MECHANICAL MEMBRANE CLEANING IN MBR
FROM RESEARCH TO LARGE-SCALE APPLICATIONS

Hoffmann, C.¹ and Prof. Krause, S.²
¹Microdyn-Nadir GmbH, Germany ²University of Applied Sciences Darmstadt, Germany
Corresponding Author: Tel. +49-1514227760 Email c.hoffmann@microdyn-nadir.de

Abstract

Membrane bioreactors (MBR) for industrial and municipal applications show advantages at space demand and effluent quality compared to conventional activated sludge systems (CAS). Their main disadvantages are a higher energy demand, which is mainly related to the module aeration for the continuous membrane cleaning (crossflow) and a limited lifetime of the membrane modules. Hence, the challenge to make MBR competitive against CAS hinges on the minimization of both, membrane surface and energy demand for crossflow aeration.

Therefore a mechanical cleaning process (MCP) was developed that keeps the membrane surface free of sludge depositions and all fouling effects. The MCP ensures a significant flux increase up to 30 % in comparison to a standard MBR-application without MCP. Since 2008 several full-scale MBR systems utilizing the MCP technology have been commissioned, demonstrating the advantages and reliability of this unique technology.

Keywords
Membranes, Wastewater treatment, MBR, Membrane Bioreactor, Submerged modules, Mechanical cleaning

Introduction

Membrane bioreactors (MBR) combine the activated sludge process for wastewater treatment with biomass separation from the mixed liquor by ultra- or microfiltration membranes. Usually the membranes are submerged directly into the activated sludge and the treated wastewater (permeate) is extracted by vacuum or by gravity flow. MBRs are usually operated at MLSS concentrations of about 10 – 12 g/L. Higher volumetric loads are possible because the reactor volume is smaller compared to CAS.

The main advantage is the superior effluent quality (which can be directly reused or, if purification is required, easily conditioned compared to conventional systems) characterized by the complete removal of solids and bacteria. Another advantage is the small footprint of the plant due to more compact aeration tanks, the absence of a final sedimentation tank and the modular construction.

The membrane module is equipped with an aeration system underneath the module to remove the dewatered sludge by inducing a crossflow. The air bubbles scour the membrane surface and reduce the fouling layer on the membrane surface. Membrane
Fouling is caused by the deposition of biosolids, colloidal species, scalants or macromolecular species on the membrane surface, which leads to a flux and permeability decline [Judd 2006]. Factors such as the biomass characteristics, extracellular polymeric substances (EPS), pore size of the membranes, surface characteristics and material of the membrane, the module construction and the operating conditions affect the fouling rate [e.g. Chang et al. 2002]. The maximum specific flux that can be maintained for a longer period (critical flux) therefore depends mainly on the filterability of the activated sludge, the module system and the control of cake layer formation by crossflow aeration [Thiemig 2011]. The challenge in operating MBRs is the control of membrane fouling and the minimization of operational expenses.

Consequently, the goal of a new process development is to avoid the described problems in order to operate MBR systems at higher fluxes and with lower energy demand, allowing a sustainable process at low costs. Therefore a non-chemical, mechanical fouling control process is investigated. Granulates were added to the activated sludge in order to have a continuous mechanical removal of the fouling layer. Questions to answer are the amount of critical flux, the type of granulates and, in particular, the resistance of the polymeric membranes towards damages (Hoffmann 2013).

**Development of MCP technology**

**The BIO-CEL® Membrane Module**

A back-washable flat sheet membrane (BIO-CEL®) from MICRODYN-NADIR was used for this investigation [described in e.g. Krause et al. 2007]. The core piece of the BIO-CEL® module is a back-flushable flat membrane sheet. The option to backwash the module is achieved by a lamination of membrane and the supporting drainage layer.

The hydraulic flow conditions of this module and the usage of mechanically strong and permanent hydrophilic flat sheet PES Nadir® UP150 membranes allow the addition of granulates to control fouling as described in the following section. In particular the soft and flexible membrane sheet in contrary to the hard and inflexible plate and frame systems absorb the forces from the granulate to the membrane.

**Mechanical cleaning approach**

The Mechanical Cleaning Process (MCP) for BIO-CEL® membrane bioreactors was developed by MICRODYN-NADIR (S. Krause), Darmstadt Technical University (Peter Cornel) and Osnabrueck University of Applied Sciences (Frank P. Helmus and Sandra Rosenberger).

The performance of the mechanical cleaning process (MCP) is based on the idea of the moving bed technology. Granulates (4 mm PU beads) are added into the filtration tank (inside the activated sludge). The beads are moving alongside the membranes with the activated sludge by the crossflow. Size, form, density and wettability of the beads have been modified in an elaborate development process to optimize the effectiveness and practical application of the technology.
**Pilot Plant**

MCP technology was developed and validated in a pilot plant for a period of about 2 years. The plant setup was an anoxic tank (0.8 m³), nitrification tank (1.2 m³) and two parallel running membrane filtration tanks (each 0.33 m³). In each filtration tank a 10 m² PES flat sheet membrane BIO-CEL® BC 10-10 of MICRODYN-NADIR, Germany with a molecular weight cut-off (MWCO) of 150 kDa was submerged. The pilot plant was operated with synthetic wastewater to enable stable inflow conditions. The pilot plant was operated at an MLSS concentration of about 10 g/L inside the aeration tank without granulate. The food to microorganism ratio (F/M-ratio) was about 0.14 kg COD/(kg MLSS·d). The volumetric loading rate was about 1.2 kg COD/(m³·d). COD influent concentrations were about 450 mg/L. Hence, operational conditions and wastewater composition were comparable to municipal wastewater.

All membrane modules were equipped with fine bubble crossflow aeration systems. Reference Line#1 and MCP-Line#2 were fed parallel with the same activated sludge from the aeration tank. In MCP-Line#2, the granulates were added and rejected by a screen, so that only this line was operated with the mechanical cleaning process. Reference Line#1 was operated with the standard chemical cleaning procedures.

**Results of the pilot trials**

In order to monitor the biological performance and membrane integrity, the effluent quality was investigated. The average COD removal was about 95%. The online turbidity measurement of the permeate showed stable values during the entire 2 years of operation. The effluent quality for the MCP line was the same in comparison to the reference line. The permeability was taken as an indicator for the actual membrane condition and the degree of fouling. The capillary suction time (CST) showed poor dewatering properties of the activated sludge compared to data from other municipal applications during the whole period.

During the first 3 months of operation both lines (reference line#1 and MCP line#2) were operated in parallel using the same parameters at a specific flux of 15 L/(m²·h). Both modules started at a permeability of about 350 L/(m²·h·bar). The permeability of the MCP line#2 stayed more or less constant during the entire period. In the reference line#1 (no granulates) the permeability decreased from the initial value (100%) by 60% within 2 months. Frequent chemical maintenance cleaning procedures (MC) of the reference line#1 using sodium-hypochlorite (15 min back-wash with 500 ppm NaOCl) were conducted and the permeability stayed constant during the next month.
Figure 1: Comparison of the permeability of both lines during start-up period

After the start-up period the flux of the MCP line#2 was increased to 18, 25, 35 and 40 L/(m²-h) (continuous flow). The maximum flux of 40 L/(m²-h) was operated over a period of 16 days, (non-stop operation 24h/d). At this high flux-rate a decrease in permeability from 330 to 260 L/(m²-h-bar) was observed. The initial permeability did not recover during the further operation. This indicates that a fouling inside the membrane pores occurred during the operation at high flux levels of 40 L/(m²-h) which could not be removed by the MCP granulate. The higher pore fouling is most likely related to a lower hydraulic residence time causing a reduced biological performance of the system. A maintenance cleaning of the MCP line at the end of the trials could recover the initial permeability. Reference line#1 was operated with a maximum flux of 22 L/(m²-h). The results show a significant increase of the maximum flux for the MCP system. The average flux over the full time span of 700 operational days were 16.6 L/(m²-h) for the reference line#1 respectively 19.8 L/(m²-h) for the MCP-line#2. Hence the average flow was increased by about 20%.

Over the full period of more than 2 years no chemical cleaning was performed with the MCP-Line. The beads remained in circulation, no sedimentation was observed.

A detailed description about the herewith summarized results can be obtained in Krause et al., 2008 or Siembida et al., 2010.

Energy demand

The main part of the energy (50-70% of the total energy) is used for the crossflow aeration. As the modules are operated with a constant specific aeration demand (SAD) the reduction of membrane area is proportional with the energy demand. According to Pöpel (1985) the energy demand for aeration is about 5.4 Wh per m³ (air) and per m depth of submergence. Hence, the depth of submergence and the aeration rate affect the energy demand.
The energy demand can be calculated with:

- $5.4 \text{ Wh/(Nm}^3 \text{ m)} \rightarrow \text{theoretical energy demand [Pöpel, 1985]}
- $0.6 \text{ m}^3/(\text{m}^2 \text{ h}) \rightarrow \text{specific aeration demand (SAD) of BC10-10}$
- $1.5 \text{ m} \rightarrow \text{depth of submergence of BC10-10}$

In case 1 (reference line#1) the energy demand for the crossflow aeration is (average):

$$E = \frac{5.4 \text{ Wh}}{\text{Nm}^3 \cdot \text{m}} \cdot \frac{0.6 \text{ Nm}^3}{\text{m}^2 \cdot \text{h}} \cdot \frac{1.5 \text{ m}}{0.0166 \text{ m}^3 \cdot \text{m}^2 \cdot \text{h}} = 293 \frac{\text{Wh}}{\text{m}^3}$$

In case 2 (MCP line#2) the energy demand for the crossflow aeration is (average):

$$E = \frac{5.4 \text{ Wh}}{\text{Nm}^3 \cdot \text{m}} \cdot \frac{0.6 \text{ Nm}^3}{\text{m}^2 \cdot \text{h}} \cdot \frac{1.5 \text{ m}}{0.0198 \text{ m}^3 \cdot \text{m}^2 \cdot \text{h}} = 245 \frac{\text{Wh}}{\text{m}^3}$$

According to this calculation about 16% of the energy for the crossflow aeration (average value) can be saved by the increase of the average flux using MCP since less membrane area is in operation. This number can be further increased if the modules are operated only under the maximum flux of $40 \text{ L/(m}^2 \text{ h)}$ about half of the time. This results in the same average flux but just half of the filtration time and with that a reduction of crossflow aeration by 50% (Thiemig 2012).

**Economic feasibility analysis**

Most of interest is the cost of the new process. A detailed economic feasibility analysis (EFA) is presented to define the circumstances under which the operation of a system with MCP is profitable for the operator of an MBR. In order to generate more relevant data, the EFA is calculated on the base of 2,000 m$^3$/d inflow (average), municipal wastewater. For the analysis the flux was reduced slightly in comparison with the pilot tests which were performed with synthetic wastewater. The data for cleaning are based on the pilot tests and experiences in full scale MBR systems.
### Table 1: Cost comparison

<table>
<thead>
<tr>
<th></th>
<th>BIO-CEL®</th>
<th>BIO-CEL®-MCP</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Flux</td>
<td>13.9</td>
<td>16.7</td>
<td>L/m²/h</td>
</tr>
<tr>
<td>Inflow</td>
<td>2,000</td>
<td>2,000</td>
<td>m³/d</td>
</tr>
<tr>
<td>Membrane Area</td>
<td>6,000</td>
<td>5,000</td>
<td>m²</td>
</tr>
<tr>
<td>Invest Membrane (45€/m²)</td>
<td>270,000</td>
<td>225,000</td>
<td>€</td>
</tr>
<tr>
<td>Volume of filtration tank (42m³/m²)</td>
<td>143</td>
<td>119</td>
<td>m³</td>
</tr>
<tr>
<td>Lifetime</td>
<td>8</td>
<td>8</td>
<td>a</td>
</tr>
<tr>
<td><strong>annual charges &quot;membrane&quot;</strong></td>
<td><strong>33,750</strong></td>
<td><strong>28,125</strong></td>
<td>€/a</td>
</tr>
<tr>
<td>Energy demand</td>
<td>365,000</td>
<td>280,769</td>
<td>kWh/a</td>
</tr>
<tr>
<td>Spec. cost of energy</td>
<td>0.1</td>
<td>0.1</td>
<td>€/kWh</td>
</tr>
<tr>
<td><strong>annual charges &quot;energy&quot;</strong></td>
<td><strong>36,500</strong></td>
<td><strong>28,077</strong></td>
<td>€/a</td>
</tr>
<tr>
<td>Invest chemical cleaning</td>
<td>75,000</td>
<td>0</td>
<td>€</td>
</tr>
<tr>
<td>Valuation readjustment</td>
<td>8</td>
<td>0</td>
<td>a</td>
</tr>
<tr>
<td>Annual charges</td>
<td>9,375</td>
<td>0</td>
<td>€/a</td>
</tr>
<tr>
<td>Chemicals demand</td>
<td>3,000</td>
<td>0</td>
<td>€/a</td>
</tr>
<tr>
<td>Personnel expenses cleaning</td>
<td>2,700</td>
<td>0</td>
<td>€/a</td>
</tr>
<tr>
<td><strong>annual charges &quot;cleaning&quot;</strong></td>
<td><strong>15,075</strong></td>
<td><strong>0</strong></td>
<td>€/a</td>
</tr>
<tr>
<td>Price Granulate-MCP</td>
<td>0</td>
<td>5.00</td>
<td>€/kg</td>
</tr>
<tr>
<td>Invest Granulate-MCP</td>
<td>0</td>
<td>2,381</td>
<td>€</td>
</tr>
<tr>
<td>Exchange rate</td>
<td>0</td>
<td>10.0</td>
<td>%/a</td>
</tr>
<tr>
<td>annual charges granulate</td>
<td>0</td>
<td>238</td>
<td>€/a</td>
</tr>
<tr>
<td>Invest Screening</td>
<td>0</td>
<td>25,000</td>
<td>€</td>
</tr>
<tr>
<td>Valuation Readjustment</td>
<td>8</td>
<td>8.0</td>
<td>a</td>
</tr>
<tr>
<td>annual charges screening</td>
<td>0</td>
<td>3,125</td>
<td>€/a</td>
</tr>
<tr>
<td>Licence</td>
<td>0</td>
<td>2,500</td>
<td>€/a</td>
</tr>
<tr>
<td><strong>annual charges &quot;MCP&quot;</strong></td>
<td><strong>0</strong></td>
<td><strong>5,863</strong></td>
<td>€/a</td>
</tr>
<tr>
<td><strong>annual charges TOTAL (incl. Invest)</strong></td>
<td><strong>85,325</strong></td>
<td><strong>62,065</strong></td>
<td>€/a</td>
</tr>
<tr>
<td>Invest only</td>
<td>345,000</td>
<td>252,381</td>
<td>€</td>
</tr>
</tbody>
</table>

In this example all annual charges are about 85,325 €/a for the “normal” MBR-Process and about 62,065 €/a for the new MCP-Process. This is a reduction of 27%.

Overall the new BIO-CEL®-MCP allows an optimized MBR process with all advantages of the MBR technology (superb effluent quality and low foot print). Additional the new process allows an eco-efficient operation with savings in resources (chemicals and energy) and in cost (Thiemig 2012).
MCP technology in full-scale systems

There is an initial application of the MCP granulate necessary to maintain a concentration of 4-10 kg granulate per m³ of activated sludge. The total amount of MCP granulate depends on the strategy of operation. In general, MCP granulate has to be separated from the activated sludge during operation by submerged screens with a gap size of 3 mm. The MCP beads can either be separated from the return sludge inside the filtration tanks (Figure 2, top) or from the excess sludge (Figure 2, bottom). The first option minimizes the amount of MCP granulate since it is limited to the filtration tanks but increases the total screen dimensions since the hydraulic volume to be separated is higher. The second option causes the existence of MCP granulate in the whole system but minimizes the screen dimensions since the MCP beads only have to be separated from the relatively small excess sludge volume.

Figure 2: Different strategies of MCP operation in full scale MBR plants

The screen should be made of a stainless steel wedge-wire- or bar-screen-type. An air diffuser at the foot of the screen ensures a constant cross-flow over the screen surface and keeps the screen free of blockings by sludge particles. The air flow volume for the screen diffuser is about 3-5 m³/(h*m_{diffusor length}).
Industrial BIO-CEL® MBR with MCP technology

In May 2012 an industrial BIO-CEL® MCP MBR was commissioned. This system is treating wastewater from a fish-processing industry. The MBR permeate offers a quality that is sufficient for direct discharge to the sea. A partial flow of the MBR permeate is further treated with ozone, activated carbon and RO to be reused in the production process.

The biology of the MBR is arranged as a pre-denitrification with an anoxic-tank followed by an aeration-tank. Sludge from the aeration tank is pumped by submerged pumps into two separate filtration tanks. Each filtration tank (FT) holds 5 BIO-CEL® modules type BC400 (400 m² each). The total membrane area of the system is 4,000 m². The sludge from the filtration tank is re-circulated into the aeration tank through submerged screens as described in the previous chapter. Hence, the MCP beads only circulate inside the filtration tanks at the membrane modules.

No excess sludge was withdrawn during the first 4 weeks of operation. Target MLSS of 12,000 mg/L was achieved mid of July 2012. Since then the plant is running under full hydraulic capacity of 1,000 m³/d.

Figure 4 displays the step-wise increase of the daily flow up to the design flow of 1,000 m³/d and the corresponding transmembrane pressure (TMP) of both filtration lines during the initial four months after start-up. TMP remained stable at around 50 to 70 mbar (Figure 4) while the hydraulic load has been increased steadily until the end of 2012. During peak periods up to 1,100 m³ of wastewater have been treated. Only one chemical cleaning has been conducted up to now when the plant operation stopped for a planned system shut-down although the wastewater from fish-canning industry contains a high fouling potential. This cleaning has only been conducted to prepare the membrane modules for storage during the plant shut-down.
Figure 4: Step-wise increase of daily flow and corresponding membrane’s TMP

The incoming COD concentration ranges from 2,000 – 3,000 mg/L. Influent and effluent quality is shown in Figure 5. COD effluent concentrations vary between 100 and 180 mg/L resulting in an elimination ratio of 90-97%. Ammonia effluent concentrations decreased during the first weeks (180 mg/L down to less than 10 mg/L) since the seeding sludge consisted of a low SRT biocenosis and therefore sufficient nitrification capacity needed some time to establish. But since the end of July 2012, Ammonia effluent concentration ranges very stable below 10 mg/L corresponding to an elimination ratio of more than 97%.

Figure 5: Influent wastewater concentrations (left axis) and corresponding effluent quality (right axis)
Summary
The BIO-CEL MCP® technology has been developed and validated by MICRODYN-NADIR since 2005 in several pilot scale tests. During a long term trial for about two years two lines of submerged BIO-CEL® modules were operated; one without granulates (reference line#1) and one with granulates (MCP line#2). The pilot tests showed a significant performance improvement regarding the maximum duration of peak flux periods and a minimization of chemical cleaning needs with the new mechanical cleaning process MCP. This increase in hydraulic performance has a strong impact on the design of full scale systems – especially for systems with a wide variation of the hydraulic load. The application of the new MCP technology can reduce the needed membrane area – depending on the specific local hydraulic conditions – down to 50%-70% of a standard MBR system. This effect has a strong impact on the total cost (CAPEX and OPEX) of the MBR. Overall the new BIO-CEL®-MCP allows an optimized MBR process with all advantages of the MBR technology (superb effluent quality and low foot print). Additionally, the new process allows an eco-efficient operation with savings in resources (chemicals and energy) and by that in the biggest cost-consuming parts of MBR operation.

Acknowledgement
The Mechanical Cleaning Process (MCP) for BIO-CEL® membrane bio reactors was developed by MICRODYN-NADIR (S. Krause), Darmstadt Technical University (Peter Cornel) and Osnabrueck University of Applied Sciences (Frank P. Helmus and Sandra Rosenberger).

References
Krause, S., Meyer-Blumenroth, U (2007). Experience with a newly developed submerged membrane system for MBR application, Proceedings of 2nd IWA National Young


