


MBR technology: future research directions

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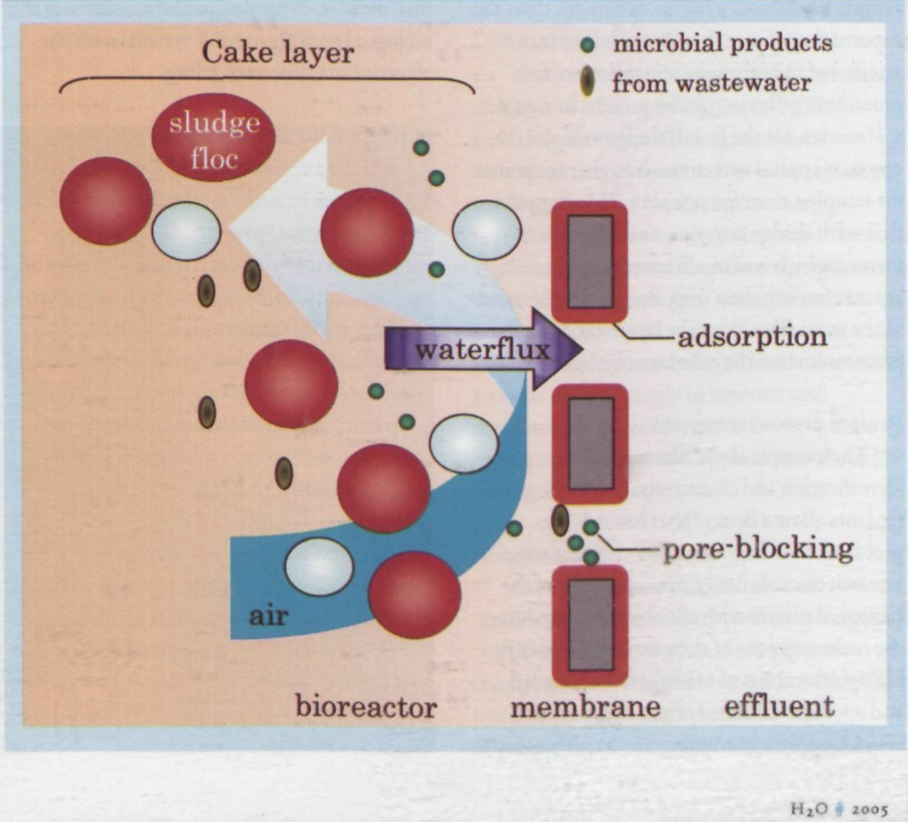
The last decade R&D on MBR technology has shown a rapid development. In spite of its advantages compared to conventional treatment systems, MBR does not yet provide a competitive alternative. The smaller required footprint and the excellent water quality are partially counteracted by high costs for membrane filtration and inefficient oxygen transfer. Reduction of costs will be the main driver for R&D on MBR technology the next years. R&D should be directed into three areas: fouling, filtration and aeration. Long-term research should focus on the improvement of the sustainability of MBR technology by exploring new concepts of wastewater treatment. Examples worthwhile to be explored are decentralised treatment of wastewater offering possibilities to treat separate streams of grey and black water to enable water reuse; anaerobic water treatment to minimize emission of greenhouse gasses and to decrease energy requirements and sludge production and to use MBR in combination with electricity production in a fuel cell to produce electricity and treat wastewater simultaneously.

Despite tremendous research efforts towards development of new MBR technology, a worldwide technological breakthrough, especially towards domestic wastewater treatment is lacking. The most important reason is the high costs of MBR technology in comparison with conventional wastewater treatment concepts. Cost reduction will be the main driver for research and development on MBR technology in the coming years. Short term research should focus on identification, characterisation and behaviour of foulants. The mechanisms of fouling should be studied. This will yield knowledge for required membrane operation, membrane properties to be chosen and new module design & operations that finally will result in reduction of costs and energy. New methods to improve the aeration efficiency at high sludge concentrations should be developed and attention is required for the effluent quality. Long term research should focus on much more sustainable MBR concepts. New MBR concepts to treat different wastewaters (e.g. grey and black) or to treat wastewater anaerobically should be explored. MBR technology offers opportunities to produce energy out of waste (membrane fuel cells) and to minimize emission of greenhouse gasses. Cutting down the operational costs of MBR technology will be the key driver for research. This article outlines some research areas and specific topics that potentially will contribute to lower costs. Special attention to these topics should be given the coming years. Long term research should focus on sustainable MBR concepts. A few innovative developments will be presented.

Figure 1: *Membrane fouling in MBR.*



Research drivers and topics

For a real worldwide breakthrough of MBR technology in domestic water treatment a significant cost reduction is necessary. The present generation membranes show very low permeabilities due to a high degree of fouling. Besides, operation of membranes is energy demanding and, although prices are decreasing, membranes are still relatively expensive. In addition, one of the advantages of MBR, i.e. a high sludge concentration is counteracted by inefficient aeration at high sludge concentrations. To reduce the operational costs of MBR technology research should be directed into three areas: fouling, filtration and aeration. Within these areas several research topics can be defined.

Fouling

When research regarding membrane fouling in MBRs is critically reviewed the conclusion must be that the main questions still are not answered. Even today it is unclear which group of compounds dominates the fouling process, whether these compounds have their origin in the wastewater or are produced by the biology, and what the most important fouling mechanisms are (figure 1).

Origin fouling

Without supporting scientific evidence the literature mentions dominant foulants varying in size or molecular weight (flocs, colloidal matter en solubles) and in chemical nature (extracellular polymers such as proteins, polysaccharides and humic compounds and inorganic precipitants). The origin of the foulants still is subject to debate although for domestic wastewater it seems that biological material such as colloidal matter produced by shear and (soluble) metabolites or lysis products are more important than wastewater constituents. In a way this is an advantage as this implies a generic character of fouling which also may allow for a generic solution.

Fouling mechanisms

The mechanism of membrane fouling in MBRs is extremely complex. Formation of a cake or gellayer, pore blocking, adsorption on the membrane surface or in the membrane pores could all be important. Equally important could be the interaction between these mechanisms. For instance, a (dynamic) cakelayer provides an additional resistance against filtration, but at the same time may protect the membrane against (irreversible) fouling. Figure 2 and table 1 provide an example of such behaviour.

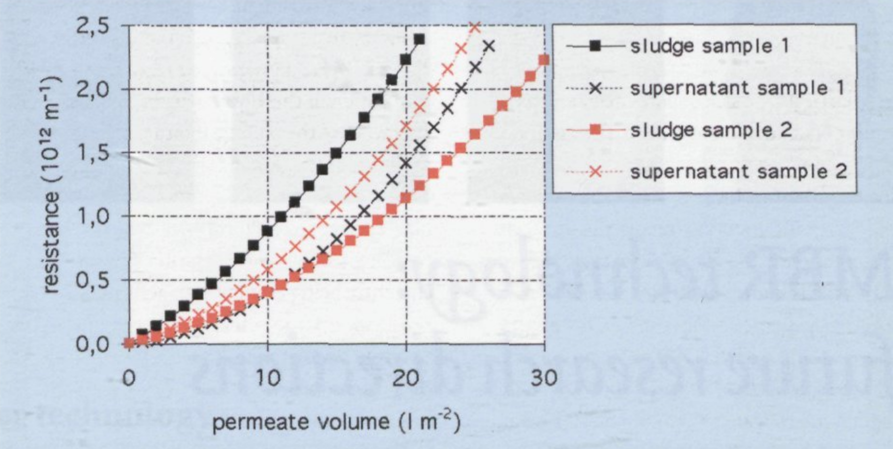


Figure 2: *Filtration resistance as function of filtered permeate volume.*

Table 1: *Composition sludge samples 1 and 2.*

	sample 1 bound mg.gVSS^{-1}	free mg.l^{-1}	sample 2 bound mg.gVSS^{-1}	free mg.l^{-1}
polysaccharides	64	118	49	170
proteins	53	17	40	62

Two sludge samples were taken from the membrane tank in the same MBR, operated at different conditions. The sludge samples and the supernatant of these samples were filtered in a specifically designed set-up and the resistance against filtration was monitored as a function of the permeate volume during cross-flow filtration (Figure 2). In addition, free and sludge bound proteins and polysaccharides were determined (Table 1). The supernatant of sample 2 exhibited a higher resistance than the supernatant of sample 1. Possibly, this can be attributed to higher concentrations of free proteins or polysaccharides present in sample 2. However, for the (total) sludge samples the opposite applies with a much higher resistance for sample 1 than for sample 2. This suggests that with sludge sample 2 a cake layer was formed which was much more protective against fouling than with sludge sample 1 and at the same time this cake layer was more permeable than the cake layer with sample 1.

Foulant process interaction

The example above illustrates that identification and characterisation of the main foulants allow a better focus towards the problem of fouling. First of all this concerns research towards design and operation of the biological reactor with the objective to reduce the concentrations of these foulants. Today the biological reactors of MBRs are not designed and operated differently from conventional systems applying secondary settlers. This seems odd as the microbial population in MBRs can be expected to be different from conventional systems and much higher sludge concentrations are maintained. Shear, water hardness, sludge and hydraulic retention time, the substrate gradient, the COD/P/N ratio of the wastewater and the redox regime all are expected to be important factors determining the concentration of foulants. Knowledge about the behaviour of these foulants in response to such factors is extremely important to allow modification of the design and operation of the biological reactors in MBR systems with the objective to minimize fouling.

In situ foulant monitoring

A second approach is to study membrane fouling more in detail, preferably using in situ and direct monitoring techniques. It is appreciated that this is extremely difficult but may become feasible once more information is available about the dominant foulants. This approach should lead to better membrane operation, not only during stable conditions, but particularly in response to varying conditions such as rain weather incidents which are known causes of severe fouling problems.

Also, this will result in a more fundamental basis for the selection of the appropriate membrane properties such as pore size, membrane material, etc., and for the development and design of new membrane modules which nowadays more or less is based on a trial-and-error approach.

Filtration

Foulants will undoubtedly have their impact on the permeability of the membranes. Other parameters that affect the permeability are the trans-membrane-pressure (TMP), shear rate, temperature and sludge composition. Especially membrane properties and membrane material are crucial elements that influence the membrane permeability.

Enhanced hydrodynamics

Current developments in membrane operation are aimed at reducing membrane fouling by selecting the proper hydrodynamic conditions. Generally this is done by creating turbulent flow conditions near the membrane surface. The shear flow rate along the boundary layer of the membrane strongly affects the membrane flux. A standard method to promote shear nowadays is to dose air bubbles. Although air bubbles enhance the membrane flux, they also have their impact on the particle size distribution and floc structure. Moreover, enforced aeration demands energy. Research should be directed to optimisation of the current coarse aeration methods for submerged membrane modules. Secondly, alternative filtration concepts to promote shear locally near the membrane surface, e.g. by mechanical means, should be developed.

Improved membrane properties

The past few decades the main areas of attention for membrane development were membrane morphology, hydrophobicity or hydrophilicity and charge. In time fouling leads to changes in porosity and pore size distribution. The size of pores decreases as a result of pore narrowing due to internal adsorption. The number of small pores also decreases due to clogging. Therefore flux and selectivity are changing during the filtration process and during the lifetime of membranes. Very little is known about the interaction between foulants and membrane properties. Understanding of the relation between foulants and membrane properties will be a challenging research item the coming years.

Aeration

Conventional activated sludge processes have an insufficient aeration performance. Less then 10-15% of the oxygen supplied is transferred to the water phase using fine bubble diffusers[1]. Hence, the electricity needed for aeration provides more than 50% of the total energy costs of municipal water treatment. In MBR systems the oxygen transfer is even less efficient due to the high concentrations of solids and therefore the energy requirements even will be higher. This stresses the need for a better understanding of the potential causes and measures to be taken to improve the poor aeration efficiency in MBR systems.

Understanding nature and impact on α-factor

MBR has many advantages over conventional treatment. One of them is the ability to apply high concentrations of activated sludge, over 10 g/l and higher. However, high levels of biomass will decrease the efficiency of oxygen transfer. The research in Beverwijk has shown there is a correlation between high viscosity and low aeration efficiency. The contribution of EPS towards lower oxygen transfer efficiencies was less obvious. More knowledge is required to allow translation of these observations to a better operation of the biology in order to improve the aeration efficiency.

New efficient oxygen transfer devices

The most efficient aeration devices currently being employed in activated sludge processes are fine pore aeration systems, either using ceramic or membrane rubber materials. Membrane diffuser technology offers the highest oxygen transfer efficiencies compared to other type of aeration systems like coarse bubble diffusers, surface aerators, brush aerators, jet aeration and venturi aeration systems.

However, the oxygen transfer efficiency at high solids concentration not only depends on the type of aeration but also on sludge characteristics. Especially mechanical stress enforced by shear could promote the oxygen transfer efficiency. On the other hand mechanical stress will change the sludge structure and will require energy. More research is needed, preferably on full scale, to explore the possibilities and limitations of new and existing aeration systems.

Enhanced oxygen transfer new configured flat sheet-frame modules

The depths of conventional activated sludge processes are usually in range of 3 to 4 meter. In case of diffused air aeration, consequently, there is a limited time for oxygen transfer from gas to liquid phase. Transfer of oxygen can be improved by new designs of flat sheet and frame modules. The idea is to increase the retention time of the air bubbles. Potential energy savings for aeration could be in the range 10-30%.

Enhanced oxygen transfer by new reactor designs

An example of a new reactor design that could promote the oxygen transfer efficiency spectacularly is the deep-shaft MBR, which could be a unique modification of the conventional MBR with even smaller footprints and oxygen transfer rates that are significantly higher. The main objective of this system is to increase the efficiency of oxygen transfer. The deep-shaft configuration increases the partial pressure of oxygen, thereby causing a high saturation concentration in the reactor. The deep-shaft technology has been successfully applied for high strength polluted wastewaters. More then 80 full-scale references are known. Possibilities for domestic water treatment could be explored.

New innovative future MBR treatment concepts

The present generation of MBR systems is far from sustainable. The treatment process is energy demanding, produces an immense amount of waste sludge, nutrients are destroyed, greenhouse gasses are produced and potential energy sources are wasted. More sustainable solutions are needed in order to recycle the water in dry areas, in order to recover nutrients like phosphates and nitrogen, and in order to produce or minimize the energy use to prevent production of greenhouse gasses. For future sustainable water treatment new concept approaches are necessary.

Decentralised sanitation

Newly developed decentralised sanitation concepts[2),3)] offers possibilities for MBR technology. Within the decentralised sanitation concept wastewater is treated close to a household with a strong focus on sustainable use of resources. Generally three wastewater streams with different origin are collected and treated: grey water (shower, kitchen), yellow water (urine) and brown water (toilet water without urine). These wastewater streams differ strongly in amount and composition. Especially towards water reuse opportunities new MBR applications should be developed.

Anaerobic MBR

Generally anaerobic treatment of wastewater has two main benefits: low energy requirements (no aeration, formation of biogas) and low sludge production. Both features are very attractive for the development of anaerobic MBR concepts for

Direct production of electricity out of wastewater using microbial fuel cells (TNO).

domestic water treatment. The role of fouling will be crucial, even more then with aerobic MBR systems. Anaerobic conditions promote the formation of struvite, an insoluble salt built up from magnesium, ammonium and phosphate. Especially near the membrane surface where concentration polarisation (accumulation of compounds) occurs, the danger of struvite being precipitated on the membrane is high[4]). Another point of interest is the way the membrane configuration is chosen. Due to the absence of air, submerged modules, attractive from an energy point of view, are less appropriate. Most anaerobic MBR concepts use hollow fiber cross flow configurations that are energy demanding. New alternative filtration / operation modules should be developed: e.g. recirculation of biogas to enhance shear locally on the membrane surface[5]).

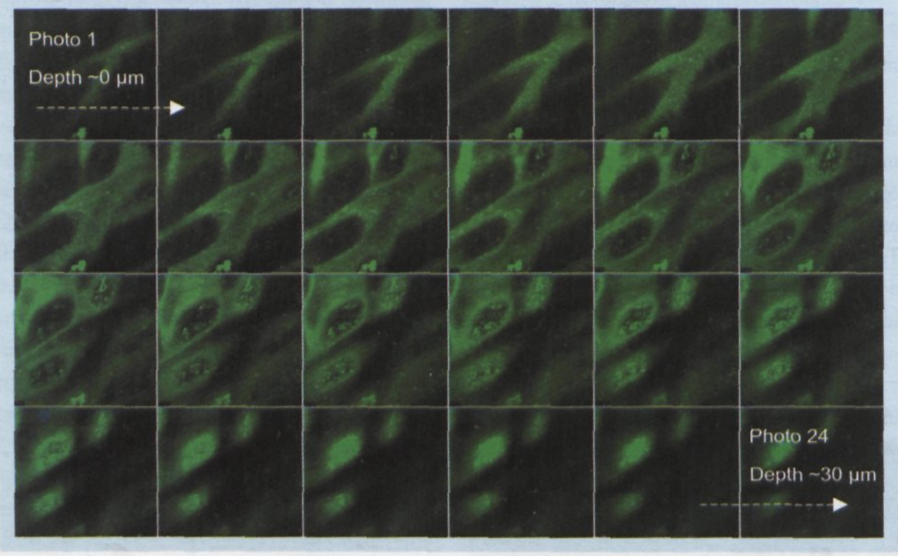
Microbial Fuel Cell

The present generation water treatment systems are wasting potential energy sources. Theoretically the combination of MBR with the microbial fuel cell principle could be used to produce electricity directly from wastewater[6]), while at the same time accomplish water treatment[7]). This new approach could lead to significant reduction of operation costs, but also creates opportunities to produce products with market value. Proof of principle is demonstrated. The next step to be taken is to study the technological and economic feasibility of the process[8]). Wetsus as well as TNO are working on the production of energy from wastewater in bio-fuel cells, which is one of their main research themes.

Conclusions

In spite of its advantages compared to conventional treatment systems, MBR does not yet provide a competitive alternative. The smaller required footprint and the excellent water quality are partially counteracted by high costs for membrane filtration and inefficient oxygen transfer. Therefore the coming years MBR research should be directed towards minimization of costs for filtration and aeration. Further it would be worthwhile to improve the sustainability of MBR technology by exploring new concepts of wastewater treatment. Examples are decentralised treatment of wastewater offering possibilities to treat separate streams of grey and black water; anaerobic water treatment with low energy requirements and low sludge production and direct energy production by combining MBR with microbial fuel cell technology. ¶

3D-analysis of flat sheet and frame membrane with Confocal laser scanning microscopy. Microbes (DNA) are visible as green.



Samenvatting

De laatste decennia is wereldwijd veel onderzoek verricht naar de MBR-technologie. Desondanks ontbreekt vooralsnog een technologische doorbraak voor zuivering van communaal afvalwater. De kosten van de MBR-technologie blijven hoger dan voor de conventionele zuiveringstechnieken. Kostenvermindering zal de komende jaren dan ook de belangrijkste stimulans zijn voor verder onderzoek en ontwikkeling van MBR-technologie voor communale waterzuivering. De aandacht zal zich moeten richten op drie gebieden: vervuiling, filtratie en beluchting. Naast onderzoek gericht op kostenreductie is ontwikkeling van innovatieve, meer duurzame MBR-concepten gewenst. Voorbeelden hiervan zijn decentrale zuivering om te komen tot gedeeltelijk hergebruik van water en wellicht nutriënten, anaërobe zuivering van afvalwater en het toepassen van MBR-technologie in combinatie met de productie van elektriciteit in een brandstofcel. De potentiële voordelen legitimeren een verdere verkenning van deze innovatieve MBR-concepten.

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