Matthias Kraume[1]
Anja Drews[2]

[1] Technische Universität Berlin, Chair of Chemical and Process Engineering, Berlin, Germany.

[2] HTW Berlin, FB II, Life Science Engineering, Berlin, Germany.

Review

Membrane Bioreactors in Waste Water Treatment – Status and Trends

Due to their unique advantages like controlled biomass retention, improved effluent quality, and decreased footprint, membrane bioreactors (MBRs) are being increasingly used in waste water treatment up to a capacity of several 100,000 p.e. This article reviews the current status of MBRs and reports trends in MBR design and operation. Typical operational and design parameters are given as well as guidelines for waste water treatment plant revamping. To further improve the biological performance, specific or hybrid process configurations are shown to lead to, e.g., enhanced nutrient removal. With regards to reducing membrane fouling, optimized modules, advanced control, and strategies like the addition of flux enhancers are currently emerging.

Keywords: Hybrid processes, Membrane bioreactor, Membrane fouling, Nutrients, Waste water

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1 Introduction

The first reported application of membrane bioreactor (MBR) technology in waste water treatment was in 1969, when an ultrafiltration membrane was used to separate activated sludge from the final effluent of a biological waste water treatment system, and the sludge was recycled back into the aeration tank [1]. Due to their unique advantages like superb and hygienic effluent and reduced footprint which has been shown on large scale [2], MBRs, which are combinations of common bioreactors and membrane filtration units for biomass retention, are becoming increasingly popular for waste water treatment. In Europe, the first full-scale MBR plant for treatment of municipal waste water was constructed in Porlock (UK, commissioned in 1998, 3800 p.e.), soon followed by the Büchel and Rödingen WWTPs (Germany, 1999, 1000 and 3000 p.e., respectively), and Perthes-en-Gâtinais WWTP (France, 1999, 4500 p.e.). Only a few years later, in November 2002, one MBR line was commissioned in Brescia, Italy, with an initial nominal flow of 38 000 m^3/d, later increased to 42 000 m^3/d. In 2004, the Nordkanal MBR plant (in Kaarst, Germany) was commissioned with a design maximum daily flow of 45 000 m^3/d to serve a population of 80 000 p.e. [3].

The diversity of microbiologically possible processes including enhanced nutrient removal (e.g., [4–8]) still offers great potential for the optimization of removal efficiency in MBR, but at the same time, by constituting a deposit on the membrane surface, the presence of the activated sludge limits the maximum hydraulic exploitation of the process.

MBR technology and fouling in particular have been reviewed in 2006 by Judd [9] and Le-Clech et al. [10]. Since then, a large number of new results has been published presenting novel process configurations, more insight into the occurring phenomena, and pointing out innovative ways to combat fouling [11, 12]. Between 2005 and 2009, the EC funded two major projects on all aspects of MBR technology (AMEDEUS and EUROMBRA), the outcomes of which can be found on www.mbr-network.eu.

This paper aims to provide an overview of where MBR technology stands today and which future trends in process configuration and fouling control are emerging. Due to the vast amount of worldwide studies on MBR, this article will not be able to reflect all ongoing developments in the same depth, but will attempt to highlight the main economic and operational trends.

2 Current Status of MBR

2.1 Market and Capacity

The global market for membrane bioreactor technology is expected to grow at a compound annual growth rate of 10.5 %, increasing in value from $296.0 million in 2008 to $488.0 million by 2013. Growth rates of MBR systems are not the same for all world regions and are not increasing from the same base. Municipal/domestic wastewater treatment was the ear-

Correspondence: Prof. Dr.-Ing. M. Kraume (matthias.kraume@tu-berlin.de), Technische Universität Berlin, Chair of Chemical and Process Engineering, Straße des 17. Juni 135, D-10623 Berlin, Germany.

liest application of MBRs and is still the largest application, accounting for 44 % of all systems. A trend towards larger capacity municipal plants is prevalent in the United States and Europe. However, satellite wastewater plants for smaller communities, housing developments, tourist resorts, schools, shopping centers, etc. also are in demand. Growth in this sector is expected to increase in all world regions, driven by the adoption of MBRs for treating numerous small domestic wastewater streams [13].

Fig. 1 exemplarily shows the development of the European MBR market where by the end of 2008 approx. 800 MBRs (industrial waste water applications >20 m^3/d and municipal plants >100 m^3/d) had been commissioned [14]. About 2/3 of these plants are industrial applications, however, based on installed membrane surface, the municipal sector holds 75 % of the market volume [15], with the 11 larger plants (>5000 m^3/d) contributing to more than half of the capacity. While the growth of industrial MBRs has been steady with approx. 65 new plants per year since 2003 [14], the municipal sector is still growing at an increasing rate (30 new plants per year between 2004 and 2005, and 45 between 2006 and 2008).

Brepols et al. [16] have shown that the life cycle costs of MBRs in municipal wastewater treatment are already competitive when compared with conventional treatment that is upgraded to achieve the same excellent effluent quality.

2.2 Typical Operational Regimes

Initially, the possibility of increasing mixed liquor-suspended solids concentration (MLSS) and sludge age were thought to intensify the overall process immensely, e.g., by
- decreased reactor volumes and footprint
- uncoupling of hydraulic and solids residence times (HRT and SRT, respectively), yielding an additional degree of freedom for process control
- establishment of slowly growing microorganisms with particular degradation features
- reduced excess sludge production due to the enhanced utilization of maintenance energy demands at high sludge ages
- tolerance to filamentous bacteria, scum development, and foaming to a certain extent as they do not affect sludge separation by membrane filtration like they affect sedimentation.

However, due to increased viscosity at higher MLSS (e.g., [17]) and thus higher energy demand for oxygen supply, pumping, and mixing, MLSS and SRT have been limited to approx. 16 g/L and 28 d, respectively [9, 18].

2.3 Operating and Maintenance Costs

The main drawback of MBR technology still is its high cost. While overall and especially membrane module costs (<50 US$/$m^2$ [9]) have declined dramatically over the last years leading to a decrease in capital costs as shown in Fig. 2, the energy demand to cope with membrane fouling has become the main contribution to the overall operating costs [19]. Fouling affects these in a number of ways:
- decreased plant productivity/permeate yield due to (i) filtration breaks and backflush: to remove the deposit layer, backflushing from the permeate side (hollow fiber modules) or relaxation (flatsheet modules) are commonly applied. Backflush/relaxation is employed for approx. 15–60 s every 3–12 min of filtration [9, 18]. (ii) Excessive cleanings (maintenance cleanings approx. every 2–7 days, main cleanings once or twice a year [9, 18]). This may also lead to environmental hazards through the formation of chemical cleaning by-products such as AOX.
- inefficient or late chemical cleaning which reduces the modules' lifespan and results in higher replacement costs
- high energy requirement for aeration: With up to 60–70 % of the total energy costs (e.g., [9, 18]), membrane aeration is the biggest contribution to operating costs.

Many fundamentals of the interaction between hydrodynamics of the multiphase flow in MBRs and fouling are still unknown and difficult to access experimentally. Therefore, applied aeration rates are normally based on previous experiences and manufacturers' recommendations. Aeration demand is often given in terms of specific values: air flow per membrane area (SAD_m in m^3/m^2h) or, economically important, air flow rate per permeate flow produced (SAD_p in m^3/m^3). In full-scale MBRs, SAD_m values range from 0.18 to 1.28 Nm^3/m^2h and SAD_p from 10 to 65 [9]. Typically, flatsheet membranes have higher SAD_m but lower SAD_p since they are commonly operated at higher flux. Significant energy savings were achieved by air-cycling or intermittent bubbling (e.g., [9, 21]) down to approx. 0.25 kWh/m^3 [22].

Long-term experiences with full-scale plants show the importance of flexible and appropriate cleaning con-

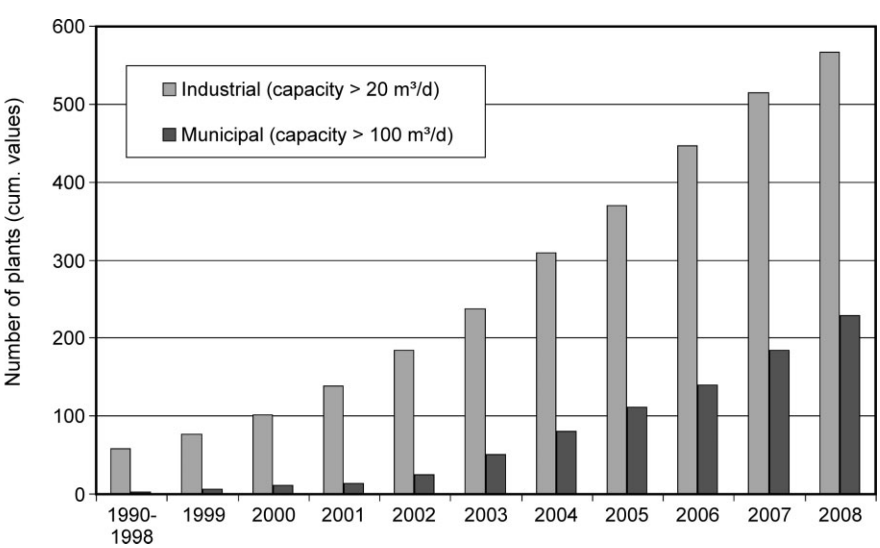

Figure 1. Global European MBR market [14].

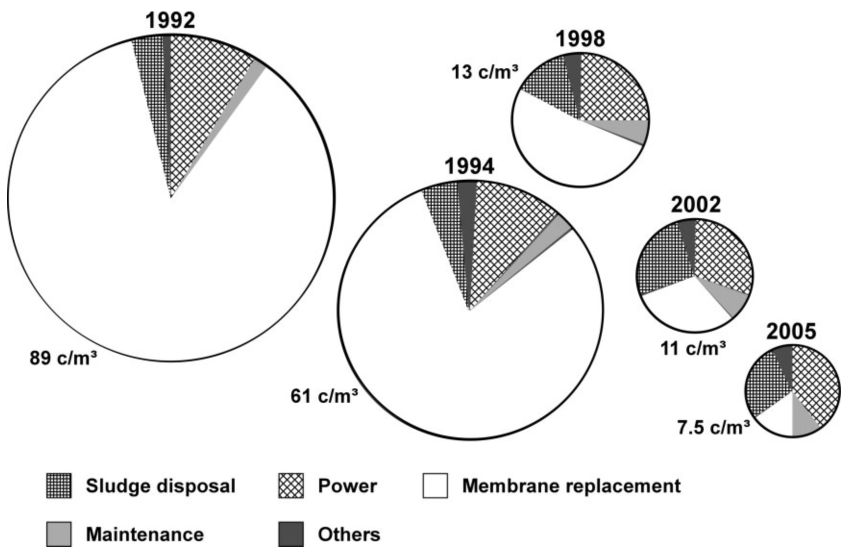

Figure 2. Development of operating and maintenance costs [19, 20].

cepts [16]. Chemical cleanings must be adapted to seasonal variations and ageing equipment to be efficient and to prolong membrane lifetime. This, however, was shown to be longer than initially expected: In Porlock, UK, only 6.4 % of the original cartridges had to be replaced in the first ten years of operation during which in-situ cleanings had been carried out every eight months on average [23].

3 Trends in MBR Design and Operation

Due to the increasing experiences with full-scale plants, a lot of information is available regarding the operating parameters of MBRs such as hydraulic retention time, sludge age, biomass concentration, flux, transmembrane pressure (TMP), and aeration rate. Currently employed values and different case studies can be found, e.g., in [9].

3.1 Biomass Concentration and Sludge Age

In the light of more stringent sludge disposal regulations and higher disposal costs, sludge minimization by prolonged SRTs has recently come into focus again. MBRs operated at high SRT generally showed good removal efficiencies [24–26]. However, increased biomass concentrations (>80 d) give rise to a deterioration of sludge properties like viscosity and dewaterability, which due to their influence on filtration and sludge handling play an important role in the overall economics. Still, Pollice et al. [26] suggest that "membrane bioreactors can be conveniently operated at sludge retention times higher than 40 days without relevant drawbacks in terms of biological activity, filterability, and cleaning needs." On the other hand, complete sludge retention appears less suitable. Nevertheless, SRTs of around 60 days or more have been shown to be economically viable [27].

3.2 Specific Process Configurations

3.2.1 Hybrid MBRs

In an attempt to improve elimination capacity even further, several combinations of MBRs with waste water technologies other than the conventional activated sludge process (CAS), so-called hybrid MBRs, have been proposed.

In a biofilm MBR (BF-MBR), biofilms grow on fluidized supports [28, 29]. This process can achieve high N-removal by simultaneous denitrification within the biofilm [28]. In addition, less biomass is suspended and the circulating media generate some scrubbing action which both improve filterability [30, 31] despite the fact that the attached biomass has a much higher fouling potential than suspended activated sludge [32].

Similar effects can be achieved in an aerobic granular sludge MBR (AGMBR), because due to the low compressibility of granules, the permeability of the cake is higher [33]. However, it has been reported that irreversible fouling is more severe than in conventional MBRs which has been attributed to the colloids and solutes generated [34].

A membrane distillation bioreactor (MDBR) can achieve effluent qualities suited for reuse in one step since pollutants are retained by their evaporation potential [35]. Thus, the residence time of recalcitrant pollutants is extended. Full-scale operation, however, is only viable if waste heat is available, e.g., in the case of industrial waste waters that are discharged at high temperatures.

In an osmotic membrane bioreactor (OMBR), a forward osmosis membrane is submerged and the treated water is extracted by means of a draw solution [36]. This yields high pollutant rejection, however, the draw solution needs to be regenerated. Additionally, with values in the range of 5–10 L/m^2h, fluxes are rather low [36].

3.2.2 Anaerobic MBR

Aerobic, submerged MBR systems represent 99 % of the total installed membrane surface in MBR [15]. Anaerobic MBRs (AnMBR), on the other hand, have a high potential for high-strength waste waters which are highly particulate, because the particles will be retained by the membrane. But even for low-strength waste waters, which are almost exclusively treated aerobically, AnMBRs could be a good alternative. Operational costs are lower because of the low anaerobic growth yields, i.e., less sludge has to be disposed [37], and because biogas is produced. Instead of aeration, fouling control can be achieved by sparging the produced biogas [38]. However, since not enough biogas is produced, it needs to be recycled and compressed, so only slightly less energy than in aerobic MBRs is required [39]. The fluxes are basically comparable (10–40 L/m^2h) to aerobic MBRs [39]. On the other hand, heating is typically required to reach the operating temperature of 30–50 /C, which makes AnMBRs mainly attractive in hot climates [39]. The absence of nutrient removal and long startup periods are further limitations.

3.2.3 Enhanced Nutrient Removal

Due to the accumulation of slowly growing microorganisms and the high biomass concentrations employed, higher metabolic rates and better nutrient removal is possible in MBRs than in conventional activated sludge processes (CAS).

Like in CAS, the safest and most commonly applied scheme for denitrification is pre-denitrification. To overcome its limited N-removal, post-denitrification can also be applied. Some characteristics of MBR technology like the insignificance of higher aeration requirements in comparison to membrane aeration or the better biomass repartition over the entire reactor (less sludge is in contact with the membrane, while more sludge is present in the anoxic zone) could actually render post-denitrification an attractive alternative in MBR [6]. Post-denitrification was thus identified as a promising configuration in MBR technology when enhanced N-removal is required and has been shown to work reliably even up to full scale [5]. In addition, MBRs have been combined with all common processes for N-elimination: simultaneous, intermittent, and alternating nitrification/denitrification, and Anammox [40–42]. Fu et al. [40] and Kimura et al. [41] achieved good removal using simultaneous denitrification.

Since MBRs usually work at elevated sludge ages, chemical P-removal is commonly installed when P-elimination is required. However, it has been shown that enhanced biological phosphorus removal (EBPR) is also possible in MBRs operating at sludge ages of up to 30 days (e.g., [8]). It has also been demonstrated that in an EBPR configuration post-denitrification is possible even without a supplementary C-source [8]. In a 10 m^3 domestic waste water plant (EBPR and post-denitrification), effluent phosphorus concentrations down to 0.1 mg/L and total N-concentrations <10 mg/L were achieved despite strong hydraulic and load fluctuations [5]. In sensitive areas a combination of EBPR and precipitation is a promising technology to constantly ensure effluent P-concentrations as low as 50 µg/L [6].

For MBR with enhanced nutrients' removal, rather complex recirculation schemes based on the biological requirements are commonly recommended. Depending on the recirculation paths and ratios, Ersu et al. [43] achieved 77–90 % total N- and 66–88 % P-elimination. In an intermittent configuration, the change of anoxic and anaerobic time ratios and HRT affected phosphorus removal more than N-removal due to the limitation of the favorable carbon source for phosphorus-accumulating organisms [44]. However, Bracklow et al. [4] showed that there were no big differences in elimination efficiency between different recirculation schemes as shown in Fig. 3 (COD elimination: 96.6–97.9 %, nitrogen removal: 90–92 %, and phosphorus removal: 97.4–99.4 %). Changes in the degradation, release, and uptake rates were leveled out by the changes in contact time and biomass distribution throughout the plant. This will allow much simpler schemes to be used, thereby saving pumping energy, and shows the still not utilized optimization potential.

3.2.4 Plant Layout and Revamping

In order to ensure stable and reliable operation of municipal MBR plants, an enhanced mechanical pretreatment of the raw waste water is essential. Removal of hair, fibrous material, and other contraries which can lead to operational problems with membrane modules is of particular importance (e.g., [45]). Upgrading screens is essential, especially for immersed hollow fiber membranes.

Submerged membrane modules can be installed directly inside the bioreactor or in a separate filtration tank. In the latter configuration, investment costs are higher but on the other hand, hydrodynamics can be optimized for the filtration task and modules are easier to clean and access [46]. Better effluent qualities can also be achieved because of the cascading effect. It is commonly applied in large plants (>200 m^3/h), while for small, compact plants that only require C-removal the inside configuration is favored [47].

To increase the capacity of existing waste water treatment plants, MBR technology is an attractive means of retrofitting because of its small footprint and enhanced effluent quality [48]. Instead of turning the whole treatment plant into an MBR which would incur high investment costs, dual configurations have been identified as more cost-effective alternatives [48]. As shown in Fig. 4, the existing plant is combined with an MBR, with either separate bioreactors (Dual 1) or with the same bioreactor feeding both a membrane chamber and a final clarifier (Dual 2®). The incoming waste water is split so that the average flow is treated by the MBR and the peak flows by the CAS, thereby saving membrane surface area. Such hybrid systems have been successfully established at full scale in the waste water treatment plants in Schilde [47] and in Heenvliet [50]. Nevertheless, there is no new plant currently planned that is based on a hybrid configuration.

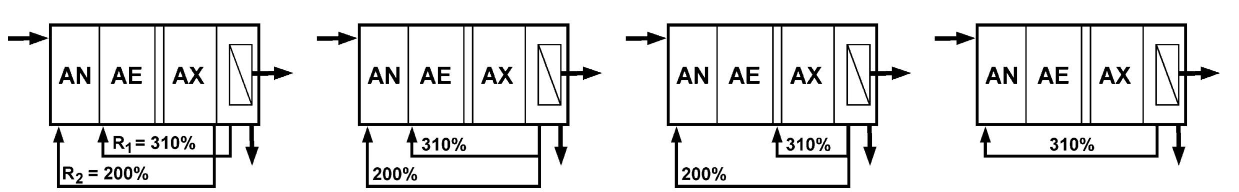

Figure 3. Examples of possible recirculation schemes for enhanced nutrient removal MBRs (post-denitrification). Zones: AN: anaerobic, AE: aerobic (nitrification), AX: anoxic (denitrification) (acc. to [4]).

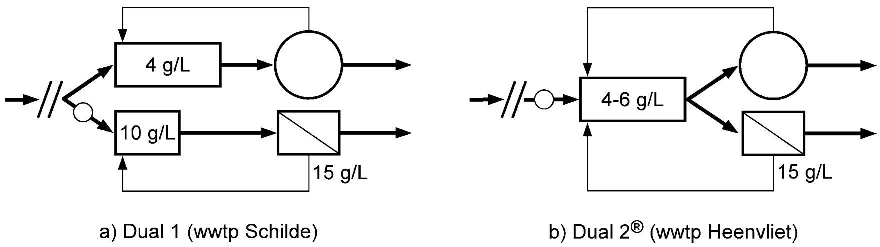

Figure 4. Schemes for waste water treatment plant revamping with MBR technology and corresponding sludge concentrations [48].

With the rising number of technical applications, end-users show a growing interest in guidelines and standards on interchangeable filtration modules. A white paper has been developed which has been accepted as a reference document to initiate standardization. A CEN workshop decided to initiate a standardization process for submerged flat sheet and hollow fiber membranes [51].

3.2.5 Textile Bioreactors

Novel nonwoven textiles might be a more economical alternative to the usually applied ultra- or microfiltration membranes due to lower production costs and potentially higher permeability, which apart from smaller filtration surface areas would also lead to savings in aeration requirements. The application of nonwovens has been recently investigated in lab-scale MBRs [52], where effluent qualities similar to "normal" MBRs were achieved except for disinfection parameters. Textile bioreactors (TBRs) will, therefore, be particularly attractive where hygienic requirements are not so strict, limited funds are available, and/or space is scarce. However, research is at an early stage and no MBR textiles are commercially available yet. Coating normal filtration fabrics with electrospun nanofibers lowers the pore size to <1 µm, and additional plasma treatment can enhance critical flux further [53]. Nanocomposite production costs were estimated at around 5 €/m^2 of which the conventional support alone amounts to approx. 75 % [54].

3.3 Membrane Fouling

Membrane fouling represents the main limitation for MBRs. Hence, the majority of membrane material and process research and development conducted is dedicated to its characterization and amelioration (extensive reviews on this topic can be found in, e.g., [10–12]). Numerous parameters that influence fouling must be considered. For years it had been generally accepted that soluble microbial products (SMPs) are the main culprit of membrane fouling as they cause fouling on their own and fouling rates could to some extent be correlated to their concentration [55]. However, using them as a measure of fouling is nowadays questioned [56–59] since fouling phenomena have been shown to be a much more complex interaction of hydrodynamics (orthogonal and parallel to the membrane surface), mass transfer, biological state, and prevailing compounds [56–60].

Resulting from advances in understanding of fouling but also from the pressing economic and ecological problems associated with it, a number of novel strategies for fouling mitigation have recently emerged. These exploit a variety of (bio-)chemical, mechanical, or hydrodynamic means, such as the development of *anti-fouling* membranes [9, 12], the use of additives (e.g., [61–63]), sponge-like carriers (e.g., [64]) or other circulating abrasive particles [65], sludge granulation (e.g., [66]), presettling of biomass from the bulk [65, 67], membrane surface modification (e.g., [12, 68]), etc.

In addition, traditional methods such as backpulsing or bubbling as well as geometric design features are being optimized systematically (e.g., [69–71]). Over the last four years, a significant amount of research has also begun to focus on advanced control to improve the efficiency of traditional and novel antifouling methods and to minimize energetic expenditure (e.g., [72–75]).

3.3.1 Antifouling Membranes

Membrane materials always show different fouling propensity due to their different pore size, morphology, and hydrophobicity. In general, membrane fouling occurs more readily on hydrophobic membranes than on hydrophilic ones because of the hydrophobic interaction between foulants and membranes. As a result, much attention has been given to reduce membrane fouling by modifying membrane surfaces from hydrophobic to hydrophilic [9, 12, 76]. To improve the antifouling property of polypropylene hollow fiber microporous membranes in an MBR for wastewater treatment, the membranes were subjected to surface modification by NH_3 and CO_2 plasma treatment [77–79]. With the introduction of polar groups on the surface, the membranes presented better filtration performances and flux recovery than the unmodified membranes.

Another approach are TiO_2-embedded polymeric membranes which can be prepared by a self-assembly process and have been applied to the filtration of MBR sludge [80, 81]. The surface of a TiO_2-embedded membrane is more hydrophilic than that of a polymeric membrane due to the higher affinity of metal oxides to water. Therefore, hydrophobic adsorption between the sludge suspension and the TiO_2-embedded membrane can be reduced, and deposited foulants are readily removed by cross-flow. As a result, lower flux decline was obtained with the TiO_2-membranes compared to that of unmodified membranes [80, 81].

In general, the development of economical, high-flux, nonfouling membranes is still needed before viable MBR processes can be achieved [82].

3.3.2 Optimized Modules and Aeration

Optimization of all parameters involved in increasing air scour efficiency is not yet at its end. Besides aeration rate and bubble size (or diffuser ports), module and tank geometry (membrane spacing, fiber slackness, liquid level, cross-sectional areas of riser and downcomer, etc.) have decisive effects on the achieved cross-flow velocity, shear stress, and bubble-membrane contact. Fig. 5 shows numerical results (validated experimentally in [71]) on the influence of bubble size and membrane spacing in flatsheet modules on maximum shear stress exerted on the membrane surface. Values differ by a factor of up to 10, showing the importance of optimized design. This coincides with a finding by Bérubé et al. [83] whereby the average and peak surface shear forces for two-phase flow around immersed hollow fibers were, respectively, approximately three and seven times greater than that observed for single-phase flow. This underlines the importance of efficient aeration to mitigate fouling as higher shear rates result in reduced fouling layers on the membrane surface.

With respect to the overall geometry, especially the abrupt flow direction change from the downcomer to the riser region and vice versa, causes significant pressure drops. Thus, a smoother draft tube edge was introduced to achieve lower bend loss and thus higher circulation velocities (see Fig. 6) [71]. An additional acceleration was achieved by locating the aerators at the bottom of the tank instead of at the entrance to the draft tube where they significantly block the available cross section and slow down the flow. Together with spargers inside the flow bodies, also a much more homogeneous bubble distribution across the whole module could thus be achieved which prevents clogging of the outer channels. With this configuration, either higher shear forces can be achieved at the same aeration or significantly lower aeration is required to achieve the same liquid velocity.

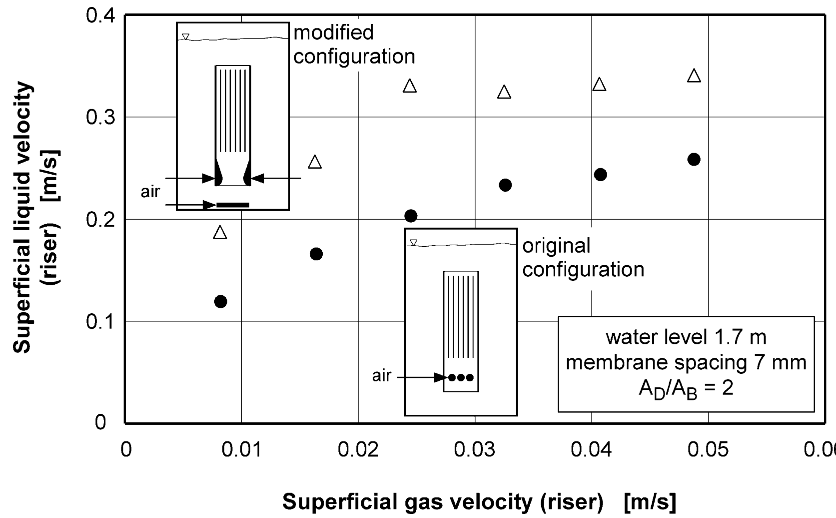

Figure 6. Circulating velocities achieved by conventional and modified aerator configuration [71].

In the NORIT AirLift™ configuration, a vertical side-stream module is installed in which high cross-flow velocities are also achieved by a combination of air-sparging and resulting circulating flow [84].

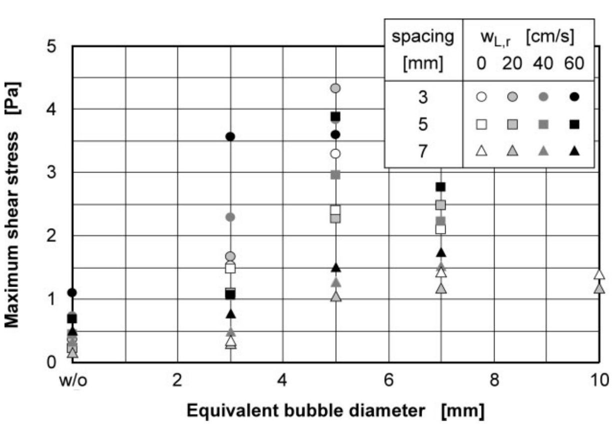

Figure 5. CFD results for maximum wall shear stress exerted by differently sized bubbles rising in channels of different widths with various superimposed liquid velocities $w_{L,r}$ [71].

3.3.3 Advanced Monitoring and Control

Feed forward control as generally applied to bubbling, permeate suction, backflushing, additive dosing, etc. can lead to losses in productivity, high energy demands, or adverse effects due to over- or underdosing of additives, e.g., the use of preset fixed filtration intervals leads to an excessive waste of permeate when backflush is applied too often or lasts too long. On the other hand, when backflush/relaxation is applied too late or does not last long enough, it promotes irreversible fouling.

First attempts on the way to feedback control have been made by, e.g., Brauns [85] who uses fuzzy logic and by Busch and Marquardt [73] who use a simple polynomial model which is calibrated after each filtration cycle and generates new decision variables for the next. Smith et al. [74] investigated feedback control of backwash, i.e., to use it only when a drop in permeability occurs. The strategy also utilizes the TMP signal during filtration backflush with the duration being terminated when TMP becomes constant. This yielded a 25 % reduction of the overall backflush duration and thus of permeate loss in 20-h trials.

A number of model-based control attempts have also been undertaken. Geissler et al. [72] set up a model to describe permeability loss of a submerged HF module based on a semi-empirical approach (resistance in series with two fitting parameters) and calibrated this at full scale over three months. Busch et al. [86] developed this further to a rigorous model with a high level of detail by including phenomena like concentration polarization, microbial growth in the biofilm, pressure drop in the permeate, etc. However, this model contains a large number of physical and empirical parameters which are subject to uncertainty. It thus needs to be calibrated very carefully.

When developing advanced control strategies, one should bear in mind that practical limitations to their use currently exist, i.e., not all decision variables can be controlled or continuously adjusted in typical full-scale plants. On the other hand, the development of successful and robust control strategies can present an incentive to invest in advanced instrumentation.

The precondition for feedback control is a reliable and robust monitoring of fouling itself (physical indicators) or of components which have a clear correlation with fouling (chemical indicators). In addition, indicators must be suited for or adapted to in-, on-, or at-line measurement and able to generate data at a higher frequency than that at which changes in fouling propensity occur. Good monitoring should then enable the selection of the most appropriate measure including numerical values for decision variables (operating parameters and application durations).

Since TMP and flux are typically measured continuously in a full-scale plant, it might appear obvious to use this information to assess the current fouling status. However, plant data cannot distinguish between fouling and clogging or between a currently badly fouling sludge and a membrane that is approaching the *TMP jump*. In other words, from a simple increase in TMP it is not possible to decide on the most appropriate measure, be it, e.g., increased aeration, prolonged backflushing, or initiation of a chemical cleaning.

Instead, in situ filtration devices can be used to determine mixed liquor fouling propensity. The applicability of the MBR-VFM [87] with its automated protocol consisting of alternating filtration and physical cleaning steps was already shown in a pilot MBR. The device detected upcoming membrane fouling approx. 2 d prior to the actual fouling event happening and thus seems to be well-suited for monitoring. The Berlin Filtration Method (BFM), a small immersed flatsheet configuration, was devised by de la Torre et al. [88]. It has also its own air-sparging at the bottom of the frame which houses a single BioCel® membrane plate (Microdyn-Nadir GmbH).

A further differentiation and an improved selection of the most appropriate measure would be possible if the exact location of fouling was known. The different possible locations of fouling necessitate different antifouling measures, e.g., a deposition inside the pores cannot be removed by increased shear (air scour) at the surfaces. Currently, no in situ observation technique is available and a simple feedback control based on permeability data cannot distinguish between locations. Instead, a model-based recognition of the underlying mechanism can provide the required information and would enable selecting the right measure, i.e., in this case backflush.

Some mechanistic cake filtration or pore blocking models which describe filtration and fouling mechanisms exist, but have not yet been fully exploited for process control. An automated model recognition for fouling control based on the above-mentioned mechanistic models was developed by Drews et al. [75]. The model discrimination automatically recognizes the nature of the currently prevailing mechanism as well as the times when new mechanisms begin to dominate or when model parameters change quantitatively.

Based on the assumption that SMP can be correlated with fouling at least under certain circumstances, a sequential injection analysis (SIA) technique was developed by Mehrez et al. [89]. It is based on automated versions of the Lowry and Dubois assays and can be used as an at-line sensor to monitor SMP concentration.

3.3.4 Addition of Flux Enhancers

Since Yoon et al. [61] presented the effects of adding a cationic polymer to the MBR mixed liquor to improve filterability, the interest in flux or "membrane performance enhancers" has greatly increased. Although a wide range of lab- and full-scale studies on different additives in MBR is available in the literature (e.g., [61, 90]), these often investigate only one or two additives or focus only on their effect on filtration behavior. Therefore, a comprehensive and impartial study including long-term pilot trials and investigations of the effects on the biology has been carried out [62, 91] to evaluate a broad range of chemicals. The removal of different organic fractions from sludge supernatant and the impact on filtration performance was investigated for two cationic polymers (flocculants), two powdered activated carbons (PACs), and a starch. It was found that the PACs remove the whole range of molecular weight compounds, while the polymers and the starch eliminated mainly larger molecules (biopolymers). Good SMP removal was achieved by both flocculants and PACs. The two polymers and the starch were studied over several months in a pilot MBR plant. They had no negative impact on the biological performance in terms of COD- and N-elimination. While both polymers increased the particle size by 17–19 % and showed a positive effect on membrane performance (see Fig. 7), the starch led to accelerated fouling and only slightly increased floc sizes (+6.5 %). The monitoring of mixed liquor characteristics (SMP, EPS, CST, biopolymer concentration, and particle size) in the pilot plant has not shown the strong improvements that were expected from short-term jar tests. This might be due to the varying conditions in the pilot plant, certain waste water compounds, and additional shear stress. It underlines the importance to evaluate flux enhancers under real operation conditions at larger scale and over longer periods.

3.3.5 Quorum Sensing

Quorum sensing is a means of bacterial communication by signal molecules (autoinducers) such as N-acyl homoserin lactone (AHL) which among others initiates biofilm formation. Yeon et al. [92] demonstrated the evidence of quorum sensing activity in MBR and could correlate quorum sensing with membrane fouling. On these grounds the authors proposed the addition of acylase which can inactivate AHL as a novel fouling control strategy. The group has overcome the technological limitations of using free enzymes by applying magnetic enzyme carriers [93]. These can be readily retained by the

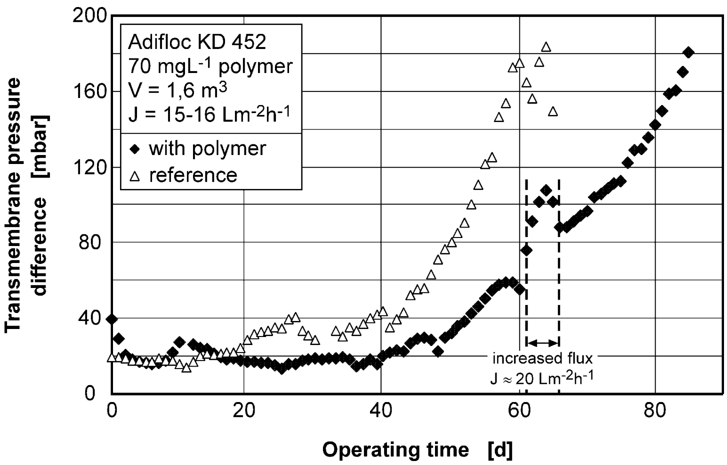

Figure 7. TMP evolution in reference plant and polymer (KD 452) added plant [62].

membrane and recovered by magnetic capture, and show a high stability which led to a significant delay in fouling.

4 Summary and Conclusions

Membrane bioreactors are not a niche process anymore and will continue to grow over the next years. The increased number and capacity of plants shows that the municipal market is still growing and is not yet saturated. Hybrid configurations may lead to even further effluent quality improvements. Future advances in fouling mitigation can be expected from further fundamental research (e.g., biocake architecture, advanced analyses of individual components, two-phase fluid dynamics, and role of specific microorganisms) but also from the development of control strategies which might well also include the manipulation of microbial populations.

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