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Numerical and Experimental Study of Raceway Pond for Production of Microalgea in Tunisia

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ABSTRACT

The objective of this work is to enhance the production of microalgae under better conditions from microalgae production units. The system studied is a raceway pond constructed in the city of Monastir in Tunisia. Using the commercial CFD software ANSYS Fluent, a series of simulations were developed to validate the hydrodynamic characteristics of the pond. The results were validated by experimental measurements of the fluid velocity in both channels of the system. The standard turbulence model k-ε was used to model the turbulence created by the impeller of the fluid flow. The meshing effect was used to reduce the computation time of the simulation. The effect of the velocity inlet and the position of the paddle wheel in the fluid channels on the system behavior was examined .The effect of the inlet velocity and the position of the paddle wheel in the fluid channels on the system behaviour was investigated. The numerical results show good agreement with the experimental measurements. In fact, the error between the numerical and the experimental results is recorded acceptable and is small than 6.38%.

1. Introduction

In the contemporary landscape, various types of microalgae are commercially cultivated across the globe, serving diverse purposes such as the production of nutraceuticals, pharmaceuticals, and biomass. Notably, microalgae have emerged as a viable energy source for biofuels. Harnessing the energy potential of microalgae involves employing different techniques, with the open raceway pond standing out as an economical technology particularly suitable for large-scale microalgae cultivation [1]. Open raceway ponds are simple technologies and require low initial investment. However, only a few species of microalgae can be cultivated monospecifically in an open environment. A variety of physicochemical and biological processes take place in the open raceway pond [2]. In addition, to maintain microalgae growth rates, pH, which controls the rate of the characteristic biochemical process, a light input for photosynthesis, and the hydrodynamic behavior that governs the process

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of mixing in the pond [3]. In open raceway ponds, algal cultures require mixing to maintain cell suspension, prevent thermal stratification of the raceway, improve CO2 uptake for photosynthesis and achieve uniform nutrient distribution [4, 5]. The open raceway pond is a practical technology for mass production of microalgae due to its low construction and operating costs [6]. A study involving modelling of the mechanical structure of microalgal cells in the raceway pond, taking into account the effects of water turbulence, needs to be carried out in order to effectively estimate microalgal cell damage and achieve improved microalgal productivity [7]. Numerous authors around the world have been interested in the design of this system and the optimization of its operating parameters. To improve the performance of microalgae cultivation in open raceway ponds, it is essential to optimize the shape of the raceway pond for better mixing. According to the literature review, pond geometry is an important parameter affecting nutrient uptake due to its direct effect on the hydrodynamic properties of ponds [8-10]. Wu and Song [11] carried out the mixing conditions in several spiral pipes by CFD calculation. Recently, the CFD method is increasingly used to optimize the geometry of raceway ponds. In particular, different shapes of raceway pond bend have been simulated by CFD. Sompech *et al.,* [12] found that the raceway pond with three semicircular deflector baffles is the most energy efficient, which obviously reduces the volume of dead zones. Xu *et al.,* [13] proposed a new configuration of raceway pond to achieve better mixing of microalgae. Rainier Hreiz *et al.,* [14] developed a novel blade shape characterized by non-aligned blades. Another important design parameter is the power consumption and the reduction of the dead zone, as it plays a role in determining the economics and productivity of the algal biomass [15]. In the raceway pond, mixing by paddle wheel was the most common tool to minimize the energy required to run the system [2]. Various experimental and analytical studies confirm that paddle wheels are the most useful devices for mixing fluid in open ponds [16, 17]. The performance of the paddle wheel depends on several elements, such as the number of blades, the speed, the distance of the blades from the bottom [17]. Benemann [1] stated that one of the most important objectives of mixing microalgae is how to circulate microalgae in and out of shaded areas. Kommareddy [18] noted that the shape of the mixing mechanism must be considered due to the increase in the working depth of the raceway pond. Mixing is an important process to eliminate the dead zone in the flow of algae and to avoid cell attachment to the walls [19-21]. However, this shear stress characteristic has not been studied in large-scale open pond systems. Furthermore, the effect of mixer geometry on the hydrodynamic characteristics has not been fully investigated, leading to a potentially incomplete understanding of the design results.

In this paper, a numerical and experimental study of an open raceway pond is carried out based on the real system built in Tunisia. The hydrodynamic analysis was developed using the commercial CFD software, ANSYS Fluent. The effects of speed and location of the paddlewheel on the hydrodynamic characteristics are studied. A validation of the numerical code is carried out by comparing the profiles of fluid velocities. The modelling of the hydrodynamic flow conditions related to the energy consumption, the occurrence of dead zones, the global shear stress characteristics and the turbulence characteristics. The approach used in this paper highlights the need for further investigation in the design of large-scale raceways. The validation of the numerical results is carried out by comparison with the experimental velocities.

The novelty of this paper lies in the comprehensive examination of an open raceway pond, based on an actual system in Tunisia, through a combined numerical and experimental approach. Employing the commercial CFD software, ANSYS Fluent, the study delves into the hydrodynamic analysis, particularly focusing on the impact of paddlewheel speed and location on the hydrodynamic characteristics. Significantly, this research emphasizes the imperative for further exploration in the design of large-scale raceways, thus providing valuable insights for the advancement of this field. The validation of numerical outcomes is rigorously conducted through a meticulous alignment with experimental velocity data, underscoring the reliability and applicability of the findings.

This study holds considerable significance within the field of microalgae production, presenting valuable insights that can potentially revolutionize various applications, particularly in the context of biofuel production. The investigation of an open raceway pond, based on a real system in Tunisia, offers a unique contribution to understanding the hydrodynamic aspects of large-scale microalgae cultivation.The study's focus on the effects of paddlewheel speed and location on hydrodynamic characteristics is crucial for optimizing the efficiency and scalability of microalgae production. This knowledge is particularly relevant in the broader context of sustainable biofuel production, where microalgae are increasingly recognized as a promising feedstock due to their high lipid content and rapid growth rates.

2. Experimental Setup

Microalgae are currently attracting a great deal of interest and many start-up companies are investing in this niche in Tunisia. With the aim of producing biofuels in Tunisia, a large-scale production of microalgae in outdoor raceway ponds has been developed. Figure 1 shows the raceway pond, the paddle wheel used and the microalgae cultivated in this system. The pond has two channels separated by a concrete wall. The purpose of this system is to produce Spirulina (Arthrospira platensis) microalgae under the weather conditions of the city of Monastir-Tunisia. Spirulina is a filamentous cyanobacterium used as a food supplementis with a high content of oleic acid and lipids. The system is set up under a large greenhouse in order to adopt the metrological characteristics. The operating conditions of the microalgae culture included mixing rate, temperature, light intensity, light quality, carbon dioxide (CO2) supply, nutrient supply and culture medium. The cultivation conditions are given in Table 1.

Table 1
The cultivation conditions

Density pond water (kg/m^3)	1139
Light flow (Lux)	2368
Ambient temperature (°C)	35.5
Pond temperature (°C)	28.9
Humidity (%)	48
pH	10
Salinity (g/l)	13

Fig. 1. Experimental system

3. CFD Method

The flow field of the raceway pond with a fluid height of 300 mm was simulated using the software ANSYS Fluent 17.0. The standard k-ε model was implemented to describe the turbulent flow behaviour of the considered system. A scalable wall function was applied to obtain a reasonable result near the wall.

3.1 Mathematical Model

3D steady-state simulations of an open raceway pond are performed using ANSYS Fluent software. The flow within the pond is defined by the Navier-Stokes equations, which consist of continuity and momentum equations:

$$\frac{\partial \rho}{\partial t} + \nabla.\left(\rho\vec{V}\right) = 0 \tag{1}$$

$$\frac{\partial \rho\vec{V}}{\partial t} + \nabla.\left(\rho\vec{V}.\vec{V}\right) = \nabla.(\tau) - \nabla.(p) + \rho\vec{g} + \vec{F} \tag{2}$$

The term τ represents the shear tensor, which is calculated from the following equation:

$$\bar{\bar{\tau}} = \mu\left(\nabla.\vec{V} + \left(\nabla.\vec{V}\right)^{t}\right) - \frac{2}{3}\left(\nabla.\vec{V}\right)I \tag{3}$$

$\vec{g}$ and $\vec{F}$ are the gravitational and external body forces respectively. The turbulent kinetic energy equation is written as follows:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_j}(\rho k u_j)=\frac{\partial}{\partial x_j}\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right)+\ G_k+G_b-Y_M-\rho\varepsilon+S_k \tag{4}$$

The dissipation rate of the turbulent kinetic energy equation is written as follows:

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_j}(\rho\varepsilon u_j)=\frac{\partial}{\partial x_j}\left(\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right)+\rho C_1 S_\varepsilon-\rho C_2\frac{\varepsilon^2}{k+\sqrt{\vartheta\varepsilon}}+C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b+S_\varepsilon \tag{5}$$

Where G_k and G_b are the generation of turbulence kinetic energy due to mean velocity gradients and buoyancy respectively. Y_M is the contribution of fluctuating dilatation in compressible turbulence to the total dissipation rate. S_k and S_ε are the user defined source terms.

3.2 Physical Model

Figure 2 shows the geometry of the concrete raceway pond studied. The system has dimensions of 23.5 m in length, 3.8 m in width and 0.5 m in depth. During the experimental operation, the fluid height was set at 0.3 m. The mixing of the culture was generated by a three-bladed paddle wheel installed inside one of the channels of the raceway pond. It was located 8 m from the bend.

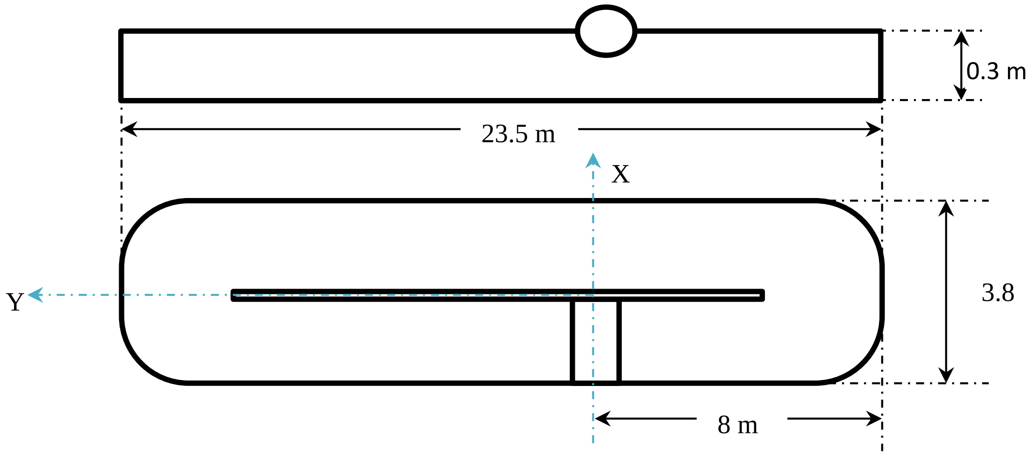


Fig. 2. Geometry of the raceway pond

It is essential to acknowledge certain limitations and assumptions that may influence the interpretation of results and their applicability. The physical properties of the materials used in the raceway pond construction and geometric details may be approximated in the simulations. Deviations from real-world material properties or variations in pond design could impact the accuracy of the findings. Therefore, the study may assume steady-state conditions, overlooking transient effects or dynamic changes that may occur in a real operational setting. This simplification might not fully capture the temporal variations and fluctuations inherent in large-scale raceway pond systems.

3.3 Boundary Conditions

The boundary condition for all walls of the pond is assumed to be a non-slip smooth wall. The symmetry condition has been applied to the upper surface of the fluid, allowing the fluid to move freely. The impeller is not taken into account. In fact, the fluid flow has been created by applying a velocity input to the zone occupied by the impeller. The value of the velocity in this zone is taken from the rotational speed and the average radius of the blades of the impeller used.

The required power consumed by the impeller is calculated using the following formula:

$$\mathrm{P} = \mathrm{Q}\,\Delta\mathrm{p} \tag{6}$$

When Q is the fluid flow and Δp is the pressure difference created by the paddle wheel.

3.4 Model Validation and Meshing Effect

A series of different simulations were carried out with different mesh sizes 50 000, 100 000, 200 000 and 400 000 cells. Hexahedral mesh was applied in all cases as shown in Figure 3.

Figure 4 shows the variation of fluid velocity along the primary channel for the four mesh sizes. According to these results, it has been observed that the simulation with 100 000, 200 000 and 400 000 cells present practically the same behavior. Therefore, we choose the case of 100 000 cells as the optimal mesh to reduce the simulation cost. In this condition, Figure 5 illustrates the numerical and experimental variations of water velocity along both channels of the raceway pond. According to these results, it can be seen a similar trends of the velocity in both methods. The difference between the numerical and experimental values appears at the dead zone when the water velocity presents the small values. This fact is owing to the measurement errors of tube pitot and the assumptions used in the simulation. The paddle wheel is not considered in the computational domain. For this end, the error is locally high. After get comparaison between the numerical and experimental velocities values, we mentionned a small difference among the model predictions and the measurements. For the eight measurment points, the maximum percent error is equal to 6.38% and the lowest percent error is limited to 4.06%. Thus, it can be confirmed that the CFD prediction of the mean fluid speed are accepted.

Discrepancies between numerical simulations and experimental values have significant practical implications. Firstly, any disparities may indicate limitations in the numerical model ability to accurately represent the complex dynamics of microalgae production in a raceway pond. Moreover, practical implications arise concerning the reliability of the numerical simulations for optimizing raceway pond conditions. If the numerical predictions significantly deviate from the experimental results, it could lead to suboptimal design and operation recommendations. Correcting and fine-tuning the numerical model based on the observed discrepancies is crucial for ensuring that the simulation results can be confidently applied in practical scenarios.

Additionally, understanding the source of discrepancies may reveal insights into aspects of the microalgae production process that are challenging to capture in either numerical simulations or experimental setups alone. This knowledge can guide researchers and practitioners in refining both approaches, fostering a more comprehensive understanding of raceway pond dynamics and contributing to the advancement of efficient and sustainable microalgae cultivation practices.

The validation process comparing numerical results with experimental data is crucial, but the scope of validation may have limitations. Certain aspects of hydrodynamics or microalgae behavior may not be fully captured in the experimental setup, affecting the comprehensiveness of the validation process.

Fig. 3. Meshing

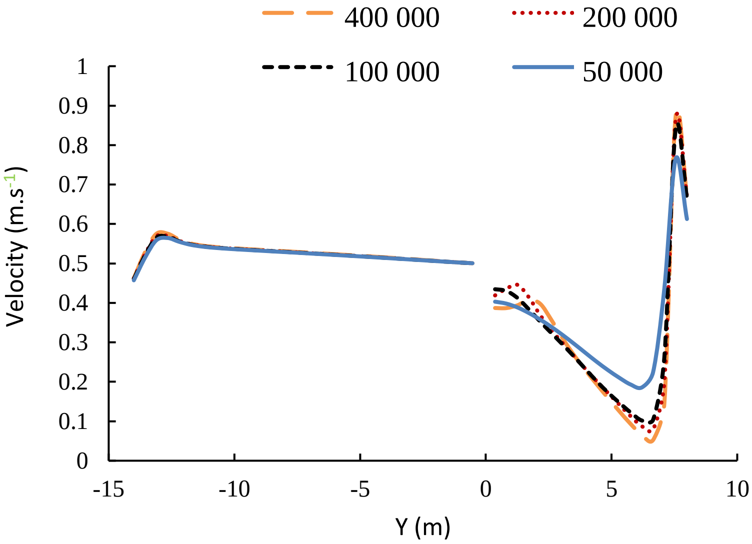


Fig. 4. Effect of the mesh density

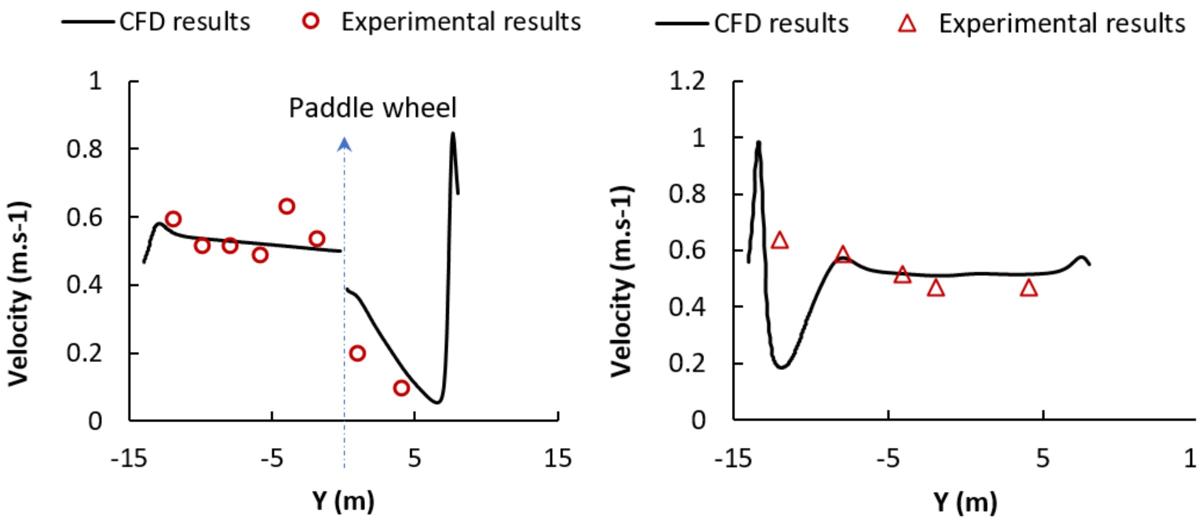


Fig. 5. Comparison with our experimental results

4. Effect of Inlet Velocity

4.1 Power and Dead Zones

Figure 6 shows the effect of the inlet velocity on the dead zone distribution and the required power. From these results it can be seen that changing the velocity has a significant effect on these parameters. Increasing the velocity decreases the average dead zone volume in the pond. Practically, when v=0.5 m/s, a large amount of dead zone was observed. This phenomenon decreased the overall efficiency of the system. However, for the high velocity, the volume of the dead zones is minimal. Furthermore, as the inlet velocity increases, the power required increases. For the experimental case when v=0.5 m/s, the power is equal to 0.24 kW and 2.1 kW when the inlet velocity is equal to 2 m/s. Based on Eq. (7), the required power depends on the flow rate Q. Therefore, the fluid velocity has a direct influence on this parameter.

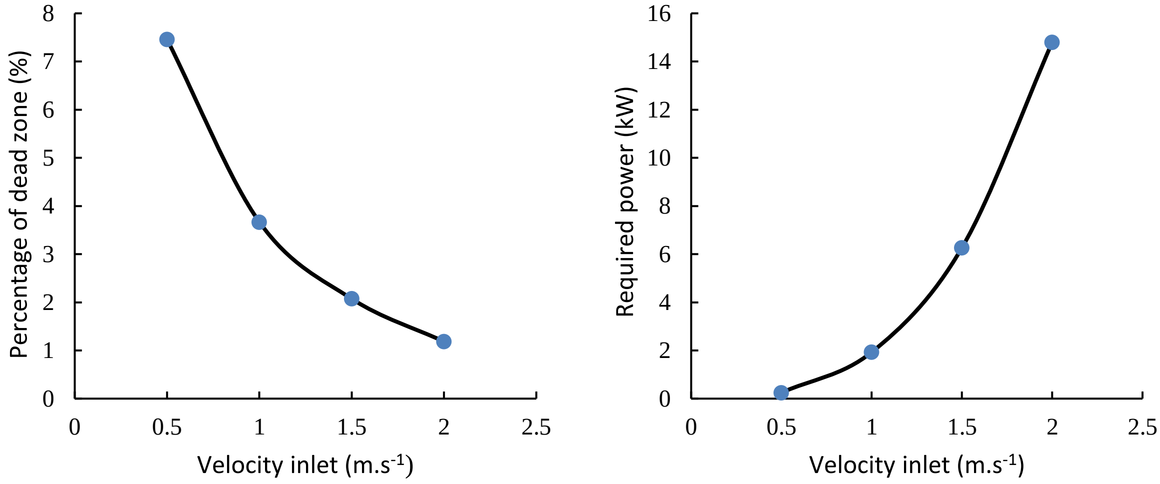


Fig. 6. Effect of velocity inlet on power and dead zone volume

Figure 7 shows the distribution of dead zones in the raceway pond for the different inlet velocities. From these results it can be seen that a dead zone is formed when a large vortex flow occurs, creating a stagnant flow at the bend zone. The dead zone reduces the residence time of the fluid in a pond by reducing the ponding capacity [1]. By increasing the inlet velocity, the presence of large vortices is reduced by the small vortices. The high turbulence in the channel increases the dispersion of the cells and thus the dead zone volume decreases.

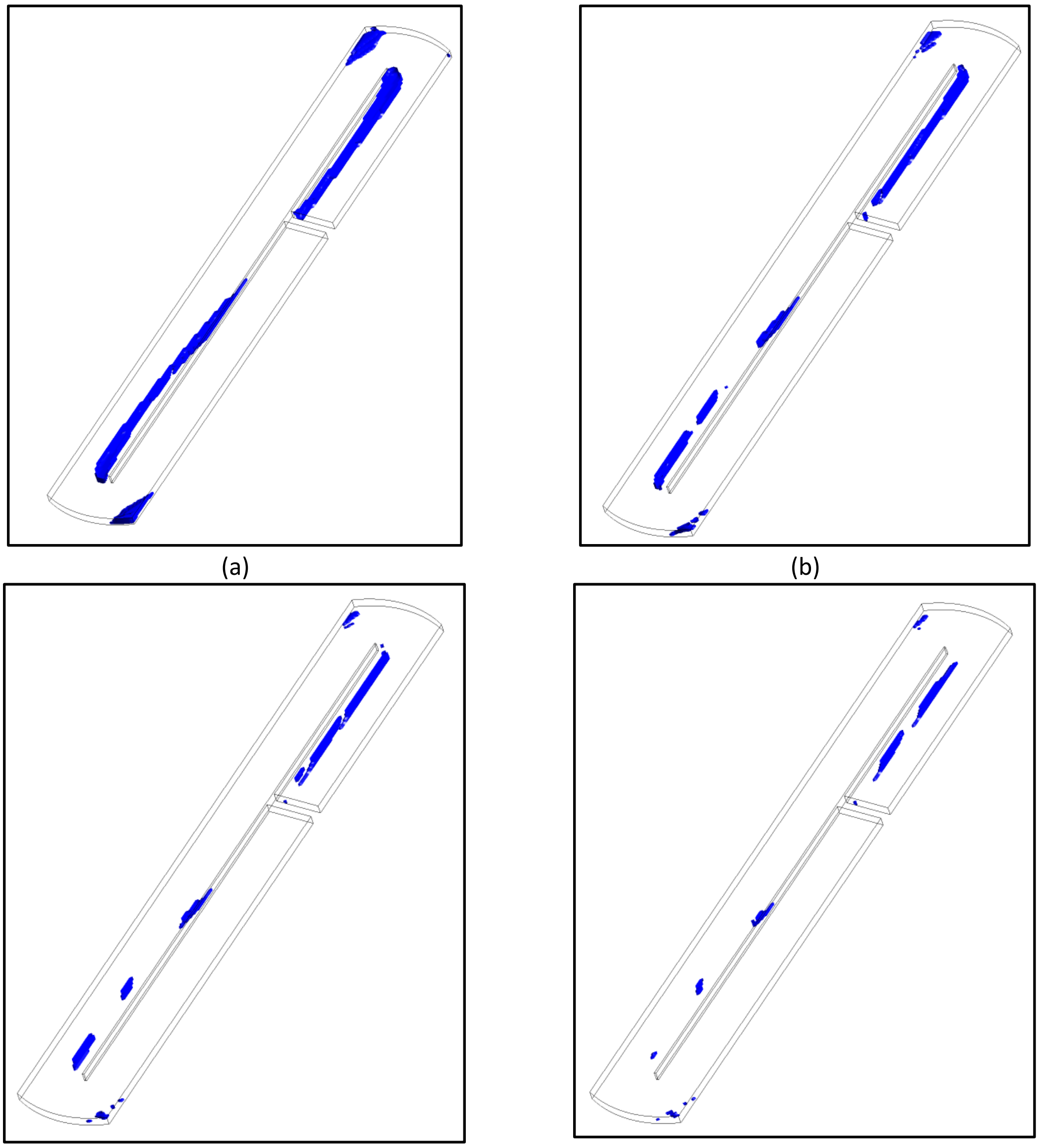

(a) (b) (c) (d)

Fig. 7. Effect of velocity inlet on dead zones distribution (a) V_{in}= 0.5 m.s^{-1} (b) V_{in}= 1 m.s^{-1} (c) V_{in}= 1.5 m.s^{-1} (d) V_{in}= 2 m.s^{-1}

4.2 Turbulent Viscosity

Figure 8 shows the distribution of the turbulent viscosity at the medium plane for the different inlet velocities; V_{in}= 0.5 m. s^{-1}, V_{in}= 1 m.s^{-1}, V_{in}= 1.5 m. s^{-1} and V_{in}= 2 m.s^{-1}. According to these results, it was observed that the turbulent viscosity has the same distribution in all cases. The difference between the four cases can be seen in the maximum values. In fact, the turbulent viscosity increases as the inlet velocity increases. This is due to the turbulence created by the impeller in the system. Comparing with the previous results, it can be seen that the high turbulent values are located in the dead zones and near the acceleration zones.

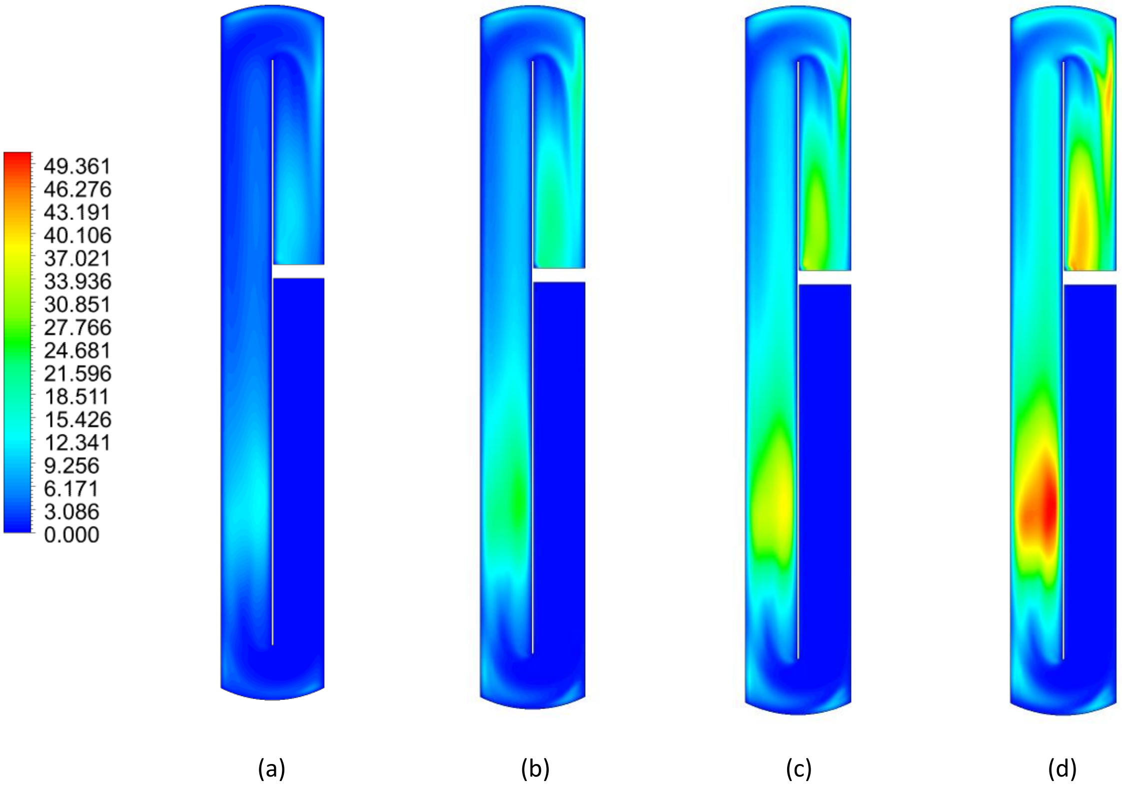


Fig. 8. Turbulent viscosity distribution (a) V_{in}= 0.5 m.s^{-1} (b) V_{in}= 1 m.s^{-1} (c) V_{in}= 1.5 m.s^{-1} (d) V_{in}= 2 m.s^{-1}

The practical implications of findings related to the design and operation of raceway ponds for the production of microalgae are significant and can influence various aspects of microalgae cultivation. Furthermore, understanding the dynamics of microalgae growth within raceway ponds allows for the development of improved operational strategies. This includes determining the most suitable nutrient dosing, monitoring water quality parameters, and establishing optimal harvesting schedules. Efficient operation is crucial for maintaining a consistent and high-yield microalgae production process.

Practical implications extend beyond the research setting to facilitate the transfer of technology from the laboratory to industry. The findings can be utilized by practitioners and entrepreneurs involved in microalgae cultivation for biofuel production, pharmaceuticals, or other applications, enabling them to implement more efficient and reliable raceway pond systems.

Insights into the interactions between microalgae, nutrients, and environmental conditions contribute to the development of more environmentally sustainable practices. This could involve minimizing nutrient waste, reducing energy consumption, and mitigating any potential environmental impacts associated with microalgae cultivation.In summary, the practical implications of findings related to raceway pond design and operation for microalgae production contribute to the development of sustainable, cost-effective, and scalable cultivation practices with potential applications in various industries.

5. Effect of the Paddle Wheel Position

In this part, we are interested in studying the effect of the position of the impeller on the local characteristics of the raceway pond at constant speed. Four configurations are proposed for this purpose, as shown in Figure 9.

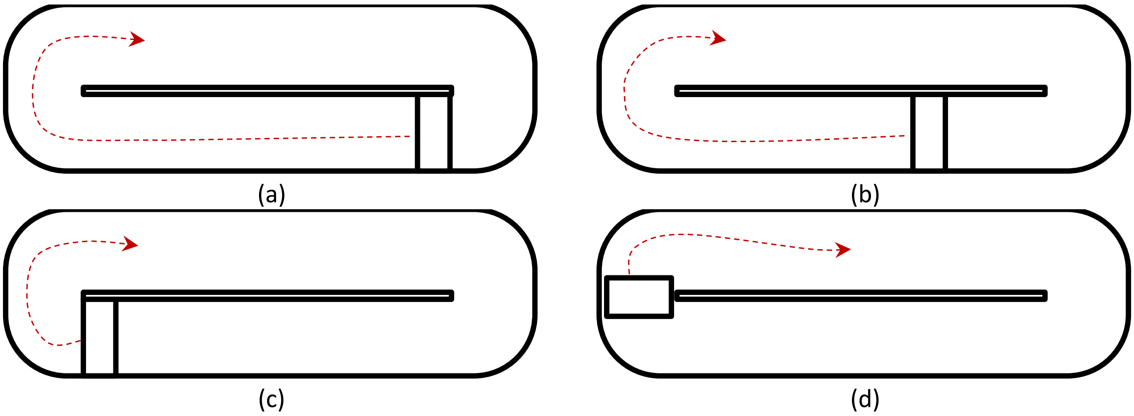


Fig. 9. Studied shapes (a) Configuration 1 (b) Configuration 2 (c) Configuration 3 (d) Configuration 4

5.1 Velocity

The fluid velocity is an important parameter in the analysis of the hydrodynamic behaviour of the raceway pond. Figure 10 shows the distribution of the velocity magnitude in the raceway pond for the four shapes considered. Overall, these results show that the velocity near the centre wall is much lower than that near the side wall of the system. For the four configurations, an acceleration zone appears after the bending zone when the fluid changes direction. Consequently, in the first configuration, there are two peak velocity zones because the impeller is located in the centre of the channel. However, for the third configuration, when the impeller is located at the beginning of the primary channel, a single acceleration zone is created. In comparison, the maximum velocity value is reached with the standard shape. At the same time, in the second and fifth shapes, the lower value is reached when the acceleration zone is large. Therefore, a raceway pond is a good system with an impeller located at the entrance of the primary channel, as this solution leads to minimising the dead zones and thus optimising the pond's efficiency

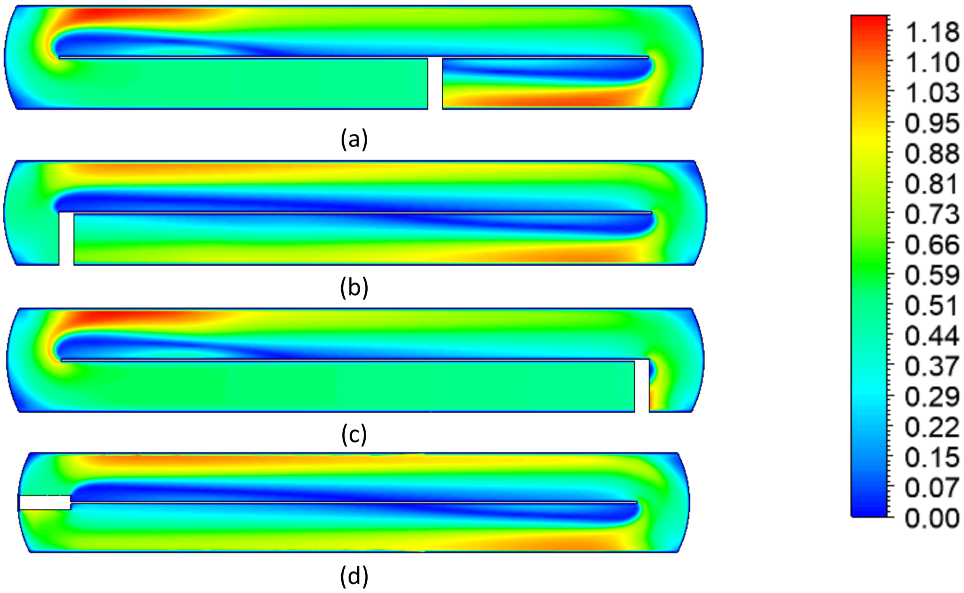
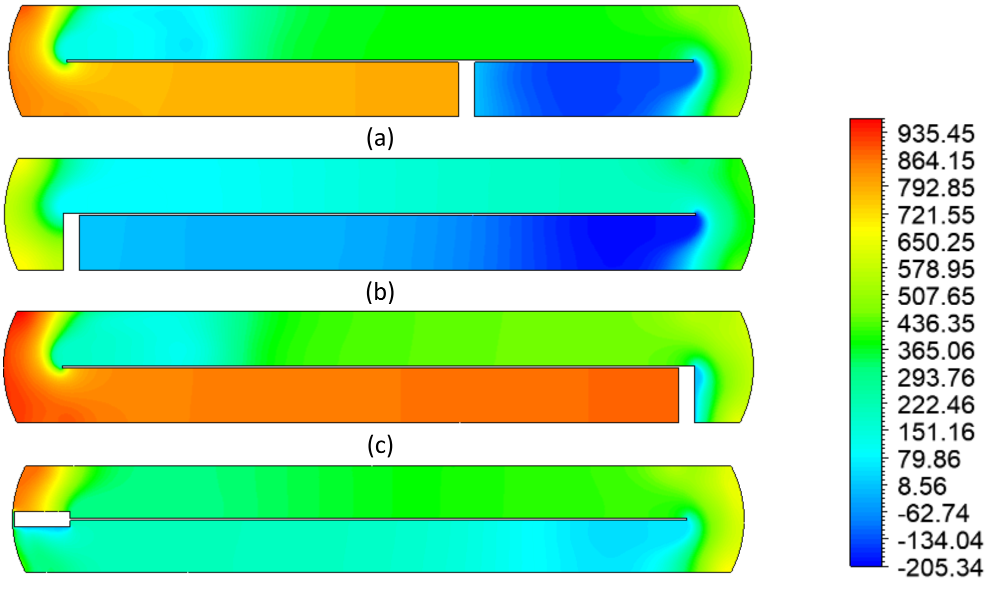


Fig. 10. Velocity magnitude distribution (a) Configuration 1 (b) Configuration 2 (c) Configuration 3 (d) Configuration 4

5.2 Static Pressure

Figure 11 shows the distribution of the static pressure in the raceway pond for the four shapes considered. According to these results, it has been observed that the static pressure has the same distribution in all the configurations. In fact, a zone of depression appears at the entrance of the primary channel of the pond, in the region after the impeller position. After this zone, the static pressure gradually increases. The maximum value is localised in the bend area, when the fluid changes direction. The difference between the four configurations appears in the maximum value. In fact, for the standard shape of the raceway pond, the maximum pressure is equal to 864 Pa. For the second configuration, with the paddle wheel located at the end of the primary channel, the maximum pressure is equal to 365 Pa. It is clear that in this configuration, the depression region presents the large distribution along the primary channel. On the other hand, when the impeller is located at the entrance of the primary duct, the pressure presents a peak zone in this duct.



(a)

(b)

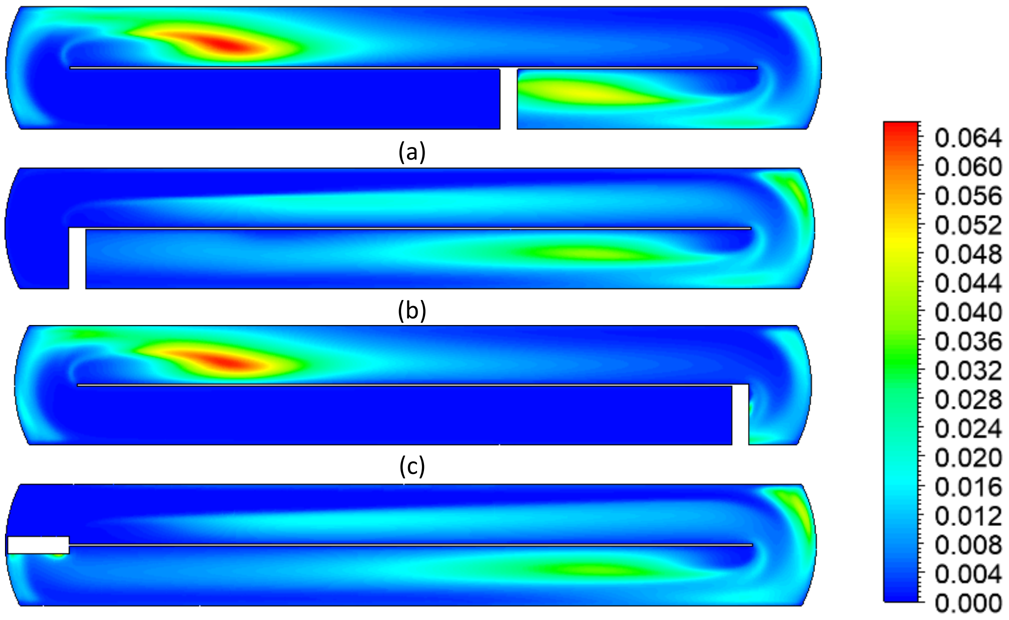
(c)

(d)

Fig. 11. Static pressure distribution (a) Configuration 1 (b) Configuration 2 (c) Configuration 3 (d) Configuration 4

5.3 Turbulent Viscosity

Figure 12 shows the distribution of turbulent viscosity at the mean plane for the four raceway pond shapes considered. From these results it can be seen that the turbulent viscosity has the same distribution for the standard case and the third case. In these cases, the maximum value is reached close to the bend region. Otherwise, this turbulent region is large at the entrance of the paddlewheel zone when the paddlewheel is far from the bend zone. However, the peak turbulent viscosity decreases in the other shapes. In these cases it can be seen that the fluid turbulence occurs along both channels. This leads to an improvement in the performance of the microalgae production.



(a)

(b)

(c)

(d)

Fig. 12. Turbulent viscosity distribution (a) Configuration 1 (b) Configuration 2 (c) Configuration 3 (d) Configuration 4

5.4 Power and Dead Zones

Figure 13 shows the percentage of power required and the volume of the dead zone for the four configurations. Compared to the standard raceway pond, the power consumption is high when the impeller is placed at the entrance of the primary channel (configuration c). In addition, the dead zone volume decreases in this configuration. The lowest dead zone volume occurs when the impeller is located at the start of the channel. In this configuration, the power consumption is the highest compared to the others. However, for the third shape, when the impeller is localised at the bend zone (d), both the dead zone volume and the power consumption are at their maximum. Therefore, this configuration is not the appropriate solution for optimising the shape of the raceway pond. The dead zone volume in configurations (a) and (c) is greater than in configurations (b) and (d). The power consumption is also high. In terms of cost, the raceway pond is the most efficient solution for configuration (c). Therefore, this configuration has a great potential in the cultivation of microalgae with high performance and low cost. These results are confirmed by Figure 14, which shows the contours of the dead zone in the four configurations considered.

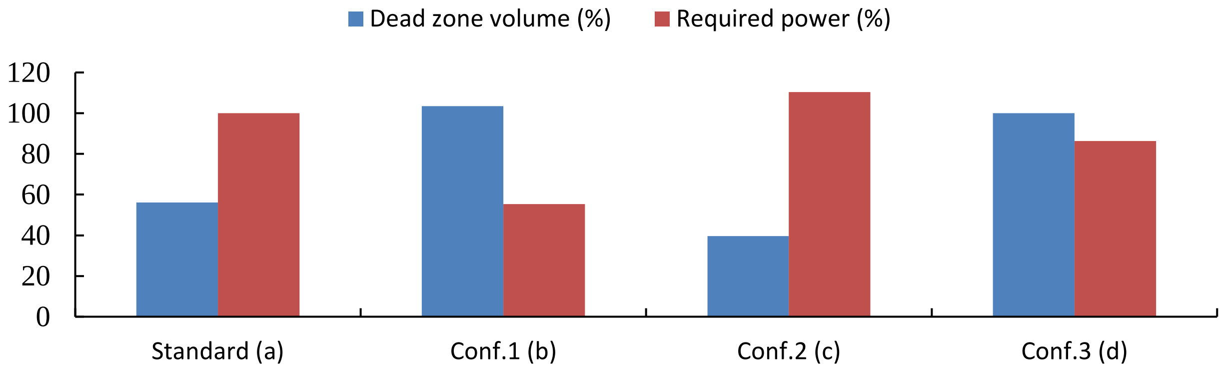
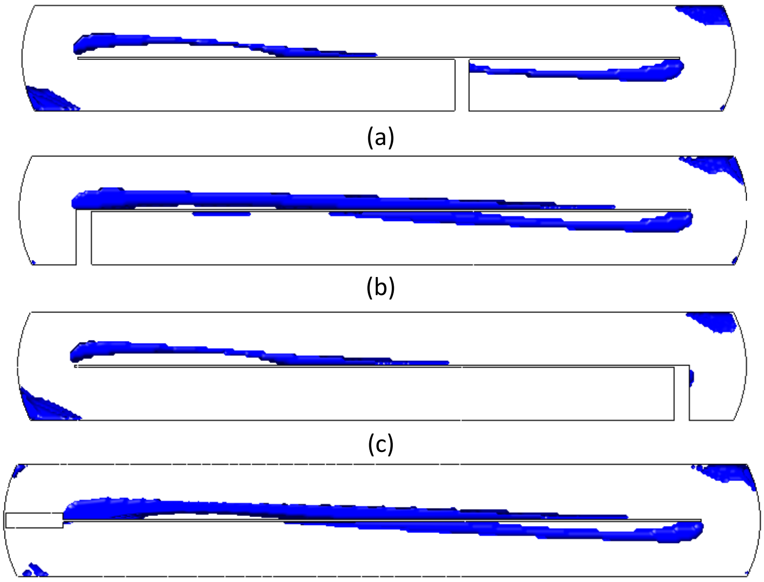


Fig. 13. Effect of paddle wheel position on dead zones volume and power


(a)

(b)

(c)

(d)

Fig. 14. Dead zones distribution (a) Configuration 1 (b) Configuration 2 (c) Configuration 3 (d) Configuration 4

6. Conclusion

In this paper, an experimental and numerical study of a raceway pond constructed in Tunisia has been developed. The effect of the velocity inlet and the position of the paddle wheel in the fluid channels on the system behaviour was studied using the commercial CFD software, ANSYS Fluent. Meshing was performed to optimise the numerical calculation. The hydrodynamic characteristics of the pond were analysed. The results were validated by experimental measurements of the fluid velocity in both channels of the system. The standard turbulence model k- ε was used to model the turbulence created by the impeller of the fluid flow. According to the simulation results, the effect of the velocity inlet and the position of the paddle wheel in the fluid channels can reduce the power consumption, increase the average velocity, and decrease the dead zone. These results will be used for the design and development of the raceway pond. For applications requiring larger-scale microalgae production, the findings can guide the scale-up process. This involves ensuring that successful design and operational strategies at the laboratory or pilot scale can be effectively applied to larger raceway pond systems, maintaining productivity and economic viability.

This research holds considerable significance within the field of microalgae production, presenting valuable insights that can potentially revolutionize various applications, particularly in the context of biofuel production. The investigation of an open raceway pond, based on a real system in Tunisia, offers a unique contribution to understanding the hydrodynamic aspects of large-scale microalgae cultivation.

Future studies could explore the use of more advanced modeling techniques or alternative CFD approaches to enhance the accuracy of predictions. This might include incorporating multiphase models to account for the interaction between microalgae and the surrounding fluid, improving the representation of turbulence, or considering non-Newtonian behavior of the culture medium. Investigating the transient behavior and dynamic responses of raceway pond systems could provide a more realistic representation of operational conditions. This would involve considering variations in environmental factors, changes in microalgae concentration, and responding to external disturbances.

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