Review on the state of science on membrane bioreactors for municipal wastewater treatment

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ABSTRACT

Over the past two decades the field of application for membrane bioreactors has broadened towards the municipal wastewater treatment sector. The Global Water Research Coalition (GWRC) determined MBR technology to be of priority for collaborative research and decided to conduct a project with the aim to determine the current state of the science in the field of MBR for municipal wastewater treatment and to develop a phased research strategy represented by priority research projects, like a State of the Science report with regard to MBR technology. This paper describes the state of the science with regard to MBR technology for municipal wastewater treatment by 2007, derived by literature review on recent publications, database analysis and international questionnaires.

The research efforts from the past seven years can be characterised by the following prioritised list: (1) membrane fouling, (2) effluent quality, (3) energy consumption (aeration) and (4) cost considerations. The research needs for the near future as identified with the questionnaire are comparable to the main topics of research as identified in the literature review:

- membrane fouling is still the main problem requiring thorough attention from scientists;
- effluent quality is a main driver for the application of the technology. There remain some important questions however, with regard to the removal of EDC and micro pollutants.

Much of the research activities on MBR are repeated more than once by research groups worldwide. This is only partially caused by a lack of knowledge exchange between researchers. However, lacking information exchange between Europe and the USA on MBR research is identified as a potential bottleneck. Another point of attention is the fast that research results can not easily be translated to other (more practical) situations, since much of the research is carried out at pilot scale.

Key words | data analysis, literature review, MBR, overview, research, state of science, wastewater treatment

INTRODUCTION

The membrane bioreactor (MBR) technology for wastewater treatment is gaining significant attention from both scientists and practitioners from universities, water boards, industry and even politicians. The expected superior effluent quality and the small footprint make the MBR technique a promising option for future wastewater treatment systems. In Europe some 40 MBRs are in operation for municipal wastewater treatment and new installations are being designed and commissioned. The scientific interest can easily be estimated by the more than 800 scientific articles on MBR for wastewater treatment that have been published during the past ten years (from a 2007 search on the Scirus search engine, www.scirus.com).
In industry, MBR is being applied for many waste streams and has reached the status of proven technology. For municipal wastewater however, the situation is different. Especially in those cases where rainwater has to be treated, MBR operation can be difficult, the more so because large buffering tanks or large membrane surfaces make the application of MBR difficult and more expensive. However, the development of MBR-technology has made major steps in the past ten years. As a result of this, the field of application has broadened towards the municipal wastewater treatment sector. To date, about 80 large full-scale installations for the treatment of municipal wastewater are in operation or under construction world-wide (Judd 2006).

In conjunction with this development there has been a lot of research activity in the field of MBR technology. The Board of Directors of the Global Water Research Coalition (GWRC) determined this technology to be of priority for collaborative research and decided to conduct a project with the aim to:

- determine the current state of the science in the field of MBR for municipal wastewater treatment;
- develop a phased research strategy represented by priority research projects (GWRC 2005).

STOWA, the Dutch organisation co-ordinating the research activities on behalf of the Dutch Water Authorities and GWRC member, was assigned with the lead of the project to prepare a State of the Science report with regard to MBR technology. This paper describes the state of the science with regard to membrane bioreactor technology for application in municipal wastewater treatment by 2007, derived by a literature review on recent publications, a database analysis and an international questionnaire, as it was conducted by Witteveen + Bos Consulting Engineers, Deventer, The Netherlands.

METHODS

Literature review

The literature review on MBR was conducted with regard to municipal wastewater treatment starting from the year 2000. For this purpose English, German, French and Dutch publications were searched for and screened on keywords and content. Since the amount of publications on MBR is quite extended a step-wise approach was applied. Per identified important field of research regarding MBR the present status of research is summarised. Within these summaries, an overview of actual research conclusions, research questions and recommendations are presented.

Database analysis

Several search engines available on the World Wide Web were used to obtain an indication of the developments in MBR research over the past five years. Based on Internet search for the selected search terms an MBR-specific database was created. By analysing this database on specific keywords (e.g. flux, TMP, filterability, fouling, cleaning, operation, energy, cost), related to publication date, trends in specific research fields were identified. An overview over these trends represents the importance and actuality of a certain research subject. The large amount of scientific and commercial information on MBR was approached in five different ways, subdivided in two categories:

- database analysis:
- a general information search via Google;
- a scientific information search via Google Scholar and Scirus;
- a scientific information search via the multidatabase search engine WebSPIRS;
- analysis of a database containing some 150 articles on MBR from the period 2000–2007;
- evaluation of review articles on MBR from 2000 to 2007.

Expert judgement

A questionnaire was prepared asking the GWRC members about their views, ideas and research projects on MBR. Input has been given by representatives of STOWA, Urban Water Cycle, KIWA Water Research (the Netherlands), Berlin Centre of Competence for Water (Germany), Water Environment Research Foundation (USA), Co-operation Research Centre for Water Quality and Treatment (Australia), Thames Water Utilities Ltd (UK), Water Research Commission (South Africa).
RESULTS AND DISCUSSION

General

MBR is a hot item, reflected by the large amount of information available on the World Wide Web. More than 48,000 websites contain information on this technology. Refining the search to scientific content decimates the amount of hits, to a few thousands. Further excluding other results than scientific papers leads to about 280 papers for the period 2000–2007 (see Figure 1a). A further selection with respect to the topics relevant for this research results in 153 papers that were screened and evaluated by means of a database.

Review papers

The database with scientific papers also contains eleven review papers. These papers are summarised in this chapter to obtain a summary of the state of the science with regard to MBR. These papers discuss the MBR according to different topics, almost the same as used for the database analyses. The same order is used for the set up of this paper.

Research approach

For MBR research many approaches are being applied. Much research is carried out on the treatment of real municipal wastewater, on pilot and full scale (see Figure 1b). This applied research is concerned with feasibility questions, like: (1) are treatment performances sufficient in terms of total solids, bacteria, viruses and nutrients, (2) are operational costs within certain boundaries, (3) what is the achievable flux, (4) which cleaning strategy should be applied, etc.? In most cases, this approach has a broad scope.

Another type of research is more fundamental and focuses on one or a few aspects of the total process. Within this group of research approaches, research into fouling and fouling phenomena is predominant. Fouling research on its own, can be subdivided in several classes. Some researches aim at controlling and avoiding fouling, others try to connect fouling with operational situations and to discover the mechanisms that cause fouling.

Pilot plant experiences and trial and error have led to improvements in design and operation by the two leading MBR suppliers resulting in lower overall costs. Fundamental research conducted by academic institutions has tended to be limited to model feed waters and small scales, and the obtained knowledge is rarely transferable to full scale plants (Judd 2006).

Research topics

The results from the search engines as well as the database analysis reveal comparable trends with respect to important research topics (see Figure 2). Most important topic of research is the hydraulic functioning of the MBR (flux) in...
relationship with membrane fouling and its causes form the core of the scientific literature on MBR. Almost every paper contains a section describing the hydraulic performance and aims at optimising it. The second important research topic is the achievable effluent quality. Many researchers try to optimise the biological process to remove as much pollutants as possible. Oxygen transfer has received a lot of attention at the end of the nineties, but the number of papers investigating this topic has been decreasing over the past three years. Membrane aeration is closely related to this topic, since firstly it was assumed that the aeration needed to scour the membrane would reduce the overall aeration needs. Interestingly cost considerations are not regarded as important as would be expected. Although cost is often mentioned as one of the disadvantages of MBR, it is not really a research topic. Of course, many researchers draw the conclusion that to minimise operating and investment cost of MBR, hydraulic performance must be optimised. In this way cost are implicitly taken into account in many studies.

Membrane fouling

Studies into the hydraulic optimisation of an MBR system are primarily concerned with avoiding or controlling fouling. Fouling is assumed to be caused by the accumulation of dissolved and suspended matter, such as EPS, SMP, on the surface of or within the membrane. There have been several approaches to cope with fouling in MBR. In literature, these approaches are divided in two groups:

1. Optimisation of the existing process via operational measures. In the past ten years several guidelines and ideas on operation philosophy emerged, resulting mainly from pilot scale experiences. There is a general trend from controlling fouling towards avoiding fouling. Therefore several steps were made to optimise cleaning strategies. Here, there is a trend towards avoid-fouling policy. This is done by periodical so-called maintenance cleanings with relatively low concentrated cleaning solution, if possible ‘on air’. Depending on the type of wastewater to be treated and applied membranes different cleaning agents can be used.

2. Fundamental research on fouling mechanisms, fouling substances and their origin. The two most important fouling mechanisms in MBR are cake layer formation and adsorption to the membrane. Cake layer formation can usually be controlled by a continuous coarse bubble aeration. Adsorption is regarded a function of the total produced volume, and can be addressed by a chemical cleaning, if needed (Wintgens et al. 2003).

Inorganic fouling in aerobic treatment can occur in the form of calcium carbonate scaling which was observed in flat plate and hollow fibre MBRs. Control is difficult, mostly by ex situ cleaning or elimination of the source of the problem.

Organic fouling is studied more extensively. The high solids concentration, coupled with varying levels of colloidal and dissolved extra-cellular polymeric substances (EPS) are widely assumed as being key foulants in MBR processes. Starting from the rather vague parameter EPS, a step forward was made by pinpointing polysaccharides as being involved in membrane fouling, (Evenblij 2006; Judd 2006).

To date the relation between biological parameters and membrane performance can not be quantified, only some qualitative indications are presented. This subject is in almost all review articles identified as one of the most important research topics. Results from lab scale experiments, confirmed by pilot plant trials, indicate the importance of microbiological aspects in relation to hydraulic performance, i.e. membrane fouling. Although conclusive results are quite scarce there is strong evidence to support the statement that fouling is directly related to the state of the biomass, provided that the other boundary
conditions are optimal in terms of equipment, shear rate, etc. (Chang et al. 2002; De Wilde et al. 2003). Recent studies discovered the relation between sludge age and fouling rate; a higher sludge age leads to a lower fouling rate, shifting from 8 to more than 25 days resulted in considerably less fouling.

### Effluent quality

The most frequent research question in the screened articles focused on the treatability of a wastewater. For many cases a pilot or lab scale study is set up, with the aim to identify the removal efficiency of parameters like COD, BOD and nutrients. These parameters are monitored in almost all studies as reference or background information.

Nutrient removal is no specific MBR matter, but related to the applied bioreactor configuration (as proposed in different kinds of biological nutrient removing concepts). The fact that the membranes keep all biomass in the system was thought to favour the growth of otherwise absent species. Although this was proved to be the case (Witzig et al. 2002), the biological conversions are not shown to be different from conventional systems. The higher effluent quality can be contributed to the absence of suspended solids.

Because of the pore size of the membrane, the MBR has rather good disinfecting capacities. Specific measurements show log-removals of total coliforms of more than 6.6. So for hygienic reasons, MBR could be applied as a suitable (post) treatment in case of recreational activities in or with the receiving water body.

Recently, treatment techniques to remove endocrine disrupting compounds (EDC) (e.g. STOWA28 2004), organic and inorganic micro pollutants (Mansell et al. 2004), have obtained a lot of attention. Many experiments were carried out, in different set-ups. From the many results that were obtained, the conclusion can be drawn that MBR does not remove these substances to the desired levels. For some substances the removal capacity is higher compared to conventional activated sludge systems, others do not show a difference at all (Joss 2004; STOWA28 2004). This seems to be related to the form in which these substances occur, either bound to colloids, the biomass or particles, or dissolved in the water phase.

The main conclusion is that what a conventional activated sludge system can do, is also possible with an MBR, with a slightly higher and definitely more stable effluent quality. The major driving force for application of the MBR technique is the disinfected effluent.

### Sludge production and handling

Due to the presence of the membrane, all activated sludge can be kept in the system, as long as the membrane can handle the MLSS concentration properly. Apart from possible problems with filtration, also aeration may cause problems at high MLSS concentration. For application in municipal wastewater treatment MLSS concentrations between 10 and 15 g/L seem practical, with respect to sludge production and excess sludge discharge. Recent developments in the USA show a trend towards lower MLSS concentration (<10 g/L) while the plant sizes are increasing (>40,000 m³/day) (Daigger et al. 2004).

The amount of excess secondary sludge produced by an MBR is somewhat lower than or equal to conventional systems. When long SRTs are applied, sludge production of course decreases (Wagner & Rosenwinkel 2000). The primary sludge production is higher, because of the higher degree of pre-treatment. Sludge treatment is almost the same compared to conventional activated sludge systems.

The dewaterability of waste activated sludge from MBR seems to be no problem, compared to aerobic stabilised waste sludge from conventional activated sludge systems (Kraume & Bracklow 2005).

The problem of waste sludge treatment in Europe is essentially different from the situation in the USA, where waste sludge has to be treated with the aim of reusing it. Within Europe the approach to sludge treatment is different per country. Some countries reuse the sludge in agriculture as fertiliser; in other countries sludge is dewatered and ultimately incinerated.

### Aeration and oxygen transfer

Aeration efficiency and the required energy input for this seems to be the limiting factor for the maximum MLSS concentration of around 15 g/L. Higher MLSS concentration will increase too much the amount of energy for oxygen transfer (Cornel et al. 2003), as well as increase the
risk of sludging or foaming of membrane modules and aerators. Measured \( \alpha \)-values in full-scale installations show \( \alpha \)-values of 0.6 at 12 g MLSS/L.

Apart from these considerations, there may be a lack of space to place all the required aeration equipment when MLSS is increased too much. This problem becomes more urgent when space reduction is required and deep tanks are necessary.

**Cost considerations**

Without taking the differences in effluent quality and possible reuse options under consideration, generally MBR is regarded as being slightly more expensive than conventional activated sludge treatment. Both investment and operating cost are higher (by 2007). The amount of energy that is consumed per unit volume of produced permeate is in the range of 0.5 – 2.5 kWh/m³, which can be up to twice the demand of conventional activated sludge systems.

Of course MBR has to be compared with a system that can produce the same effluent quality, which is not just an activated sludge process. At this point the calculations may differ, depending on the process to which MBR is compared (Adham et al. 2001).

**Membranes**

Several membrane types can be applied in MBR, which can be divided in side-stream systems and external systems. Most commonly applied in municipal wastewater MBRs are the submerged membranes. To date two types of submerged modules are available on the market for MBR applications: flat sheet membranes and hollow fibre membranes. An analysis of the current applications for municipal wastewater treatment shows that the flat sheet system is competitive for smaller units (below 20,000 p.e.) whereas larger plants are favourably equipped with the hollow fibre system (Lesjean et al. 2004). The choice of membrane material for activated sludge filtration is in practice limited to organic membranes, like hydrophilised polyvinylidene fluoride (PVDF) or chlorinated polyethylene. Organic membranes are still less expensive than ceramic membranes, and have the advantage that they can be operated submerged, i.e. with air scouring and low suction pressure. Ceramic membranes are commonly tubular which still requires more energy for recirculation. Tubular organic membranes are up until now only applied in industrial MBRs but with recent process developments will become competitive with submerged systems.

**Expert judgement**

The results of the questionnaire confirm the results from the database analyses about current research activities: **membrane fouling** and **effluent quality** are the most important issues at this time. For the future no big change is expected: fouling control and improving the effluent...
quality are expected to be topics requiring the most attention. Although higher cost is a major impediment for further application, cost minimisation as such is not mentioned as one of the future research items. Here again, it is supposed that it is implicitly accounted for by hydraulic optimisation.

When fouling prevention and flux optimisation are combined, the third important point of research becomes: sludge handling. There are several aspects that need further research in this field. Because of the absolute barrier formed by the membrane, a fraction of small particles is retained in the system that would be washed out with a conventional activated sludge system. This fraction can only exit the system together with the discharge of excess sludge. It is supposed that this fraction interferes with the further treatment of the excess sludge. Furthermore, the sludge is likely to contain a higher content of priority substances that need further treatment.

CONCLUSIONS

Much of the research activities on MBR are repeated more than once by research groups world-wide. This is only partially caused by a lack of knowledge exchange between researchers. However, lacking information exchange between Europe and the USA on MBR research is identified as a potential bottleneck. Another point of attention is the fast that research results can not easily be translated to other (more practical) situations, since much of the research is carried out at pilot scale. The research efforts from the past seven years can be characterised by the following prioritised list of research topics:

1. membrane fouling;
2. effluent quality;
3. energy consumption (aeration);
4. cost considerations.

The research needs for the near future as identified with the questionnaire are comparable to the main topics of research as identified in the literature review:

- membrane fouling is still the main problem requiring thorough attention from scientists;
- effluent quality is a main driver for the application of the technology. There remain some important questions however, with regard to the removal of EDC, micro pollutants, etc.

Most of these revealed knowledge gaps are incorporated within the work packages and the research deliverables within the European Union Research Programmes on MBR, EUROMBRA, MBR-Train and AMEDEUS united in the MBR-network (see Figure 3, www.mbr-network.eu). Finally, there is an expectation that with the ongoing research and design activities and developments in the market and new discharge legislation, new applications of innovative MBR concepts will emerge.

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