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Investigation of the Performance of an Intermittent Anoxic/Aerobic MBBR: The Need to Transition from Conventional Modelling to a CFD-Based Approach †

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Abstract

Computational Fluid Dynamics (CFD) was applied to an intermittent anoxic/aerobic Moving Bed Biofilm Reactor (MBBR) operated under six different aeration intermittency cycles and dissolved oxygen concentration levels. Experimental results showed that most aeration cycles did not provide a sufficiently long anoxic phase to sustain effective denitrification, thereby limiting NOx removal efficiency. This behavior was not adequately captured by simulations performed using conventional biological models (BioWin), which rely on the assumption of complete mixing. In contrast, the CFD model implemented in ANSYS Fluent 2024 R2 enabled a detailed characterization of reactor hydrodynamics and the identification of several inefficiencies, including short-circuiting, back-mixing, and the presence of dead zones. Notably, the simulations revealed a pronounced asymmetric distribution of carriers within the reactor, with the majority accumulating along one side, leaving a significant fraction of the reactor volume largely unoccupied. Further analysis indicated that this phenomenon was caused by a design flaw—specifically, the asymmetric placement of the aerators—combined with an excessively high air injection flow rate.

Keywords: Computational Fluid Dynamics; MBBR; denitrification; compartmental modelling; carrier distribution

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1. Introduction

Traditional Wastewater Resource Recovery Facilities (WRRFs) are typically characterized by separate treatment units in which oxidation and nitrification processes occur, as well as by long hydraulic retention times (HRTs). These features result in large reactor volumes and high energy consumption. Modern facilities, by contrast, aim to achieve the simultaneous removal of organic matter and nitrogen within a single reaction tank, thereby reducing overall plant volume. However, such designs are inherently more complex and require the support of advanced mathematical modeling.

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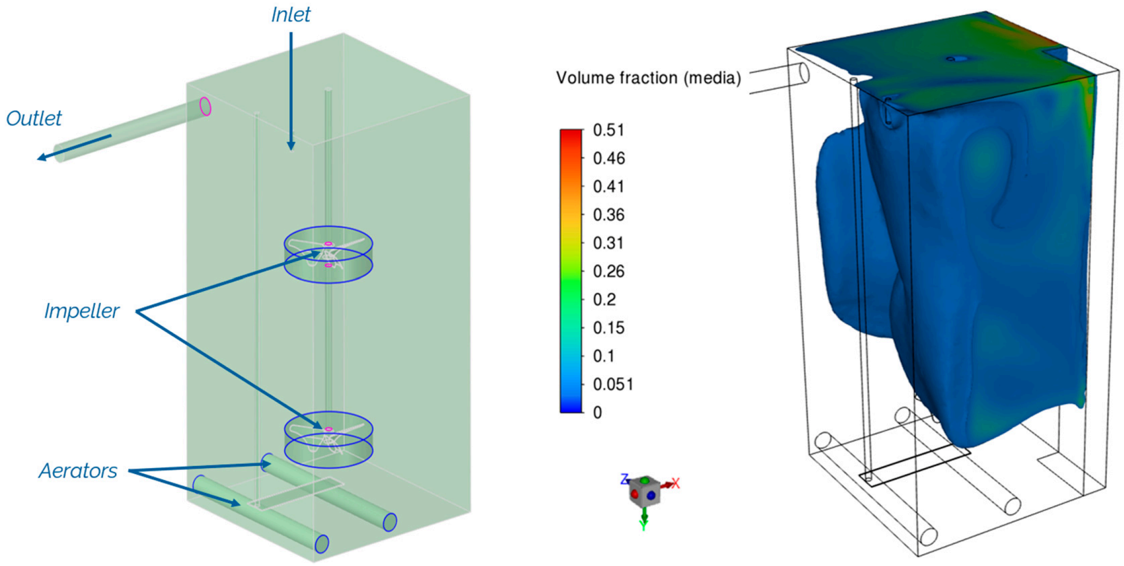
In this work, an intermittent anoxic/aerobic pilot-scale Moving Bed Biofilm Reactor (MBBR) is presented, operating under six different aeration intermittency cycles and dissolved oxygen concentration levels. The proposed treatment unit is intended to fully replace conventional pre-denitrification and oxidation tanks, together with their associated recirculation systems. This highly integrated technological solution requires detailed design to optimize both carrier utilization and aeration cycle strategies. Moreover, it is essential to ensure that the entire reactor volume is effectively exploited.

To optimize the performance of such systems, mathematical models have been developed to represent the alternation between anoxic and aerobic phases, as well as biofilm growth on the carriers. Nevertheless, it has been observed that conventional mathematical models, such as those belonging to the Activated Sludge Model (ASM) family, when implemented under the assumption of a completely mixed reactor, are unable to capture several key aspects of the plant's actual behavior.

For this reason, the adoption of Computational Fluid Dynamics (CFD) modeling is essential. CFD models enable a detailed characterization of reactor hydrodynamics and allow the identification of potential inefficiencies, such as short-circuiting, back-mixing, dead zones, and non-uniform carrier distribution within the reactor. The application of these models supports the correction of design shortcomings, the optimization of operating conditions, and the development of a compartmental model capable of accurately reproducing the dynamic behavior of the system under real operating conditions.

2. Materials and Methods

The WRRF investigated in the present work is a single pilot-scale tank (Figure 1a, Volume = 3.3 m^3), continuously operated at a flow rate of 0.033 L s^{-1}. Parameters measured at the outlet included VS, TS, COD (total and soluble), N-NH4+ and N-NOx. Aeration cycles were controlled through an ON/OFF system regulated by the dissolved oxygen concentration. Moreover, during selected cycles, aeration was entirely suspended for a defined period to enhance denitrification. The six aeration cycles are described in Table 1.



(**a**) (**b**)

Figure 1. (**a**) Reactor design, showing the inlet, outlet, impeller, and aerators. (**b**) Carriers' volume fraction inside the reactor, with colors corresponding to the color bar. Only regions with a carriers' volume fraction ≥ 0.05 are displayed.

Table 1. Intermittent aeration cycles operation.

Cycle	On/Off (O_2 Conc) [mg L^{-1}]	Period of Full Aeration Shutdown [h d^{-1}]
1	0.2–2.0	0
2	0–1.0	0
3	0–1.0	4
4	0–1.0	8
5	0–1.0	12
6	0–1.0	16

The ASM1 model was adopted as the biological framework. Biofilm growth on the carrier surface was estimated using the formulations proposed by [1]. Model simulations were validated against experimental data. CFD analyses were conducted using ANSYS Fluent 2024 R2, employing the Eulerian multiphase approach to represent the three interacting phases (water, air, and carriers). The stress tensor in the solid-phase momentum equation was resolved according to the granular temperature theory of [2]. A constant granular viscosity (1×10^{-5} kg m^{-1} s^{-1}) was assumed, while granular pressure was computed using the correlation proposed by [3]; drag was selected as the most significant interphase force. Furthermore, the Discrete Phase Model (DPM) was applied to estimate the average Residence Time Distribution (RTD) of the liquid phase; the DPM is a multiphase model in which the dispersed phase is modeled by the Lagrangian method.

Boundary Conditions were defined as follows:

- The inlet and outlet were both defined as velocity-inlet boundaries (with a negative velocity assigned at the outlet).
- The free surface was modeled as a wall with zero shear stress for all the phases. To account for air outflow, a negative mass source was introduced within the first centimeter below the surface.

The CFD simulation of the aerobic operational phase was performed using a steady-state model, in which the impellers were simulated through a moving reference frame approach. Both aerators were modeled as air source terms.

Model calibration was primarily based on the spatial distribution of carriers within the reactor, which was qualitatively compared with physical observations. These results set the basis for the future development of the CM and its calibration and validation steps [4,5].

3. Results

Experimental results indicated that the most effective aeration cycles were those with an aeration shutdown of 8 h or longer. This outcome can be attributed to the aeration settings, which did not provide a sufficiently long anoxic phase for the denitrifying bacteria, thereby limiting NOX removal efficiencies. This behaviour was only partially captured by the BioWin simulation, which also failed to accurately predict the soluble COD concentration, which was inaccurately estimated by a factor of 2 to 3. This discrepancy suggested that the complete mixing assumption was inaccurate and the model layout required the integration of hydraulic information.

A CFD study was therefore carried out to investigate potential issues in the fluid dynamics of the three-phase system. The simulations revealed an asymmetric distribution of carriers within the reactor volume (Figure 1b), which were predominantly concentrated along a single side, leaving a substantial portion of the volume nearly unoccupied.

This observation was corroborated by visual inspections of the carrier distribution on the reactor surface.

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The asymmetric placement of the aerators, together with an excessively high air injection flow rate, constituted the main design flaw leading to inefficient utilisation of the reactor volume. This result was corroborated by the particle flow lines. As illustrated in Figure 2, a significant number of water particles are trapped within the inner region of the reactor due to the combined action of the air-induced lift force and the vortex generated by the mixers.

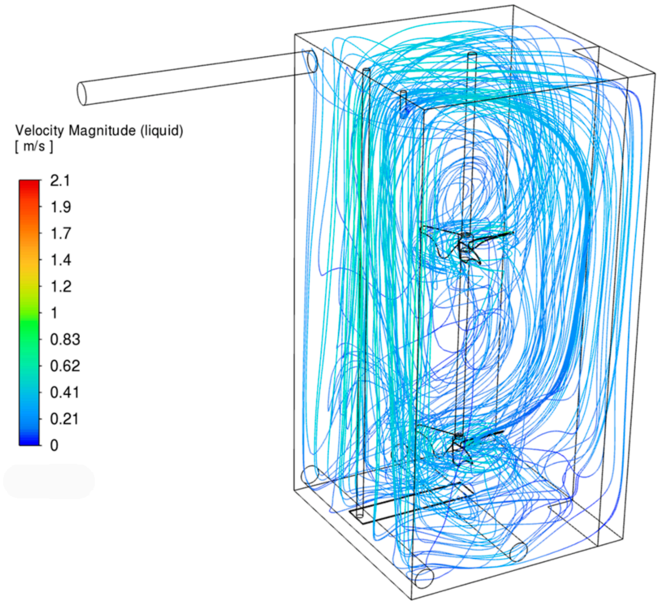

Figure 2. Liquid-phase pathlines coloured by velocity magnitude; black lines indicate the reactor geometry and internal components.

The DPM simulation, carried out to estimate the RTD, could not be completed due to excessive computational requirements. Notably, after 40 h of operation (approximately 1.5 HRT), only 40% of the particles had exited the reactor, thus confirming the outcomes of the Eulerian model.

4. Conclusions

This study highlights the need to transition from conventional biological modelling to a CFD-based approach when designing and optimising highly integrated WRRFs, such as intermittent anoxic/aerobic MBBRs. While traditional models (e.g., BioWin) operating under a perfect-mixing assumption could identify low NOX removal issues during cycles with short aeration shutdowns, they critically failed to accurately predict effluent parameters and the complex hydrodynamics of the system.

The main conclusion of this research is that conventional complete-mixing assumptions are inadequate for intermittent MBBRs, making CFD analysis indispensable. Through the CFD Eulerian multiphase approach, it was possible to detect critical design flaws that traditional models missed entirely, specifically, the asymmetric placement of the aerators combined with an excessively high airflow rate. These flaws led to an asymmetric distribution of carriers, significant dead zones and poor volume utilisation. The severity of this hydrodynamic inefficiency was quantified, demonstrating that after an operational period equivalent to 1.5 HRT, only 40% of the liquid particles had exited the reactor.

Finally, overcoming these physical and hydrodynamic constraints is a fundamental prerequisite for achieving the expected biological performance. Based on the main conclusion of this study, the optimisation of plant operation will proceed through the following future steps:

- Sensitivity analysis of the airflow rate to determine the most suitable value for this configuration;
- Model calibration based on a tracer test to estimate the residence time distribution;
- Compartmental Modelling to overcome the limitations of the traditional simulations performed with BioWin.

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