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Research paper

Enhancing the efficiency of air bubbles using a finned panel spacer for membrane fouling control in activated sludge filtration

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ABSTRACT

Membrane fouling remains a critical challenge in membrane bioreactors (MBRs). The main objective of this study was to systematically investigate a newly developed finned spacer that direct air bubbles to enhance foulant scouring. Lab-scale tests and computational fluid dynamics (CFD) simulations revealed that the spacer enhanced permeability by 30 % (from 289.2 ± 2.1 to 396.3 ± 9.3 L m^{-2} h^{-1} bar^{-1}). This improvement was attributed to enhanced bubble-membrane contact and liquid recirculation, enabling effective cleaning at relatively low aeration (0.25 L min^{-1}) and thus reducing energy demands. While smaller fin gaps optimized the bubble trajectory, it also slightly increased drag forces. Intermittent aeration further halved the energy use. Overall, the finned represents a cost-effective and energy-efficient strategy for mitigating membrane fouling in MBRs.

1. Introduction

Membrane bioreactors (MBRs) are considered advanced technology for the treatment of wastewaters, particularly to produce high-quality effluent suitable for reuse [29], including for the treatment of emerging contaminants [41,47]. The technology has matured and has been widely implemented with a growing market share at about a 15 % rate, mainly when aiming for effluent reuse [9,19] and sustainability [2]. Recent advancements in MBR systems have further improved their performance and energy efficiency, with studies leveraging machine learning to optimize operational parameters while reducing fouling and energy consumption [24]. However, the major obstacle to boosting the widespread acceptance of MBRs is still the membrane fouling. The need to manage membrane fouling led to inflated operational expenditure, enhanced energy footprint, complicated operation, and eventually reduced confidence in the technology. The complexity of MBRs operation in response to controlling the fouling has become the downside when compared to other simpler technologies [17,54]. A high energy input associated with membrane cleaning via the coarse bubble aeration is also still an important obstacle [53].

Attempts to address the membrane fouling issues in MBRs have been widely reported [8]. Membrane fouling is traditionally managed by lowering the flux -at the expense of higher membrane area and costs-, incorporating cleanings during the operation, and embedding in situ fouling control strategies [11,40]. Fouling typically arises from biofouling, cake layer formation, and concentration polarization, all of which deteriorate membrane performance and increase costs [1]. Yet, the combination of those factors still resulted in low throughput, with sustainable fluxes ranging from 12 to 32 L m^{-2h-1}) in the full-scale MBR installations [29]. An improved control of membrane fouling would increase the system throughput, hence the sustainability and the economy of the MBRs [27]. Strategies for fouling control now include periodic backwashing, chemical cleaning, and use of advanced fouling-resistant membrane materials [1,24]. Additionally, environmental considerations such as potential microplastic release from spacer materials warrant further study, especially at pilot and commercial scales.

Most full-scale MBRs are equipped with membrane aeration for

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membrane fouling control [50]. Improvement of the aeration system can thus be implemented not only to the new but also to the existing MBRs installations. The use of air bubbles in the membrane tank was initially aimed to also provide dissolved oxygen and at the same time induced local shear and mixing for membrane fouling control. The function has recently been focussed on fouling control by constant foulant removal or limiting its accumulation from the membrane surface [35]. Unfortunately, the air bubbles are effective for fouling control under very high aeration rates (i.e., slug-flow condition) [52], leading to a high energy input contributing to the major energy demand in MBRs [14]. Without efficient engineering, only limited improvement could be expected from air bubbling due to few critical inherent limitations [4]. Shear imposed by air bubbles is weak and the impact plateaus largely due to poor contacts with the membrane surface. The air bubbles reside in the centre of the feed channel with random contacts to the panel sides diminishing their foulant scouring roles. To reduce energy demands while improving fouling control, recent studies have explored hybrid systems and the integration of innovative membrane materials such as nanocomposites and covalently crosslinked structures that improve structural integrity and permeability [26,30,37]. These approaches contribute to more sustainable and cost-effective MBR operation.

A bubble generator device was proven effective in enhancing the filtration throughput [20]. It was coincidentally achieved by a horizontal membrane placement in which the active side facing bottom from which intense air bubbles provided enhanced membrane cleaning. The horizontal placement of the membrane maximized air bubbles/membrane contacts in scouring off the foulant. We recently proposed a tilted module panel system to enhance air bubbles membrane contact [13], inspired by the earlier report. The tilted panel showed up to 270 % permeability in the filtration of *C. vulgaris* broth [13] and achieved maximum reversible foulant removal in activated sludge filtration [12]. Others attempted to improve the bubble/membrane contact by exploiting membrane surface topography (via surface patterning) [3,21,32,38] or by the addition of bio-carriers [5,48,55]. However, those module systems are hard to scale up due to engineering difficulty, a low membrane packing density or dynamic system (i.e., panel switching).

Recently, plate-and-frame module incorporating a spacer has been explored for providing enhanced membrane fouling control [33,36,45]. Some spacers were customized to manipulate the fluid dynamics in the feed channel [15,16]. The feed spacer is typically placed on the feed side of the membrane to manipulate the fluid dynamics favourable for membrane fouling. Spacer alters the flow regime of liquid and ait bubbles to promote local mixing and disrupt foulant accumulation and concentration polarization, eventually increasing the mass-transfer rate [15]. However, most of the recently reported engineered spacers were sophisticated in geometry requiring production using 3D printing technologies. The micro-scaled spacer customed for activated sludge filtration required the energy-inefficient high liquid crossflow velocity. Another spacer build for activated sludge filtration was 3D printed and involved vibration [51]. It offered 48 % fouling reduction but seemed a challenge to be applied on a full scale due to obstacles to maintain the defect-free membrane attributed to the harsh shear rates. Recently, we reported a new type of finned spacer that was proven effective in providing sort of control in membrane fouling for oil/water emulsion [44] and microalgae broth membrane filtrations [46]. The finned spacer was placed in the feed flow channel that encouraged the air bubbles toward the membrane surface. Despite of the design's simplicity, it offered attractive approaches for controlling membrane fouling in MBRs, which was explored in this study.

This study applied a newly developed module system in the form of a finned spacer to address membrane fouling in activated sludge filtration. The key novelty lies in the straightforward spacer design that can be retrofitted into existing MBRs with minimal complexity. It involved inserting a panel comprising of fins in between two adjacent plate-and-frame module that maximize to roles of air bubbles for scouring off foulant from the membrane surface. The efficacy of the finned spacer in enhancing the cleaning capacity of air bubbles was initially proven. Subsequently, the impact of various operational parameters (i.e., aeration intensity, intermittent aeration, and fins gap) were investigated. A simple 2D multiphase Volume of Fluid visualization of computerized fluid dynamics simulation was also performed to acquire insights into the dynamics of fluids nearby the membrane surface.

2. Materials and methods

2.1. Activated sludge feed and membrane

The summary of experimental conditions and parameters are provided in Table 1. The filtration tests were done using an activated sludge feed obtained from a nearby full-scale activated sludge treating domestic wastewater. The plant was stable, meeting the local requirement for effluent quality. The mixed liquor had the suspended solid content of 4.1 ± 0.5 *g*/L and the volatile content of 3.2 ± 0.3 *g*/L. Those values were far lower than the typical sludge in MBRs (i.e., suspended solid of 6–12 g/L). The sludge feed was used as the filtration feed immediately upon collection and was refreshed daily to avoid physiological stress of the microorganism over prolonged usage. The filtration was not tested in "the full" MBR mode because the sludge from of a small-scale MBR also had significant differences in properties in comparation to the one from a full-scale MBR. The current focus is merely on evaluating the finned panel system for membrane fouling control but can provide a good insight into its application in MBR.

Table 1
Summary of experimental parameters and conditions.

Parameter	Description/Setting	Notes/Additional Details
Membrane		
Type	Lab-made microfiltration membrane	Custom-prepared for study
Material	Polyvinylidene difluoride	Phase-inverted
Pore size	0.11 μm	Mean-flow pore size
Thickness	330 μm	Measured from cross-section
Contact angle	66.5 ± 3.0°	Indicates hydrophilicity
Clean water permeability	850 $L \cdot m^{-2} \cdot h^{-1} \cdot bar^{-1}$	Baseline permeability
Feed		
Source	Activated sludge from full-scale plant	Treating domestic wastewater
Suspended solids	4.1 ± 0.5 g/L	Total suspended solids
Volatile suspended solids	3.2 ± 0.3 g/L	Organic content of sludge
Filtration		
Mode	Constant-pressure mode	Vacuum filtration setup
Transmembrane pressure	−0.1 bar	Controlled by airflow valve
Aeration rates tested	0.25, 0.5, 0.75, 1.0 $L \cdot min^{-1}$	Used to evaluate fouling reduction
Default aeration rate	0.5 $L \cdot min^{-1}$	Applied unless varied
Filtration cycle duration	10 min	Total per cycle
Relaxation duration	0.5 min	No permeation phase
Fin Parameters		
Orientation configurations	Free-flowing, projected, non-projected	Refers to bubble direction relative to membrane
Tilt angle	45°	Empirically optimized
Distance from fins to membrane	0.3 cm	Measured gap for bubble redirection
Vertical gap between fins	2, 4, 6, 8 cm	Varied to assess fluid dynamics
Default vertical gap	2 cm	Standard setting
CFD simulation		
Software	ANSYS Fluent (Academic version)	Used for 2D flow simulation
Model type	2D multiphase Volume of Fluid	Simulated liquid–gas interface
CFD assumptions	Water and air phases, no-slip, non-porous wall	Simplified boundary conditions

The filterability assessments were done by employing a lab-made phase inverted polyvinylidene difluoride microfiltration membrane. The details on the membrane preparation, characterization and membrane panel assembly were reported elsewhere [34]. The applied membrane had a contact angle of 66.5 ± 3.0°, a mean-flow pore size of 0.11 μm, an overall membrane thickness of 330 μm, an asymmetric morphology, and a clean water permeability of 850 L m^{-2h-1} bar^{-1}.

2.2. Finned spacer filled flow channel

The filtration system was equipped with a custom-made finned spacer to provide a proof of concept and the effect of parameters in a finned spacer filtration system for activated sludge filtration (Fig. 1). The membrane panel was fully immersed in the feed solution and the filtrations were done in the constant-pressure mode. The pump was connected to the permeate pipe and the pressure in the permeate side was vacuum and set at a constant value of −0.1 bar for all filtration tests by adjusting the airflow control valve. The air pump provided the aeration at variable rates of 0 to 1 L min^{-1} depending on the requirement, with a default value of 0.5 L min^{-1}. The filtrations were run under 10 min cycle consisting of 9.5 min actual filtration followed by 0.5 min relaxation (no permeation). During the relaxation, the permeate in the chamber was collected, the volume was measured then returned to the feed tank.

The finned spacer consists of two platforms and the two edges of the panel sides where many fins were mounted at certain vertical distance (Fig. 1). The details of the finned spacer specification are provided in our earlier work [44]. The fins were tilted at 45° based on preliminary tests indicating an optimal balance between bubble-membrane contact and minimized drag, with a gap of 0.3 cm to the membrane surface, as also demonstrated in our earlier report [44]. According to the requirement, the fins' location in the spacer could be adjusted to 2, 4, 6, and 8 cm. The default fins' gap was set constant at 2 cm.

2.3. Filtration test

The filtration performance was evaluated from the permeability profile over time. The flux (J, L m^{-2h-1}) and permeability (L, L m^{-2h-1} bar^{-1}) were calculated using Eqs. (1) and 2.

$$J = \frac{V}{A\ \Delta t} \quad (1)$$

$$L = \frac{J}{\Delta P} \quad (2)$$

where, V is the volume of permeate (L), A effective membrane area (m^2), t filtration time (h), and Δ_P trans-membrane pressure (bar). During the filtration, the permeability was measured every cycle (10 min), and the reported data are the net-permeability by counting the time for relaxation.

The performance of the finned spacer system was evaluated under varying parameters, namely: fins orientation (free-flowing air, projected and non-projected), aeration intensity of 0.25, 0.50, 0.75, and 1.00 L min^{-1}, the vertical gap between two adjacent fins of 2, 4, 6 and 8 cm) and the interval of the intermittent aeration of 0, 2.5, 5.0 and 10.0 min. A constant fins gap of 2 cm and aeration rate of 0.5 L min^{-1} were applied for all filtration but for the study on the effect of the fins gap and the aeration rate, respectively. Three configurations were applied when evaluating the effect of fins orientation: (1) the flow channel was left empty to resemble the typical plate-and-frame MBR (referred to henceforth as the free-flowing aeration), (2) the fins were tilted toward the membrane panel to direct the air bubbles (projected panel), and (3) the membrane panel was placed in the opposite side of projected panel (non-projected panel).

2.4. Computerized fluid dynamic simulation

The CFD was applied to visualize the fluid flow in the feed channel and to enrich the understanding of the flow dynamics in justifying the findings. The detail of the method to generate two-dimensional (2D) flow visualization simulations can be obtained from our earlier work [44]. The modelling was done using an Academic Version ANSYS Fluent. It was mainly done for tracking the fluid (gas and liquid) interface and extracting the velocity profile in the flow channel where the finned spacer was placed. The multiphase model and visualization were done using the Volume of Fluid. The liquid was assumed as pure water and the gas was air at ambient temperature and pressure to simplify the process. A no-slip boundary condition and non-porous walls were imposed to replicate the experimental scenario.

2.5. Statistical analysis of the filterability data

The filterability data were statistically analyzed using one-way

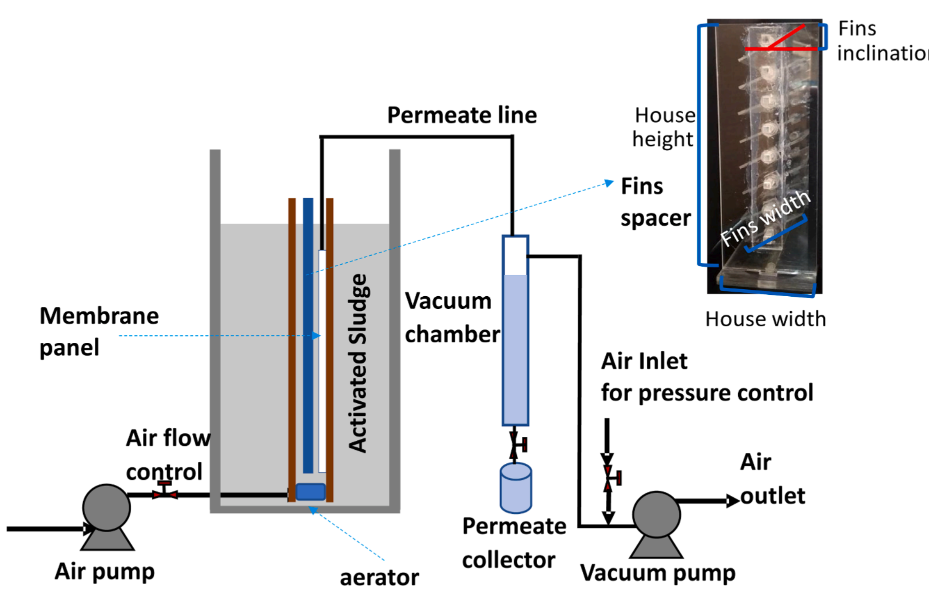

Fig. 1. Illustration of the experimental setup. The inset shows the picture of the finned spacer placed in between two vertical plates on both sides of the membrane panel.

analysis of variance (ANOVA) and the Tukey's Honest Significant Difference (HSD) post-hoc, whichever applicable. The significance of each operating condition in membrane fouling control was evaluated using ANOVA of two means at 95 % confidence intervals (p-values < 0.05) (i.e., projected vs. non-projected and free-flowing vs. finned spacer). Then, the Tukey's HSD analyses were performed to identify multiple pairs of mean values [43]. In particular, Tukey's HSD helps detect which specific groups differ significantly after finding an overall ANOVA effect, allowing us to interpret the influence of aeration rate, intermittent aeration interval, and fin gap on permeability. All statistical calculations were performed using standard statistical software, and significance thresholds were set at $p < 0.05$.

3. Results and discussion

3.1. Effectiveness of air bubbles projection for membrane fouling control

Fig. 2 demonstrates the clear advantage of the air bubbles projection toward the membrane surface in enhancing activated sludge permeability. It increased the permeability by 32.5 %, significantly higher (p-value = 0.0002) than when compared to the free-flowing air bubble in the feed channel. The findings are consistent with our previous work handling oil/water emulsion [44] and microalgae broth filtrations [46], validating the enhanced efficacy of air bubbles in cleaning the foulant out of the membrane surface. The presence of fins in the system improved the contact, thereby increasing the membrane surface's cleaning efficacy. As proven by the CFD simulation, the buoyancy force helps the bubbles travel upwards. The tilted fins dragged the air bubbles to the opposite side of the panel, where the membrane was located and maintained its position in contact with the membrane surface until the bubble exit the tank. As shown in Fig. 3, the velocity contour proved that the velocity of bubbles as they moved upwards increased from 0.02 to 0.1 m/s on the membrane surface. The velocity profiles also show that the terminal velocity of 0.08 −0.1 m/s was achieved. High-velocity bubbles increased the shear rates on the bubbles and membrane interface to scour off the foulant. Air bubbles had excellent contact with the membrane after sliding through the fins and maintaining high velocity. The drag force produced by the slanted fins did not affect the bubbles' velocity until the bubbles contacted the membrane surface. Nevertheless, the fluids dynamics during the filtration could result in minor fluctuation that fluctuate the permeability values.

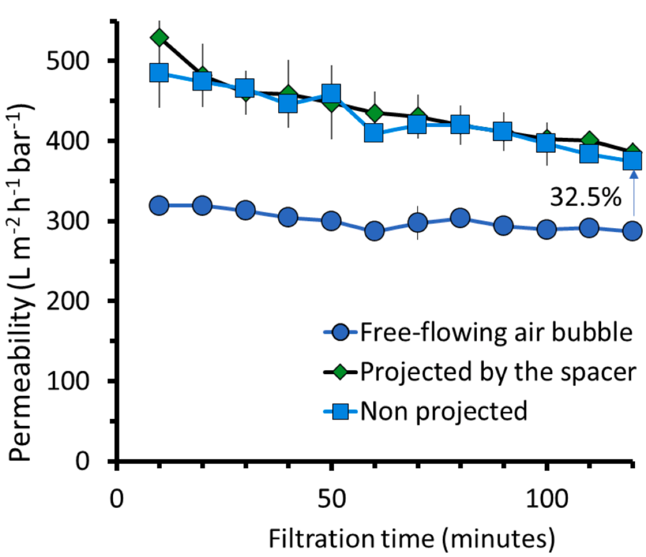

Fig. 2. The effectiveness of projecting the air bubble toward the membrane surface in imposing membrane fouling control, showing $a > 32$ % increase in permeability. The filtration tests were done at a constant aeration rate and a fins gap of 0.5 L min^{-1} and 2 cm.

Apart from the scouring impact from the shear rate imposed on the membrane surface, the augmented fluid velocity near the membrane surface also generates lift forces that help remove foulant. Consequently, air bubble cleaning improved the systems by (1) reducing the aeration intensity−and thus operational expenditure−, and (2) increasing operational flux, thereby lowering the required membrane area (reducing the capital expenditure) [28].

The initial permeability of the membrane under free-flowing air (319.2 L m^{-2h-1} bar^{-1}) was significantly lower than under the finned module system (529 and 482 L m^{-2h-1} bar^{-1}) for the projected and the non-projected, respectively), even though the same membrane and initial conditions were used. It suggests that most of the permeability loss for the free-flowing air system occurred during the first 10 min of the filtration. The convective flow of the permeate under a constant-pressure operation, typically very high for a clean membrane, dragged the foulant onto the membrane surface and caused fouling. Since the air bubbles were somewhat away from the membrane surface, their effect on membrane cleaning and preventing the initial membrane fouling was lower than the projected system. The apparent faster reduction is attributed to stronger, initial bubble–membrane scouring on the projected side, causing an initially steep decline. However, the overall flux remained higher for the projected side, and eventually, both sides benefited from secondary flow as confirmed by CFD visualization (Fig. 3). It is worth noting that the filtration was only started after the system was stationed in place, including the aeration. This way, the membrane cleaning effect could be seen even at the start of the filtration. The foulant accumulation for the aerated system occurred gradually and did not reach a steady value even after the two-hours filtration.

Remarkably, with the membrane modules placed in the finned spacer system, no significant difference (p-value of 0.0684, one-way ANOVA) was observed between the projected and the non-projected. Only a slight increment was observed for the projected surface (2.8 %). This finding seemed baffling when considering that no means of membrane cleaning was imposed on the non-projected side of the flow channel. However, the CFD simulation results clearly show the secondary flow on the non-projected side of the feed flow channel (Fig. 3), which provided the membrane cleaning effect and explained the enhanced permeability in the non-projected membrane.

Fig. 3 shows that secondary flow generated by centrifugal motion leads to a radial effect near fin edges. This poloidal motion acts as a turbulent promoter on the opposite (non-projected) side of the flow channel, enhancing shear rates and scouring away foulant.. Consequently, both sides of the channel benefit from effective cleaning, accounting for the elevated permeability of the non-projected membrane in Fig. 2.

3.2. Aeration intensity

Fig. 4 depicts the combined impact of air bubble projection and aeration intensity on activated sludge permeability. Under the finned spacer, permeability rose from 289.2 ± 2.1 to 434.2 ± 2.1 L m^{-2h-1} bar^{-1} (projected side) and 401.3 ± 10.8 L m^{-2h-1} bar^{-1} (opposite side). The findings agree with prior work indicating that higher aeration intensity increases shear rates, thus mitigating fouling [22,42]. Nonetheless, it should be noted that the short-term impact of high aeration intensity might differ from the long-term impact, in which the biofouling played a crucial impact [10]. Increasing aeration intensity effectively raised the number and volume of bubbles available for foulant scouring, reinforcing that bubble quantity aligns with fouling control capacity [6].

The increasing trend in the permeability was consistent for both projected and projected panel. The phenomenon of increasing permeability at higher aeration for the non-projected panel can be explained by the liquid recirculation, as discussed earlier and visualized using CFD modelling in Fig. 2. Fig. 4 clearly shows a clear trend of increasing permeability for the non-aerated side, as also confirmed by the Tukey's HSD p-values of <0.005. Higher aeration intensity on the projected side

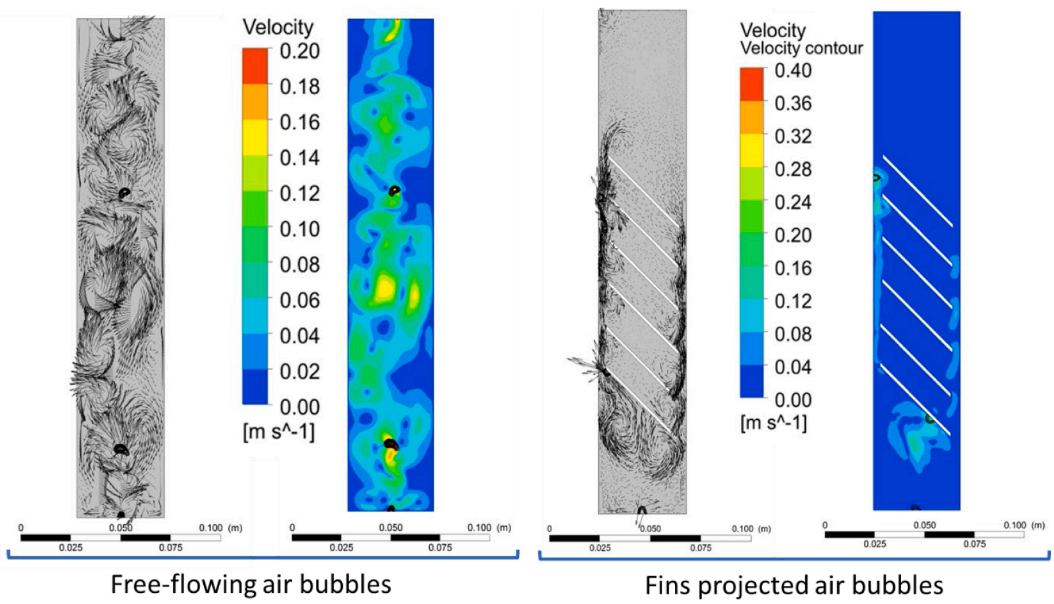

Fig. 3. The flow visualization in the feed channel of the module filtration system with free-flowing and the projected air bubbles. Notice the difference in the scales for the contour velocity plots.

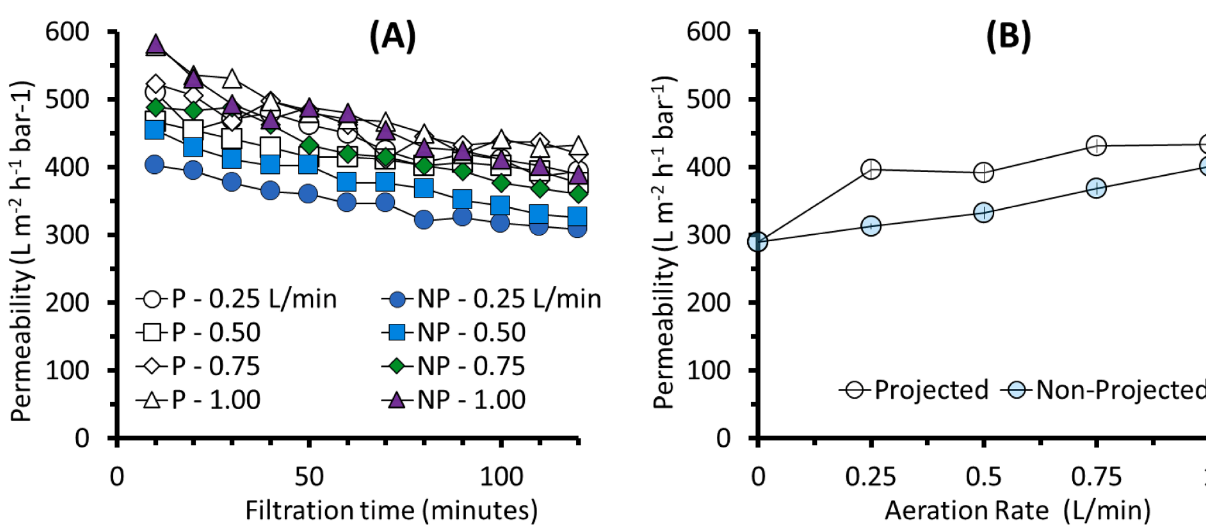

Fig. 4. The effect of aeration intensity on the activated sludge permeability when the membrane surface was projected and non-projected by the air bubbles. The filtration tests were done at a constant aeration rate and a fins gap of 0.5 L min^{-1} and 2 cm.

increased the liquid circulation velocity, beneficial for foulant removal. In contrast to the projected panel, the permeability differences between the data were minor, almost reaching a plateau, indicating a less significant impact of higher aeration intensity. This suggests that optimizing aeration can balance shear enhancement with energy considerations.

The primary increment of permeability occurred when comparing the free-flowing air bubbles with the aeration rate of 0.25 L min^{-1}. Beyond this poit, no significant changes were observed (Fig. 4B). This finding highlights the efficacy of the finned spacer in enhancing the throughput of filtration without requiring higher airflow. Indeed, directing bubbles near the membrane surface proved more critical than simply increasing aeration, corroborating reports that a controlled bubble trajectory reduces fouling [20]. Consequently, operating at lower aeration intensities mitigates irreversible fouling in prolonged filtration [10] and can be further optimized when renewable energy sources are employed [18].

3.3. Fins gap

Figure 5 shows the impact of fins gap on permeability for both projected and non-projected configurations. Although projection slightly increased permeability, it was statistically insignificant.. As discussed earlier, projection slightly increased the permeability but was statistically insignificant. Notably, the permeability peaked at a gap of 4 cm for both configurations, reaching 419.9 ± 4.9 and 389.2 ± 10.1 L m^{-2} h^{-1} bar^{-1} for projected and non-projected panels, respectively.. Going from 2 to 4 cm boosted performance, but further widening (to 8 cm) led to a significant drop ($p = 0.0164$ for projected and $p = 0.003$ for non-projected). Thus, there appears an optimal gap of about 4 cm under these activated sludge conditions.

The decreasing trend of the permeability at larger fin gaps (from 4 to 10 cm) arises from reduced bubble-membrane interaction. As fins become more widely spaced, bubbles move further from the membrane surface, diminishing their scouring effect, resulting in a permeability decrease. Conversely, a narrower fin gap preserves bubble trajectories near the surface, thereby maintaining strong shear and fouling removal.

Apart from guiding bubbles upward, fins also enhanced bubble contact. Overly tight spacing can cause excessive bubble coalescence and energy dissipation, explaining the improved permeability when the gap shifts from 2 to 4 cm. Excessive bubble accumulation can lower kinetic energy for scouring, especially on the non-projected side, where local mixing drives coalescence. Furthermore, an overabundance of bubbles on the membrane may obstruct the permeation area, as seen in tilted panel systems at high aeration rates [12,23].

Interestingly, the presence of an optimum fins gap was not observed in our earlier reports on the finned spacer system treating oil/water emulsion [44]and microalgae broth [46]. Both reached the maximum permeability at the lowest fins gap of 2 cm. This suggests that optimal fin gap depends on feed properties (i.e., high viscosity of activated sludge); less viscous feeds may achieve peak permeability with smaller gaps, whereas higher viscosity sludge requires a slightly wider gap (4 cm) for optimal performance.

3.4. Intermittent aeration

Providing aeration intermittently in MBR is beneficial in reducing the aeration energy. In this study, 50 % aeration was used by periodically stopping the aeration half of the time. The filtration data in Fig. 5 varied in terms of the cycle interval period between aeration and non-aeration. The intermittent aeration interval of 5 min corresponded to 5 min with constant aeration followed by5 min without aeration forming an aeration cycle, and so on.

Fig. 6 depicts the effect of the interval period of intermittent aeration on the membrane permeability in the filled panel system. The final permeability for the intervals of 2.5, 5, and 10 min were 448.6 ± 28.3, 380.0 ± 62.6, and 374.3 ± 26.3 L m^{-2h-1} bar^{-1}, respectively. The intermittent aeration interval of 2.5 min was significantly higher than the others (p-values of 0.015 and 0.0086 from the Tukey's HSD analysis). A short interval helps minimize foulant build-up during non-aeration and promotes removal during aeration [39]. In contrast, longer aeration intervals (>5 min) do not effectively remove of foulant due to a larger accumulation between aeration cycles [7]. Nevertheless, the permeability did not change significantly for the intermittent aeration intervals of 5 and 10 min (p-value = 0.7141). The permeabilities of sub-optimized finned spacer system shown in Fig. 6 correspond to operational fluxes of around 40–80 L m^{-2h-1} assuming the operational vacuum pressure of 0.1 to 0.2 bar, which is highly competitive than what currently applied in commercial MBRs [29]. It is worth noting that further scale-up trials are warranted to confirm long-term stability and cost advantages relative to standard commercial MBR systems.

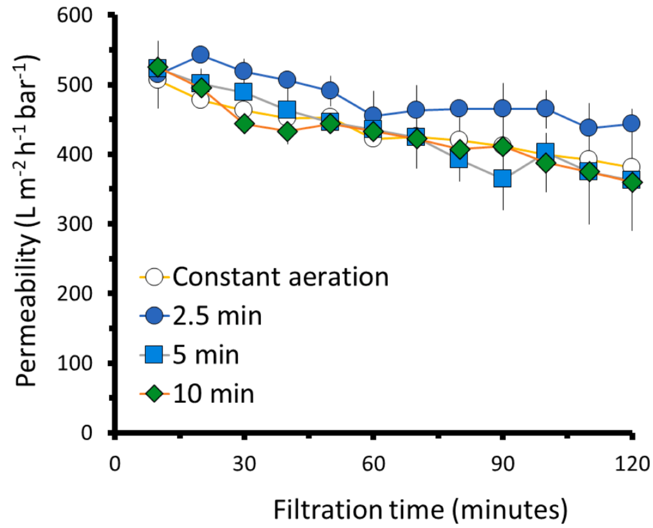

Fig. 6. Effect of the interval of intermittent aeration on the activated sludge permeability. The data represent the average permeability of the projected and the non-projected membrane sides in the flow channel.

Remarkably, the permeabilities for a system operated under intermittent-aeration were similar to continuous aeration, suggesting that substantial aeration energy saving are possible without productivity loss. This may arise from liquid recirculation that persist during non-aeration period. Accordingly, a short aeration interval combined with longer relaxation yields notable energy saving for the finned spacer system in MBR. The low energy footprint can also encourage resource recovery from wastewater [31]. Thanks to the high efficacy of the finned spacer, the aeration can be restricted and maintained low, yet still can offer benefit of removal performance of over 90 % was achieved for biochemical oxygen demand, total Kjeldahl nitrogen, ammonia-nitrogen, and suspended solids, as reported elsewhere [25] under prolonged sludge retention time. In addition, the spacer material could play important role in affecting the long-term performance of the system due to the adverse effect of the eroded microplastics that has

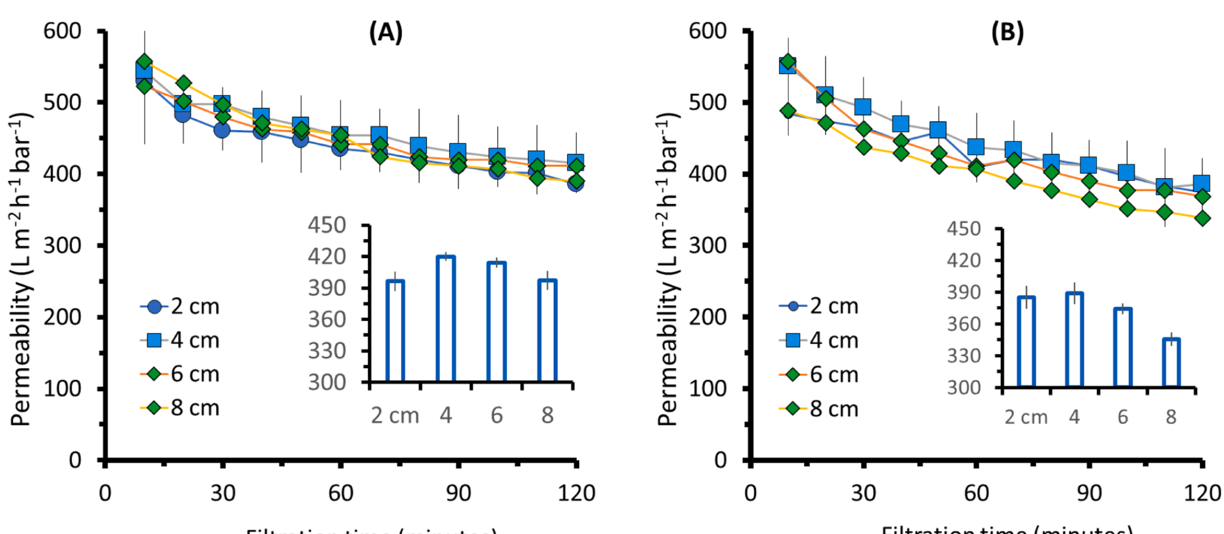

Fig. 5. Effect of fins gap on the membrane permeability when projected (A) and non-projected (B) with the air bubbles. The filtration tests were done under a constant intensity of aeration of 0.5 L min^{-1}.

been proven affecting the microbial community and removal rate of MBR system [49].

4. Conclusion

This paper demonstrated the effectiveness of a finned spacer for fouling control in activated sludge filtration, offering an avenue to enhance MBR performance. Notably, finned spacer use altered bubble trajectory, yielding a permeability jump from 289.2 ± 2.1 to 396.3 ± 9.3 L m^{-2} h^{-1} bar^{-1} (projected configuration) and 389.9 ± 10.8 L m^{-2} h^{-1} bar^{-1} (non-projected). Secondary flow recirculation also supported fouling control on the non-projected side, as validated by CFD. Although increasing aeration marginally enhanced permeability, bubble projection was more critical than sheer airflow. An optimal fins gap of 4 cm produced the highest flux (419.9 ± 4.3 and 389.2 ± 10.1 L m^{-2} h^{-1} bar^{-1} for projected and non-projected, respectively). Furthermore, intermittent aeration saved up to 50 % in aeration energy without compromising throughput. Going forward, a systematic optimization of the finned spacer—considering fins gap, aeration intensity, and intermittent cycles—should be conducted via experimental design and response surface methodology to maximize flux and minimize energy use.

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CRediT authorship contribution statement

Ratri Rahmawati: Writing – original draft, Visualization, Validation, Formal analysis, Data curation, Conceptualization. **Gita Anggia Puspita:** Data curation, Formal analysis, Investigation, Methodology. **Afiq Mohd Laziz:** Data curation, Formal analysis, Investigation, Methodology, Software. **Yusuf Wibisono:** Supervision, Validation, Writing – review & editing. **Femiana Gapsari:** Data curation, Formal analysis, Validation, Writing – review & editing. **Teguh Dwi Widodo:** Data curation, Formal analysis, Validation, Writing – review & editing. **Muhammad Roil Bilad:** Writing – review & editing, Supervision, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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