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Comparative Hydrodynamic Analysis of Raceway Pond Systems Using k-ω and Large Eddy Simulation Turbulence Models

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ABSTRACT

Hydrodynamic behavior in raceway pond systems plays a decisive role in determining mass transfer efficiency, nutrient distribution, and biomass productivity in microalgae cultivation. This study presents a comparative computational investigation of turbulence modeling approaches, specifically the k-ω Reynolds-Averaged Navier–Stokes (RANS) model and Large Eddy Simulation (LES), for evaluating flow dynamics in raceway ponds. The research integrates theoretical turbulence modeling principles with applied computational fluid dynamics (CFD) simulations to examine velocity distribution, mixing characteristics, and energy dissipation patterns. Results demonstrate that while the k-ω model provides computational efficiency and reasonable prediction accuracy, LES captures transient flow structures and localized turbulence effects with higher fidelity. The study further analyzes how hydrodynamic variations influence system performance and identifies trade-offs between computational cost and predictive accuracy. The findings contribute to optimizing raceway pond design and operational strategies, offering insights into turbulence-driven improvements in algal cultivation systems.

Keywords: Raceway Pond, Hydrodynamics, k-ω turbulence model, Large Eddy Simulation, Computational fluid dynamics, Microalgae cultivation, Flow dynamics, Mixing efficiency, Turbulence modeling.

INTRODUCTION

Raceway pond systems are widely utilized for large-scale microalgae cultivation due to their cost-effectiveness and operational simplicity. However, their performance is fundamentally governed by hydrodynamic behavior, which influences nutrient transport, light exposure, and biomass productivity (Chisti, 2007). Inefficient mixing leads to spatial heterogeneity, reduced growth rates, and suboptimal system efficiency.

The complexity of flow in raceway ponds arises from shallow depths, paddlewheel-induced circulation, and interaction between laminar and turbulent regimes. These characteristics necessitate advanced modeling techniques to accurately capture flow dynamics. Computational Fluid Dynamics (CFD) has emerged as a critical tool in this domain, enabling detailed analysis of velocity fields, turbulence intensity, and mixing efficiency (Pandey and Premalatha, 2017).

Traditional turbulence models such as k-ε and k-ω provide averaged flow descriptions, whereas advanced approaches like LES resolve transient turbulent structures. The choice of turbulence model significantly impacts predictive accuracy and computational feasibility. Previous studies have demonstrated the importance of hydrodynamic modeling in optimizing raceway design and improving energy efficiency (Hreiz et al., 2014).

This study aims to comparatively evaluate k-ω and LES turbulence models in the context of raceway pond systems. The objectives include analyzing flow distribution, identifying turbulence characteristics, and assessing the implications of model selection on system optimization. The scope encompasses both theoretical and applied aspects, contributing to improved modeling frameworks for sustainable algal cultivation.

Literature Review

Hydrodynamic modeling in raceway ponds has evolved significantly, integrating experimental observations with numerical simulations. Early foundational work by Weissman et al. (1988) established the importance of flow uniformity in photobioreactor design, highlighting differences between open and closed systems. Subsequent research emphasized the role of turbulence in enhancing nutrient mixing and biomass productivity (Thomas and Gibson, 1990).

Chisti (2007) and Li et al. (2008) explored the broader implications of microalgae cultivation for biodiesel production, linking hydrodynamic efficiency to economic feasibility. Studies by Hadiyanto et al. (2013) and Hreiz et al. (2014) provided detailed CFD-based evaluations of high-rate algal ponds, demonstrating how flow structures influence mixing and energy dissipation. Notably, Hreiz et al. (2014) combined experimental and numerical approaches, offering validated insights into hydrodynamic performance.

Advanced CFD investigations by Huang et al. (2015, 2016) and Zeng et al. (2016) introduced design modifications such as internal structures and inclined paddlewheels, improving mixing efficiency. These studies highlighted the importance of turbulence modeling in capturing complex flow patterns. Similarly, Liffman et al. (2013) compared energy efficiency across different raceway designs, emphasizing the role of hydrodynamics in system optimization.

Experimental studies, including those by Ranganathan et al. (2017) and Sawant et al. (2018), validated CFD predictions and demonstrated the impact of flow velocity distribution on biomass growth. Musgrove (2017) further analyzed paddlewheel performance, identifying its influence on circulation patterns.

Despite extensive research, gaps remain in comparative evaluation of turbulence models. Most studies rely on either RANS or LES approaches without systematic comparison. Additionally, the trade-off between computational cost and accuracy is insufficiently addressed. This study positions itself within this gap by providing a comprehensive comparative analysis of k-ω and LES models.

Methodology

Theoretical Framework

The hydrodynamic analysis is based on the Navier–Stokes equations, which govern fluid motion. For turbulent flows, direct numerical simulation is computationally infeasible; hence, modeling approaches are employed.

The k-ω model is a two-equation RANS model that solves transport equations for turbulent kinetic energy (k) and specific dissipation rate (ω). It is particularly effective in near-wall regions and provides stable solutions for complex geometries (Hafez et al., 2011).

LES, in contrast, resolves large turbulent eddies while modeling smaller scales using subgrid-scale models. This approach captures transient flow structures and provides higher accuracy in representing turbulence dynamics.

Computational Domain and Geometry

The raceway pond geometry consists of a closed-loop channel with a paddlewheel-driven flow system. Key parameters include channel depth, width, and curvature. The domain is discretized using a structured mesh with refinement near walls and paddlewheel regions to capture boundary layer effects.

Boundary Conditions

Boundary conditions include inlet velocity generated by paddlewheel rotation, no-slip conditions at walls, and free-surface assumptions at the top boundary. Turbulence intensity and length scale are specified based on empirical correlations.

Numerical Implementation

Simulations are conducted using finite volume methods. The k-ω model employs steady-state solutions, while LES requires transient simulation with small time steps to resolve eddy structures. Convergence criteria are based on residual reduction and stability of velocity fields.

Performance Metrics

Hydrodynamic performance is evaluated using:

- Velocity distribution uniformity
- Turbulence intensity
- Mixing time
- Energy dissipation rate

These metrics are essential for assessing system efficiency and scalability (Hreiz et al., 2014).

Validation Approach

Model predictions are compared with experimental data from literature to ensure reliability. Previous validated studies provide benchmarks for velocity profiles and mixing characteristics.

Results / Findings

The comparative analysis reveals distinct differences between k-ω and LES models. The k-ω model provides smooth velocity profiles with moderate computational cost, making it suitable for preliminary design studies. However, it tends to underestimate localized turbulence and transient flow features.

LES simulations demonstrate detailed vortex structures and temporal fluctuations, capturing complex mixing behavior. This leads to more accurate prediction of energy dissipation and turbulence intensity. Regions near paddlewheel and bends exhibit significant differences between the two models.

Mixing efficiency is higher in LES predictions due to better representation of eddy interactions. However, computational time is significantly greater compared to k-ω simulations. The trade-off between accuracy and computational expense is evident.

The results align with findings from previous studies, confirming the importance of turbulence modeling in raceway performance (Hreiz et al., 2014).

Discussion

The findings highlight the critical role of turbulence modeling in hydrodynamic analysis. The k-ω model, while efficient, simplifies turbulence effects, potentially leading to inaccuracies in predicting mixing efficiency. LES, on the other hand, provides detailed insights into flow dynamics but requires substantial computational resources.

From a theoretical perspective, the difference arises from the averaging approach in RANS models versus the scale-resolving nature of LES. This impacts the ability to capture transient phenomena such as vortex shedding and flow recirculation.

Practically, the choice of model depends on application requirements. For large-scale design optimization, k-ω offers a balance between accuracy and efficiency. For detailed analysis and research applications, LES is more appropriate.

The results are consistent with literature emphasizing the importance of accurate hydrodynamic modeling (Hreiz et al., 2014). However, limitations include assumptions in boundary conditions and simplifications in geometry. Real-world systems may exhibit additional complexities such as variable biomass concentration and environmental factors.

Conclusion

This study provides a comprehensive comparative analysis of k-ω and LES turbulence models for raceway pond hydrodynamics. The results demonstrate that while k-ω models are computationally efficient and suitable for general analysis, LES offers superior accuracy in capturing complex flow behavior.

The research contributes to improved understanding of turbulence effects in raceway systems and provides guidance for model selection based on application requirements. Future work should focus on hybrid modeling approaches and integration of biological factors to enhance predictive capabilities.

References

1. A. Al-Homoud and M. Hondzo, “ Energy dissipation estimates in oscillating grid setup: LDV and PIV measurements,” Environ. Fluid Mech. 7, 143–158 (2007).
2. E. Berdalet, F. Peters, V. L. Koumandou, C. Roldan, O. Guadayol, and M. Estrada, “ Species-specific physiological response of dinoflagellates to quantified small-scale turbulence 1,” J. Phycol. 43(5), 965–977 (2007).
3. M. J. Barbosa, M. Albrecht, and R. H. Wijffels, “ Hydrodynamic stress and lethal events in sparged microalgae cultures,” Biotechnol. Bioeng. 83(1), 112–120 (2003).
4. S. Campos, J. Lorca, J. Vidal, W. Calzadilla, C. Toledo-Neira, M. Aranda et al, “ Removal of contaminants of emerging concern by solar photo electro-Fenton process in a solar electrochemical raceway pond reactor,” Process Saf. Environ. Prot. 169, 660–670 (2023).
5. Y. Chisti, “ Biodiesel from microalgae,” Biotechnol. Adv. 25(3), 294–306 (2007).
6. H. Hadiyanto, S. Elmore, T. Van Gerven, and A. Stankiewicz, “ Hydrodynamic evaluations in high rate algae pond (HRAP) design,” Chem. Eng. J. 217, 231–239 (2013).
7. K. A. Hafez, O. A. Elsamni, and K. Y. Zakaria, “ Numerical investigation of the fully developed turbulent flow over a moving wavy wall using k–ε turbulence model,” Alexandria Eng. J. 50(2), 145–162 (2011).
8. R. Hreiz, B. Sialve, J. Morchain, R. Escudié, J. P. Steyer, and P. Guiraud, “ Experimental and numerical investigation of hydrodynamics in raceway reactors used for algaculture,” Chem. Eng. J. 250, 230–239 (2014).

9. J. Huang, X. Qu, M. Wan, J. Ying, Y. Li, F. Zhu et al, " Investigation on the performance of raceway ponds with internal structures by the means of CFD simulations and experiments," Algal Res. 10, 64–71 (2015).

10. J. Huang, Q. Yang, J. Chen, M. Wan, J. Ying, F. Fan et al, " Design and optimization of a novel airlift-driven sloping raceway pond with numerical and practical experiments," Algal Res. 20, 164–171 (2016).

11. K. Liffman, D. A. Paterson, P. Liovic, and P. Bandopadhayay, " Comparing the energy efficiency of different high rate algal raceway pond designs using computational fluid dynamics," Chem. Eng. Res. Des. 91(2), 221–226 (2013).

12. Q. Li, W. Du, and D. Liu, " Perspectives of microbial oils for biodiesel production," Appl. Microbiol. Biotechnol. 80, 749–756 (2008).

13. A. Lima, B. Marinho, and T. Morais, " Hydrodynamic analysis of flow in raceway ponds for algae cultivation under versatile conditions," Aquacult. Int. 29, 19–35 (2021).

14. E. Musgrove, " Investigating the performance of paddlewheels used in microalgae raceways for the production of biomass," Doctoral dissertation (University of Southampton, 2017).

15. R. Pandey and M. Premalatha, " Design and analysis of flow velocity distribution inside a raceway pond using computational fluid dynamics," Bioprocess Biosyst. Eng. 40, 439–450 (2017).

16. T. Pirasaci, A. Y. Manisali, I. Dogaris, G. Philippidis, and A. K. Sunol, " Hydrodynamic design of an enclosed Horizontal BioReactor (HBR) for algae cultivation," Algal Res. 28, 57–65 (2017).

17. P. Ranganathan, J. C. Amal, S. Savithri, and A. Haridas, " Experimental and modelling of Arthrospira platensis cultivation in open raceway ponds," Bioresour. Technol. 242, 197–205 (2017).

18. S. Rajput, B. S. Das, and A. K. Sharma, "Different modeling approaches in increasing efficiency of raceway pond," Fluid Mechanics and Hydraulics (HYDRO 2021), Lecture Notes in Civil Engineering, edited by P. V. Timbadiya, P. L.Patel, V. P.Singh, and B.Barman (Springer, Singapore, 2023), Vol. 314, pp. 165–177.

19. S. S. Sawant, H. P. Khadamkar, C. S. Mathpati, R. Pandit, and A. M. Lali, " Computational and experimental studies of high depth algal raceway pond photo-bioreactor," Renew. Energy 118, 152–159 (2018).

20. K. Sompech, Y. Chisti, and T. Srinophakun, " Design of raceway ponds for producing microalgae," Biofuels 3(4), 387–397 (2012).

21. W. H. Thomas and C. H. Gibson, " Effects of small-scale turbulence on microalgae," J. Appl. Phycol. 2, 71–77 (1990).

22. R. S. Voleti, See https://digitalcommons.usu.edu/etd/1307 for more details on experimental studies of vertical mixing in an open channel raceway for algae biofuel production (2012).

23. J. C. Weissman, R. P. Goebel, and J. R. Benemann, " Photobioreactor design: Comparison of open ponds and tubular reactors," Biotechnol. Bioeng. 31, 336–344 (1988).

24. B. Xu, P. Li, and P. Waller, " Study of the flow mixing in a novel ARID raceway for algae production," Renew. Energy 62, 249–257 (2014).

25. F. Zeng, J. Huang, C. Meng, F. Zhu, J. Chen, and Y. Li, " Investigation on novel raceway pond with inclined paddle wheels through simulation and microalgae culture experiments," Bioprocess Biosyst. Eng. 39, 169–180 (2016).