannot be measured by device	All the characteristics of microalgal cells have being assumed to be the same, including the light availability per cell. Whereas the each real microalgal cell has different specific characteristic
A lot of flow parameters can be collected from the simulation results before performing the practical experiments	It could spend much simulation time for the complex model. A super computer might be required for such a complex model
The simulation results can contribute to more understanding of flow problem than that of the experiments	
The time and cost consuming is lower than that of experiments	

found at 14 mm. There is no significant change by further decreasing the size of the mesh. The mesh can be arranged into 1.02×10^6 cells [28].

The simulation can be set up with the tetrahedral mesh, 209.96 nodes, and 183.615 elements [29]. Selecting the element and mesh which are appropriate for the simulation model gives the results with the required precision and makes the computer spend less time resolving it. The value of mesh skewness can be adjusted to 0.2704, where the minimum value of mesh skewness is 1.3×10^{-10}, and the maximum value of mesh skewness is 0.92 [30]. To obtain a steady-state simulation in multiphase flow, Reynold-averaged Navier–Stokes terms in the transient mode were used for modeling the turbulence [29].

Since a raceway system has turbulent flow, the Reynolds number is at its highest value of 2.4×10^4 along with the utilization of the viscous model tabs. The standard k-ε turbulence model has a wide range of applications. The volume of fluid (VOF) method can be used to track the free interface of air and water. The values of surface tension was set up to 72 Nm^{-1} at 25 °C [29], water density to 998 kg m^{-3}, and water viscosity to 0.000899 kg m^{-1} s^{-1} [31, 32]. This simulation is applicable to both unicellular and filamentous algae [33]. Microalgal cells can be simulated by spherical solids, which are determined by their diameter based on the type of the microalgal cell. The diameter of algae was defined as 0.008 mm [34].

Discretizing the QUICK scheme for convective terms and adjusted the paddlewheel velocity to 10 rpm in the boundary conditions was selected in this configuration. The time duration was set up in the solution tab of ANSYS FLUENT to 0.01 s for the simulation [28]. The time step was defined based on the mesh and the velocities. The time step should be able to resolve the flow in the smallest cell. Table 3 provides a list of raceway designs based on CFD software simulation.

Factors affecting the design of raceway ponds

Numerous studies provide information for effective design and operation [35]. Hydrodynamic effects play a significant role in determining dimensions and mixing velocity [36]. Culture mixing is essential for nutrient transfer to the cells. It increases the mass transfer of dissolved oxygen and carbon between the fluid and the atmosphere. Culture mixing reduces dead zones and prevents microalgae sedimentation. In addition, flow and depth in raceway ponds influence cell suspension, nutrients distribution, and thermal stratification [21]. A safe choice for the turbulence rate is a Reynolds number of 8000. Higher turbulence rates can increase shear stress on the cells, thereby decreasing growth rates [37].

Although the number of scientific information regarding algal biotechnology is provided by some pieces of literature and numerous studies have reported modifications of the raceway system, a certain knowledge gap exists that prevents greater utilization of this technology. Because of the limited supply of CO_2 combined with hydraulic, the productivity of algae in the raceway system is still relatively low, and raceway efficiency still needs improvement to minimize the production cost of biofuel from algae [38]. The operational parameters, such as bend geometry, depth, and mixing need to consider the fluid flow hydraulics and the design configuration to improve energy efficiency. Marshall et al. and Liffman et al. reported that different mixing rates affect energy efficiency. They invented a novel bend, which can decrease energy loss by 87% compared to the conventional bend and by 82% compared to a vane design [23, 36]. Sompech et al. observed that a reduction of the dead zones can enhance the net energy ratio for biofuel production [39]. This study also posed that efficient mixing is able to improve the outcome energy ratio. Increasing the number of baffles along with a modification of the divider design can completely eliminate dead zones. Pirez et al. improved the paddlewheel design to reduce energy consumption [40].

Turbulence fluid dynamics model in CFD

Turbulence plays a vital role in the movement of microalgal cells in raceway ponds, and it also influences light distribution. The Reynolds-averaged Navier–Stokes (RANS) model is commonly used for simulating a multiphase turbulent reacting flow in a raceway system. There are three methods for liquid–gas turbulence simulations: the dispersed turbulence model, the mixture turbulence model, and the per-phase turbulence model. They use the same model constants but have distinct equations to estimate turbulence viscosity [41]. The dispersed turbulence model utilizes eddy viscosity or Reynolds stress for modeling liquid phase turbulence. The low flow is usually conducted so that the gas phase is in a laminar regime. The two-phase k-ε model is used to determine the k and ε transport equations for each phase [42, 43]. The mixture k-ε is convenient to use since the phases are separated for terraced multiphase flows, and the density ratio between the phases is about 1.

The Eulerian–Eulerian approach

This approach uses the mass and momentum equations to find the solid and fluid phases and the volume fraction. However, if the phases are either dispersed or continuous, they will be found from a single pressure field. The Eulerian multiphase model enables the modeling of multiple, separate, yet interacting phases. The phases can be liquids, gases, or solids in almost any combination. The Eulerian approach is utilized for each phase. The model describing the interaction between the average flows of phases is based

Table 3 List of raceways investigated using CFD

Strain	Dimension of raceway	CFD Code	Turbulence model	Paddlewheel velocity (rpm)	Focus of study	Cultivation biomass (g/l)	References
C. vulgaris	1.4 m in length, 0.5 m depth, 0.35 m width	FLUENT	k-ε	10	Investigated the algal productivity in open raceway ponds with CFD	0.48	[36]
Nannochloropsis salina	57 m in length, 0.25 m depth, 4.1 m width	FLUENT	k-ε	5	The making of model in CFD for investigating the growth of *Nannochloropsis salina*	0.45	[38]
Nannochloropsis gaditana	10 m in length, 0.3 m depth, 4.1 m width	FLUENT	k-ε	10	Analyzed microalgae growth in raceway ponds with CFD	0.62	[16]
Chlorella sp	0.7 in length, 0.2 m depth, 0.2 m width	FLUENT	k-ε	8	Simulated the light/dark cycle of microalgal cells with CFD to improve microalgal growth	1.75	[43]
Chlorella sp	0.7 m in length, 0.09 m in depth, 0.2 m in width	FLUENT	k-ε	8	Investigated the flashing light effect with up-down chute baffles for enhancing microalgal growth	1.2	[44]
Spirulina	0.2 m in length, 0.35 m in depth, 0.6 m in Width	FLUENT	k-ε	30	Improved the baffle for increasing the microalgal productivity with using of CFD simulation	3	[10]
Arthrospira platensis	2 m in length, 0.15 m in depth, 0.5 m in width	FLUENT	k-ε	6	Integrated CFD model for raceway cultivation of *Arthrospira platensis*	0.425	[45]
Chlorella vulgaris	1.4 m in length, 0.5 m in depth, 0.35 m in width	FLUENT	k-ε	10	Investigated the hydrodynamics and light transfer for getting the biomass production with CFD	0.41	[46]
N. salina	57 m in length, 0.25 m depth, 4.1 m width	FLUENT	k-ε	16.7	Integrated computational fluid dynamics (CFD) model for open pond cultivation of *Nannochloropsis salina*	0.8	[38]
Chlorella pyrenoidosa	4.5 m in length, 0.35 m depth, 1.9 m width	CFX	k-ε	10	Compared the paddle wheels speed in simulation and microalgae culture experiments	0.9	[47]

on the interaction term, the attraction force, and the virtual mass effect. This approach is convenient for modeling systems with liquid–liquid or liquid–gas phases. Its applications include aeration boilers, evaporation, and separators. On the other hand, this approach is not recommended for stratified free-surface flows due to its need for the precise interface boundary.

The Lagrangian–Eulerian approach

In this approach, the influence of small-scale motions around individually dispersed phase particles is solely modeled circumstantially while viewing the particle motion in the dispersed phase. The Eulerian and the Lagrangian frames are used for modeling particle movement in the continuous and dispersed phases. The modeling in the continuous phase requires to put particle trajectories in the flow. This approach can simulate the reaction, the mass transfer, and the heat processes for each particle.

The simulation of a huge number of particle trajectories in the turbulent flow yields valuable averages. The Lagrangian–Eulerian approach also works for the simulation of a dispersed multiphase flow that has a volume fraction of less than 10% of the dispersed phase. The Lagrangian particle tracking enables the establishment of the accepted light scheme in association with Han's models of photo production and photoinhibition [29].

The volume of fluid (VOF) approach

This method can be used to model two or more immiscible fluids by solving both a single set of momentum equations and tracking the volume fraction of each of the fluids via the domain. VOF approach contains the jet breakup prediction, the motion of liquid after dam break, the motion of huge bubbles in the liquid, and the transient and steady tracking of any liquid–gas interface. The tracking of the interface between the phases is resolved by the solution of a continuity equation for the volume fraction of the phases. The mixture fluid momentum equation is accomplished utilizing the mixture material properties; hence, the mixture material properties will demonstrate the jump across the interface. The turbulence and energy equation have the ability also to accomplish the mixture fluid. The VOF approach may also comprise the impacts of the surface tension throughout the interface between phases. The model can be enhanced by the ancillary specification of the touch angles between the walls and the phases. In the column of fluid, the VOF approach has the strong ability to investigate the rise trajectories of bubbles, the size, and shape, as well as the rise velocity on the bubble dynamics and gas hold-up. Also, other benefits of VOF are to simulate the bubble rising and coalescence in a low hold-up particle–liquid suspension system [28]. VOF approach can model several dispersed phase particles. It is not appropriate for the simulation of dispersed multiphase flows in a piece of huge equipment because the estimation for each particle uses enormous computational resources. This method can improve the results of the Eulerian–Lagrangian and the Eulerian–Eulerian methods [29].

Challenges in raceway system design and analysis based on CFD simulation software

Understanding light penetration

As photoautotrophic microorganisms, microalgae require light as energy source to catch up atmospheric CO_2. They capture and convert light energy into chemical energy. Chen et al. showed that light/dark (L/D) cycles of microalgal cells by CFD approach through calculating both the hydrodynamics of culture media and the trajectories of cell. The work of study is to investigate both the impacts of paddlewheel velocity and flow-deflector baffle installation on the L/D cycle. The results expressed that L/D cycles of algal cells lessened with the enhancing of the paddlewheel velocity; when the paddlewheel velocity was set up from 5 to 12 rpm, the mean L/D cycles set up from 22.58 to 20.15 s. Moreover, the installation of the flow-deflector baffles could highly increase both the light time for algal cell from 33.8 to 54.8% and the ratio of light time to L/D cycle from 3.5 to 26.5% because the flow deflector could contribute to more residence time of algal cell residing in the light zones [26]. The results revealed that the flow-deflector could minimize the downward flow of bulk fluid.

The study posed that CFD software has been developed to stimulate L/D of algal cell by CFD in the raceway system [44, 45]. The software allows for setting the light and dark zones [46]. However, the preferred L/D cycle of each cell in culture is specific to the provisional algal procedure (PAAP) [47]. When CFD simulation software is utilized, it analyzes the cell trajectory through Lagrangian particle tracking and flow field simulation. Yang et al. also studied L/D of algal cells by CFD in the raceway system. The study is to investigate the L/D cycle period under the distinction of paddlewheel velocity and algal concentration. The authors revealed that the L/D cycle period decreased by 24% (from 5.1 to 3.9 s) and vertical fluid velocity enhanced by 75% when the raceway set up the up--down chute baffles with the rotation speed of paddlewheel at 30 r/m [43]. They obtained a 22% increase in biomass yield without changing paddlewheel speed. Other factors that influence the L/D cycle include the viscosity of the culture media and the density of the microalgal cells.

Understanding particle distribution

The technique used to trace microalgal cells in CFD modeling [how relates to that] of gas–solid flow fluidized beds. The [what sort of] results from the Lagrangian method are in better agreement with experiments than those from the Eulerian [48]. On the other hand, numerical simulations conducted with the Lagrangian simulation are far more time consuming because of the large number of particles and their interactions at each time step [48].

Understanding CO_2 mass transportation/transfer

Recently, CO_2 gas via bubbles at the bottom of an open raceway system was familiarly used for gas transfer/distribution. Modeling the hydrodynamics of bubble flow in the airlift and bubble column is good advancement which has been established [37]. Nevertheless, the mixing of chemical species and the mass transfer prediction in bubble flow is still good defiance due to bubble flow, the interfacial transfer rates do not comply with interfacial transfer laws for isolated bubbles [49]. An adopted model for interphase mass transfer should be representative of various operational, fluid, and geometric conditions [37]. The prediction of mass transfer in the bioreactor is substantial for the advancement of process and large scale. The parameters influencing mass transfer rate in bioreactors include liquid and gas velocity, fluid properties, and photobioreactor (PBR) geometry [49]. Mass transfer is typically evaluated using the volumetric mass transfer coefficient. The prediction and optimization of that search for the optimal mass transfer with the lowest energy input [50].

A study by Dhotre et al. evaluated the performance of a bubble column photobioreactors (PBR) via re-checking the patterns of flow at the downstream and the upstream distributors. The procedure has been recommended for hub gas chamber to the bubble column [51]. The study analyzed the flow patterns in the gas chamber and the velocities through all holes to establish uniformity in gas distribution. The study revealed both the raising in the distribution pressure drop and lessening in the inlet kinetic head of the gas. They also argued that the main factors to optimize mass transfer are the inlet nozzle size and its location with respect to the distributor. Simonnet et al. demonstrated how to visualize regime transition in the bubble column reactor via CFD simulation. The work of the study is to investigate the regime transitions which happen in the bubble column, which is highly necessary for the design. Their study revealed the occurrence of bubble–bubble interaction via the drag coefficient, which is based on the fraction of the local void (one of the parameters that characterize the foaming results) [52].

Understanding biological kinetics

Optimal growth rate and productivity of microalgae can be achieved by considering many factors, including environmental conditions and physical processes.

Studies on mixing and mass transfer have been conducted, but those demonstrating the effect of hydrodynamic factors are rare. Researchers prefer to optimize the experimental conditions for performing simulations. Binxin Wu developed viable modeling methods by integrating biological processes of growth with a physical flow model. The result was a kinetic mass equation suitable for use in CFD simulation software [53]. In addition, Park et al. successfully integrated biological kinetics and CFD modeling to increase microalgae productivity by 17.6% and increase the concentration of dissolved CO_2 from 0.0006 to 0.150 g L^{-1} [30].

Case study

The effects of paddlewheel velocity

The effects of paddlewheel velocity appeared in several dynamic models. Amini et al. tested and validated CFD simulation results about variable channel depth and paddlewheel velocity (Fig. 1) [28]. They integrated a radiation-transport model with CFD to simulate both the hydrodynamics of multiphase flow and the light transfer in raceway systems. They validated their CFD model by experimental data in the lab-scale of raceway pond. They claimed that an increase in paddlewheel velocity of 0.1–0.3 m s^{-1} can improve cell concentration by 0.4 g L^{-1}, and make it more uniform. Nevertheless, the study indicated that the increase in paddlewheel velocity leads to culture overflow outside and need higher energy consumption. Installation of flow deflector baffles and modifying the design of paddlewheel in a raceway help reduce energy consumption [39]. Liffman et al. tested the energy efficiency of distinct high-rate raceway pond designs using CFD [23]. The traditional design of the raceway was compared to six bend geometries deflecting flow to the outer edge of the bend and withstanding the channel cross-sectional region, a result of that diminishing the loss of energy due to the centrifugal forces. They also found that novel bend designs can alleviate energy losses by 87% compared to conventional bend design, and 82% compared to the design of vane. The authors in [22] erased the evaluation of hydrodynamics in the raceway pond by CFD. The authors stimulated the ratio of length–width (*L/W*) and various velocity, as well as the shear stress. The results indicated that the ratio of *L/W* higher rather than ten yields better results in line with the uniformity of velocity and the shear stress.

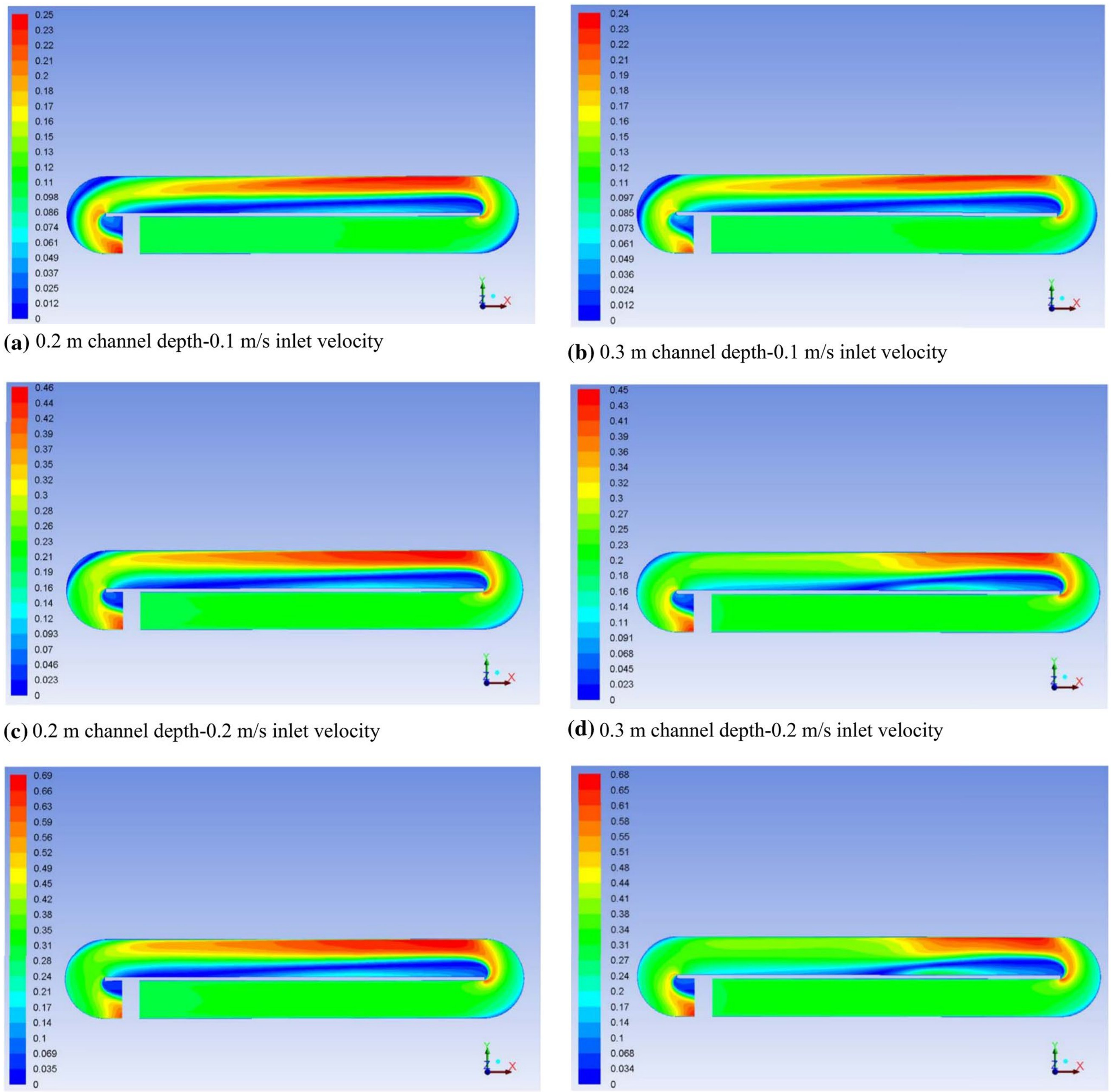

Fig. 1 Contour plots of predicted velocity profile at depths of 0.2 m and 0.3 m, for operation at 0.1 m/s, 0.2 m/s, and 0.3 m/s inlet velocities [57]

The effects of light penetration

The authors conducted an experiment on how raceway design influences the distribution of light [27]. The radiative intensity was measured regarding the spatial position and the angular direction. The possible application of scattering, absorbing, and non-emitting medium was evaluated by the radiative transport equation (RTE). The discrete ordinate (DO) radiation model in the FLUENT software can model light transfer in the medium culture of microalgae [56]. The boundary condition for lighting includes considerations of the bottom and the side walls of the raceway system. The authors of [34] investigated the effects of the photosynthetic reaction with respect to the temporal and spatial facets of light patterns. The work [57] focused on the simulation of the hydrodynamics of multiphase flow and the resulting light intensity distribution by varying the medium depths. The CFD simulations were validated by experimental data of the paddlewheel velocity and the light attenuation. They found that the increase of the paddlewheel speed affects the uniformly distributed light intensity in the area near the surface of the medium (e.g., 0.05 m depth from the surface) because of enhanced mixing. There was a sudden drop in light intensity a few centimeters below the surface of the medium.

Conclusions

CFD performance was taken into account as an appropriate tool to explain the exceptional design and performance of a raceway system for heightening biomass production and lowering its cost. In recent decades, some studies utilized CFD not only for investigating but also analyzing the hydrodynamics of fluid flow in raceway systems. The cultivation system was selected due to the effective mass transfer, good mixing, and low energy consumption presented in CFD simulation results. The paddlewheel speed is one of the important parameters in CFD simulations that strongly affect the performance of microalgae growth in the raceway. The VOF multi-phase model will be an appropriate selection due to it is fit to track the free interface of air and water. As for the turbulence flow, the k-ε turbulence model is the most widely used in CFD simulation. Nevertheless, based on the specific flow conditions, the researchers have to understand the capabilities and limitations of CFD before selecting a suitable model. Even CFD is an efficient tool to rapidly obtain the simulation results of hydrodynamics. There are still significant challenges in the application of CFD for the optimization of microalgae in open raceway systems as well as CFD design and analysis for light penetration, particle distribution, mass transfer, and biological kinetics.

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