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The biofilm membrane bioreactor (BF-MBR)—a review

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ABSTRACT

Membrane bioreactors (MBR) based on the activated sludge process is a relatively new technology, with implementation worldwide increasing over the last 20 y. In parallel to commercial development, a lot of research work has been done in fundamental studies, development and optimization of this technology. Although the main focus has been on activated sludge processes, several research groups have been investigating biofilm based MBR systems. The biofilm processes have several advantages over activated sludge process and can be used as complementary, assisted to activated sludge MBR (aBF-MBR) or self standing, pure biofilm based MBRs (pBF-MBR). This article reviews the status of MBR technology with biofilm implementations for wastewater treatment, excluding membrane aerated/supported biofilm reactors (MABR). Reports published within the last 10 y are reviewed with respect to aBF-MBR and pBF-MBR studies, highlighting advantages proposed of this approach over activated sludge MBRs, identifying performance and operational characteristics given, and taking an outlook of perspectives in further development of this concept.

Keywords: Activated sludge membrane bioreactor AS-MBR; Biofilm membrane bioreactor BF-MBR; Assisted biofilm membrane bioreactor aBF-MBR; Pure biofilm membrane bioreactor pBF-MBR; Biofilm carriers; Membrane fouling

1. Introduction

The MBR technology, for both municipal and industrial wastewater treatment, has seen significant growth in the last 10 y, boosted by a need for more advanced wastewater treatment, more strict legalization and increasing scarcity of fresh water resources [1]. This technology is primarily based on the conventional activated sludge concept where secondary clarifiers are normally replaced by submerged low pressure polymeric membranes for solid/liquid separation. The MBR technology has gained popularity due to several outstanding advantages over conventional process i.e., high quality effluent (very often hygienically highly purified), lower footprint, lower net sludge production, and improved nutrient removal [2]. Major disadvantages of the process are membrane fouling - which limits sustainability and wider applications, higher energy demand - mostly caused by air scouring demand, and higher capital costs due to the price of membranes. Better understanding of membrane fouling mechanisms, optimization of energy consumption and cheaper membrane materials have overcome some of these disadvantages, making this technology even a more realistic and viable choice by the end of last decade [3–6].

In addition to the main focus of development of conventional MBRs, several research groups have been working on biofilm assisted and biofilm based MBRs (BF-MBR), trying to combine advantages of biofilm and MBR process in order to overcome some of the limitations of conventional MBR based on the activated sludge process (AS-MBR). Implementation of

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biofilm processes in MBR could be done by addition of media (e.g., biofilm carriers) in moving or fixed bed configurations, or aerated membranes in the bioreactor as a support (i.e.,substratum) for biofilm growth. In principle numerous materials could be used for biofilm support, however, only a few are commercially applied in full scale systems, such as cord media, RBC media, sponge and plastic media and granular activated carbon (GAC).

A combination of activated sludge (AS) and biofilm processes is also possible. Addition of biofilm carriers in activated sludge processes can assist in the biodegradation, improving nutrient removal and reducing solids retention time, which leads to increased capacity and overall improved performance of existing AS reactors [7,8]. The activated sludge can also be completely replaced by a biofilm system, shifting the process of biodegradation from suspended to attach growth only [9].

This paper presents a short review of publications in the field of assisted biofilm processes (aBF-MBR) and pure biofilm based MBRs (pBF-MBR) for wastewater treatment, based on 50 scientific articles published in last 10 y. Paper does not include publications related to membrane aerated/supported biofilm reactors (MABR). Advantages and anomalies of this approach of using biofilm processes are discussed with respect to overall system performances and membrane fouling.

2. Biological treatment by biofilm processes

Major advantages of biofilm process over activated sludge process are typically defined in that they are simpler to operate compared to activated sludge process, have higher biomass activity due to accumulation, and where the biomass has a higher resistance to toxic substances [9–11]. Additionally, biofilm processes favor selective development of slow growing microorganisms such as autotrophs (i.e., nitrogen oxidizing bacteria, NOB) and phosphorus accumulating microorganisms (i.e., PAO) and reduces their washout from the system [12]. Biofilm processes are comprised of moving or fixed bed schemes, with media that serves as housing for biofilm growth. Implementation of freely moving medias has an advantage over fixed media beds due to their ability to utilize the whole volume of the bioreactor, minimize or eliminate the need for biomass recirculation, and are less prone to clogging, which is typical a problem in fixed bed biofilm process with high particulate loading. In order to meet requirements for nitrification (<2 mg NH_4–N/L in effluent) of typical municipal wastewater (e.g., COD = 250 mgO_2/l and NH_4–N = 25 mg/l) studies have been done to determine the conditions required to achieve nitrification. A unified model that computes required surface area of biofilm as a function of mean cell residence time MCRT (or solids retention time SRT) needed for full nitrification was evaluated [7]. The results are shown in Fig. 1. Design of an activated sludge process for full nitrification according to this model should be with a minimum SRT of 6 d. However, by adding biofilm media in bioreactors the activated sludge system can be converted to an integrated (bio)film activated sludge (IFAS) reactor, resulting in the opportunity to reduce SRTs for full nitrification. Shorter SRT require higher biofilm surface, where typical SRT values for an IFAS process are between 2 and 6 d. Subsequently, addition of carriers with biofilm growth reduces the SRT of an activated sludge bioreactor, which leads to increased capacity of the bioreactor or opens the possibility to operate the bioreactor on lower mixed liquor suspended solids (MLSS). This approach is beneficial for upgrading activated sludge processes. From Fig. 1, it can further be seen that addition of a high biofilm surface area will lead to sufficient biodegradation where activated sludge is no longer needed. This is typically the case in a moving bed biofilm reactor (MBBR) where degradation becomes a function of the biomass available on the carriers and HRT, virtually without suspended matter (i.e., no activated sludge). The high biofilm surface area in MBBR is typically achieved by adding biofilm carries with a high surface area at high volumetric filling fractions, typically up to 2/3 of the reactor volume [13].

By applying the model illustrated in Fig. 1 it can be concluded that by adding biofilm surface area it is possible to decrease the SRT of an activated sludge reactor, consequently increasing the capacity of existing reactors. It is also possible to design the treatment plant based on a pure biofilm process without applying activated sludge (i.e., decoupling SRT and HRT) if a large enough surface for biofilm growth is provided. There are different kinds of media (i.e., biofilm carriers) that can be used for the applications described above. Examples of types

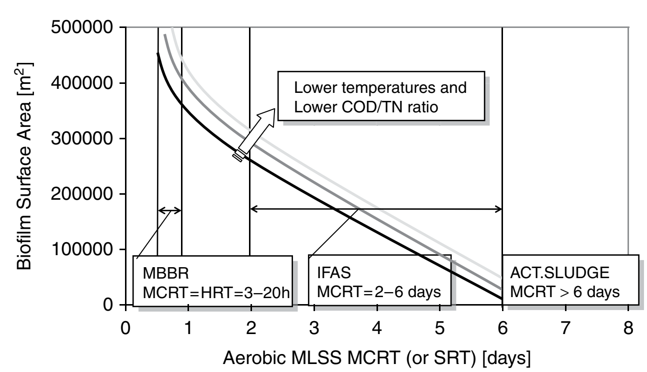

Fig. 1. Threshold of required biofilm surface area for reaching full nitrification for typical municipal wastewater as a function of MCRT (SRT) – adapted from [7].

Table 1
Several commercial types of media mostly used in full scale plants worldwide, adapted from [8]

Name of media	Type of bed	Specific surface area of bare media (m^2/m^3)	Typical filling fraction [%]
Ringlace	Fixed	50–100	25–50
BioWeb	Fixed	150–200	25–50
RBC	Moving	10–50	n/a
Linpor Sponge	Moving	10	15
Captor Sponge	Moving	50	5–15
Kaldnes K1	Moving	500–600	15–70

of commercially available media typically used in IFAS and MBBR applications, with basics characteristics, are given in Table 1.

3. Assisted biofilm MBR (aBF-MBR)

By adding biofilm carriers in a conventional MBR process the result is what has been called an assisted biofilm MBR (aBF-MBR). In aBF-MBR biodegradation is carried out by suspended growth (i.e., activated sludge) and assisted by attached growth on carriers (i.e., biofilm). This approach has been studied by several research groups and often is at times defined as a hybrid MBR by some authors [2]. The motives for using carriers are different and include; reduction of the negative effect of suspended solids, improved filterability and lower membrane fouling, improved nutrient removal, and reduction of membrane cake layer formation by scouring effects of the suspended carriers [9,12,14–17,19–22].

3.1. Organic (COD) removals and nitrification

The ratio between the level of biodegradation carried out by the suspended and attached biomass depends on the amount of biomass present in either form. The filling fraction of carriers, surface area for biofilm growth, MLSS concentration in suspended growth and biomass activity are the main parameters that affect the degradation ratio. A comparison in a MBR with suspended and attached growth demonstrated that the biomass in the attached form has a higher activity, where about 1/3 lower concentration of biomass in the attached form was able to achieve the same removal rates as biomass in the suspended form [9]. Other studies also reported higher specific oxygen uptake rates (SOUR) in aBF-MBR compared to conventional AS-MBR, confirming a higher activity of the biomass in aBF-MBR type of configuration [16,20]. Generally there is no difference in the degree of organic removal between an AS-MBR and aBF-MBR. Both systems can sustainably achieve high COD removals typically around 95–99%, when operated at similar HRT and SRTs.

Furthermore, no significant differences in nitrification rates between aBF-MBR and AS-MBR configurations has been reported operated under similar conditions, i.e., the same COD/TN ratios, and HRTs and SRT, aeration rates etc. Normally a satisfactory nitrification degree >96% was achieved. However, it should be noted that some authors observed 2–4% lower nitrification rates in AS-MBR compared to aBF-MBR [19,20] (Fig. 2).

3.2. Nutrients removal

Total nitrogen removal is reported to be higher in aBF-MBR systems compared to conventional AS-MBR by several authors [15,16,20]. Higher total nitrogen (TN) removal rates have been mostly attributed to simultaneous nitrification/denitrification (SND) that takes place in deeper layers of the biofilm component where anoxic/anaerobic conditions occurred. The sponge carriers seem to provide good SND conditions since they provide anoxic conditions inside the carrier element. Findings by Liang et al. (Fig. 2) differ from most reports, which is attributed to the lack of significant biofilm formation on chosen carriers in their study, as pointed out by other authors [18].

Phosphorus can be removed from the feedwater by assimilation for biomass growth and by phosphorous accumulating organisms (PAOs). Enhanced phosphorus removal with the addition of biofilm carries in a process has been reported by several authors [16,23–25]. The higher phosphorus removal was attributed to PAO organisms in the anoxic/aerobic zones found in the deeper biofilm layers. A 1.7% to 20.1% higher total phosphorus removal in aBF-MBR with sponge carriers

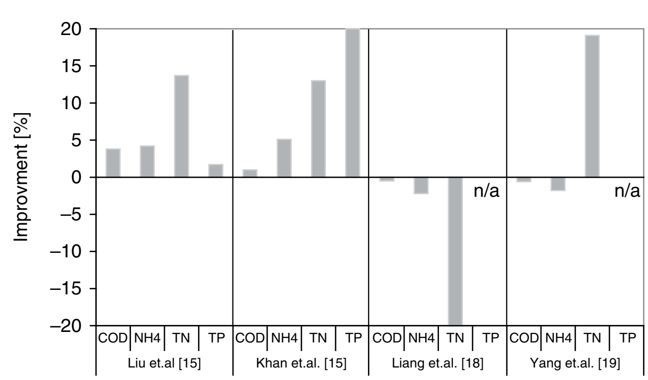

Fig. 2. Efficiency of organic and nutrient removal in aBF-MBR compared to AS-MBR.

compared to AS-MBR was reported, where COD/TP ratio and amount of excess sludge removed played an important role in the phosphorus removal efficiency.

Generally, organic (COD) removal and nitrification were in the same range when aBF-MBR was compared to AS-MBR under similar operating conditions. However, TN and TP removal could be significantly improved in aBF-MBR, due to the smaller floc sizes, higher microbial activity and more diverse microbial community present in the biofilm component.

3.3. Membrane performances

Membrane fouling is a common phenomenon in all membrane applications, including MBR systems [24–26]. Since liquid suspension (i.e., activated sludge and/or surplus of biofilm) is rather complex it is still unclear which fraction or compounds are mostly responsible for membrane fouling in MBR [3,5]. Colloidal and soluble organic content (i.e., biopolymers, SMP/EPS), suspended solids (MLSS), physical properties (i.e., particle size and viscosity) are mainly reported to contribute to membrane fouling.

3.3.1. Filtration characteristics

Improved filterability and lower fouling rates by implementation of attached biomass are commonly reported in aBF-MBR configurations. Reduced total resistance by 48% was reported by Wang et al. that results it three times longer operational cycles [14]. Better filterability was related to lower bound EPS values measured. Another study by Liu et al. reported significant prolongation of operational cycles (from 57–65 to 92 d) as a result of adding biofilm carriers [15]. Several other studies have reported better filterability, lower fouling rates and longer operational cycles, when MBR were operated with assistance of a biofilm [16–18]. Contrary to those findings, Yang et al. showed worse membrane performance after addition of carriers [20]. This was explained by overgrowth of filamentous bacteria that resulted in higher EPS values [21].

3.3.2. Colloidal and soluble organic content

Soluble microbial products (SMP) and extracellular polymeric substances (EPS) are considered the main contributor to membrane fouling in MBR technology [5,26]. However, their significance and role are still debated [27]. In aBF-MBR configurations, production of SMP/EPS by attached biomass does not seem to be higher than in AS-MBR systems [9,17]. In these studies, similar values of SMP/EPS in aBF-MBR and AS-MBR are reported, suggesting no fundamental changes in biological activities. Other studies reported a reduction of SMP in aBF-MBR due to the ability of the biofilm to adsorb and bind soluble microbial products [14,15,28]. Contrary to these findings, other studies have reported measuring higher content of proteins and polysaccharides in aBF-MBR due to an overgrowth of filamentous bacteria, which could be due to a new type of non-woven carrier that was used in the study [21].

3.3.3. Effects of MLSS on fouling

In the resistance in series model, cake resistance has been indentified as a main contributor to the total resistance of flow through a membrane [9]. Reduction of the negative effect of cake formation on the membrane has been extensively studied and several methods have been proposed to reduce this impact, including air scouring, backwashing, operation below critical flux, addition of additives, novel configurations etc. [3,5,27]. The main source that creates cake formation is suspended matter (i.e., activated sludge), however, reduction of MLSS does not ultimately lead to better membrane performance [29]. Yang et al and Lee et al. [9] tried to reduce the concentration of MLSS by implementing biofilm carriers in the reactor [9,20]. Contrary to expectations, higher fouling rates were observed for the membranes in the aBF-MBR at lower MLSS concentrations. The membrane operated at very low MLSS concentration were exposed to formation of a dense and less porous cake layer that led to higher resistance and thus higher fouling rates. Higher MLSS concentrations led to formation of a dynamic cake layer on the membrane surface, which was confirmed by SEM and AFM images [9]. The unexpected higher fouling observed with a very low MLSS environment was additionally reviewed by Lee et al. where the review commented a connection between lower SRT and higher SMP when the low MLSS was applied [30]. However, in AS-MBR systems it is commonly understood that membrane operation at lower concentrations of MLSS is beneficial due to lower viscosities, lower DO diffusion resistance and lower sludging /clogging problems [5].

3.3.4. Effects of particle size distribution on fouling

It is commonly accepted that smaller particle sizes lead to a higher fouling potential [5,27,31,32]. The presence of carriers in aBF-MBR system could lead to floc brakeage and thus an increase in smaller flocs [17,18]. However, this does not seem to be the problem in aBF-MBR since studies similarly reported better filterability and lower membrane fouling rates than in comparable AS-MBR configurations. The size of the biofilm carries and filling fraction do seem to have an important role and effect on particle size distributions. Studies have reported that larger carries and lower filling fractions are able to flocculate suspended biomass, thus promoting formation of lager flocs and consequently lower fouling rates [14,16,19,21,23].

4. Pure biofilm MBR (pBF-MBR)

In pure biofilm based MBR (pBF-MBR) biodegradation is exclusively carried out by attached biomass (i.e., biofilm), where activity of suspended matter is neglected due to very low concentrations and low biologically active MLSS in the bioreactor [9]. An high surface area is required for growth of attached biomass, which can be achieved by addition of media in a fixed bed or moving bed configuration. Moving bed configuration has an advantage over a fixed bed since the whole volume of the bioreactor is utilized and, if it is designed properly, does not suffer from clogging problems during high particulate loadings [6,13,33]. It is desirable that the media has a high surface area that provides protection for biofilm growth and from intensive detachment mechanisms. Another important parameter is the filling fraction (i.e., volume of bioreactor occupied by media), where higher filling fractions are certainly desirable leading to more compact bioreactor though a free movement of the media may then be more difficult. Types of media commonly used in commercial, full scale applications are given in Table 1. In the design of such a process it has been proposed that the membrane unit in pBF-MBR should built as an external submerged unit in order to avoid accumulation of suspended matter in the biofilm reactor and to keep the attached biomass (i.e., biofilm) process separated from influence of suspended growth [34]. Furthermore, designing the membrane reactor as an external submerged membrane unit opens the possibility of decoupling the biological and particle separation processes, thereby creating one more level of freedom in designing pBF-MBR systems.

Initial studies of a pBF-MBR process demonstrated that it could be operated in extremely compact configurations at high organic loading rates (OLR) with the same efficiency it terms organic removals and permeate quality as for AS-MBR systems [34–36]. Flexibility in choice of membranes was indicated for the pBF-MBR configuration, since a microfiltration membrane of 0.1 μm pore size reduced COD in the same range (86–87%) as a 30 kDa membrane pore size at low OLR with HRT 3–4 h [36]. The study also demonstrated an ability of a pBF-MBR system to operate at higher sustainable fluxes than commonly reported in AS-MBR systems. The importance of submicron particles and their contribution to membrane fouling in pBF-MBR systems has further been demonstrated [37,38]. It was found that the relative number % of submicron particles vary as a function of OLR. A discussion of the fate of submicron particles in this process is summarized in Fig. 3. Lower OLR in the biofilm reactors led to reduced residual organic loads (i.e., soluble COD) on the membrane surface, and consequently lower fouling rates. Higher OLR, resulted in a suspension with fragile flocs that easily brake under aeration supplied for air scouring, which led to higher production of submicron particles and higher fouling rates. This effect has also been confirmed by Ivanovic et al. where lower filterability and dewaterability of retentate in pBF-MBR at high OLR configuration was related to a high amount of submicron particles in the range of 0–04 to 0.1 μm, higher soluble organic content (FCOD) and a higher presence of filamentous bacteria [39]. Reduction in the amount of submicron particles in a pBF-MBR system was proposed by integrating a flocculation zone beneath the membrane aeration port [40,41]. In the flocculation zone submicron particles are caught by larger particles that were retained by the membrane separation and further settled in a sedimentation zone at the bottom of the membrane reactor.

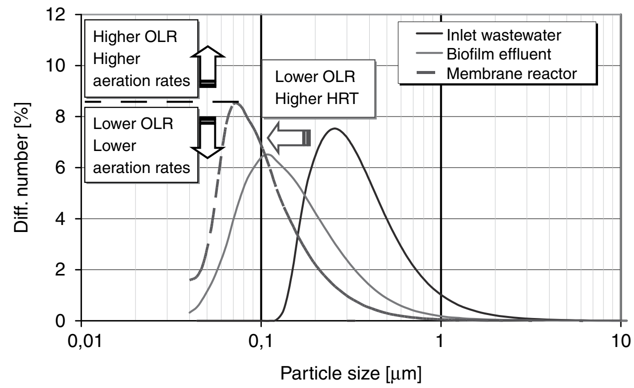

Fig. 3. Fate of submicron particles in pBF-MBR in different stages of process – adapted from [38].

Application of pBF-MBR for shipboard wastewater treatment (including oily bilge wastewater) was demonstrated in a study by Sun et al. [42–45]. Good and stable biodegradability of oil and other organic compounds was ensured by application of this process using both very compact dead-end and side stream schemes. A great recovery capacity of the pBF-MBR process from oil and salt shock loads in the feed water was demonstrated. The prefered process configuration was found to be a side-stream design that employs membranes with tighter pores and combined sedimentation beneath the membrane unit.

The flexibility in alternative designs of the biofilm reactor was demonstrated by Phattaranawik et al. where a double-deck aerobic pure biofilm reactor was employed [46]. The new double-deck concept was able to enhance the effect of aeration for the biological process and to minimize the load of detached suspended matter to the membrane unit. A higher packing density of a new modified flat sheet membrane module design was achieved due to an extremely low concentration of MLSS in the membrane reactor (<50 mg/l). The modified membrane module applied for the purpose of this study displayed lower fouling rates and longer operating cycles compared to a module designed for an AS-MBR system. In another study the potential of a combination of a biofilm process with a cold digester, also in double-deck configuration, was demonstrated, that enabled reduced sludge production, lower fouling rates and higher HRT [47]. The possibility of designing pBF-MBR systems with an energy recovery unit has also been experimentally demonstrated [48]. By choosing an alternative hydrodynamic arrangement the pBF-MBR system was able to produce low MLSS (~100 mg/l) in the reactor, opening the possibility to use UV inactivation as a fouling control method. Addition of a UV unit resulted in 24% lower fouling rates.

An alternative approach has been proposed where a compact tertiary membrane treatment as a polishing step after a moving bed biofilm reactor in combination with disc filtration and flotation (DAF) [49]. This approach relies on a sequential removal of detached biomass from biofilm reactor, first disk filtration and/or flotation unit, resulting in low solids loads on the membrane unit. Given approach resulted in membrane fluxes in the range of 40–80 LMH being achieved. However, this approach adds another unit of operation in the treatment train and higher configuration complexity. In addition, the reported higher cleaning frequency and use of coagulant and cationic polymer for the membrane filtration are obvious drawbacks of this approach.

A recent comparative study with a fixed bed pBF-MBR and AS-MBR was conducted by Ng et al. where a 71% lower production of total SMP (60% less carbohydrate and 77.6% less total protein) in the pBF-MBR compared to the AS-MBR was demonstrated, which resulted in 25–30% higher fluxes for the biofilm process [50]. This study further demonstrates the potential of a biofilm process compared to an activated sludge process applied to membrane bioreactor technology.

5. Conclusions

Implementation of a biofilm process for wastewater treatment is beneficial due to the potential of simplicity for operation compared to activated sludge, higher biomass activity, higher resistance of the biomass to toxic substances/shock loads, and development of a higher biodiversity of the microorganisms responsible for the biological treatment. Although not commonly commercially available to date, biofilm processes in membrane bioreactor technology have been shown to be potentially beneficial. Application of biofilm processes in AS-MBRs is beneficial due to the ability of the biofilm process to reduce the high SRT and MLSS values typically required for complete biodegradation of constituents in the wastewater. Inclusion of a biofilm process is practically achieved by addition of a support media that provides a high surface area for biofilm growth. Higher specific surfaces area and higher filling fractions are desirable since this can lead to more compact bioreactors and increase capacities of existing activated sludge systems. The aBF-MBR can achieve the same organic removal and nitrification rates as comparable AS-MBR designs. Higher total nitrogen and total phosphorus removals can also be achieved within a single through-put process. Other benefits include the potential for simultaneous nitrification and denitrification (i.e., through existence of anoxic/anaerobic zones in the deeper layers of the biofilm component), smaller floc sizes, higher microbial activity and more diverse microbial community present in biofilm which mainly contribute to improved nutrient removals. Filterability is generally reported as improved, where lower fouling rates and higher fluxes were observed in most studies. Less bound EPS and less SMP are generated or adsorbed by the biofilm, which is considered to lead to improved membrane performances. Reduction of MLSS concentration is certainly a desirable option in MBR technology and is easily feasible by addition of biofilm carriers in existing AS-MBR systems. Operating MBRs at lower suspended solids concentration is beneficial due to lower viscosities, lower DO diffusion resistance, and lower sludging /clogging problems.

pBF-MBR systems are operated without activated sludge and where the biodegradation is exclusively carried out by a biofilm process. This system shows a great flexibility in process design and configurations, decouples the biological and particle separation processes, has the potential of membrane operation at higher fluxes/less fouling, and offers stabile operation under high organic loading. The pBF-MBR may also be used as complementary to other technologies such as activated sludge and anaerobic digestion, resulting in novel systems designs and treatment concepts, giving a flexibility and reliability for sustainable operation.

References

[1] S. Judd, The MBR Book, Elsevier, 2006.
[2] M. Kraume and A. Drews, Membrane Bioreactors in Waste Water Treatment – Status and Trends, Chem. Eng. Technol., 33(8) (2010) 1251–1259.
[3] A. Drews, Membrane fouling in membrane bioreactors - Characterization, contradictions, cause and cures, J. Membr. Sci., 363(1–2) (2010) 1–28.

[4] A. Santos, W. Ma and S.J. Judd, Membrane biorectors: Two decades of research and implementations, Desalinations, 273(1) (2010) 148–154.
[5] F. Meng, S.R. Chae, A. Drews, M. Kraume, H.S. Shin and F. Yang, Recent advances in membrane bioreactors (MBR's): Membrane fouling and membrane material, Water Res., 46(6) (2009) 1489–1512.
[6] P. Le-Clech, V. Chen and T.A.G. Fane, Fouling in membrane bioreactors used in wastewater treatment, J. Membr. Sci., 284(1–2) (2006) 17–53.
[7] D. Sen and C.W. Randal, Improved computational model (AQUIFAS) for activated sludge, IFAS, and MBBR systems, Part III: analysis and verification, Water Environ. Res., 80(7) (2008) 633–645.
[8] D. Sen, R.R. Copithorn and C.W. Randall, Successful evaluation of ten IFAS and MBBR facilities by applying the unified model to quantify biofilm surface area requirements for nitrification, determinate accuracy in predicting effluent characteristics, and understanding the contribution of media towards organic removal and nitrification, WEFTEC 2006, proceedings.
[9] J. Lee, W.Y. Ahn and C.H. Lee, Comparison of the filtration characteristics between attached and suspended growth microorganisms in submerged membrane bioreactor, Water Res., 35(10) (2001) 2435–2445.
[10] V. Lazarova and J. Manem, Innovative biofilm treatment technologies for water and wastewater treatment: In: Bryers, D.J.(Ed.), Biofilms II, Willey, New York (pp 159–206).
[11] S.H. Hosseini and S.M. Borghei, The treatment of phenolic wastewater using moving bed biofilm reactor, Process Biochem., 40(3–4) (2005) 1027–1031.
[12] W.N. Lee, I.J. Kang and C.H. Lee, Factors affecting characteristics in membrane-coupled moving bed biofilm reactor, Water Res., 40 (2006) 1827–1835.
[13] H. Ødegaard, A new moving bed biofilm reactor - applications and results, Water Sci. Technol., 29(10–11) (1994) 157–165.
[14] X.C. Wang, Q. Liu and Y.J. Liu, Membrane fouling control of hybrid membrane bioreactor: Effect of extracellular polymeric substances, Sep. Sci. Technol., 45 (2010) 928–934.
[15] Q. Liu, Z.C. Wang, Y. Liu, H. Yuan and Y. Du, Performance of a hybrid membrane bioreactor in municipal wastewater treatment, Desalination, 258 (2010) 143 –147.
[16] S.J. Khan, S. Hyas, S. Javid, C. Visvanathan and V. Jegatheesan, Performance of suspended and attached growth MBR systems in treating high strength synthetic wastewater, Bioresour. Technol., in press (2010).
[17] K. Sombatsompop, C. Visvanathan and R.B. Aim, Evaluation of biofouling phenomenon in suspended and attached growth membrane bioreactor systems, Desalination, 2010 (2006) 138–149.
[18] Q.Y. Yang, T. Yang, H.J. Wang and K.Q. Liu, Filtration characteristics of activated sludge in hybrid membrane bioreactor with porous suspended carriers, Desalination, 249 (2009) 507–514.
[19] Z. Liang, A. Das, D. Beerman and Z. Hu, Biomass characteristics of two types of submerged membrane bioreactor for nitrogen removal, Water Res., 44 (2010) 3319–3320.
[20] S. Yang, F. Yang, Z. Fu and R. Lei, Comparison between a moving bed membrane reactor and conventional membrane reactor on organic carbon and nitrogen removal, Bioresour. Technol., 100 (2009a) 2369–2374.
[21] S. Yang, F. Yang, Z. Fu and R. Lei, Comparison between a moving bed membrane reactor or and conventional membrane reactor on membrane fouling, Bioresour. Technol., 100 (2009b) 6655–6657.
[22] X. Huang, C.H. Wei and K.C. Yu, Mechanism of membrane fouling control by suspended carriers in a submerged membrane bioreactor, J. Membr. Sci., 209 (2008) 7–16.
[23] C.H. Wei, X. Huang, C.W. Wang and X.H. Wen, Effect of suspended carrier on membrane fouling in a submerged membrane bioreactor, Water Sci. Technol., 53(6) (2006) 211–220.
[24] H.H. Ngo, M.C. Nguyen, N.G. Sangvikar, T.T.L. Hoang and S.W. Guo, Simple approach towards a design of an attached-growth sponge bioreactor (AGSB) for wastewater treatment and reuse, Water Sci. Technol., 54 (2006) 191–197.
[25] C. Psoch and S. Schiewer, Direct filtration of natural and simulated river water with air sparging and sponge ball application for fouling control, Desalination, 197 (2006) 190–204.
[26] W. Yang, N. Cicek and J. Ilg, State-of-the-art of membrane bioreactors worldwide research and commetcial applications in North America, J. Membr. Sci., 207 (2006) 201–211.
[27] A. Drews, M. Vock, U. Bracklow, V. Iversen and M. Kraume, Does fouling in MBRs depend on SMP? Desalination, 231(1–3) (2008) 141–149.
[28] X.Y. Li and S.F. Yang, Influence of loosely bound extracellular polymeric supstances (EPS) on flocculation, sedimentation and dewaterability of activated sludge, Water Res., 41 (2007) 1022–1030.
[29] M.L. Ferreiera, S. Geilvoet, A. Moreau, E. Atasoy, P. Krzeminski, A.V. Neiuwenhuijzen and J.V.D. Graaf, MLSS concentration: still a poorly understood parameter in MBR filterability, Desalination, 250 (2010) 618–622.
[30] H.S. Lee and C.G. Kim, Comment on “Comparison of the filtration characteristics between attached and suspended growth microorganisms in submerged membrane bioreactor, Water Res., 36 (2002) 4838–2939.
[31] A.L. Lim and R. Bai, Membrane fouling and cleaning in microfiltartion of activated sludge wastewater, J. Membr. Sci., 216(1–2) (2003) 279–290.
[32] J.S. Kim, C.H. Lee and I.S. Chang, Effects of pump shear on the performance of a cross flow membrane reactor, Water Res., 35(9) (2001) 2138–2144.
[33] B. Rusten and B. Eikebrokk, Design and operations of the Kaldnes moving bed biofilm reactors, Aquacult. Eng., 34(3) (2006) 322–331.
[34] T.O. Leiknes and E.C.S. Knudsen, Microfiltration of effluent produced by a moving bed biofilm reactor by an immersed hollow fiber membrane module, Proceedings EuroMembrane 2000, Jerusalem, Israel, September 2000.
[35] T.O. Leiknes and H. Ødegaard, Moving Bed Biofilm Membrane Reactor (MBB-MR): Characteristics and potential of a hybrid process design for compact wastewater treatment plants, Engineering with Membranes, Proceedings, Granada, Spain, 3–6 June 2001.
[36] E. Melin, T.O. Leiknes, H. Helness, V. Rasmussen and H. Ødegaard, Effect of loading rate on a wastewater treatment process combining moving bed biofilm and membrane reactor, Water Sci. Technol., 51(6–7) (2005) 421–430.
[37] T.O. Leiknes and H. Ødegaard, The development of a biofilm membrane bioreactor, Desalination, 202 (2007) 135–143.
[38] R.M. Åhl, T.O. Leiknes and H. Ødegaard, Tracking particle size distributions in a moving bed biofilm membrane reactor for treatment of municipal wastewater, Water Sci. Technol., 53(7) (2005) 33–42.
[39] I. Ivanovic, T.O. Leiknes and H. Ødegaard, Influence of loading rates on production and characteristics of retentate from a biofilm membrane bioreactor (BF-MBR), Desalination, 199 (2006) 490–492.
[40] T.O. Leiknes, H. Bolt, M. Engmann and H. Ødegaard, Assesment of membrane reactor design in the performance of a hybrid biofilm membrane bioreactor (BF-MBR), Desalination, 199 (2006) 328–330.
[41] I. Ivanovic, T.O. Leiknes and H. Ødegaard, Fouling control by reduction of submicron particles in a BF-MBR with an integrated flocculation zone in the membrane reactor, Sep. Sci. Technol., 43(7) (2008) 1871–1883.
[42] C. Sun, T.O. Leiknes, J. Weitzenböck and B. Thorstensen, Development of a biofilm-MBR for shipboard wastewater treatment: The effect of process configuration, Desalination, 250 (2010) 745–750.
[43] C. Sun, T.O. Leiknes, J. Weitzenböck and B. Thorstensen, The effect of bilge water on a biofilm-MBR process in an integrated

shipboard wastewater treatment system, Desalination, 236 (2009) 56–64.
[44] C. Sun, T.O. Leiknes, J. Weitzenböck and B. Thorstensen, Development of an integrated shipboard wastewater treatment system using biofilm-MBR, Sep. Purif. Technol., 75 (2010) 22–31.
[45] C. Sun, T.O. Leiknes, J. Weitzenböck and B. Thorstensen, Salinity effect on a biofilm-MBR process for shipboard wastewater treatment, Sep. Purif. Technol., 72 (2010) 380–387.
[46] J. Phattaranawik and T.O. Leiknes, Double-deck aerated biofilm membrane bioreactor with sludge control for municipal wastewater treatment, AIChE J., 55 (2009) 1291–1297.
[47] J. Phattaranawik and T.O. Leiknes, Study of hybrid vertical anaerobic sludge-aerobic biofilm membrane bioreactor for wastewater treatment, Water Environ. Res., 82(3) (2010) 273–280.
[48] J. Phattaranawik and T.O. Leiknes, Extractive biofilm membrane reactor with energy recovery from excess aeration and new membrane fouling control, Bioresour. Technol. (2010), in press, doi:10.1016/j.biortech.2010.10.060.
[49] H. Ødegaard, U. Mende, E.O. Skjerping, S. Simonsen, R. Strube and E. Bundgaard, Compact tertiary treatment based on the combination of MBBR and contained hollow fibre UF-Membranes, MDIW, Proceedings, Trondheim, Norway, 20–30 June 2010.
[50] K.K. Ng, C.F. Lin, S.K. Lateef, S.C. Panchangam, P.K.A. Hong and P.Y. Yang, The effect of soluble microbial products on membrane fouling in a fixed carrier biological system, Sep. Purif. Technol., 72 (2010) 98–104.