CIE4485
Wastewater Treatment

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4. Membrane BioReactors
Membrane BioReactors

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1-Introduction
1.1 Background

"Water scarcity affects one in three people on very continent of the world" [WHO, 2009]

Water exploitation index (percentage) [EC, 2010]

1.1 Background

Widespread concern about biodiversity loss

Causes of biodiversity loss [EC, 2010]

Nature 2000- network of natural habitat and species sites-aimed at preserving biodiversity. The Netherlands 10 % of the territory are Nature 2000 sites [PBL 2003]. Protected areas: mainly major water bodies (surface area of inland waters and the North Sea, in a total of about 2900 km²)

⇒ wetlands have to achieve good ecological status by 2015 (WFD)
1-Introduction
1.1 Background

Water cycle should be optimal!!

All wastewater should undergo a certain level of treatment.

In certain locations
Advanced treatment
Followed by reuse

1-Introduction
1.2 Membrane bioreactors

Conventional activated sludge system: activated sludge separated from treated water (effluent) by sedimentation in secondary clarifier (settling tank).
1-Introduction
1.2 Membrane bioreactors (MBRs)

MBRs are a compact wastewater treatment system in which sludge and clear water are separated by membrane filtration.

MBRs produce a high quality and largely disinfected effluent, therefore especially suitable for reuse purposes or for discharging in environmentally sensitive water bodies.

Pre-treatment: sieves to remove coarse and fine materials.

Bioreactor: removal of carbonaceous material and, if properly designed, phosphorus and nitrogen.

Membranes: usually submerged in the activated sludge of the bioreactor.

Effluent (permeate): no suspended solids and largely disinfected.
1-Introduction
1.2 Membrane bioreactors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Removal efficiency (%)</th>
<th>Permeate quality</th>
<th>WWTP effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSS, mg/L</td>
<td>&gt;99</td>
<td>n.d.</td>
<td>5-8</td>
</tr>
<tr>
<td>Turbidity, NTU</td>
<td>98.8-100</td>
<td>&lt;.3</td>
<td></td>
</tr>
<tr>
<td>COD, mg/L</td>
<td>89-98</td>
<td>10-30</td>
<td>30-70</td>
</tr>
<tr>
<td>BOD, mg/L</td>
<td>&gt;97</td>
<td>&lt;5</td>
<td>4-15</td>
</tr>
<tr>
<td>NH₃-N, mg/L</td>
<td>80 – 90</td>
<td>&lt;5-6</td>
<td>5-12</td>
</tr>
<tr>
<td>NTD, mg/L</td>
<td>36 – 80</td>
<td>&lt;10</td>
<td></td>
</tr>
<tr>
<td>Floc, mg/l</td>
<td>62-97</td>
<td>0.3 – 3</td>
<td>1-3</td>
</tr>
<tr>
<td>Total coliforms, CFU/100 m</td>
<td>5 – 8 log</td>
<td>&lt;100</td>
<td></td>
</tr>
<tr>
<td>Fecal coliforms, CFU/100 mL</td>
<td>-</td>
<td>&lt;20</td>
<td></td>
</tr>
<tr>
<td>Bacteriophages, PFU/100 mL</td>
<td>&gt;3.8 log</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

2- MBR technology background

MBR process:
- Introduced late 1960s
- Invented by Dorr-Oliver Inc
- Application for ship-board sewage treatment
- Activated sludge bioreactor with a cross-flow membrane filtration loop

Early MBR systems:
- Expensive (due to membranes and fouling)
- High energy consumption (10 kWh/m³ produced permeate)
2- MBR technology background

In 1989 Yamamoto presented a new MBR design with submerged membranes; membranes submerged in activated sludge tanks where the static pressure contributed for the extraction of permeate.

New MBR systems:
- Modest fluxes were applied (25% less than earlier systems);
- Air was used to control fouling;
- New MBR design, and decreasing membrane costs, stimulated MBR applications, since mid 1990s.

MBR process configuration: submerged

New MBRs:
- Fouling decreased;
- Membrane cleaning simplified;
- Energy consumption ± 1 kWh/m³ produced permeate.

Commercial options

<table>
<thead>
<tr>
<th></th>
<th>Early MBRs</th>
<th>New MBRs</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRT</td>
<td>100 d</td>
<td>20 d</td>
</tr>
<tr>
<td>MLSS</td>
<td>30 g/L</td>
<td>8-15 g/L</td>
</tr>
</tbody>
</table>

MBR process configurations (a) sidestream (b) submerged [Judd, 2008]
2- MBR technology background

![Diagram of MBR process during the 1990s and the current decade.](Lousada-Ferreira, 2011)

3- Membrane technology

Membrane operations

- Reverse osmosis- separation by different solubility and diffusion rates of water and solutes in water;

- Nanofiltration- separation through combination of charge rejection, solubility-diffusion and sieving through micropores;

- Ultrafiltration- separation by sieving through mesopores;

- Microfiltration- separation of suspended solids from water through macropores.

Components removed by each pressure-driven membrane operation [Judd, 2006]
4 - Process configuration

Membrane process configuration
- Extractive MBRs - membrane used to extract specific components from the bioreactor;
- Diffusive MBRs - membrane used to introduce gas into the bioreactor;
- Rejection MBRs - Biomass is retained in the bioreactor while clarified water goes through the membrane.

**Rejection MBRs**
Biological treatment + membranes (inside or outside the bioreactor)

**Side-stream MBRs**
- Higher fluxes; greater hydrodynamic control
- Lower permeability

**Submerged MBRs**
- Lower fluxes;
- Higher permeability

**Membrane configuration**
- Hollow fiber (HF)
  - Submerged applications
  - Cheaper than FS
  - More cleaning than FS
- Multi-tubular
  - Side-stream applications
- Flat sheet (FS)
  - Submerged applications

Schematic flows through FS (a), HF (b) and tube (c)
4 - Process configuration

- Membranes mounted in modules;
- Modules composed of: membranes, support structures, inlets and outlets.
- Pumps, placed in the clean water side of the membranes, draw the water through the membrane while solids are retained in the bioreactor.
- Compressed air is introduced, by a distribution manifold at the base of the modules, to:
  - keep the biomass in suspension;
  - continuously scour the membrane;
  - provide dissolved oxygen to biomass (if necessary in membrane tanks).

MBRs work in cross-flow filtration mode, i.e. for a single passage of activated sludge across the membrane only a fraction is converted into permeate.

5- Relevant operational parameters

- Trans-membrane pressure (TMP)
  \[ \text{TMP} = \Delta P = P_{\text{feed}} - P_{\text{permeate}} \]
- Flux (J)
  \[ J = \frac{\text{TMP}}{\mu R_t} \]
  - permeate dynamic viscosity [Pa.s]
  - total filtration resistance [m⁻¹]
  - \( J \) [L/m².h]
- Total resistance (Rₜ)
  \[ R_t = R_m + R_f \]
  - clean membrane resistance [m⁻¹]
  - fouling resistance
- Permeability (P)
  \[ P = \frac{J}{\text{TMP}} \]
5 - Relevant operational parameters

- MBRs work with constant flux.

**General operating conditions for submerged MBR:**
- Transmembrane pressure $\rightarrow \pm 20$ kPa
- Flux sustainable long-term $\rightarrow 15 – 30$ L/m²·h
- Solids retention time $\rightarrow > 20$ days
- Hydraulic retention time $\rightarrow 1 – 9$ hours
- Food to mass ratio $\rightarrow < 0.2$ kg COD/ (kg MLSS·day)
- Sludge production $\rightarrow < 0.25$ kg SS/ (kg COD·day)

6 - Advantages vs. disadvantages of MBR technology

**Advantages of MBR technology**
- High quality and largely disinfected effluent (permeate)
- Smaller footprint
- Operation at high MLSS concentration (usually between 8 and 15 g/L)
- Higher volumetric loading rates $\Rightarrow$ shorter HRT
- Longer SRT $\Rightarrow$ less sludge production
- Operation at low DO with potential for simultaneous nitrification-denitrification, in long SRT designs
- Independent control of SRT and HRT

**Disadvantages of MBR technology**
- High capital costs (membranes)
- Potential high cost of membrane replacement (limited data on membrane life time)
- High energy costs
- Need to control membrane fouling
  - Fouling: process leading to deterioration of flux due to surface or internal blockage of the membrane
6 - Advantages vs. disadvantages of MBR technology

Energy consumption at MBR Terneuzen (c) and MBR Heenvliet (a).
(Krzeminski et al. (2012))

7- Fouling

Fouling: Process dealing to deteroration of the flux due to surface or internal blockage of the membranes (Judd, 2006)
Clogging: blockage of the channels between the membranes and/or aerator ports (Judd, 2008)

Schematics of the fouling mechanisms: cake filtration (B), adsorption (C1), pore blocking (C2).
7- Fouling

Fouling during constant flux operation [Kraume, 2009].

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6- Fouling

How to minimize fouling:
• Operate at high shear (more air; more cross-flow velocity...);
• Operate at low flux.

How to remove fouling:
• Physical cleaning: membrane relaxation;
• Chemical cleaning: enhanced backwash, maintenance cleaning or intensive cleaning.

How to limitate fouling:
• Optimizing membrane properties and operating conditions;
• Adding sludge coagulants/flocculents or adsorbent agents.
• (...)

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7- Fouling

- Extracellular Polymeric Substances (EPS)
  - Macromolecules: polysaccharides, proteins, nucleic acids, lipids, etc
  - Function: Substances that bound the particles together
- Soluble microbial products (SMP)
  - Soluble part of EPS, that is, materials that are not integrated in biological flocs
- Dissolved organic matter
- Submicron particles

EPS
microorganisms

7- Fouling

Raw influent

Pre-treatment

Influent characteristics

Flow rate
Suspended solids
Nitrates
Temperature
Toxic substances

Membrane operation

Biomass operation

Recirculation flow
Sludge retention time
Hydraulic retention time
Aeration
Excess sludge removal
Chemical cleaning
Recirculation flows
Solvent concentration
Colloidal matter
Fixed / free EPS, COD, TOC
Salts
pH
Biological activity
Particulate size / shape
Fixed / free EPS, COD, TOC

Sludge / water characteristics

MLSS concentration
Colloidal matter
Fixed / free EPS, COD, TOC
Salts
pH
Microbial activity
Particulate size / shape
Fixed / free EPS, COD, TOC
Dissolved salts
7.1 The Delft Filtration Characterization method

The Delft Filtration Characterization method (DFCm) [Evenblij, 2005] comprises:
1. Measurement of membrane resistance
2. Measurement of sludge filterability
3. Cleaning of the membrane

The Delft Filtration Characterization Installation (DFC)
- Single Tube UF (X-Flow); nominal pore size 0.03 μm
- Constant operation: \( J = 80 \text{ L/m}^2 \cdot \text{h} \); \( V = 1 \text{ m/s} \)

\[ y = 0.0058x^{1.2813} \]
\[ R^2 = 0.9353 \]

- Mass balance
- pH
- O2
- T
- P1
- P2
- P3
- F
- NaOCl
- Demi-water
- Activated sludge
- Back flush pump
- Permeate
- UF
- Membrane
- Sewer
- Sewer
- A
- i
- r
- Centrifugal pump
- Peristaltic pump
- Damper
- Compute
- Peristaltic pump

The volume of sub-micron particles is likely to be a better indicator of sludge filterability than EPS/SMP [Geilvoet, 2010].

8- MBR Technology questions and challenges

• Design and operation:
  • Is a separate membrane tank needed?
  • Which are the optimal operational parameters, such as MLSS concentration or flux?
  • How to further reduce energy consumption in MBRs?

Nordkanal MBR, Germany

8- MBR technology questions and challenges

<table>
<thead>
<tr>
<th>Low MLSS concentration</th>
<th>High MLSS concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design</strong></td>
<td></td>
</tr>
<tr>
<td>Separate membrane tank not required</td>
<td>Separate membrane tank preferable</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td></td>
</tr>
<tr>
<td>Less clogging</td>
<td>More clogging</td>
</tr>
<tr>
<td>Less air required to scour the membrane and provide DO to the biomass</td>
<td>More air required to scour the membrane and provide DO to the biomass</td>
</tr>
<tr>
<td>Less air preferable to promote floc growth</td>
<td>Less air preferable to promote floc growth $\Rightarrow$ Air flow requires optimization</td>
</tr>
<tr>
<td>Applied return ratio is irrelevant</td>
<td>Low return ratio, i.e. lower than 2, preferable to achieve improved filterability</td>
</tr>
</tbody>
</table>

Questions?