

Membrane bioreactors hit the big time - ten years of research in The Netherlands

DR.IR. RENZE VAN HOUTEN, TNO ENVIRONMENT, ENERGY AND PROCESS INNOVATION
IR. HERMAN EVENBLIJ, TU DELFT, FACULTY OF CIVIL ENGINEERING AND GEO SCIENCES
DRS. MICHA KEIJMEL, BRCC-MILIEUGROEP

Membrane bioreactor technology has been subject to keen interest, rapid development and extensive penetration of the European market in the last ten years. From a research point of view, the last couple of years systems selection and application established. Long term operational limits, such as membrane fouling and cleaning, became more and more important. Membrane fouling and cleaning strategies reflect the properties of both membranes and the biology involved. So, it needs a comprehensive perception of all aspects involved in the operation of membrane bioreactors. Membrane fouling and cleaning cannot be overcome by application of some wonder-chemical but by a better understanding of the entire process and by interfering in the most effective way and on a scientific bases. This article shows that all those aspects are studied in detail at Dutch universities and research institutes. However, particularly for scale up, there are several practical matters to be resolved. Therefore, still new operational methods and strategies are developed that may prove to be useful techniques in the future.

Membrane bioreactor technology has been subject to keen interest, rapid development and extensive penetration of the European market in the last ten years, for many reasons. This technology combines best of two worlds: membrane separation and biological conversion. Combination of those two technologies have led to the development of three generic membrane processes in biological treatment:

- solid-liquid separation bioreactors using micro- or ultrafiltration modules for the retention of biomass,
- bubbleless oxygen transfer to degradative bacteria present in the bioreactor;
- extractive membrane processes for the transfer of degradable organic pollutants from hostile industrial wastewaters, via non-porous membranes.

In this article we focus on the first type: membrane bioreactors for solid-liquid separation.

History

In the space of barely ten years membrane bioreactors (MBR) have gone from lab scale research through development to full scale application for flows in excess of 10.000 m³/d. Indeed the development over the last five years has seen a dramatic increase in both the number of operational plants and their scale. In parallel with this, the number and diversity of applications increased considerably. This has had a large impact on MBR research over the last decade.

About ten years ago MBR research was mainly focused at on-site pilot research. In The Netherlands MBR research also focused at many different industrial applications and landfill leachate treatment. Treatment of municipal wastewater with a cross-flow MBR was also studied but, by that time, cost evaluations by Dutch consultants showed that this MBR technology was not competitive with conventional techniques.

Then, a rapid development of MBR systems occurred. A more rational comparison between different systems and configuration was made. During various research trials, submerged and side-stream systems were compared and slowly a more defined operational window for each system was determined. In this period many (small) companies entered the market, each with their own specific MBR system.

From a research point of view, the last couple of year however, system selection and application established and long term operational limits became more important. Simultaneously, various systems were scaled-up for application in municipal wastewater treatment, e.g. from 4.000 p.e. in 1998 to over 25.000 p.e. in 2001.

Current research in The Netherlands

Along with international developments, current MBR research in The Netherlands is concentrating at long term operational stability. Membrane fouling, membrane cleaning and energy consumption are key issues in that respect. Various projects are running. For each topic, a brief description is given below.

Membrane fouling and cleaning, engineering aspects

Concentration polarization, cake formation and pore fouling lead to a performance loss in most micro- and ultrafiltration membranes that manifest itself as a permeate flux reduction. This phenomenon is often called 'biofouling'. Research on this subject is currently focused at fouling behaviour as a function of membrane material composition and hydrodynamic parameters. This holds for both aerobic and anaerobic membrane bioreactors.

Delft University of Technology runs a research project 'Membrane fouling in MBR for treatment of wastewater'. Although the starting point is the treatment of municipal wastewater, industrial water streams are also taken into account.

The first objective in this research is the development of a filtration protocol to monitor the fouling capacity of the activated sludge broth in a MBR. Recent results show that the filtration protocol can discern between different types of systems. Fluctuations in fouling capacity were also demonstrated.

Resistance measurements

In the process of membrane filtration of activated sludge, the permeate flux is hindered by the formation of a cake layer, pore blocking and other types of membrane fouling. This fouling can be measured as a filtration resistance. The filtration resistance increases with time, dependent on the operating conditions, such as the applied TMP.

In figure 1 three different types of MBR sludge are filtered under similar conditions, and the development of the total filtration resistance is plotted against the produced volume.

Comparison with other experiments show that the form of this graph is typical for each sludge type. By applying different cleaning methods more information can be gained on the different types of fouling that occur. The apparatus that is used for the measurement consists of a membrane module with 0.20 m² membrane area. It is operated in cross flow mode and uses tubular ultrafiltration membranes. This gives the opportunity to switch between different types of feed stream.

Fig. 1: Filtration resistance in time from three systems.

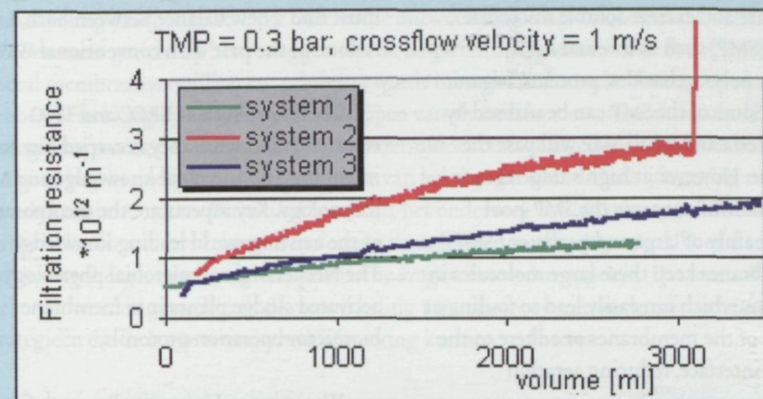


Fig. 2: Filtration resistance development during measurement.

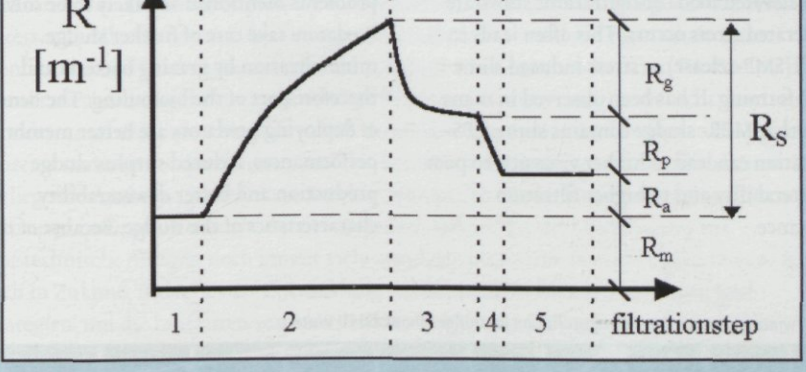
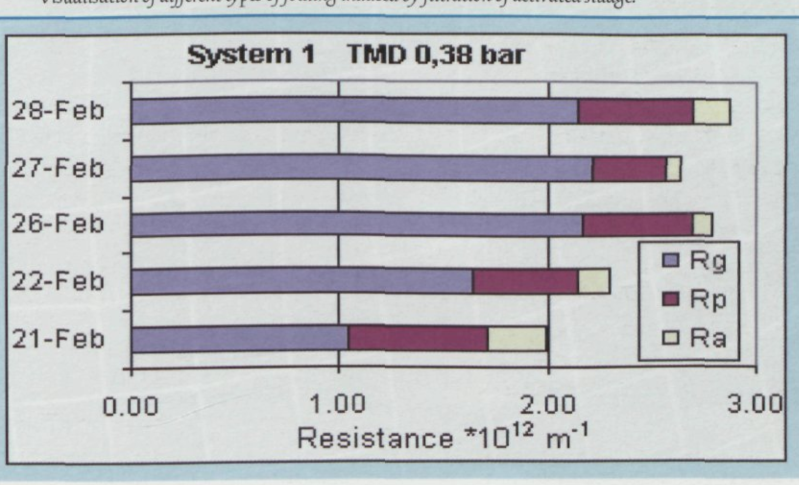


Fig. 3: Visualisation of different types of fouling induced by filtration of activated sludge.



Filtration protocol

In order to compare the resistance measurements, a filtration protocol had to be determined. Different combinations of cleaning methods and operating conditions were tested and the following strategy was found to produce the most useful information.

Initially, the resistance of the clean membrane is determined by measuring the clean water flux. Subsequently, MBR sludge is filtered. After producing a certain amount of permeate, a forward flush with demineralised water is applied as a first cleaning method. By doing this, the cake layer that is deposited on the membrane is (partially) removed. When the resistance stabilises a back flush is applied to remove particles that are stuck inside the membrane pores. Finally the hydraulically irreversible part of the fouling is removed chemically.

Thus the total resistance due to filtration of activated sludge (Rs) can be divided in three parts, called cake layer/ gel layer resistance (Rg), pore blocking resistance (Rp) and irreversible fouling resistance (adsorption) (Ra).

In figure 2 the development of the resistance during a measuring session is shown. The results of this graph can also be visualised by a column that is divided according to the different types of fouling that occur. This is done in figure 3 where activated sludge from one installation is sampled at different days. This figure shows an increase in filtration resistance over a period of one week.

Future applications

Now that a filtration protocol has been established, the next step is to connect the results with experience that is gained in the installations where the sludge is taken from. Relevant parameters will be monitored and linked to the results gained by the short-term filtration experiments. Having done this, another step is taken towards the understanding of the interactions between activated sludge and membrane filtration in a membrane bioreactor.

At TNO a large research project, in co-operation with Grontmij, is dedicated to the development of an anaerobic membrane bioreactor. For this type of bioreactor different fouling problems need to be solved. First, anaerobic treatment gives a sludge broth that contains very fine colloidal material that gives specific fouling problems. In addition, various precipitates can be formed that lead to pore blocking of the membranes. Finally, formation of biogas results in gas permeation through the membranes. This will greatly influence performance of the membrane module. All these challenging problems are investigated.

During various research trials, several membrane materials are used to study in detail the relation between material composition (hydrophilicity, surface charge, pore size) and flux stability. Once this problem is solved, various module configurations will be tested to deal with gas permeation through the membranes. It is expected that within one year a pilot scale reactor will be available.

Furthermore, research is focused more generally at determination of biofouling, to get a better understanding of the different phenomena involved. To this, frequent membrane autopsies are applied to pilot scale membrane bioreactors that operate with domestic wastewater. After optical inspection, small pieces of membranes are subjected to analytical techniques such as SEM, XRMA and spectroscopic analysis. Besides, different washing steps are performed to dissolved or remove different types of fouling that can by analysis in the solute in great detail. Together with research like that performed at the Delft University of Technology, this research will lead to a better understanding of the origin of 'biofouling'.

Twente University will soon start research on a similar subject but dedicated solely to aerobic membrane bioreactors. Here, also different flow regimes and module configurations will be tested. Research is however extended to cleaning procedures. The aim is to find a correlation between absorbed components and cleaning agents used. Keeping the biological environment undisturbed is an important restriction set.

Membrane fouling and cleaning, microbial aspects

Because of the importance of a good effluent quality, the settlebility and thus the characteristics of the activated sludge plays a major role in conventional wastewater treatment plants (WWTPs). This results in a fine balance between influent characteristics, WWTP-management and microbiology, which has to be maintained. In MBR-systems the membranes function as a barrier between biomass and effluent. As a result sludge characteristics and free bacteria or even microbiology as a whole seem to play a minor role. In practice this does not seem to be the whole story.

For competing with conventional WWTPs, MBR-systems need, besides a good effluent quality, low investment costs. Therefore, they are more compact than conventional WWTPs and operated at (much) higher biomass-concentrations and thus at much lower food/micro-organisms (F/M) ratios. In conventional WWTPs these low F/M-ratios would lead to sludge disintegration and to bad effluent quality. In MBRs it can lead to other microbiology related problems.

Lower F/M-ratios lead to less sludge growth and to higher sludge ages. This is beneficial because it reduces the costs of processing excess sludge. At too high sludge ages micro-organisms and sludge tend to disintegrate and excrete soluble microbial products (SMP) such as low and high molecular polysaccharides, proteins, organic acids etc. Some of the SMP can be utilised by other bacteria and small SMP will pass the membrane. However at high sludge ages as observed in MBR-systems the SMP-pool consists mainly of large and persistent SMP. The membranes keep these large molecules in the systems which can easily lead to fouling or blockages of the membranes or adhere to the air/water interface, reducing aeration efficiency.

Low F/M-ratios results in starvation of the bacteria (sludge) at the end of the system. When recycled to the first compartment or the beginning of the reactor and suddenly faced with elevated food concentrations substrate accelerated stress occurs. This often leads to death (SMP-release) or stress induced slime (EPS)-forming. It has been observed in many cases that MBR- sludge contains slime. EPS-formation can lead to higher viscosity, to poor dewaterability and to higher filtration resistance.

EPS-formation and slime-related viscosity is also directly related to the F/M-ratio. At a too high or too low F/M-ratio, sludge viscosity and filtration resistance increases. MBR-systems are often operated at much lower F/M-ratio's than the optimum ratio at which viscosity and filtration resistance are lowest.

This is only a selection of the different relationships between microbiology and MBR-performances. The microbiology in a MBR-system can't be ignored if costs, such as energy costs for aeration or filtration or membrane costs are to be minimised. By understanding the combination biology and technology one must find a new balance between both. Like it is done in the past with conventional WWTPs.

Therefore, both at BRCC and TNO research and consultancy is carried out on the integration of microbial knowledge and MBR technology. Key aspects are the incorporation of the existing world leading knowledge in The Netherlands of microbial physiology of activated sludge plants into membrane bioreactor operation protocols.

Wageningen University Research Centre runs a project with a different, biological focus to solve and diminish the problems that are related to biofouling. Here, higher organisms of the natural food chain are used. By use of sludge predators, like oligocheate worms, the problems mentioned are likely to be solved. Predators take care of further sludge mineralization by grazing bacteria and therefore part of the biofouling. The benefits of deploying predators are better membrane performances, reduced surplus sludge production and better dewaterability characteristics of the sludge. Because of their

A fish swimming in permeate of a installation for sludge (photo: DHV Water).

high proteins content, an additional economical effect is the possible use of predators as a new protein source for glues, coatings or surfactants.

Energy consumption

Aerobic membrane bioreactor power requirement comes from pumping feed water, recycling retentate, occasional permeate suction and (module) aeration. Submerged membrane bioreactors generate the necessary crossflow velocity through air movement in the reactor and the necessary pressure through the hydraulic head above the membrane, with additional permeate suction in some cases. In contrast, sidestream systems have large pumping requirements to circulate biomass around the membrane loop at sufficient high pressures and velocities. Hence, the overall energy requirement for submerged systems tend to be lower than for sidestream operation. Recent years however, Stork/NUON developed the so-called Airflush sidestream system (described elsewhere in this journal) for which the classical sidestream crossflow module is orientated vertically with simultaneous aeration. Thus, energy consumption is radically diminished an equal to energy consumption of submerged systems.

Since large improvements have been made by various system manufacturers, hardly any MBR research on this subject is carried at Dutch universities and research institutes.

Samenvatting

Membraanbioreactortechnologie (MBR) heeft de afgelopen tien jaar een stormachtige ontwikkeling doorgemaakt. Door deze snelle ontwikkeling is het onderzoek de laatste jaren meer en meer gericht op het verleggen van de lange termijn grenzen in de bedrijfsvoering. Vooral membraanvervuiling en -reiniging wordt intensief onderzocht. Strategieën hiervoor hebben betrekking op zowel de eigenschappen van de membranen en modules als de biologische processen. Aangezien geen wondermiddel bestaat tegen membraanvervuiling, is een goed begrip nodig van alle aspecten die van belang zijn voor de bedrijfsvoering van membraanbioreactoren. Dit artikel beschrijft het onderzoek aan al deze aspecten zoals dat bij de Nederlandse universiteiten en onderzoeksinstellingen wordt uitgevoerd. Vooral voor de opschaling dienen echter nog veel praktische vragen te worden opgelost. Daarom zal ook in de toekomst worden gewerkt aan de ontwikkeling van nieuwe operationele methoden en strategieën die de lange termijn bedrijfsvoering kunnen verbeteren.

Zusammenfassung

Die Membranbioreaktor-Technologie hat in den letzten zehn Jahren eine stürmische Entwicklung vollzogen. Bedingt durch diese schnelle Entwicklung, konzentrierte sich die Forschung in den letzten Jahren mehr und mehr auf die Verlängerung der Laufzeiten der Reaktoren. Vor allem Fäulnisprozesse der Membranen und ihre Reinigung wurden intensiv untersucht. Hierfür entwickelte Strategien beeinflußten sowohl die Eigenschaften der Membranen und Module als auch die der beteiligten biologischen Prozesse. Die Fäulnis der Membranen und ihre dadurch notwendige Reinigung konnten zwar noch nicht durch ein Wundermittel verhindert werden, jedoch durch das Verständnis der beteiligten biologischen Prozesse und eine entsprechend optimierte Betriebsführung der Membranbioreaktoren. Der vorliegende Artikel zeigt, daß diese Aspekte zwar an den niederländischen Universitäten und Instituten intensiv untersucht werden, es jedoch speziell bei der Übertragung auf großtechnische Anlagen noch immer viele ungelöste praktische probleme gibt. Darum besteht auch in Zukunft Bedarf an der Entwicklung neuer prozeßtechnischer Losüngen und Strategien, um die Laufzeiten von Membranbioreaktoren zu verlängern.

Resumé

Depuis une dizaine d'années, les techniques de bioréacteurs à membranes se sont développées d'une manière fulgurante. Par ce développement rapide, l'etude s'est dirigée de plus en plus sur la prolongation de la durée de vie des membranes. Les phénomènes d'encrassement des membranes et les procédures d'entretien font l'object d'une étude intensive. Les stratégies à ce niveau se penche aussi bien sur les caractéristiques des membranes et des modules que sur les processus biologiques. Etant donné qu'il n'existe pas de méthode miracle en ce qui concerne l'encrassement en l'entretien des membranes, la connaissance de tous les aspects importants pour la gestion des bioréacteurs membranaires est primordiale. Cet article décrit l'étude de ces aspects comme cela se déroule dans les universités et les institutions de recherche hollandaises. Beaucoup de questions pratiques doivent cependant encore être résolues avant de passer à la réalisation d'installations 'full-scale'. C'est pourquoi, il est important et nécessaire de travailler dans le futur à de nouvelles méthodes opérationnelles et stratégies qui amélioront la gestion des bioréacteurs membranaires à long terme.

Conclusions

Membrane fouling and cleaning strategies reflect the properties of both membranes and the biology involved. Fundamental aspects include membrane autopsy, filtration resistance measurements, the integration of monitoring techniques for early detection of 'biofouling' and a thorough understanding of the microbial physiology in the bioreactors. So, it needs a comprehensive perception of all aspects involved in the operation of membrane bioreactors.

Thus, membrane fouling and cleaning cannot be overcome by application of some wonder-chemical but by a better understanding of the entire process and by interfering in the most effective way and on a scientific bases. This article shows that all those aspects are studied in detail at Dutch universities and research institutes. However, particularly for scale up, there are several practical matters to be resolved. Therefore, still new operational methods and strategies are developed that may prove to be useful techniques in the future. ¶

dr.ir. Renze van Houten
project manager/scientist Bioprocesses
Department of Environmental Biotechnology
TNO Environment, Energy and Process Innovation
Postbus 342, 7300 AH Apeldoorn
tel. +31 (0) 55 549 3628
fax. +31 (0) 55 549 3523
e-mail: houten@mep.tno.nl

ir. Herman Evenblij
Ph.D. student, Faculty of Civil Engineering and Geo Sciences Delft University of Technology
Stevinweg 1, 2628 CN Delft
tel. +31 (0) 15 278 2258
fax. +31 (0) 15 278 4918
e-mail: h.evenblij@citg.tudelft.nl

drs. Mischa Keijmel
external consultant/scientist BRCC-Milieu-groep
Zernikepark 8a, 9747 AN Groningen
tel. +31 (0) 50 577 7850
fax. +31 (0) 50 577 8910
e-mail: m.keijmel@brcc.nl