CFD Based Performance Prediction Model for Paddle Wheel Aerator

Priyambodo Nur Ardi Nugroho[1][a], Muhammad Anis Mustaghfirin[1][b], Dwi Sasmita Aji Pambudi[1][c], Eky Novianarenti[1][d], Dyah Arum Wulandari[2][e] and Shuichi Torii[3][f]

[1]*Shipbuilding Engineering Department, Politeknik Perkapalan Negeri Surabaya, Indonesia*
[2]*Department of Mechanical Engineering, Universitas Negeri Jakarta, Indonesia*
[3]*Department of Advanced Mechanical System Engineering, Kumamoto University, Japan*

Keywords: Paddlewheel Aerator, Performance Prediction Model, Computational Fluid Dynamics (CFD), Water Quality, Aeration Process.

Abstract: The intensive aquaculture industry is mainly affected by the ability to maintain water quality, and low dissolved oxygen could be improved through the aeration process. The paddlewheel aerator is one of the supporting devices required for the intensive aquaculture pond system. The paddlewheel aerator still has a low aeration performance, resulting in higher operational costs. This paper presents an analytical model to predict the optimal performance of a paddle wheel aerator. The model considers the most influential factors affecting the performance of the paddlewheel aerator. Then, Computational Fluid Dynamics (CFD) is employed to simulate and validate the developed analytical model. The simulation results demonstrate that the model is accurate enough to estimate the paddlewheel aerator's optimal operational condition.

1 INTRODUCTION

Aquaculture has become an important global source of food and commercial products. According to a technical report by Gillet (2008) for the Food and Agriculture Organization of the United Nations, the annual worldwide production of shrimp, both farmed and caught, is approximately 6 million tonnes, with more than 40% coming from farming. Aquaculture is generally divided into marine and inland categories. Unlike marine aquaculture, which takes place in finite spaces surrounded by an open environment such as a river or sea, inland aquaculture occurs in isolated coastal vessels or ponds with little connection to the external environment. In these isolated spaces, biological conditions can deviate from the natural environment, leading to technical problems such as low dissolved oxygen (DO) levels in the water, which can pose a challenge for aquatic organisms in shrimp culture (Itano, 2018).

Aeration is the mechanism by which a certain amount of oxygen is added to the water to provide sufficient oxygen. Aeration is achieved by increasing the contact of water and air using an aerator. One type of aerator widely used in pond culture is the paddle wheel aerator (Laksitanonta, 2003). The paddlewheel aerator is the most suitable due to its aeration mechanism and the sizeable drive power (Romaire, 2007). Several parameters affect the aeration rate, including water and air surface contact, differential oxygen concentration, membrane surface coefficient, and turbulence (Boyd, 1988). A single paddle wheel aerator's performance in shrimp ponds has been examined (Ong, 2005). On the other hand, a comprehensive review of the state-of-the-art

[a] https://orcid.org/0000-0001-7111-5866
[b] https://orcid.org/0000-0002-9669-1015
[c] https://orcid.org/0000-0002-4869-4326
[d] https://orcid.org/0009-0002-7869-1692
[e] https://orcid.org/0000-0001-5803-0227
[f] https://orcid.org/0000-0001-9327-741X

Nugroho, P., Mustaghfirin, M., Pambudi, D., Novianarenti, E., Wulandari, D. and Torii, S.
CFD Based Performance Prediction Model for Paddle Wheel Aerator.
DOI: 10.5220/0012114600003680
In *Proceedings of the 4th International Conference on Advanced Engineering and Technology (ICATECH 2023)*, pages 103-106
ISBN: 978-989-758-663-7; ISSN: 2975-948X

paddlewheel aerators in aquaculture is also available (Saucedo-Teran, 2019).

Some researchers have examined the aeration efficiency of a single paddle wheel aerator in aquaculture (Duan, 2015). The paddle wheel's shape, size, and speed can impact aeration efficiency (Moulick, 2002). Low aeration efficiency can result in the need for higher drive horsepower due to higher drag, which can lead to increased operating costs, including electricity and fuel consumption. Various models of paddle wheel aerators are available in the market, with Taiwan-designed aerators being widely used due to their affordability and lightweight design, as depicted in Figure 1 (Wyban, 1989). However, their efficiency is relatively low, with the paddle wheel aerator having a Standard Aeration Efficiency (SAE) value of 1.063 kg O_2 kW h^{-1}, which is lower than other designs (Peterson, 2002).

Previous research has used computational fluid dynamics (CFD) modelling to examine the performance of paddle wheel aerators in aquaculture, providing insights into the aerator's flow pattern and oxygen transfer efficiency (Akintoye, 2018). Other studies have also employed CFD simulations to analyze the flow pattern of a paddle wheel aerator tank (Kiatkittipong, 2007) and to investigate flow and mixing patterns in an aerated paddlewheel tank (Prasertsri, 2009). The current study aimed to predict the optimal performance of a paddle wheel aerator based on numerical analysis of the current model design, serving as a baseline for future improvement.

Figure 1: Paddle Wheel Aerator based on Taiwan design.

2 MATERIALS AND METHODS

A hydrodynamic model was performed using the continuity and momentum equations for Newtonian incompressible fluids to represent the flow structure through a paddlewheel aerator. This study refers to previous studies about the hydrodynamic characteristics of a paddle wheel aerator using CFD simulation (Yu, 2021). Recently, a numerical study based on CFD simulation to investigate the hydrodynamic characteristics of the impeller of a paddle wheel aerator have been conducted (Miao, 2018). Reynolds terms were resolved to fluctuate time-averaged values and averaged in the longitudinal direction to yield the depth-integrated three-dimensional Reynolds equation (Schlichting, 1979). The paddlewheel aerator's thrust effects are considered a mass force to produce the acceleration and are included in the Reynolds equation (Peterson, 2002). The governing equations can be deduced in the x, y, and z directions to give the following equations (Chen, 1994).

$$\frac{\partial \eta}{\partial t}+\frac{\partial HU}{\partial x}+\frac{\partial HV}{\partial y}+\frac{\partial HW}{\partial z}=0 \quad (1)$$

$$\frac{\partial HU}{\partial t}+\frac{\partial \beta HU^2}{\partial x}+\frac{\partial \beta HUV}{\partial y}+\frac{\partial \beta HUW}{\partial z}=HF_{pwx}-gH\frac{\partial \eta}{\partial x}-\frac{\tau_{bx}}{\rho}+\bar{\varepsilon}H\left[\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}+\frac{\partial^2 U}{\partial z^2}\right] \quad (2)$$

$$\frac{\partial HV}{\partial t}+\frac{\partial \beta HUV}{\partial x}+\frac{\partial \beta HV^2}{\partial y}+\frac{\partial \beta HUW}{\partial z}=HF_{pwy}-gH\frac{\partial \eta}{\partial y}-\frac{\tau_{by}}{\rho}+\bar{\varepsilon}H\left[\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}+\frac{\partial^2 V}{\partial z^2}\right] \quad (3)$$

$$\frac{\partial HW}{\partial t}+\frac{\partial \beta HUW}{\partial x}+\frac{\partial \beta HUW}{\partial y}+\frac{\partial \beta HW^2}{\partial z}=HF_{pwz}-gH\frac{\partial \eta}{\partial z}-\frac{\tau_{bz}}{\rho}+\bar{\varepsilon}H\left[\frac{\partial^2 W}{\partial x^2}+\frac{\partial^2 W}{\partial y^2}+\frac{\partial^2 W}{\partial z^2}\right] \quad (4)$$

Where η is water surface elevation; t is time; x, y, and z are Cartesian coordinates; U, V, and W are depth-averaged velocity components in the x-, y-, and z- directions; and H is total depth. The paddlewheel aerator pushes the water mass forward, creating horizontal circulation. On the other hand, it splashes water particles vertically. Figure 2 shows the operation of the paddlewheel aerator in a fish pond. Water particles are projected and dispersed in an area of constant height and width at the front of the impeller. The blades of the paddlewheel aerator have some holes in the body to improve reaeration. However, the swept mass of the blades may not be equal to the mass pushed forward by the paddlewheel aerator, resulting in a mass imbalance. To correct this, a simple mass correction factor can be used.

Figure 2. Pushing and splashing of water particles by paddlewheel operating in the pond.

Figure 3 shows the computational domain after running approximately 10,000 iterations. This study aimed to create a relationship between laboratory data and a computational fluid dynamics model. The Ansys Fluent software was used to perform a series of simulation experiments on the developed model. The Reynolds-averaged Navier-Stokes equations were applied to the stable, incompressible, three-dimensional flow of the pond. The transport equations of the Standard $k-\varepsilon$ turbulence model were utilized to calculate the turbulence kinetic energy k and its dissipation rate ε.

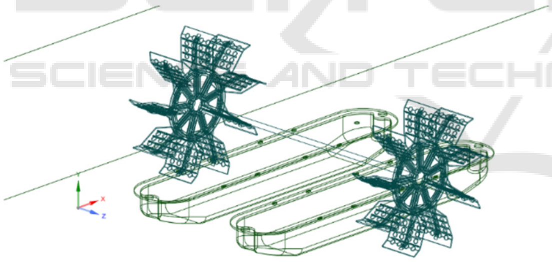

Figure 3. Computational Domain.

3 RESULTS AND DISCUSSION

Figure 4 provides a visualization of the velocity vector changes in the computational domain, observed from the x-y side view. The highest recorded velocity vector was found to be 5 m/s, while the average velocity, based on the velocity volume represented in Figure 5, was approximately 2 m/s. The results were confirmed through experimental analysis. It is important to note that various factors, such as wind, pond shape, floor topography, turbulent diffusivity, and paddlewheel aerator arrangement, influence the pond's flow characteristics.

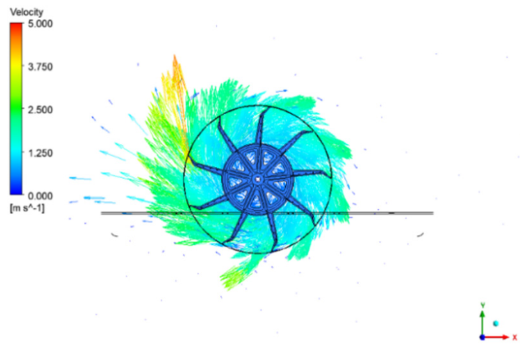

Figure 4: Velocity Vector.

A physical experimental analysis is necessary to separate the individual effects of wind, pond shape, floor topography, turbulent diffusivity, and the arrangement of paddlewheel aerators on the flow characteristics in the pond. However, controlling and quantifying all these effects simultaneously is not easy. Therefore, laboratory experiments using proportional models are needed to control the parameters and obtain data for analysis. It is suggested that further research should be conducted to verify the model prediction and clarify the flow characteristics of paddle wheel aerators using fluid dynamics experiments in a controlled laboratory, as previously recommended (Kang, 2004).

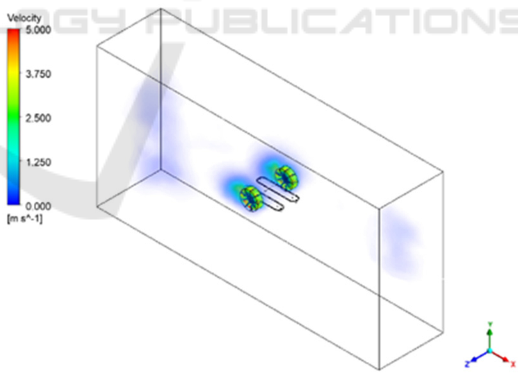

Figure 5: Velocity Volume.

4 CONCLUSIONS

In conclusion, optimizing various factors affecting aeration can lead to improved efficiency, ultimately reducing operating costs and improving overall aquaculture productivity. Computational fluid dynamics models have proven to be useful tools in predicting the performance of paddle wheel aerators and can aid in the development of more efficient designs. However, laboratory experiments using proportional models are still necessary to fully understand the flow characteristics and optimize the design of paddle wheel aerators. Future research should focus on combining both computational and experimental approaches to improve the understanding and optimization of aeration in aquaculture.

ACKNOWLEDGEMENTS

This research was supported by the Ministry of Research, Technology and Higher Education Indonesia and The Indonesia Endowment Funds for Education (LPDP) through an applied scientific research funding program. Such funding is crucial in advancing research and promoting innovation, and it is a positive step toward promoting sustainable aquaculture practices. The results of this study can provide valuable insights into the aquaculture industry, which can help them optimize their production processes and increase their productivity while minimizing their environmental impact.

REFERENCES

Akintoye, H. A., Ogunyemi, S. O., & Ogunbiyi, O. A. (2018). CFD modelling of paddle wheel aerator performance in aquaculture. *Aquacultural Engineering*, 81, 77-86.

Boyd, C. E. (1988). Pond water aeration systems. *Aquaculture Engineering*, 18, 9-40.

Chen, Y., & Falconer, R. (1994). Modified forms of the third-order convection, second-order diffusion scheme for the advection-diffusion equation. *Advances in Water Resources*, 17(3), 147-170.

Duan, J., & Wang, Y. (2015). Study on the aeration efficiency of the single paddle wheel aerator in aquaculture. *Journal of Aquaculture Research & Development*, 6(2), 2-7.

Gillet, R. (2008). Global study of shrimp fisheries. *FAO fisheries technical paper* 475.

Kang, Y. H., Lee, M. O., Choi, S. D., & Sin, Y. S. (2004). 2-D hydrodynamic model simulating paddlewheel-driven circulation in rectangular shrimp culture ponds. *Aquaculture*, 231(1-4), 163-179.

Kiatkittipong, W., Reungsang, A., & Chansiripornchai, N. (2007). CFD simulation of fluid flow pattern in paddle wheel aerator tank. *Chemical Engineering Journal*, 133(1-3), 259-266.

Laksitanonta, S., Singh, S., & Singh, G. A. (2003). A review of aerators and aeration practices in Thai Aquaculture. *Agricultural Mechanization in Asia, Africa and Latin America*, 34, 64-71.

Miao, J., Wang, Y., Wang, J., & Yan, H. (2018). Numerical study on hydrodynamic characteristics of the paddle wheel aerator impeller based on CFD simulation. *Journal of Aquaculture Research & Development*, 9(6), 1-5.

Moulick, S., Mal, B. C., & Bandyopadhyay, D. (2002). Prediction of aeration performance of paddlewheel aerators. *Aquaculture Engineering*, 25(3), 217-237.

Ong, B. K., Wong, K. W., & Ho, Y. B. (2005). Performance of single paddle wheel aerator in shrimp ponds. *Aquacultural Engineering*, 33(3-4), 277-288.

Peterson, E. L., & Walker, M. B. (2002). Effect of speed on Taiwanese paddlewheel aeration. *Aquaculture Engineering*, 26(2), 129-147.

Prasertsri, P., Thiansem, S., & Thammasorn, T. (2009). Simulation of flow and mixing in the paddlewheel aerated tank using CFD. *Chemical Engineering Journal*, 150(1), 70-78.

Romaire, R. P., & Merry, G. E. (2007). Effect of paddlewheel aeration on water quality in crawfish pond. *Applied Aquaculture*, 19(1-2), 61-75.

Saucedo-Teran, R. A., & Magana-Esparza, D. (2019). Paddlewheel aerators in aquaculture: a review of the state-of-the-art. *Aquaculture International*, 27(4), 1199-1222.

Schlichting, H. (1979). *Boundary Layer Theory*. 6th edition. McGraw-Hill, New York. 742.

Tomoaki Itano, Taishi Inagaki, Choji Nakamura, Ren Hashimoto, Naohiro Negoro, Jinsuke Hyodo, Syuta Honda (2018). Water circulation induced by mechanical aerators in a rectangular vessel for shrimp aquaculture. *Aquacultural Engineering*, 81, 59-66.

Wang, J., Li, Y., Li, W., Chen, J., Yang, Y., & Wang, S. (2020). Numerical simulation of flow and mass transfer in the paddlewheel aerated tank based on the LBM method. *Aquacultural Engineering*, 89, 102014.

Wang, Y., Wang, J., Miao, J., & Liu, B. (2019). Numerical simulation on flow characteristics and oxygen transfer of the paddle wheel aerator. *Journal of Aquaculture Research & Development*, 10(2), 1-5.

Wyban, J. A., Pruder, G. D., & Leber, K. M. (1989). Paddlewheel effect on shrimp growth, production, and crop value in commercial earthen ponds. *Journal of the World Aquaculture Society*, 20(1), 18-23.

Yu, D., Li, D., Li, D., Li, Y., & Li, L. (2021). Study on the hydrodynamic characteristics of paddle wheel aerator based on CFD simulation. *Journal of Aquaculture Research & Development*, 12(6), 1-9.