HUNGARIAN JOURNAL
OF INDUSTRIAL CHEMISTRY
VESZPRÉM
Vol. 38(2). pp. 181-185 (2010)

ANAEROBIC MEMBRANE BIOREACTORS

E. SZENTGYÖRGYI✉, K. BÉLAFI-BAKÓ

Research Institute of Chemical and Process Engineering, University of Pannonia
Egyetem u. 10, Veszprém, HUNGARY
✉E-mail: szentgyorgyi@almos.uni-pannon.hu

The aim of this work was to give a general overview on the type and behaviour of anaerobic membrane bioreactors, which are intensively studied for waste water treatment processes. The role of the membrane, the possible design, structures of the bioreactors, the effect of environment are presented here.

Keywords: wastewater treatment, biogas, membranes, anaerobic conditions

Introduction

The process of wastewater treatment in general includes various steps, where biological degradation and separation techniques play important roles. Recently membranes are often applied for the separations. To intensify the processes, biodegradation and separation can be integrated, thus membrane bioreactors (MBRs) are introduced in the particular field. Membrane bioreactors may work under aerobic as well as anaerobic conditions. This paper focuses on the anaerobic membrane bioreactors.

Anaerobic waste water treatment

Low biomass yields and low growth rates represent one of the important advantages of anaerobic biotechnology, since they translate into the generation of low amounts of waste sludge, up to ten times less than during aerobic treatment. However, during the first developments of anaerobic processes this feature represented a major drawback when trying to increase the biomass concentration in anaerobic reactors [1].

Since the installation of the first full scale upflow anaerobic sludge blanket (UASB) reactor, three decades ago [2], anaerobic process has been successfully used for the treatment of many kinds of industrial wastewaters as well as sewage. Nowadays, it can be considered an established technology that offers the possibility of an efficient treatment with low capital and operational cost [2].

The success of anaerobic wastewater treatment can be attributed to an efficient uncoupling of the solids retention time from the hydraulic retention time through biomass retention, which is usually accomplished through biofilm or granule formation. With this strategy, a high concentration of biocatalyst is obtained, leading to high volumetric treatment capacities [1].

From the available anaerobic technologies, sludge bed reactors are by far the most applied. At present close to 80% of all full-scale anaerobic installations are sludge bed reactors in which biomass retention is attained by the formation of sludge granules. Biomass retention can also be accomplished by biofilm formation, which greatly facilitates biomass-liquid separation. Biofilms are very useful in environmental biotechnology since they ensure an effective uncoupling of sludge retention time from liquid retention time, enabling the treatment of large volumes of diluted aqueous solutions, at short liquid retention time [3].

The role of membranes in anaerobic waste water treatments

In situations where biofilm or granule formation cannot be guaranteed, such as extreme salinity and high temperatures, or when complete biomass retention must be ensured, membrane assisted physical separation can be used to achieve the required sludge retention [2]. Membrane bioreactors (MBR) ensure biomass retention by the application of micro or ultra filtration processes. Furthermore, since the permeate is free of solids or cells, water would eventually require les post-treatment steps if reuse or recycle is of interest, in comparison with sludge bed technologies.

Regarding the structure of the membrane bioreactor systems, two MBR process configurations can be identified: side-stream (or external-loop) and submerged. In side-stream (external) MBRs membrane modules are placed outside the reactor *(Fig. 1),* and the reactor mixed liquor circulates over a recirculation loop that contains the membrane.

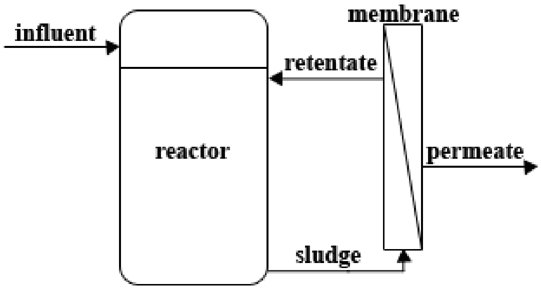

Figure 1: External-loop membrane bioreactor

In submerged MBRs, the membranes are placed inside the reactor, submerged in the mixed liquor *Fig. 2).* Side-stream MBRs involve much higher energy requirements, due to higher operational trans-membrane pressure and the elevated volumetric flow required to achieve the desired cross-flow velocity. However, side-stream reactors have the advantage that the cleaning operation of membrane modules can be performed more easily in comparison with submerged technology, since membrane extraction from the reactor is needed in the later case. Submerged MBRs involve lower energy needs, but they operate at lower permeate fluxes, since they provide lower levels of membrane surface shear. The latter means higher membrane surface requirements. Nowadays, most of the commercial applications are based on the submerged configuration, due to lower associated energy requirements [4].

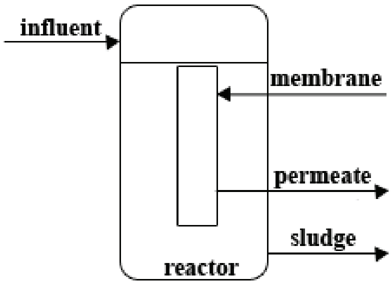

Figure 2: Submerged membrane bioreactor

Most of the reported research done with anaerobic membrane bioreactors has been performed with side-stream configuration [5].

So far the drawback of MBR systems is related with membrane costs, energy requirements and membrane fouling [6, 7, 8]. However, important advances have been made in the development of new types of membranes, of which the costs have been significantly reduced [4]. In addition, research is being conducted in order to find reactor configurations and operational procedures that reduce fouling and energy consumption.

Membrane fouling is definitively the main drawback of the application of MBRs for wastewater treatment [9]. Membrane themselves represent a relevant capital cost, so everything that can reduce their lifetime or the applied flux will directly affect the economic feasibility of the process. Moreover, membranes cleaning activities directly affect reactor operation due to the need for process interruptions. The flux reduction phenomenon is usually analysed in terms of filtration resistances. Three categories of factors affecting applicable flux can be identified: membrane material and pore size, suspension properties, and operational conditions.

Membrane hydrophobicity has shown in some studies to play a significant role [1, 7, 10]. Hydrophobic proteins residues can form strong attachments by hydrophobic membranes resulting in strong fouling [1, 11]. Indeed, surface modification of hydrophobic polymeric membranes by grafting more hydrophilic polymers can reduce fouling and improve flux [7, 11, 12]. Membrane material can also determine the applicable fluxes [13, 14, 15]. Membrane pore sizes used in wastewater treatment applications are in the range of 0.02–0.5 µm [1].

Increasing the suspended solid concentration usually produces a decrease in the attainable flux [16, 17]. Particle size distribution can also strongly influence solid deposition over the membrane surface.

Membrane fouling is usually prevented applying shear over the membrane surface. In side-stream MBRs this is accomplished by applying high cross-flow velocities. An increase in the cross-flow velocity usually results in an increase of the applicable flux [18, 19, 20]. Gas sparging is the most common way to provide high shear conditions in submerged MBRs. In anaerobic MBRs biogas can be recirculated in order to achieve a similar effect. The applied gas flow represents an important operational parameter for controlling cake layer development, but will affect energy requirements for the applied system.

Several operational procedures have been reported in order to reduce membrane fouling in MBRs: flux stoppage and permeate back-flush are the most common strategies [1].

The critical flux concept was introduced over 10 years ago, and has proven useful to characterize membrane fouling in membrane applications, especially in MBRs [21]. The critical flux is defined as the flux over which the relation between flux and TMP becomes non-linear [22]. Different methods have been used to determine the critical flux, such as direct membrane observation [23], mass balance [24] and TMP observation in flux step or cycling experiment [22, 25, 26]. Mass balance and microscopic observation are unlikely to be used in full-scale installations or in submerged MBRs. However, pressure increase at constant flux operation can be easily applied for critical flux determination in any type of membrane process, both at lab and full scale.

The membrane resistance of the thermophilic reactor is clearly lower than that of the mesophilic reactor [1].

Results show that the change in diffuser type (fine diffuser, coarse diffuser) is as effective in decreasing cake formation rate, as an increase in gas superficial velocity of close to 300% (gas volume from 18 to 54 m/h) [26].

In mesophilic anaerobic SMBR sludge concentration is the main operational parameter for cake layer formation.

Operation over critical flux inevitably implies cake formation *(Fig. 3)*.

Biomass concentration showed to be an important factor determining cake formation in mesophilic MBRs. Under mesophilic conditions, biomass concentration affects linearly critical flux. An increase from 25 to 50 g TSS/L reduces critical flux from 21 L/m^2h to 9 L/m^2h

[24]. Even though gas sparging level also influences critical flux, its effect is much smaller than biomass concentration.

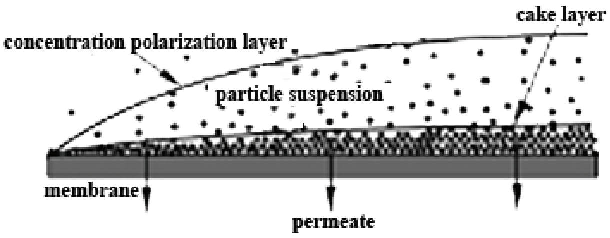

Figure 3: Cake layer formation on membranes

Thermophilic operation reduces drastically the effect of biomass concentration and gas sparging on cake layer formation, in comparison with mesophilic conditions. Biomass concentration and gas superficial velocity presented a value, below and over which no further effect on critical flux was found. Thermophilic MBR requires much lower levels of gas sparging in comparison with mesophilic MBR [27]. For achieving similar levels of effluent flux at a fixed biomass concentration, gas requirements under thermophilic conditions were below 50% of those required for mesophilic conditions.

Even though cake formation is mainly reversible in short term experiment, particle deposition proceeds fast once critical flux has been exceeded. At 50 g TSS/L, a flux increase of only 3 L/m^{2}h over the critical flux results in a TMP increase rate of over 1 and a 5 bar/h for the mesophilic and thermophilic reactors, respectively [27]. The operational flux is, therefore, likely to be restricted to values close to the critical flux for both temperatures.

Since reversible cake formation was identified as the limiting factor for the operational flux, increasing surface shear should result in higher fluxes. Preliminary test showed that cross-flow operation may be a feasible alternative to reduce particle deposition [1, 24]. This will be the case only if the high shear stress does not negatively affect the physical properties of the sludge, i.e. including a decrease in particle size.

Thermophilic anaerobic wastewater treatment offers several potential advantages in comparison with mesophilic processes, such as higher loading potentials, effective removal of pathogenic microorganisms and the elimination of cooling needs when wastewater is already discharges at high temperature [27, 28]. Granulation and biofilm formation seems to be more difficult to achieve under thermophilic conditions, in comparison with mesophilic conditions. Moreover, lower net biomass yield are expected under thermophilic conditions, in the range of 50% of those possible under mesophilic temperatures, as the result of higher maintenance requirements and higher decay rates [1, 27]. In membrane bioreactor, biomass is retained independently of its capacity of forming flocks or biofilms, and irrespective of its growth rate or yield.

In principle, operation at high temperatures should be beneficial for membrane filtration due to the effect of temperature on sludge and permeate rheological behaviours. Temperature affects the relation between shear stress and shear rate, which in Newtonian fluids is represented by the viscosity [28]. During the operation of an anaerobic submerged MBR, attained fluxes showed to be determined by the development of fraction of small particles. Under these conditions, temperature showed little effect on the attainable fluxes, indicating that the physiological effects of temperature on the properties and composition of the sludge can be much more of importance for membrane filtration than the physical effect of temperature on sludge or permeate rheology [28].

The wastewater organic matter concentration determines to a high extent the applied hydraulic retention time, which in turn defines the flow of permeate that has to be achieved. For a given flux, the latter value will determine the membrane requirements, influencing capital and operational costs [2]. Therefore, even though the application of anaerobic MBR technology to low strength wastewaters may become technically feasible, its economical feasibility will be strongly determined by the prevailing membrane prices and flux levels that can be achieved.

Low pore fouling may attribute to cake layer formation. If the membrane is covered by cake layer, it is no longer exposed to the suspension, and pore blocking and other fouling mechanisms are less likely to occur. Cake formation also implies that the membrane material and exact pore size may not play a significant role in determining the flux. Once the membrane surface is covered by sludge, its properties do not play anymore a role in the further deposition of particles. Under these conditions only the suspension properties and operational conditions will determine the relation between back-transport and convective transport. Two types of cake formation were identified: short-term, mainly reversible cake formation and a long term consolidated cake formation. The short term cake formation is the main responsible phenomenon determining the critical flux. The long term formation slowly increases the membrane resistance, until a point when the TMP may be too high and a physical cleaning procedure is required. Cake formation can be controlled by increasing the surface shear. Surface shear is an efficient way of controlling particle deposition, as long as it does not affect suspension properties. However, usually this is not the case, since high shear rates will most likely reduce particle size, increasing particle deposition.

High temperature operation positively affects membrane filtration, due to the temperature effect on the rheology of both permeate and sludge. A lower sludge viscosity means that lower shear rates will suffice for providing the same shear stress, resulting in lower energy requirements. A lower permeate viscosity increases membrane permeability, decreasing the trans-membrane pressure. These properties result a better filtration performance for the thermophilic MBR compared to the mesophilic MBR.

For aerobic MBRs, submerged configurations are favoured, owing to the relative low energy requirement compared to the side-stream configuration. Due to the low bacterial growth rates, anaerobic MBRs need to be operated at higher biomass concentration in order to provide an efficient treatment at high organic loading rates. Under these conditions, cake layer formation has shown to be the key factor determining the permeate flux. Minimizing cake layer formation by applying higher shear rates resulted in higher permeate flux in side-stream MBRs. However, changes in sludge properties likely off-sets the benefits of the high surface shear.

Higher fluxes can be achieved using the side-stream (external) configuration. However, the side-stream MBR operation proceeds at a lower biomass concentration than the submerged MBR.

ACKNOWLEDGEMENT

The research work was supported by the Ányos Jedlik project, entitled: “Development of new bioethanol and biogas production technologies” (2007-2010), grant No. BIODDFPE.

REFERENCES

1. D. JEISON: Anaerobic membrane bioreactors for wastewater treatment: feasibility and potential applications, PhD thesis, Wageningen University, Wageningen, The Netherlands (2007).
2. G. LETTINGA, J. FIELD, J. VAN LIER, G. ZEEMAN, L. W. H. POL: Advanced anaerobic wastewater treatment in the near future, Water Science and Technology, 35, 1997, 5–12.
3. C. NICOLELLA, M. C. M. VAN LOOSDRECHT, J. J. HEIJNEN: Wastewater treatment with particulate biofim reactors, Journal of Biotechnology, 80, 2000, 1–33.
4. S. JUDD: The MBR book, Elsevier, Oxford (2006).
5. B. Q. LIAO, J. T. KRAEMES, D. M. BAGLEY: Anaerobic membrane bioreactors: Applications and research directions, Critical Reviews in Environmental Science and Technology, 36, 2006, 489–530.
6. L. VAN DIJK, G. C. G. RONCKEN: Membrane bioreactors for wastewater treatment: The state of the art and new developments, Water Science and Technology, 35, 1997, 35.
7. K. H. CHOO, I. J. KANG, S. H. YOON, H. PARK, J. H. KIM, S. ADIYA, C. H. LEE: Approaches to membrane fouling control in anaerobic membrane bioreactors, Water Science and Technology, 41, 2000, 363–371.
8. STOWA: MBR for municipal wastewater treatment (2002).
9. H. C. FLEMMING, G. SCHAULE, T. GRIEBE, J. SCHMITT, A. TAMACHKIAROWA: Biofouling – the Achilles heel of membrane processes, Desalination, 113, 1997, 215–225.
10. S. CHANG, C. H. LEE: Membrane filtration characteristics in membrane-coupled activated sludge system – the effect of physiological states of activated sludge on membrane fouling, Desalination, 120, 1998, 221–233.
11. G. RUSSOTTI, K. E. GOKLEN, W. K. WANG: Crossflow membrane filtration of fermentation broth, Membrane Separation in Biotechnology, New York, Marcel Dekker Inc (2001).
12. A. SAINBAYAR, J. S. KIM, W. J. JUNG,. Y. S. LEE, C. H. LEE: Application of surface modified polypropylene membranes to an anaerobic membrane bioreactor, Environmental Technology, 22, 2001, 1035–1042.
13. J. KANG, S. H. YOON, C. H. LEE: Comparison of the filtration characteristics of organic and inorganic membranes in a membrane-coupled anaerobic bioreactor, Water Research, 36, 2002, 1803–1813.
14. W. R. GHYOOT, W. H. VERSTRAETE: Coupling membrane filtration to anaerobic primary sludge digestion, Environmental Technology, 18, 1997, 569–580.
15. P. R. BÉRUBÉ, E. R. HALL, P. M. SUTTON: Parameters governing permeate flux in an anaerobic membrane bioreactor treating low-strength municipal wastewaters: A literature review, Water Environment Research, 78, 2006, 887–896.
16. N. K. H. STROHWALD, W. R. ROSS: Application of the Aduf process to brewery effluent on a laboratory scale, Water Science and Technology, 25, 1992, 85–105.
17. V. L. PILLAY, B. TOWNSEND, C. A. BUCKLEY: Improving the performance of anaerobic digesters at wastewater treatment works – the coupled cross-flow microfiltration digester process, Water Science and Technology, 30, 1994, 329–337.
18. A. BEAUBIEN, M. BATY, F. JEANNOT, E. FRANCOEUR, J. MANEM: Design and operation of anaerobic membrane bioreactors: Development of a filtration testing strategy, Journal of Membrane Science, 109, 1996, 173–184.
19. S. ELMALEH, L. ABDELMOUMNI: Cross-flow filtration of an anaerobic methanogenic suspension, Journal of Membrane Science, 131, 1997, 261–274.
20. C. WISNIEWSKI A. GRASMICK, A. L. CRUZ: Critical particle size in membrane bioreactors – Case of a denitrifying bacterial suspension, Journal of Membrane Science, 178, 2000, 141–150.
21. P. BACCHIN, P. AIMAR, R. W. FIELD: Critical and sustainable fluxes: Theory, experiments and applications, Journal of Membrane Science, 281, 2006, 42–69.
22. D. X. WU, J. A. HOWELL, R. W. FIELD: Critical flux measurement for model colloids, Journal of Membrane Science, 152, 1999, 89–98.
23. H. LI, A. G. FANE, H. G. L. COSTER, S. VIGNESWARAN: Direct observation of particle deposition on the membrane surface during cross flow microfiltration, Journal of Membrane Science, 149, 1998, 83–97.
24. D. Y. KWON, S. VIGNESWARAN, A. G. FANE, R. BEN AIM: Experimental determination of critical flux in cross-flow microfiltration, Separation and Purification Technology, 19, 2000, 169–181.

25. S. BESZÉDES, Z. LÁSZLÓ, G. SZABÓ, C. HODÚR: Enhancing of biodegradability of sewage sludge by microwave irradiation, Hungarian Journal of Industrial Chemistry, 36, 2008, 11–16.
26. P. LE CLECH, B. JEFFERSON, I. S. CHANG, S. J. JUDD: Critical flux determination by the flux-step method in a submerged membrane bioreactor, Journal of Membrane Science, 227, 2003, 81–93.
27. J. B. VAN LIER: Thermophilic anaerobic wastewater treatment; temperature aspects and process stability, PhD thesis, Wageningen University, Wageningen, The Netherlands (2003).
28. M. H. GERARDI: Microbiology of anaerobic digesters, Wiley-Interscience, Hoboken, NJ (2003).