CFD simulation of the aeration process and baffle influence in a full-scale commercial flat sheet module

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ABSTRACT

The goal of the present paper is to investigate the aeration process and the enhanced effect of baffles in a full-scale commercial membrane bioreactor (MBR) system configured with a flat sheet (FS) membrane module. Through a computational fluid dynamics (CFD) simulation, two aerated FS membrane modules for full-scale applications with 26 membrane sheets were simulated. The numerical results indicate that the presence of baffles and the distances between the baffle and the outmost membrane sheet have a minor influence on the area-weighted shear stress for full-scale MBRs. In addition, bubble size and the bottom distance between the aerator and membrane bottom do not affect the average shear stress of full-scale FS membrane modules much. However, an increase in air flow rate has a significant effect on the area-weighted shear stress. A large FS membrane module is recommended, as it could achieve the same cleaning effect as the small one with a lower specific aeration demand for membranes.

Key words | aeration process, baffle, CFD, flat sheet module, full-scale MBRs

HIGHLIGHTS

- This study provided a hydrodynamic perspective to understand the aeration process on fouling mitigation in FS modules fundamentally.
- This study suggested that conclusions from previous studies with simplified numerical models might be unreliable.
- This study gave recommendations for the design and operation of FS membrane models.

INTRODUCTION

As one of the most commonly used wastewater treatment technologies in domestic fields, the membrane bioreactor (MBR) has distinct advantages compared to the conventional activated sludge process, including the low production of excess sludge and the high removal efficiency of both biological oxygen demand and chemical oxygen demand. However, membrane fouling is still the main drawback of this technology, hindering its broader application. The aeration process, as one of the most effective fouling mitigation methods, has taken up ~70% of the total energy demand (Böhm et al. 2012), resulting in extremely high operating costs.

Numerous studies on membrane fouling control have been carried out to improve the performance of the MBR system. Shear stress was proven to be one of the determining parameters in predicting membrane performance, as it can reduce the particle deposition effectively. Previous studies have shown that the configurations of the flat sheet (FS) module have significant effects on shear stress, especially the presence of baffles. Ndinisa et al. (2006a, 2006b) were the first to reveal the beneficial impact of baffles in FS membrane modules on fouling control, both experimentally and numerically. Their numerical results confirmed an enhanced air scouring effect with the presence of baffles installed in the MBR tank. They further investigated the influence of the number of baffles on hydrodynamics in the FS module, and they found that as the number of baffles increased, shear stress also increased. In addition, Kim &
Chung (2018) found that the shear stresses between the membrane and the baffle were higher than the shear stress between membrane sheets. Their results are contrary to the numerical results in a previous study by Amini et al. (2015), who revealed that the wall shear stress was lower between the outmost membrane sheet and the tank wall than between membrane sheets. The reason for the contradiction between these two conclusions might lie in the presence of baffles – to be precise, the distance between the outmost membrane sheet and the tank wall or baffle wall. In Kim and Chung’s computational fluid dynamics (CFD) study, baffles were installed into the MBR tank. The distance between the outmost membrane sheet and baffle was identical to the gap distance between membrane sheets, whereas in the Amini et al. study, there were no baffles and the distance between the outmost membrane sheet and tank wall was three times as large as the gap distance. This contradiction proved that the presence of baffles plays an essential role in hydrodynamics in laboratory-scale MBRs. Furthermore, Yan et al. (2015, 2016) performed detailed research on baffles in an FS membrane module on a laboratory scale. They found that baffle locations and baffle sizes could affect the hydrodynamics in MBRs significantly, particularly at lower aeration intensities. They revealed that a higher shear stress on the membrane surface was obtained with side baffles rather than front baffles installed and the highest value was found where both side baffles and front baffles were installed in FS modules. Moreover, changing the baffle angle from 90° to 85° was reported to be able to increase wall shear stress and hence mitigate membrane fouling (Khalili-Garakani et al. 2011). In a hollow fiber membrane module with baffles installed, a significant effect on flow field characteristics (Wang et al. 2014) and up to a 30% enhanced shear effect were found in the regions that were most susceptible to membrane fouling (Liu et al. 2016).

To save computing time and resources, given the large amount of computing resources required for a full-scale MBR system, the simulations mentioned above were conducted on a laboratory scale with smaller membrane module configurations and with limited membrane sheets or fibers. The presence of baffles in MBRs could increase the shear stress by up to 10–74%, as reported in the studies conducted on a laboratory scale (Yan et al. 2015; Liu et al. 2016). However, for practical use of the FS module, many more membrane sheets were installed in the MBR system. The difference in the number of membrane sheets between simulations and the real situation might lead to non-reliable numerical results, because the distribution of wall shear stress on the membrane surface of each membrane sheet was found to be related to membrane sheet numbers (Wang et al. 2018). Moreover, the enhanced influence of baffles on shear stress was reported to be much weaker in FS modules with more membrane sheets (Yang et al. 2017), where the flow in these channels would be much more stable than that in one channel. Shear stress was found to be 6.67% higher in FS modules with the presence of baffles compared to that without baffles in full-scale MBRs (Yang et al. 2017). At the laboratory scale, it was 19.53% higher in MBRs with five membrane sheets (Yang et al. 2017) and 38.9% and 74% higher in the FS module with only one membrane channel (Yan et al. 2015). Baffles could thus affect the hydrodynamic characteristics considerably in laboratory-scale MBRs, whereas their effect is much lower in full-scale MBRs.

The overall aim of the present work is to study and analyze the hydrodynamic characteristics of membrane fouling control in two commercial FS membrane modules by conducting CFD simulations. In this study, shear stress was mainly examined numerically using OpenFOAM in the FS modules with 26 membrane sheets that applied in the treatment of municipal and industrial wastewater. The average shear stress was compared and analyzed by varying the operational and geometrical parameters (i.e. the gas flow rate and the distances between baffle and membrane) to determine the effect of these parameters on membrane performance during the aeration process.

MATERIAL AND METHODS

Two full-scale commercial submerged FS membrane modules were simulated with OpenFOAM, an open-source CFD tool, in this study. The small FS module, which is based on BIO-CEL C25, was supplied by MICRODYN-NADIR GmbH. This module (0.526 m × 0.432 m × 0.190 m) consists of 26 membrane sheets with a size of 0.5 m × 0.002 m × 1.0 m, which are separated from one another by 0.008 m. Four aeration tubes with an interval of 0.060 m are located 0.27 m below the FS cassette bottom perpendicular to the membrane sheets. Baffles (0.500 m × 1.0 m) with a thickness of 0.010 m are installed parallel to membrane sheets at various distances to the FS cassette wall. The large model, based on the BIO-CEL 52, is 1.016 m long, 0.432 m wide, and 3.0 m high, as illustrated in Figure 1. It also consists of 26 membrane sheets with a total filtration area of 26.83 m². Seven aeration tubes (simplified in the model as stripes at the bottom, as depicted in Figure 1) instead of four are equipped below the FS
membrane module, delivering process air at an intensity of 26.25 Nm³/h for the large FS module. The baffle for the large model has dimensions of 0.5 m × 0.01 m × 2.10 m.

Air enters the FS membrane module through the simplified aerator, which was set to use patch boundary conditions. An initial rise flow rate was set for the gas phase, and the velocity of the liquid phase was set to zero. The top of the computing domain, where gas and water leave the system, had an outflow condition. The membrane sheets, baffles, and FS cassette walls are considered as non-slip walls. Given the symmetric layout of the FS module, symmetric boundary conditions were used to reduce the computing efforts. As a result, the final domain with two symmetries through the center of the FS module was only a quarter of the original model.

The mixed liquor in the aerated FS membrane module is a gas–liquid–solid three-phase mixture in reality. However, the effect of activated sludge rheology on the hydrodynamics in MBRs was found to be minor (Brannock et al. 2010; Wei et al. 2015; Böhm & Kraume 2015). As a result, the complex mixture was simplified as a gas–liquid two-phase flow in this study. The multi-phase flow was simulated with a Eulerian–Eulerian approach, as it is broad in activated sludge tanks or MBR systems (Karpinska & Bridgeman 2016). In this model, each phase is treated as an interpenetrating continuum with the concept of volume fractions. The mass and momentum conservation equations are solved individually for each phase, and all phases share a single pressure (Moraveji et al. 2012).

The standard $k–\varepsilon$ model (SKE) was used for the prediction of turbulence in FS membrane modules. The SKE model has advantages over other turbulence models; for example, it is robust and economic. In addition, it can provide reasonable accuracy for the multi-phase flow in MBRs, as demonstrated by Vlaev & Tsibranska (2016), who compared the numerical results from different turbulence models and observed only minor differences between them.

Shear stress was calculated in the various tank and baffle variations at various aeration conditions to evaluate membrane performance. The design variations included the two commercial FS modules with different sizes, the presence of additional baffles parallel to membrane sheets on both sides, the varying distance between the baffle and the wall of the FS membrane cassette, and the various distances between the aerator and the bottom of the FS cassette. Simulations were performed at a flow rate ranging from 0.02 to 0.1 m/s with constant bubbles (1–4 mm). The total computing time was ~60 s when bubbles reached the top of the computing domain.

### RESULTS AND DISCUSSION

Simulations of air bubbling in the FS module with different distances between the baffles and the outmost membrane sheets were carried out to investigate whether baffles have a significant influence on wall shear stress along the membrane surface for small and large models. Figure 2 illustrates that as the distance between the baffle and membrane increases, shear stress remains almost the same for both models, which is contrary to previous studies (Yan et al. 2015, 2016; Liu et al. 2016; Yang et al. 2017). In baffled FS modules for a laboratory-scale application, Yan et al. (2016) reported improvement by 74% and Yang et al. (2017) observed an increase in the area-averaged shear stress by 24.3%. The discrepancy between studies might be because large numbers of membrane sheets were installed in the FS module in the full-scale version, and the addition of baffles in the FS led to only a slightly higher degree of confinement of flow channels. This is also confirmed by Yang et al. (2017), who compared the baffle effect on shear stress along the membrane for full-scale and laboratory-scale MBRs and found a significant enhancement in a laboratory-scale baffled MBR, whereas the effect was minor in a full-scale baffled FS membrane module.

Air sparging is the key process and the most energy-consuming process in MBRs. A proper arrangement of aerators might be one of the simplest and most effective ways to improve hydraulic conditions in the FS module so that an optimum in the aeration process could be achieved. In this work, the average shear stress along membrane surfaces was investigated at various bottom distances (0.27–0.67 m) between the aerator and the bottom of membrane sheets,
which is experimentally proven to be an important design variable (Zhang et al. 2014). Figure 3 demonstrates the average shear stress at various distances between aerators and membrane bottoms under the same aeration conditions, where it revealed a minor influence of this design variable. As the position of aerators changes, the average shear stress is nearly unchanged. This is consistent with the numerical results for a full-scale FS membrane module reported by Yang et al. (2017), who also found that shear stress is not sensitive to this distance in full-scale MBRs. However, this is inconsistent with most of the results in previous studies, where the aeration position was found to play a vital role in hydrodynamics in laboratory-scale MBRs (Yan et al. 2015, 2016; Liu et al. 2016; Yang et al. 2017). Yang et al. (2017) reported a 65.6% improvement in shear stress at the most appropriate distance between an aerator and a membrane bottom at a laboratory scale. The variance in laboratory-scale and full-scale MBRs could be attributed to the ratio of bottom distance to the height of membrane sheets and aerator arrangements in different studies.

Despite the nearly unchanged trend in shear stress, the maximum average shear stress could be found at a bottom...
distance of 370 mm for both large and small models (Figure 3). Increasing it from 270 mm to 370 mm, the average shear stress increased from 0.462 Pa to 0.477 Pa, by 3.18%. With a further increase to 670 mm, the average shear stress decreased by 5.19%. A possible reason for this shear stress trend might be that at a low bottom distance, velocities might not be fully developed, whereas at a high distance, kinetic energy could be converted into friction head loss (Yang et al. 2016). An enhancement in shear stress at the bottom in the range of 300–450 mm has also been reported in previous studies (Yang et al. 2017). Therefore, for the FS membrane modules investigated in this study, a bottom distance of 370 mm is recommended, as maximum shear stress could be achieved in both small and large models.

Area-averaged shear stresses under different air flow rates are plotted for a large model and small model in Figure 4, where a general rising trend in average shear stress with increasing aeration intensity could be observed for both models. The same trend has been reported in previous studies (Ndinisa et al. 2006a, 2006b; Yang et al. 2016). As the airflow rate increased from 0.02 to 0.1 m/s, the average shear stress increased by 129% and 112% for the large model and the small model, respectively. Given the beneficial effect of high shear stress on membrane filtration performance, more intensive aeration would be more effective for membrane fouling control. However, high aeration intensity is generally accompanied by high energy consumption and hence high operation costs. There is thus a trade-off between a beneficial membrane cleaning effect and the operation cost of the aeration process in aerated FS membrane modules when choosing an appropriate airflow rate for the system.

The shear stress in the large and small full-scale FS membrane modules was evaluated separately. Both models used the same grid size, the same numerical approach, and the same boundary conditions. At the same gas velocity on the aerator cross-section, area-averaged shear stress was higher in the small model than in the large model. The difference could be attributed to different specific aeration demands for membranes (SADm) in these two models. The SADm was 0.332 m³/(m² h) in the small model, whereas it was only 0.138 m³/(m² h) in the large model at a gas velocity of 0.04 m/s at aerator inlets. Despite a large increase in SADm from the large model to the small model, the average shear stress is enhanced by only 6.27%. Yan et al. (2015, 2016) have also reported average shear stress in the range of 0.5–5.0 Pa at an SADm between 0.5 and 9.0 m³/(m² h) in a laboratory-scale FS membrane module with smaller membrane sheets. It is concluded that compared to small membrane sheets, large membrane sheets could achieve the same cleaning effect with a lower SADm.

The effect of the bubble size on area-weighted shear stress under a constant air flow rate of 0.04 m/s is illustrated in Figure 5, showing a rising trend in average shear stress with increasing bubble sizes from 1 to 4 mm. The average shear stress induced by large bubbles with a constant diameter of 4 mm is 21.9% higher than that created by 1-mm bubbles in an unbaffled FS membrane module. This is in agreement with findings in previous work (Wei et al. 2015), where large bubbles were observed to have a stronger influence on wake turbulence and hence on shear stress.

Figure 4 | Area-averaged shear stress on membrane sheets of small and large models under different aeration intensities.
Figures 4 and 5 also illustrate that airflow rate had a more significant influence on the average shear stress compared to bubble size.

CONCLUSIONS

CFD simulations were performed in this study to investigate the baffle effect and the effect of aeration characteristics on the area-weighted shear stress along the membrane surfaces of two full-scale FS membrane modules. The main findings are as follows:

- The numerical results revealed that the area-weighted shear stress for both small and large full-scale MBRs is not sensitive to the presence of baffles and the distances between the baffle and the outmost membrane sheet. Baffles and their locations might be a critical design variable for laboratory-scale FS membrane modules with several membrane sheets. However, almost no effect of baffles was found on hydrodynamic conditions in full-scale MBRs with many membrane sheets.

- Bubble size was found to affect the average wall shear stress only slightly. Over the investigated bubble sizes, an increase in bubble size from 1 mm to 4 mm only led to a 0.08 Pa increase in the average shear stress under the same aeration intensity. Nevertheless, large bubbles are recommended with respect to reducing membrane fouling.

- Despite the minor influence of the bottom distance between the aerator and the bottom of membrane sheets, there might be an optimal bottom distance at approximately 370 mm, where the maximum area-weighted shear stress could be obtained in both small and large FS membrane modules for a full-scale application.

- The numerical results indicate that the gas flow rate is an imperative parameter in membrane fouling control. As the airflow rate increased from 0.02 to 0.1 m/s, the area-weighted shear stress on membrane surfaces in the large FS membrane module increased by 129%.

- The large FS membrane module is recommended instead of the small one, as the increase in SADm by a factor of 1.4 at gas inlet velocity of 0.04 m/s led to an increase in area-weighted shear stress of only 6.27%. Therefore, in the large membrane module, a comparable cleaning effect could be achieved with a lower SADm.

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