



Effect of Gas Flow Rate on Hydrodynamics and Dissolved Oxygen Characteristics in a Fine-Bubble Aeration System: A CFD-Based Study

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ABSTRACT

This study evaluates the effect of gas flow rate on hydrodynamic behavior and dissolved oxygen (DO) profiles in a lab-scale fine-bubble aeration system using computational fluid dynamics (CFD). Triplicate experiments were conducted in a 17.06 L batch reactor containing domestic wastewater, with a disk aerator operated at gas flow rates of 0.5, 1.0, and 1.5 L/min. CFD was applied to interpret internal flow behavior through velocity contours and streamline patterns. The results showed that DO increased significantly with higher gas flow rates ($p < 0.05$), with 1.5 L/min achieving the highest final DO of 6.73 ± 0.12 mg/L. CFD analysis indicated that higher gas flow rates produced more developed circulation patterns, although the area-weighted average velocity magnitude on the selected plane decreased from 0.0317 m/s at 0.5 L/min to 0.0203 m/s at 1.5 L/min. These findings suggest that oxygenation improvement was governed not only by mean liquid velocity, but also by gas input and internal flow organization. This study uniquely integrates experimental DO measurements with CFD-predicted hydrodynamic behavior in a laboratory-scale domestic wastewater aeration system.

1. INTRODUCTION

Aeration is the most energy-intensive unit in wastewater treatment plants, providing the dissolved oxygen required for microorganisms to degrade organic pollutants and achieve optimal treatment performance. Accounting for up to 50% of total energy demand, aeration design must balance efficiency and energy optimization (Gu et al., 2023; Sun et al., 2024). Furthermore, the Computational Fluid Dynamics (CFD) applications in wastewater engineering to simulate and interpret the influence of hydrodynamic behavior (such as shear stress, mixing, and mass transfer) are increasing, which can not be achieved by empirical observation alone (Prades-Mateu et al., 2025; Samstag et al., 2016).

Fine-bubble aeration is the most applied aeration technology because it has a smaller bubble size that provides a larger gas-liquid interfacial area to increase oxygen transfer performance. Shah et al. (2024) noted that fine-bubble aeration

systems have been used in aeration tanks due to their improved oxygenation capabilities and adaptability to oxygen demand. Terashima et al. (2016) used the CFD simulation, emphasized that oxygen transfer performance is highly sensitive to diffuser bubble size, and showed that diffuser type can strongly influence the representative bubble diameter used in simulation. The study of Tauviquirrahman et al. (2024) showed that the different fine-bubble aeration system configurations can produce different DO distributions and more mixing patterns, indicating that hydrodynamic conditions were generated by the aerator configuration itself. Recent studies have demonstrated that both bubble size and diffuser configuration strongly influence DO distribution and mixing patterns (Si et al., 2025). Previous experimental work on a microbubble generator also showed that increasing gas flow rate enhanced oxygen transfer performance, as reflected by higher DO and K_La values under clean-water testing conditions (Mistoro et al., 2023). However, that study focused

on experimental KLa evaluation without CFD-based interpretation of internal hydrodynamic behavior. These findings suggest that the effectiveness of fine-bubble aeration systems depends not only on operational parameters, such as gas flow rate, but also on the internal hydrodynamic conditions generated by the aerator setup.

The hydrodynamic behavior within an aeration tank has an important effect on determining the oxygen transfer performance and distribution throughout the liquid phase. Local velocity, gas holdup, recirculation pattern, and non-uniform flow structure affect mixing quality and, consequently, the spatial distribution of dissolved oxygen. Fayolle et al. (2007) clearly stated that oxygen transfer in deep aeration tanks remains difficult to predict when local parameters such as bubble size, gas holdup, and local axial velocity are not adequately considered. Stickel et al. (2018) also demonstrated that hydrodynamic differences, such as stronger recirculation, can lead to a more favorable oxygen distribution pattern in aerated reactors. Then these studies indicate that bulk DO values alone are often insufficient to explain the internal behavior of aerated systems, because oxygen transfer is closely coupled with hydrodynamics.

Because direct observation of multiphase flow inside aeration systems is difficult, computational fluid dynamics (CFD) has become an important tool for studying wastewater treatment hydrodynamics. Samstag et al. (2016) described CFD as a rapidly emerging field in wastewater treatment with applications across many unit processes. Karpinska & Bridgeman (2016) further explained that CFD has been increasingly used to model aeration unit in activated sludge systems in order to improve treatment efficiency and reduce energy input. Their later lab-scale study also showed that CFD can be used to investigate turbulence, bubble-flow generation, and concentration patterns in aeration tanks for sewage treatment (Karpinska & and Bridgeman, 2017). Relate to the study of Shah et al. (2024) that showed the CFD simulation can predict gas-liquid flow fields, DO distribution, and hydrodynamic behavior in a fine-pore aeration tank, while SeyedSharifi et al. (2024) emphasized that CFD enables visualization of the flow field, mixing quality, and bubble-plume distribution in configurations that are difficult to assess by physical modeling alone. Thus, CFD is highly relevant for interpreting how gas flow rate may influence internal flow behavior and dissolved oxygen characteristics in a fine-bubble aeration system.

Most studies have provided valuable insights on hydrodynamic behavior, but only focused on aeration full-scale tank simulations, diffuser configuration optimization, oxygen transfer prediction, or CFD model development. For Instance, the study conducted by Fayolle et al. (2007) developed and validated a CFD-based tool for predicting oxygen transfer performance in an aeration system with fine-bubble diffusers and mixers. Shah et al. (2024) investigated vertical and horizontal DO distribution in a full-scale industrial aeration tank, mainly to identify representative sensor locations. SeyedSharifi et al. (2024) compared five diffuser patterns in a full-scale activated sludge tank to evaluate air distribution and mixing quality. Karpinska & Bridgeman (2017) concentrated on building a robust lab-scale CFD framework for sewage-treatment aeration tanks, while Stickel et al., (2018) examined gas-liquid mass transfer, oxygen uptake, and oxygen distribution in large-scale aerobic

bioreactors. Although the studies show strong interest in oxygen transfer, diffuser behavior, and CFD-assisted aeration analysis, studies that directly relate gas flow rate variation, CFD-predicted hydrodynamics, and experimentally measured DO behavior in a simple laboratory-scale fine-bubble aeration system using real domestic wastewater remain limited. This research gap highlights the importance of investigating the relationship between gas flow rate, hydrodynamic behaviour, and dissolved oxygen characteristics in a laboratory-scale fine-bubble aeration system.

Based on those studies and research gap, this study aims to evaluate the effect of gas flow rate on hydrodynamics and dissolved oxygen characteristics in a fine-bubble aeration system using CFD analysis. The novelty of this work lies in its integration of experimental DO measurements with CFD-predicted hydrodynamic behavior in a laboratory-scale reactor using real domestic wastewater, which differentiates it from previous studies that mostly focused on full-scale systems, idealized CFD configurations, or single-method approaches. Experimental observations under varying gas flow rates were interpreted alongside CFD results to clarify how operational conditions influence internal flow and oxygenation, providing a practical and experimentally grounded understanding for small-scale aeration applications.

2. METHOD

2.1 Experimental setup and procedure

A laboratory-scale experiment, as shown in a schematic illustration in Figure 1, was conducted using a batch reactor made of glass with dimensions of 30 cm in length, 25 cm in width and filled with the domestic wastewater at a water depth of 25 cm or in the volume unit of 17.06 L.

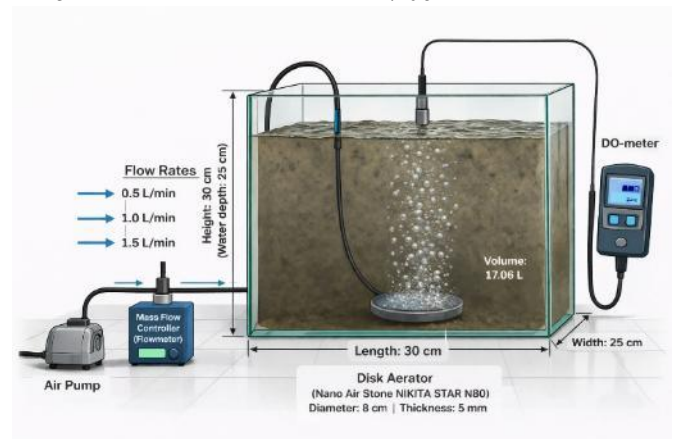


Figure 1. Schematic illustration of the lab-scale fine-bubble aeration system

A disk aerator was placed at the centre of the tank bottom. The aerator used in this study was a Nano Air Stone NIKITA STAR N80 with a diameter of 8 cm and a thickness of 5 mm. Air was supplied by an air pump and regulated using a flowmeter. Dissolved oxygen (DO) was measured using a single DO probe connected to a DO meter. The use of a membrane-electrode-based DO probe is consistent with standard practice for dissolved oxygen measurement in water and wastewater analysis under Standard Methods 4500-O G.

The domestic wastewater used for this experiment was collected from the septic tank of the Faculty of Civil Engineering and Planning, Universitas Islam Indonesia,

Indonesia. The wastewater was filled into the 17.06 L batch reactor, and an aeration experiment was performed at three gas flow rates (0.5, 1.0, and 1.5 L/min) in triplicate for each variation. The DO concentration was continuously monitored from the beginning of aeration until the reading approached saturation or stabilized. The DO values were recorded at 1-min intervals for a total of 60 min. This experimental setup observed changes in DO profiles at different gas flow rates and was used to evaluate aeration performance and to support the interpretation of the CFD results. In addition to supporting hydrodynamic and aeration interpretation, it has also been reported in previous aeration studies (Fayolle et al., 2007; Shah et al., 2024).

2.2 Dissolved oxygen evaluation

The measured DO data were used to construct dissolved oxygen profiles as a function of aeration time for each gas flow rate. Since each operating condition was tested in triplicate, the DO value at each observation time was expressed as the mean of the three replicate measurements. The mean DO concentration at time t was calculated using Equation (1):

$$\bar{DO}_t = \frac{1}{n} \sum_{i=1}^n DO_{i,t} \quad (1)$$

where \bar{DO}_t is the mean dissolved oxygen concentration at time t , $DO_{i,t}$ is the dissolved oxygen concentration measured in replicate i at time t , and n is the number of replicates.

To describe the variability among replicate measurements, the standard deviation at each observation time was calculated using Equation (2):

$$SD_t = \sqrt{\frac{\sum_{i=1}^n (DO_{i,t} - \bar{DO}_t)^2}{n - 1}} \quad (2)$$

where SD_t is the standard deviation of the dissolved oxygen concentration at time t .

The oxygenation behavior under different gas flow rates was evaluated by comparing the overall shape of the DO–time profiles, the rate of DO increase during aeration, and the final condition at which the DO reading became stable within the 60 min observation period. In this study, the DO profile characteristics become the primary indicator of oxygenation behavior, whereas the CFD analysis was subsequently used to interpret the associated hydrodynamic behavior within the aeration tank. A similar approach, in which measured DO behavior is interpreted together with simulated flow characteristics, has been applied in previous studies on aeration systems (Fayolle et al., 2007; Shah et al., 2024).

2.3 CFD model and simulation conditions

To support the interpretation of the experimental dissolved oxygen behavior, computational fluid dynamics (CFD) simulation was performed based on the actual laboratory-scale aeration system. In addition to visual interpretation, quantitative hydrodynamic indicators were extracted from the CFD results, including average velocity magnitude to support comparison among gas flow rate conditions. CFD has been widely applied in wastewater treatment studies to provide

hydrodynamic insight into flow structure, circulation behaviour, and multiphase interactions that are difficult to observe directly in experiments (Karpinska & Bridgeman, 2017; Samstag et al., 2016). In the present study, the CFD model was used primarily to examine the internal flow behaviour generated by air injection under different gas flow rates and to support the interpretation of the measured dissolved oxygen profiles.

The geometry and computational mesh used in the simulation are shown in Figure 2, which captures the reactor tank and a circular disk aerator at the center of the tank bottom. The simulation was performed in ANSYS Fluent using a three-dimensional, pressure-based, steady-state approach, with air and wastewater represented as the gas and liquid phases, respectively. A steady-state simulation was selected because the primary objective was to evaluate average hydrodynamic patterns, circulation zones, and velocity distribution under different gas flow rates. While aeration is inherently dynamic, steady-state assumptions are sufficient to capture the representative flow characteristics relevant to oxygen transfer interpretation and allow computational efficiency without compromising the reliability of hydrodynamic insights. The Eulerian multiphase model was used to represent the gas–liquid flow system, while species transport was included to support oxygen-related analysis. Turbulence was modeled using the SST $k-\omega$ model. The computational domain was discretized into approximately 172,018 cells, designed to adequately represent the tank volume, the liquid region, and the aeration zone around the disk aerator. Previous studies have shown that a reliable numerical setup and proper CFD model practice are essential for depicting representative flow behaviour in aeration systems (Karpinska & Bridgeman, 2017; Wicklein et al., 2015).

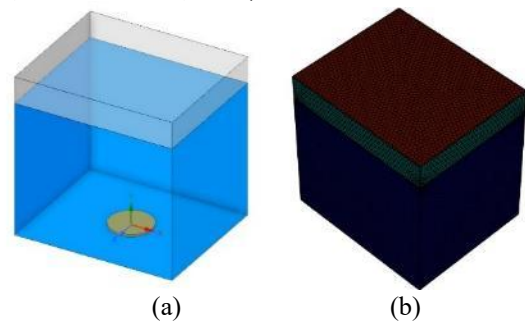


Figure 2. Geometry and computational mesh of the CFD model: (a) computational domain and (b) mesh configuration.

The operating conditions in the CFD simulation followed the experimental aeration conditions. Three gas flow rate settings were applied: 0.5, 1.0, and 1.5 L/min. These flow rates were imposed as air inlet conditions at the aerator location using mass flow rates of 1×10^{-5} , 2×10^{-5} , and 3×10^{-5} kg/s, respectively. The tank walls were treated as no-slip boundaries, while the upper boundary was defined as a pressure outlet to represent the open top of the tank. The main CFD input parameters used in this study are summarized in Table 1. For pressure–velocity coupling, the phase-coupled SIMPLE scheme was employed. Pressure interpolation was performed using the PRESTO! scheme, and momentum, volume fraction, and transport equations were solved using QUICK-based schemes. The CFD outputs in this study were velocity contours and streamlines, which were used to evaluate the distribution of flow intensity, circulation zones, and general hydrodynamic behaviour inside the aeration tank.

Similar CFD outputs have been used in recent studies to interpret aeration performance and oxygen transfer efficiency (SeyedSharifi et al., 2024; Shah et al., 2024).

Table 1. Summary of the CFD model and simulation conditions.

Category	Parameter	Description / Value
Geometry	Tank dimensions	30 cm × 25 cm × 30 cm
Geometry	Water depth	25 cm
Geometry	Working volume	17.06 L
Geometry	Aerator type	Disk aerator
Geometry	Aerator diameter	8 cm
Geometry	Aerator thickness	5 mm
Geometry	Aerator position	Center of tank bottom
Software	CFD platform	ANSYS Fluent
Model	Simulation type	3D, steady, pressure-based
Model	Multiphase model	Eulerian
Model	Species model	Species transport
Turbulence	Turbulence model	SST $k-\omega$
Mesh	Number of cells	172,018
Phase properties	Gas phase	Air
Phase properties	Liquid phase	Domestic wastewater
Boundary condition	Air inlet location	Aerator at bottom center
Boundary condition	Top boundary	Pressure outlet
Boundary condition	Tank walls	No-slip wall
Operating condition	Gas flow rate 1	0.5 L/min (1×10^{-5} kg/s)
Operating condition	Gas flow rate 2	1.0 L/min (2×10^{-5} kg/s)
Operating condition	Gas flow rate 3	1.5 L/min (3×10^{-5} kg/s)
Numerical scheme	Pressure-velocity coupling	Phase-coupled SIMPLE
Numerical scheme	Pressure discretization	PRESTO!
Numerical scheme	Transport discretization	QUICK
Output analysis	Main outputs	Velocity contours and flow trajectories

To ensure the reliability of the CFD results, a mesh independence study was conducted. Three different mesh densities were tested, and the resulting velocity and air volume fraction fields showed negligible differences (<2%) between the medium and fine meshes, indicating that the chosen mesh (approximately 172,018 cells) provides a sufficiently accurate representation of the flow field. Additionally, convergence criteria were strictly monitored, with residuals for momentum, volume fraction, and species transport equations reduced below 10^{-5} . This procedure ensures that the CFD simulations are not affected by discretization errors and that the predicted hydrodynamic patterns are robust and reliable for interpretation alongside the experimental DO measurements.

2.4 Hydrodynamic analysis

The hydrodynamic behavior obtained from CFD simulations is presented as velocity contours and streamline patterns. Velocity contours capture the distribution of flow velocities and identify regions of high and low flow intensity,

while streamlines represent the overall flow pattern, including the formation of circulation zones, flow paths, and potential stagnant regions. These hydrodynamic variables influence liquid mixing and the distribution of oxygen transfer performance (Fayolle et al., 2007; SeyedSharifi et al., 2024). The hydrodynamic results were compared qualitatively among the three gas flow rate variations to assess how changes in gas input affected the internal flow structure of the system. Recent research has focused on active flow regions, recirculation characteristics, and the presence of low-velocity zones, which are indicative of reduced mixing efficiency. These findings demonstrate that such hydrodynamic characteristics are closely related to oxygen transfer behavior and overall aeration performance (Stickel et al., 2018; Terashima et al., 2016). In addition, the CFD-predicted flow behavior was interpreted in conjunction with experimentally observed dissolved oxygen profiles. This combined experimental-numerical analysis was used to explain whether differences in DO response under different gas flow rates were associated with variations in circulation pattern, velocity distribution, and mixing conditions inside the tank. Integrating CFD simulations with experimental DO measurements has been previously shown to effectively support interpretation of oxygen distribution and hydrodynamic behaviour in aeration systems (Karpinska & Bridgeman, 2017; Shah et al., 2024).

3. RESULTS AND DISCUSSION

3.1 Dissolved oxygen profiles

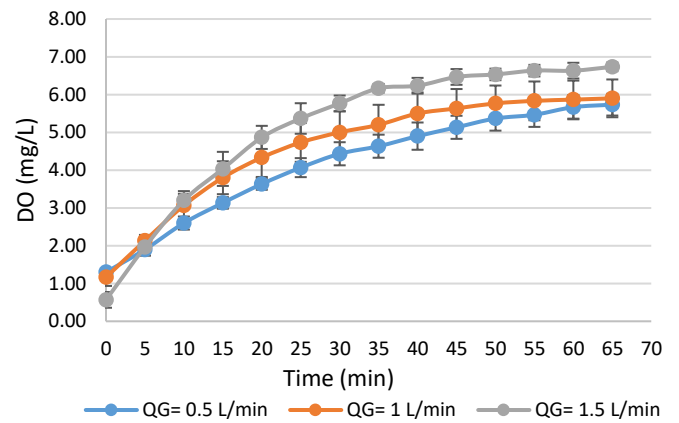


Figure 3. Dissolved oxygen profiles, data are presented as mean ± SD ($n = 3$).

The dissolved oxygen (DO) profiles at different gas flow rates showed that DO concentration increased in parallel with aeration time, indicating that the fine-bubble aeration system enhanced oxygen availability in domestic wastewater. However, the rate of increasing DO differed across the three gas flow rate conditions, suggest that gas input affected the system's oxygenation behavior. At the beginning of the aeration, the three conditions have relatively low initial DO concentrations, ranging from 0.57 to 1.30 mg/L, which then increased more rapidly at higher gas flow rates. The highest gas flow rate, 1.5 L/min, consistently produced the highest DO values throughout most of the observation period, reaching 6.73 ± 0.12 mg/L at 65 min. In comparison, the DO concentration at 1.0 L/min increased to 5.90 ± 0.50 mg/L, whereas the lowest gas flow rate, 0.5 L/min, reached $5.73 \pm$

0.29 mg/L at the end of the observation period. These results indicate that increasing gas flow rate improved the oxygenation performance of the aeration system, particularly during the intermediate and late stages of aeration.

Differences of the DO profiles were evident from the curves' slopes. The 1.5 L/min condition showed the steepest increase during the early aeration time, followed by 1.0 L/min and 0.5 L/min. This trend suggests that a greater gas supply promoted more effective gas-liquid interaction and accelerated oxygen transfer into the wastewater. Recent studies showed the addition of aeration or diffuser flow conditions can improve dissolved oxygen levels and overall aeration efficiency (Gu et al., 2023; Tauviqirrahman et al., 2024). While the three curves gradually approached a more stable trend toward the end of the experiment, the higher gas flow rate had a higher of final DO level. The standard deviation attained from the triplicate experiments is still relatively small in all conditions, indicating the acceptability of the measurements. The error bars did not obscure the separation among the three curves, which suggests that the observed differences were sufficiently consistent to represent the effect of gas flow rate on DO behavior. Overall, the experimental results demonstrate that gas flow rate influenced not only the rate of DO increase but also the final oxygenation condition achieved in the tank. These differences in DO behavior were further interpreted through CFD-based hydrodynamic analysis in the following subsection, in order to clarify how changes in gas flow rate affected the internal flow behavior of the aeration system.

3.2 CFD-predicted hydrodynamic behavior

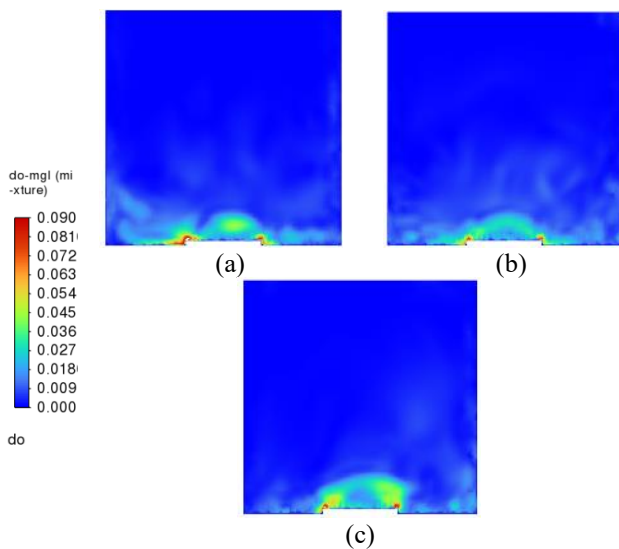


Figure 4. CFD-predicted velocity contours at gas flow rates of (a) 0.5, (b) 1.0, and (c) 1.5 L/min.

The CFD-simulated hydrodynamic behavior under different gas flow rates is presented in Figures 4 and 5. Figure 4 depicts the velocity contours and the streamline patterns in Figure 5 for gas flow rates of 0.5, 1.0, and 1.5 L/min. In general, the simulation results indicate that gas flow rate affected both the distribution of velocity magnitude and the internal flow structure within the tank. As visualized in Figure 4, the areas of higher velocity were concentrated mostly in the lower part of the tank, particularly in the near of disk aerator. In contrast, most of the upper region remained dominated by lower velocities across all operating conditions. This result

presented that the aerator performed as the main source of momentum transfer, generating localized flow activity in the area of near the bottom reactor. Similar behavior has been reported in previous CFD studies of aeration systems, where the strongest hydrodynamic activity was commonly observed in the vicinity of the diffuser or aeration zone (Fayolle et al., 2007; Shah et al., 2024).

The distinction of three gas flow rates is shown in the form of the spatial extent of the active flow region. At 0.5 L/min, the higher-velocity region appeared relatively limited and remained concentrated near the bottom reactor. When the gas flow rate increased to 1.0 L/min, the active region became more pronounced, indicating stronger flow development around the aerator. The velocity contour at 1.5 L/min showed broader active flow zones, indicates stronger momentum input into the liquid phase at the lower depth of the reactor. Given the overall flow field remained non-uniform flow, the increasing gas flow rate intensified local hydrodynamic behavior, which is consistent with earlier findings with the conclusion is the stronger aeration conditions can enhance mixing and modify the internal velocity distribution in aerated tanks (SeyedSharifi et al., 2024; Stickel et al., 2018). To further support the visual interpretation, the area-weighted average velocity magnitude was extracted from the selected vertical plane for each gas flow rate condition. The results showed that the average velocity magnitude decreased from 0.0317 m/s at 0.5 L/min to 0.0262 m/s at 1.0 L/min and 0.0203 m/s at 1.5 L/min. This finding indicates that the higher gas flow rate did not simply increase the mean liquid velocity on the selected plane, but altered the internal flow organization and circulation structure, as further illustrated by the streamline patterns in Figure 5.

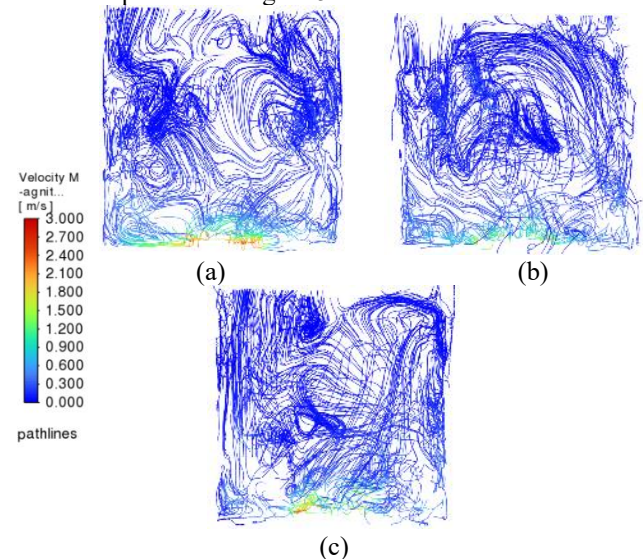


Figure 5. CFD-predicted streamline patterns at gas flow rates of (a) 0.5, (b) 1.0, and (c) 1.5 L/min.

The streamline patterns in Figure 5 illustrate the influence of gas flow rate on internal flow behavior which indicates the flow generated by the aerator did not simply move upward in a straight path but developed into multiple recirculating trajectories within the reactor. This indicates the air-induced internal circulation and redistributes the liquid motion throughout the domain. At the lower gas flow rate, the streamline pattern appeared less extensive, with circulation paths that were relatively more confined. As the gas flow rate increased, the flow trajectories became more developed and

occupied a larger portion of the tank, indicating stronger internal circulation and more complex flow interaction. This observation complements the quantitative velocity result, which showed a decrease in area-weighted average velocity magnitude at higher gas flow rates. Therefore, the more developed streamline pattern at 1.5 L/min should not be interpreted as a simple increase in mean liquid velocity, but rather as a change in flow organization and circulation structure within the reactor. The simulated streamlines suggest the presence of recirculation zones and low-activity regions in several parts of the reactor. These features are essential in the aeration process reflecting the non-uniformity of mixing and affect the distribution of oxygen in the liquid phase. Other research emphasized that hydrodynamic characteristics like recirculation, local flow patterns, and diffuser-induced circulation, have a relation to the mixing process and hydrodynamic behavior (Tauvqirrahman et al., 2024; Terashima et al., 2016). The CFD results indicate that the increasing gas flow rate promoted a more active hydrodynamic behavior, particularly in the near of disk aerator. Overall, the CFD results demonstrate that gas flow rate influenced the hydrodynamic behavior of the laboratory-scale fine-bubble aeration system. Higher gas flow rates tend to produce broader active flow regions and develop more circulation patterns, whereas lower gas flow rate are associated with weak and more localized flow activity. These CFD-predicted hydrodynamic differences provide a basis for interpreting the variations observed in the experimental dissolved oxygen profiles, which are discussed further in the next subsection.

3.3 Linking hydrodynamics and dissolved oxygen characteristics

The experimental dissolved oxygen (DO) profiles and the CFD-predicted hydrodynamic behavior showed a consistent relationship across the three gas flow rate conditions. In general, the condition that generated a more active internal flow field and more developed circulation pattern also produced a higher DO level during aeration. This trend indicates that the oxygenation performance of the fine-bubble aeration system was influenced not only by the amount of gas supplied, but also by the way of the injected gas modified the internal hydrodynamic regime of the tank. This interpretation supports the statement which says aeration performance is mostly affected by the interaction between gas input, mixing behavior, bubble movement, and gas-liquid mass transfer processes. Improvements in aeration conditions may therefore affect both oxygen availability and process efficiency simultaneously (Amaral et al., 2018; Drownowski et al., 2019; Gu et al., 2023). This is also supported by Lu et al. (2021), who showed that the aeration rate can influence oxygen mass transfer by changing bubble movement and flow-field characteristics in a microporous aeration system.

At the lowest gas flow rate of 0.5 L/min, the DO profile increased more gradually and reached the lowest final DO level among the three operating conditions. This behavior corresponded to the CFD results, which showed that the relatively active flow region remained limited and concentrated mainly near the aerator zone. The streamline pattern at this condition also suggested a less extensive circulation structure within the reactor. Such a flow field has

reduced the overall mixing effectiveness and limited the redistribution of oxygen-rich liquid to the upper and outer parts of the tank. In the aeration process, slow circulation and localized flow activity areas commonly followed by less effective oxygen transfer process and reduced degrading pollutant performance, specifically when the hydrodynamic influence of the diffuser remains restricted (Fayolle et al., 2007; Ikhwan, 2022; Shah et al., 2024). The same interpretation was also reported by Matko et al. (2021) that the heterogeneous flow patterns and local hydrodynamic conditions can affect DO distribution in aerated wastewater treatment systems.

A different trend was observed at 1.0 L/min with the DO profile increased rapidly to a higher final value than at 0.5 L/min. The following CFD simulation results showed a broader active flow region and a more developed circulation pattern, indicating stronger interaction between the injected gas and the surrounding liquid. This suggests that the higher gas flow rate promoted more effective internal mixing and improved oxygen transport within the tank. This interaction makes a stronger circulation and more developed local hydrodynamics that can enhance gas-liquid contact and improve oxygen transfer in aerated systems (Amaral et al., 2018; Stickel et al., 2018; Terashima et al., 2016). Numerical models revealed that oxygen transfer performance is responsive to hydrodynamic behavior, bubble behavior and interfacial transport, highlighting the importance of coupling flow model with DO profiles (Mohan T et al., 2021). Chen et al. (2023) also stated that the coupled processes of air bubbles, liquid motion, and oxygen transfer should be considered due to interactions among the gas, liquid, and solid phases. The highest gas flow rate, 1.5 L/min, produced the most favorable oxygenation, as reflected by the highest DO values throughout most of the observation period and the highest final DO concentration. This condition is related with the strongest hydrodynamic regime in the CFD results, particularly in the lower part of the reactor where the influence of the disk aerator was most pronounced. The streamline pattern further suggested a more developed circulation structure occupying a larger portion of the tank, which likely promoted better liquid recirculation and oxygen redistribution. Research on fine-bubble aeration and diffuser-driven flow fields also resulted in increasing aeration conditions or diffuser-related flow characteristics, enhanced oxygen distribution and aeration performance (Behnisch et al., 2020; SeyedSharifi et al., 2024; Tauvqirrahman et al., 2024). Besides, Behnisch et al. (2020) focused on clean-water oxygen transfer testing rather than domestic wastewater, their long-term evaluation of fine-bubble diffuser performance still supports the broader view of aeration effectiveness linked to diffuser-driven oxygen transfer behavior. According to Chen et al. (2024) the gas flow rate is one of the factors controlling bubble formation during bubble rise, then higher gas flow conditions can increase the oxygenation by gas input and modified bubble-driven hydrodynamics.

Taken together, these results suggest that the differences in DO profiles observed in this study were not governed solely by gas supply as an isolated operating variable, but were also closely associated with the hydrodynamic conditions created inside the tank. A higher gas flow rate not only introduced more gas into the system, but also generated a more active internal flow structure that likely supported better mixing and

oxygen dispersion. This interpretation supports that the oxygenation performance in aeration systems is strongly affected by local hydrodynamics, circulation behavior, and gas–liquid interaction rather than by airflow rate alone (Karpinska & Bridgeman, 2017; Karpinska & Bridgeman, 2016; Samstag et al., 2016). In this sense, the present findings support the use of CFD as a practical tool for interpreting how operating conditions influence internal flow behavior and, consequently, oxygen-related performance in aeration tanks (Karpinska & Bridgeman, 2017). Newest CFD-approached research has moved toward integrated analysis of hydrodynamics, mass transfer, dissolved oxygen, and water quality responses, supporting the ability of numerical modelling to give the insight for aeration evaluation and optimization in wastewater treatment systems (B. Chen et al., 2023; Matko et al., 2021; Shen et al., 2025a).

Overall, the combined experimental and numerical results indicate that hydrodynamics and dissolved oxygen characteristics were closely linked in the laboratory-scale fine-bubble aeration system. The CFD results helped explain why the 1.5 L/min condition showed the best oxygenation performance, whereas the 0.5 L/min condition produced the weakest DO response. Therefore, the present study suggests that gas flow rate influenced the aeration system through two related mechanisms, namely increasing gas input and modifying the internal hydrodynamic regime of the tank. This integration analysis is consistent with updated aeration system research and provides a deeper understanding of the relationship between flow behavior, transfer processes, and operational performance in wastewater treatment systems (Amaral et al., 2018; Drewnowski et al., 2019; Mohan T et al., 2021; Shen et al., 2025b).

4. CONCLUSION

This study evaluated the effect of gas flow rate on the hydrodynamics and dissolved oxygen characteristics of a lab-scale fine-bubble aeration system using experimental observation and CFD analysis. The experimental results showed that the dissolved oxygen profile increased with aeration time under all tested conditions, while higher gas flow rates produced faster oxygenation and higher final DO concentrations. Among the three operating conditions, the gas flow rate of 1.5 L/min showed the most favourable oxygenation performance, whereas 0.5 L/min resulted in the lowest DO response.

The CFD simulation indicated that gas flow rate influenced the internal hydrodynamic behaviour of the reactor. Higher gas flow rates produced broader active flow regions and more developed circulation patterns, while lower gas flow rates generated weaker and more localized flow activity around the aerator zone. Quantitative extraction from the CFD results showed that the area-weighted average velocity magnitude on the selected vertical plane decreased from 0.0317 m/s at 0.5 L/min to 0.0262 m/s at 1.0 L/min and 0.0203 m/s at 1.5 L/min. This result indicates that the improved oxygenation at higher gas flow rate was not governed solely by an increase in mean liquid velocity, but was also associated with greater gas input and changes in flow organization, recirculation pattern, and oxygen redistribution within the reactor.

The combined experimental and numerical interpretation suggests that differences in DO behaviour were associated not only with air supply input, but also with the hydrodynamic conditions created inside the tank. Overall, this study demonstrates that CFD can be used as a useful supporting tool to interpret oxygenation behaviour in fine-bubble aeration systems and to improve understanding of the relationship between gas flow rate, flow behaviour, and dissolved oxygen characteristics in domestic wastewater aeration. From a practical perspective, these findings may support the optimization of small-scale wastewater treatment systems by helping identify suitable aeration flow rates that enhance oxygen availability while avoiding unnecessary air supply. The results also suggest that aeration optimization should not be based only on increasing airflow, but should also consider how airflow modifies circulation structure and oxygen redistribution inside the reactor. Therefore, the combined use of DO monitoring and CFD-based hydrodynamic interpretation can provide useful guidance for improving aeration operation, oxygen transfer efficiency, and energy-conscious design in simple domestic wastewater treatment applications.

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