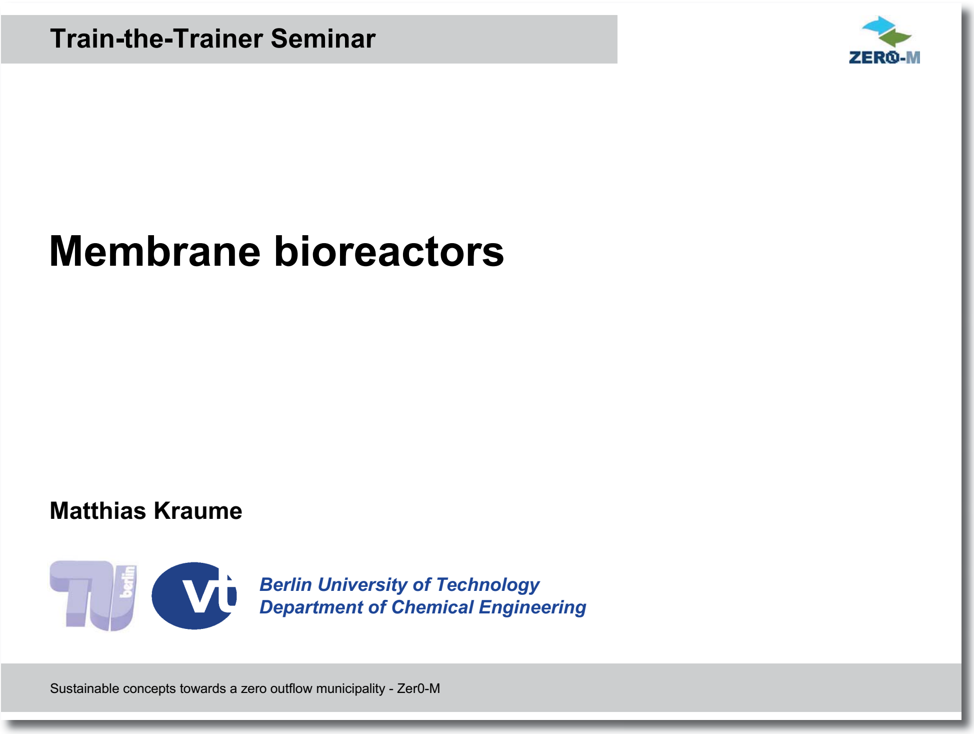

Membrane bioreactors

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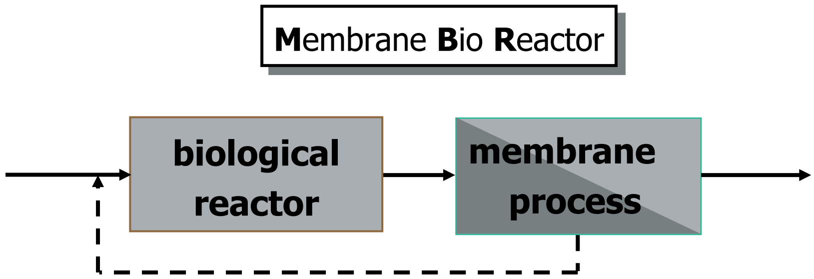
What is an MBR?



combination of a biological reactor and a membrane process to retain the biomass

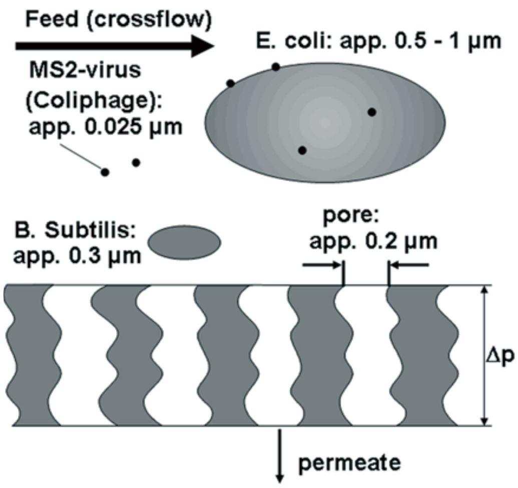
- keep biomass in the biological reactor (reactor performance)
- mechanical disinfection (effluent hygienic quality)

Membrane Bioreactors – 2

What is an MBR?

Combining membrane technology with biological reactors for the treatment of wastewaters has led to the development of three generic membrane bioreactors (MBRs): for separation and retention of solids; for bubble-less aeration within the bioreactor and for extraction of priority organic pollutants from industrial wastewaters. Membranes, when coupled to biological processes, are mostly used as a replacement for sedimentation i.e., for separation of biomass. Systems as such are well documented (Stephenson et al., 2000).

Membrane selection



Membranes:
Micro- or ultrafiltration
hydrophilic material

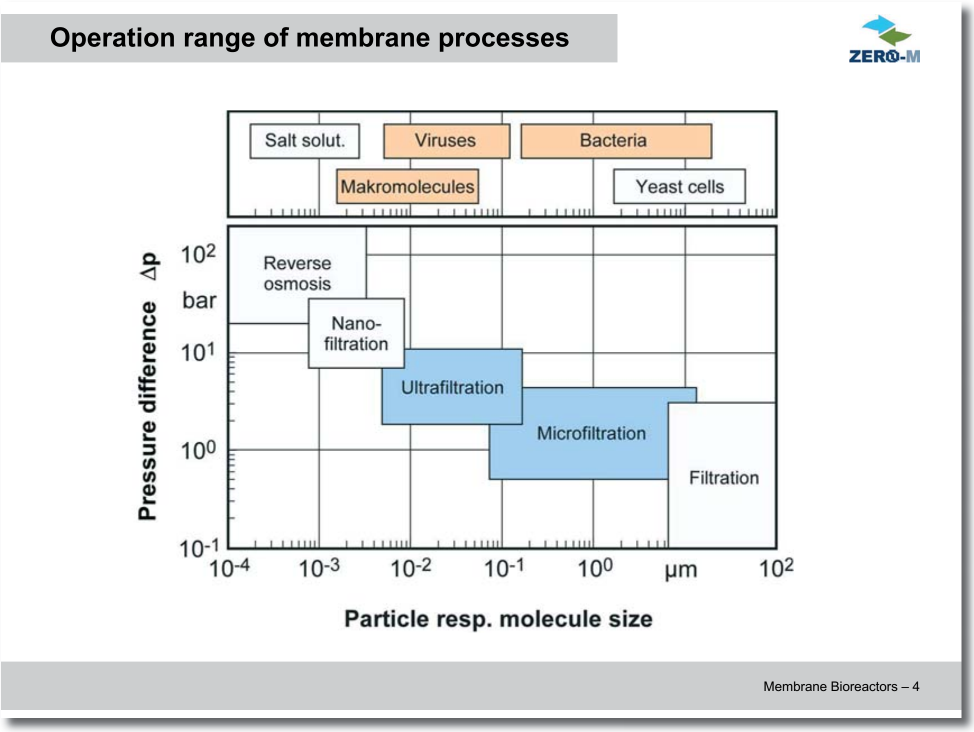
Typical pore sizes:
0,02 - 0,4 µm

Operation:
Parallel flow to membrane surface (**crossflow**) necessary to remove particles

Membrane Bioreactors – 3

Membrane selection

A membrane can be thought of as a material in which one type of substance can pass through more readily than others, thus presenting the basis of a separation process. It is therefore the property of the membrane to separate components of the water to be treated which is of key interest when selecting or designing membrane separation systems duties arising as such in the water industry. For many processes the membrane acts in a way to reject the pollutants, which may be suspended or dissolved and allow the “purified” water through it.



Operation range of membrane processes

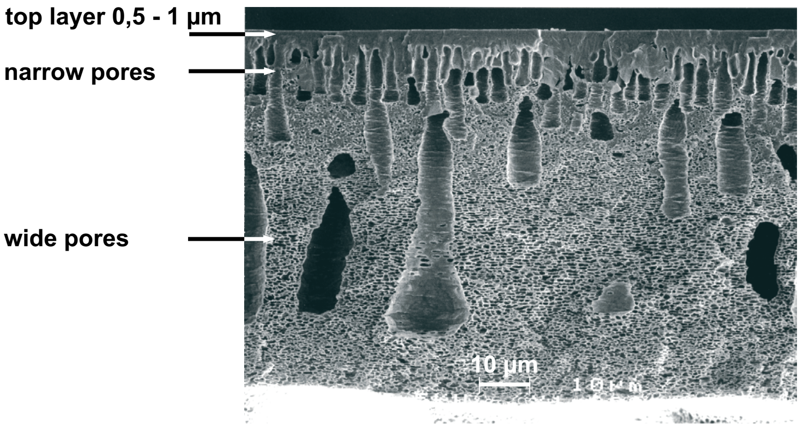
The principal objective in membrane manufacture is to produce a material of reasonable mechanical strength and which can maintain a high throughput of a desired permeate with a high degree of selectivity. These last two parameters are mutually counteractive, since a high degree of selectivity is normally only achievable using a membrane having small pores and thus an inherently high hydraulic resistance (or low permeability). The permeability increases with an increase of density of the pores, implying that a high material porosity is desirable. The overall membrane resistance is directly proportional to its thickness. Finally, selectivity will be compromised by a broad pore size distribution. It stands to reason, therefore, that the optimal physical structure for any membrane material is based on a thin layer of material with a narrow range of pore size and a high surface porosity.

The range of available membrane materials is very diverse. They vary widely both in chemical composition and physical structure, however the most fundamentally important property is the mechanism by which separation is actually achieved. On this basis, membranes may be categorised as either dense or porous.

Separation by dense membranes relies to some extent on physico-chemical interactions between the permeating components and the membrane material and relate to separation processes having the highest selectivity (Figure). **Reverse osmosis** and **nanofiltration** processes are thus able to separate ions from water.

Porous membranes, on the other hand, achieve separation mechanically (i.e. ostensibly by sieving) and are thus mechanistically closer to conventional filtration processes. **Ultrafiltration** can remove colloidal and dissolved macromolecular species and as such their ability to reject material is defined by the molecular weight cut-off (MWCO) in Daltons (i.e. the relative molecular weight) of the rejected solute, rather than its physical size. **Microfiltration**, on the other hand, is capable of removing only suspended materials – generally down to around 0.05 μm in size. It is the porous membranes that are used in MBRs to retain the suspended solids material, mainly biomass, within the reactor while producing a clarified effluent.

Nanofiltration membrane



Membrane Bioreactors – 5

Nanofiltration membrane

A more convenient practical categorisation of membranes depends on the material composition which is generally either organic (polymeric) or inorganic (ceramic or metallic). The physical structure of the membrane based on these materials can vary according to the exact nature of the material and/or the way in which it is processed. In general, membrane materials that are employed in pressure-driven processes tend to be anisotropic; they have symmetry in a single direction so that their pore size varies with membrane depth. It is only the very top layer of the membrane which actually demonstrates substantial permselectivity and the remainder merely provides mechanical support.

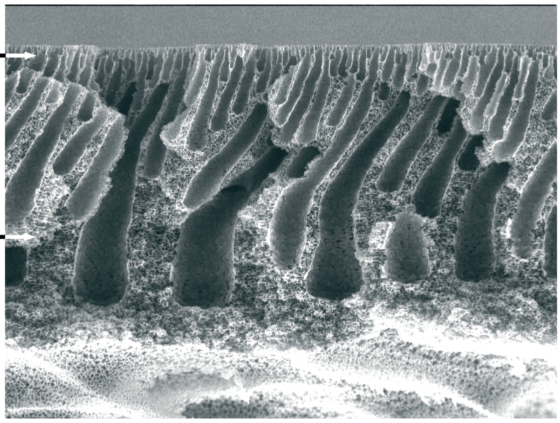
Membrane manufacture primarily refers to the production of a porous material. The cost of the membrane is therefore dependent not only on the raw material but also on the ease with which pores of the desired size or size distribution can be introduced. This can vary considerably between different types of materials and according to the precision of the pore size distribution (or degree of isoporosity).

Inorganic membranes, for example, are formed by the pressing and the sintering of fine powders onto a pre-prepared porous support. This tends to be a very expensive process particularly if a membrane layer of an even thickness and narrow pore size distribution is to be produced. The cost of microfiltration or ultrafiltration membranes that is derived from titanium and/or zirconium may exceed up to € 1500 per m². At the opposite end of the spectrum are simple, homogenous polymeric membranes produced by extrusion (stretching) of partly crystalline sheets perpendicular to the orientation of crystallites possibly with the assistance of a fibrulating agent, such as microscopic glass beads that promote the formation of pores. To produce, these microporous materials cost less than € 15 per m², but are limited in their permeability, isoporosity and mechanical strength.

Ultrafiltration membrane

narrow pores

wide pores



Membrane Bioreactors – 6

Ultrafiltration membrane

Membrane geometry/configuration

Characteristics of optimum geometry or configuration for an individual membrane element:

- high membrane area to module bulk volume ratio
- high degree of turbulence for mass transfer promotion on the feed side
- low energy expenditure per unit product water volume
- low cost per unit membrane area
- a design that facilitates cleaning
- a design that permits modularisation

Membrane Bioreactors – 7

Membrane geometry / configuration

The geometry of the membrane, i.e. the way it is shaped, is crucial in determining the overall process performance. Other practical considerations concern the way in which the individual membrane elements, that is the membranes themselves, are housed to produce modules.

Some of these characteristics are mutually exclusive. For example, promoting turbulence results in an increase in the energy expenditure. Furthermore, direct mechanical cleaning of the membrane is only possible on a comparatively low area: volume units where the membrane is accessible. It is not possible to produce a high-membrane area to module bulk volume ratio without producing a unit that has narrow feed channels, which then adversely affect the cleaning regime and turbulence promotion.

Permeate flux

Flux: quantity of material passing through a unit area of membrane per unit time

The key elements of any membrane process are the influence of the following parameters on the overall permeate flux:

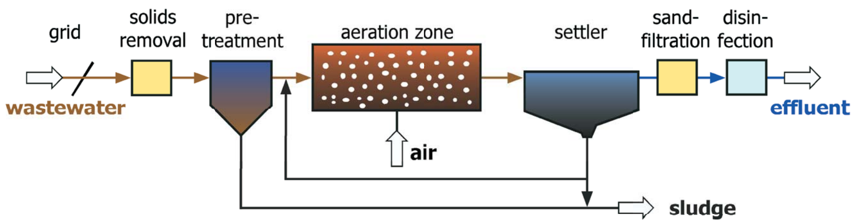
- membrane resistance
- operational driving force per unit membrane area
- hydrodynamic conditions at the membrane: liquid interface
- fouling and subsequent cleaning of the membrane surface

Membrane Bioreactors – 8

Permeate flux

The flux is determined by both the driving force and the total resistance offered by the membrane and the interfacial region adjacent to it. The resistance of the membrane is fixed, unless it becomes partly clogged (or fouled internally) by components in the feed water. The interfacial region resistance is, on the other hand, a function of both feedwater composition and permeate flux, since for a conventional pressure driven process, the materials rejected by the membrane tend to accumulate within the interfacial region at a rate dependent on the flux. These materials may then foul the membrane through a number of physicochemical mechanisms. The process operational efficiency is therefore determined by the extent to which the forces opposing the driving force predominate.

Conventional wastewater treatment plant



Conventional activated sludge process
• well known and established

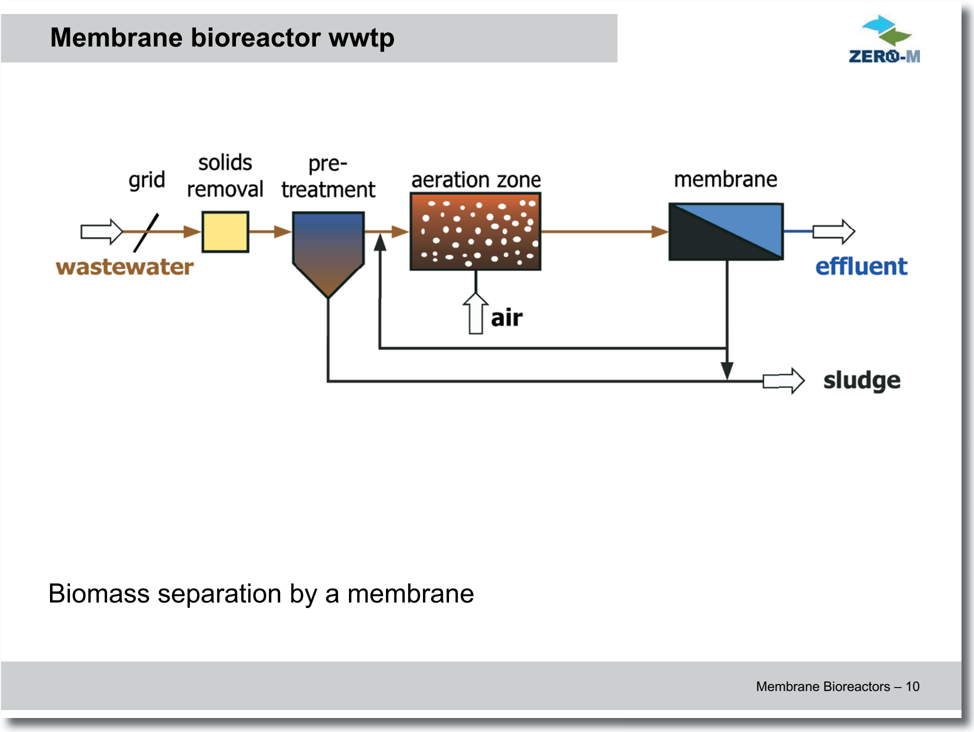
Bottleneck
• biomass separation by gravitation in the settler
(hygienic problems with effluent)

Membrane Bioreactors – 9

Conventional wastewater treatment plant

The conventional activated sludge process (ASP) is the most common biological process in municipal wastewater treatment. Discovered in 1914 by Arden and Lockett, after that commercialised as a continuous process by John and Atwood in 1920, ASP is nowadays well understood and mathematically modelled. However, increasingly stringent effluent quality requirements in industrialised countries and a rising need for water reclamation call for further development of ASP. Current and impeding legislation on wastewater treatment effluent has led to the need of improved treatment processes capable of removing higher percentages of nutrients, suspended solids, bacteria etc.

A several of minimum standards for effluent concentrations exist. Requirements for effluents depend on the type of receiving water (e.g. lakes, lagoons, rivers, aquifers) and its quality category (e.g. in Japan), on the regulations concerning the wastewater treatment technology (e.g. in the USA: Best Practical Technology Standards of Environmental Protection Agency), as well as on special demands locally adapted to the particular receiving water.



Membrane bioreactor wwtp

The implementation of membrane bioreactors (MBR) to wastewater treatment offers the possibility of overcoming a lot of the current problems in activated sludge processes, which are mostly linked to the separation of biomass from the treated water. In MBR the settling process which is normally used for separation of biomass from treated water is replaced by micro- or ultrafiltration. The filtration step can be realised in the form of external side-stream modules or directly immersed modules in the activated sludge tank. With a complete retention of bacteria and viruses this allows a very high effluent quality. Furthermore, it is possible to increase the biomass concentration considerably and thus decrease reactor volumes or sludge production rates. Technical SS concentrations in MBR vary between 8 and 15 g/L for municipal and up to 40 g/L for industrial wastewater treatment.

A number of MBR plants have been established over the last couple of years. The very first applications of MBRs in wastewater treatment date back to the early 70´s. In the meantime, three generations of MBR treatment plangs have been developed and an increasing number of technical plants is coming into operation. Although several practical experiences and data are available for MBR processes there is still considerable optimisation potential.

The advantages and disadvantages of MBRs

Advantages

• Good effluent quality with high hygienic standards

• High possible biomass concentration (10-25 g MLSS/L)

• Reduced reactor volume and footprint

• Reduced net sludge production

Disadvantages

• High investmest costs of membrane modules

• Membrane integrity (failure detection, lifetime)

• High operating costs (energy consumption)

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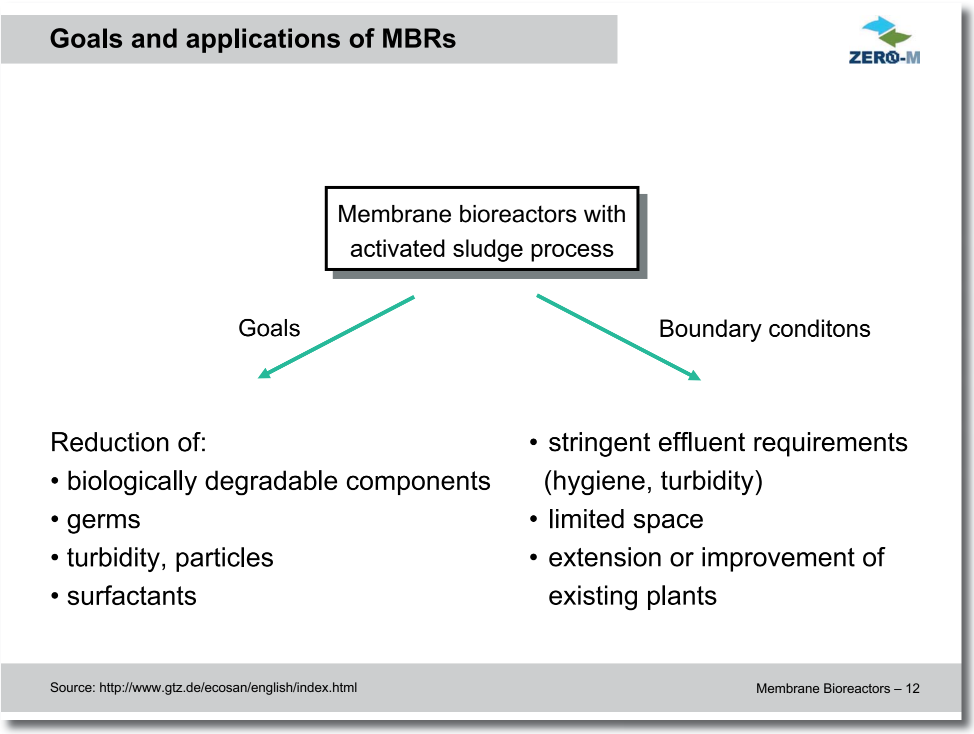
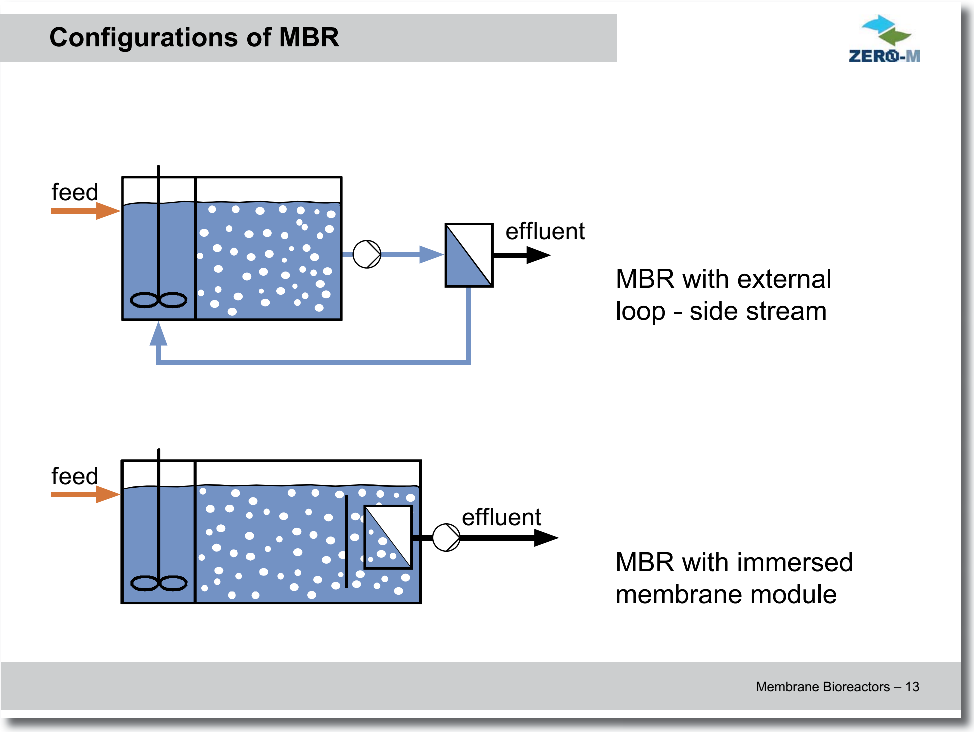
The advantages and disadvantages of MBRs

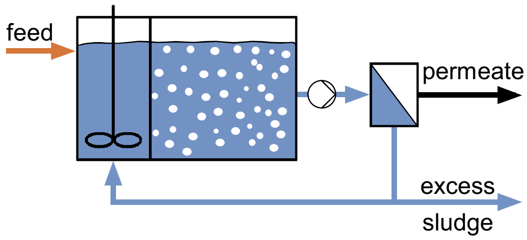


Goals and applications of MBRs



Configurations of MBR

MBR configuration – side stream



Main applications: industrial wastewater treatment

Transmembrane pressure drop:	0.5 - 5 bar
Crossflow velocity:	2 - 5 m/s
Permeate flux:	40 - 120 L/(m² h)
High energy demand	(2 - 10 kWh/m³ permeate)

Source: Stephenson et al. 2000

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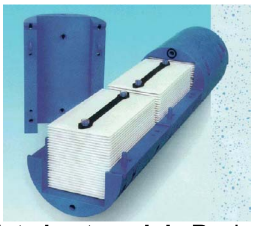
MBR configuration – side stream

Side stream modules

Tubular modules X-Flow

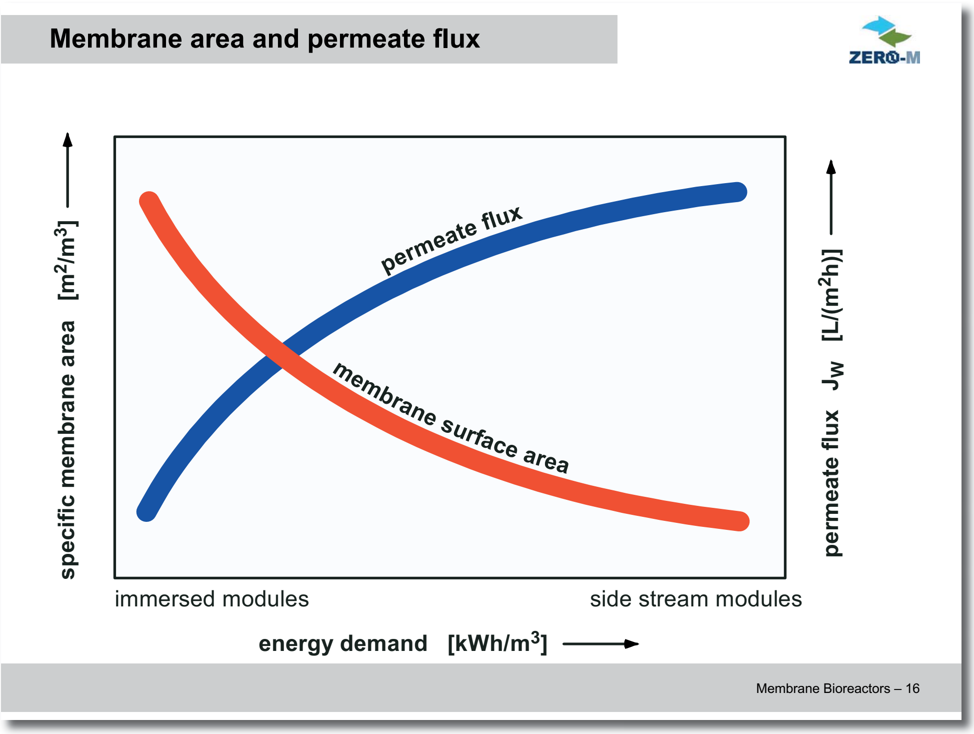
Tubular modules Koch



Flat sheet module Rochem

Housed modules
Tube diameter: 5-15 mm
Membrane material PVDF, PE, PES, PAN

Side stream modules

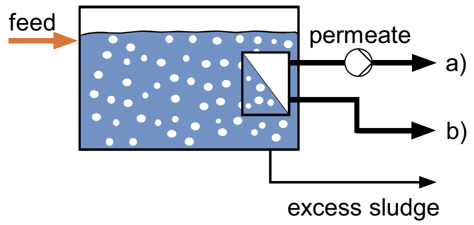


Membrane area and permeate flux

The generation of a cross flow velocity is decisive for a membrane filtration energy demand. A goal of numerous R&D activities is to minimize using the energy required for cross flow necessary to keep the permeate flux on a high level. By this operational and investment costs can be minimized.

The diagram shows the theoretical correlation between membrane area, energy demand, and permeate flux for MBRs.

MBR configuration – immersed membrane modules



Main applications: municipal wastewater treatment

Transmembrane pressure drop:	50 - 500 mbar (pump (a) or gravity flow (b))
Crossflow achieved with special aeration at the bottom of the module	
Permeate flux:	10 - 60 L/(m^2 h)
Low energy demand:	0.2 – 0.8 kWh/m^3 permeate
Large membrane area required	

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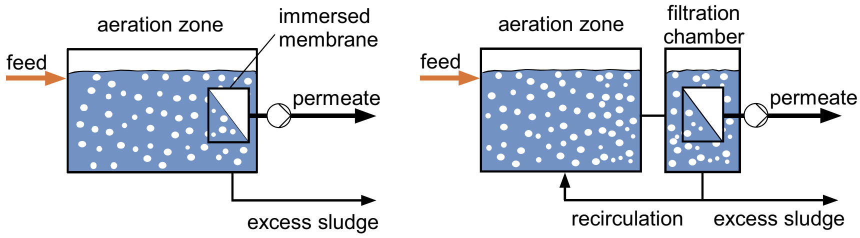
MBR configuration – immersed membrane modules

As with most other membrane applications, the preferable membrane materials for MBRs are invariably polymeric on the simple basis of cost. Geometries employed in key commercial systems range from flat plate/ plate and frame (Kubota, Japan, Rhodia Pleiade-based MBR system, France) to tubular (Milleniumpore, UK) or hollow fibre (Zenon, Canada). The choice of configuration is profoundly influenced by the MBR process configuration, namely by whether the membrane element is placed within the bioreactor or external to it.

Immersed membranes – internal/external



internal installation

- higher biomass concentartion
- no recirculation
- simple construction

external installation

- more flexibilty for maintainance and repair
- no short cuts

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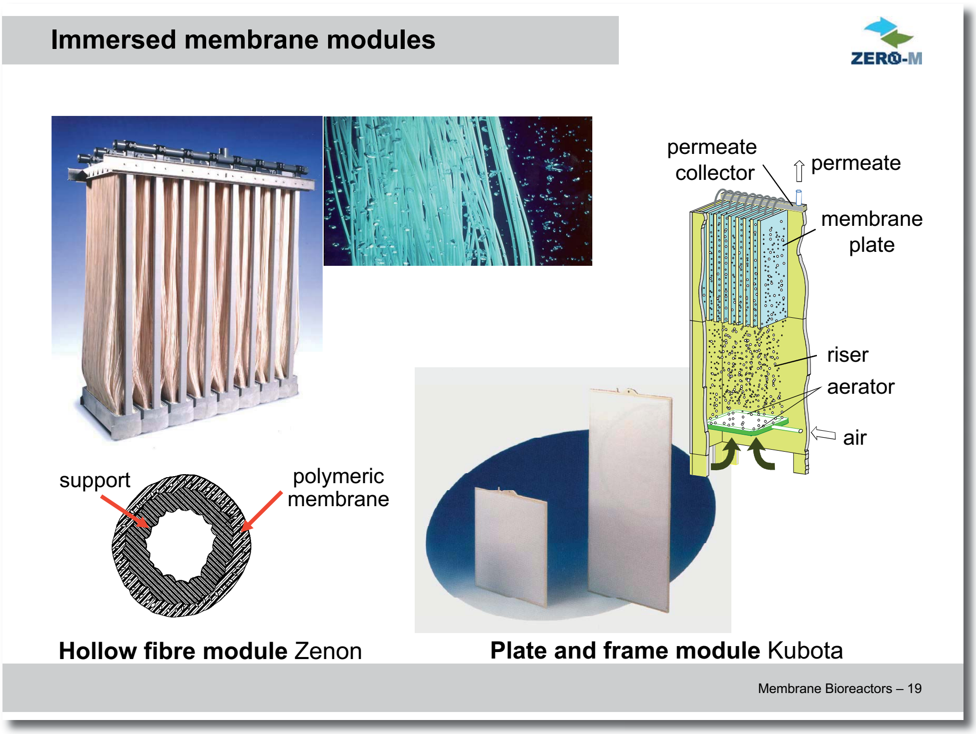
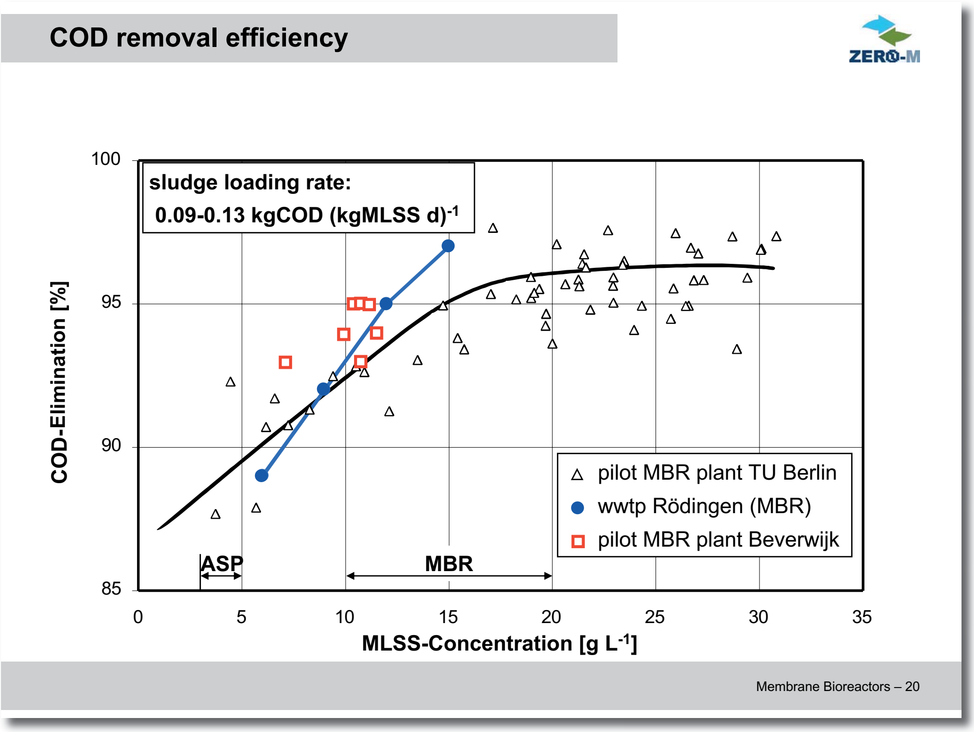
Immersed membrane – internal/external

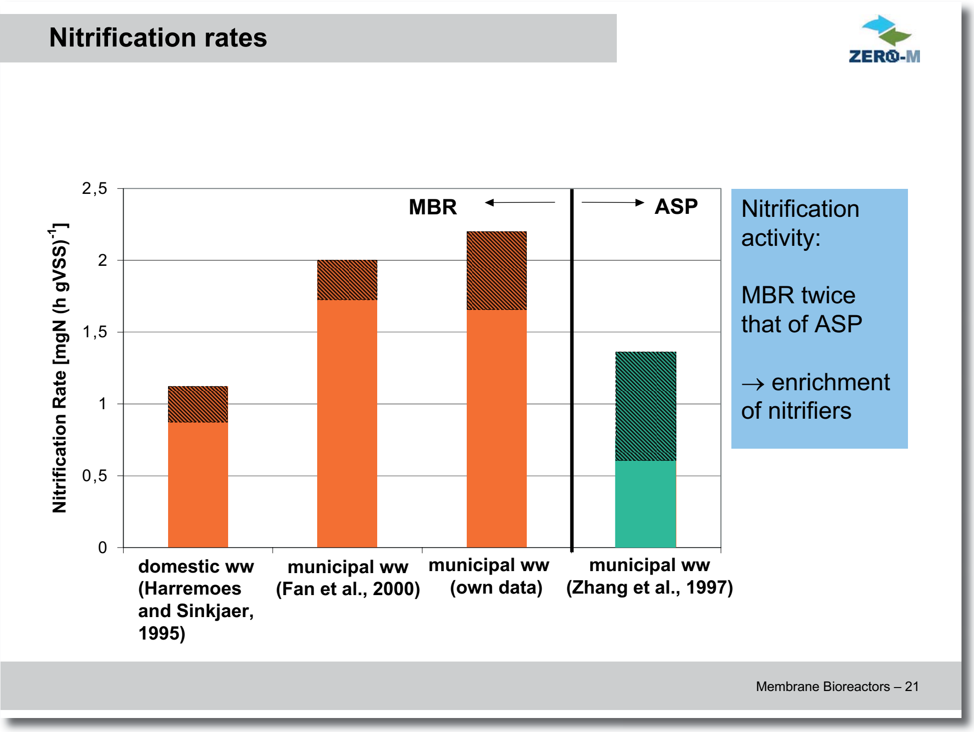


Immersed membrane modules



COD removal efficiency

Simply due to the high number of microorganisms in MBRs, the substrate uptake or reaction rate can be increased. This leads to better degradation in a given time span or to smaller required reactor volume. COD and BOD_5 removal are found to increase with MLSS concentration. Arbitrary high MLSS concentrations are not employed, however, as oxygen transfer is limited due to higher and non-Newtonian viscosities (Rosenberger et al., 2001). Kinetics may also differ due to easier substrate access. In ASP, flocs may reach several 100 µm in size (Wisniewski et al., 1999). This means that the substrate can reach the active sites only by diffusion which causes an additional resistance and limits the overall reaction rate (diffusion controlled). Hydrodynamic stress in MBRs reduces floc size (to 3.5 µm in sidestream MBRs (Cicek et al., 1999)) and increases the apparent reaction rate.



Nitrification rates

Since the amount of energy gained by nitrification is relatively low, nitrifiers are slow growing and a minimum sludge age of > 5 days is necessary in order to ensure complete nitrification (Fan et al., 2000). Therefore, the design of MBR treatment plants is based on a minimum SRT of 8 to 10 days at 10 °C, as can be seen from plant data shown on page II.4.25.

Nitrification is an aerobic process where oxygen is used as the electron acceptor and is therefore necessary for the process to occur. It has been reported that the half-saturation constant for dissolved oxygen (DO) is in the range of 0.3 - 1.3 mg L^{-1} (Charley et al., 1980). MBR plants are usually operated at high MLSS concentrations which lead to an increase in viscosity and a change of rheology (Rosenberger et al., 2002). As a consequence, the degree of mixing decreases and anoxic (nitrate but no oxygen present) micro zones can be present in the aerated tank resulting in simultaneous denitrification. On the other hand, exceeding MLSS concentrations cause problems with membrane performance and oxygen mass transfer rate because of high sludge viscosity (Rosenberger et al., 2001). These considerations currently lead to optimal MLSS concentrations of around 15 g L^{-1} for the most effective MBR operation. Typically MBR plants of technical size achieve total nitrification with effluent ammonia concentrations of below 1 mg NH_4-N L^{-1}.

The maximum specific nitrification rates reported are e.g.: 1.7 - 2.0 mg NO_3-N (gVSS h)$^{-1}$ for municipal wastewater (Fan et al., 2000), 0.91 - 1.12 mg NO_3-N (gVSS h)$^{-1}$ for domestic wastewater (Harremoes and Sinkjaer, 1995), and 0.78 - 1.81 mg NO_3-N (gSS h)$^{-1}$ for synthetic wastewater (Muller, 1994). However, the mean nitrification activity has been demonstrated to be more than twice that of an equivalent ASP: 2.28 g NH_4- N (kgMLSS h)$^{-1}$ for an MBR compared to 0.96 g NH_4-N (kgMLSS h)$^{-1}$ for an ASP (Zhang et al., 1997).

Loading rates

wastewater treament plant	reactor volume (incl. MF) [m³]	PE	loading rate [$kgBOD_5/(m^3 \cdot d)$]
Rödingen	480	3000	0,38
Markranstädt	1780	12000	0,4
Monheim	1660	9700	0,35
Simmerath	136	750	0,33
Büchel	190	1000	0,32
Knautnaundorf	68	900	0,79

➔ Loading rates range from 50-100 % higher than for conventional ASP

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Loading rates

Process conditions and degrees of removal

	Unit	Conventional ASP	MBR I	MBR II	ZenoGem Milton (USA)	6 German 750-12,000 EP plants
SRT	d	10 - 25	< 30	30	> 15	25-28
HRT	h	4 - 8	> 6	8	3	< 10
MLSS	kg m^{-3}	5	12-16		15-20	8-16
BOD_5						
loading rate	kg m^{-3} d^{-1}	0.25		0.4 - 0.7	2.5	0.32 - 0.79
removal	%	85 - 95		98 - 99	> 99	98
effluent conc.	mg L^{-1}	15			< 2	< 5
COD						
removal	%	94.5		99		96.1
effluent conc.	mg L^{-1}		< 30			< 25
NH_4^+ removal	%	98.9		99.2		

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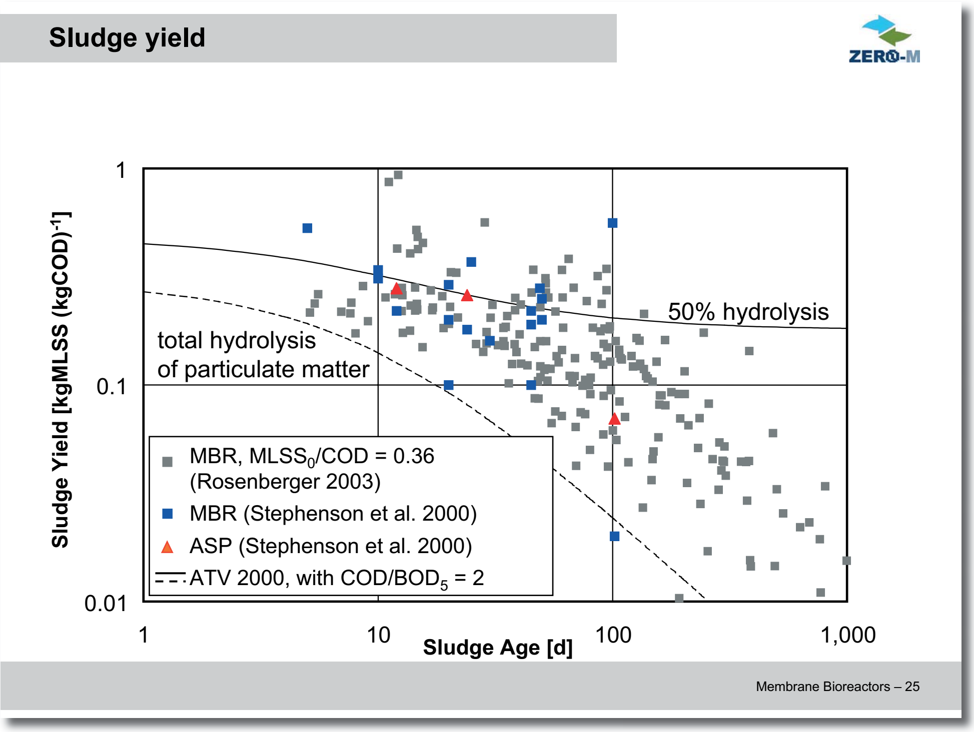
Process conditions and degrees of removal

As shown in the table, sludge ages or SRTs in the realised MBR plants and processes exceed only slightly those in ASP. HRTs are in the same range. With around 15 kg m^{-3}, MLSS concentrations in the MBR process are three times higher than in ASP. BOD_5 loading rates can thereby be increased accordingly, by yielding F:M ratios in a similar range. With regards to organic load, discharge standards are always met. Effluent BOD_5 is always < 10 mg L^{-1}. The higher removal rates can also be attributed to complete particulate retention of suspended COD and BOD_5, high molecular weight organics and biomass (no washout problems as encountered in ASP) (Stephenson et al., 2000).

Membrane area required – permeate flux

Wastewater treatment plant (Germanny)	module system	area [m²]	max. feeding rate [m³/h]	max. net flux [L/(m²h)]	average net flux [L/(m²h)]	capacity [m³/d]
Rödingen	Zenon	4416	135	25,5	12,7	450
Markranstädt	Zenon	8800	180	20,5		2124
Monheim	Zenon	12300	288	23,4	13,2	1820
Simmerath	Puron	940	26,1	27,8	15,2	
Büchel	Kubota	960	50			630
Knautnaundorf	VRM	756	-	24,3	17,6	112,5

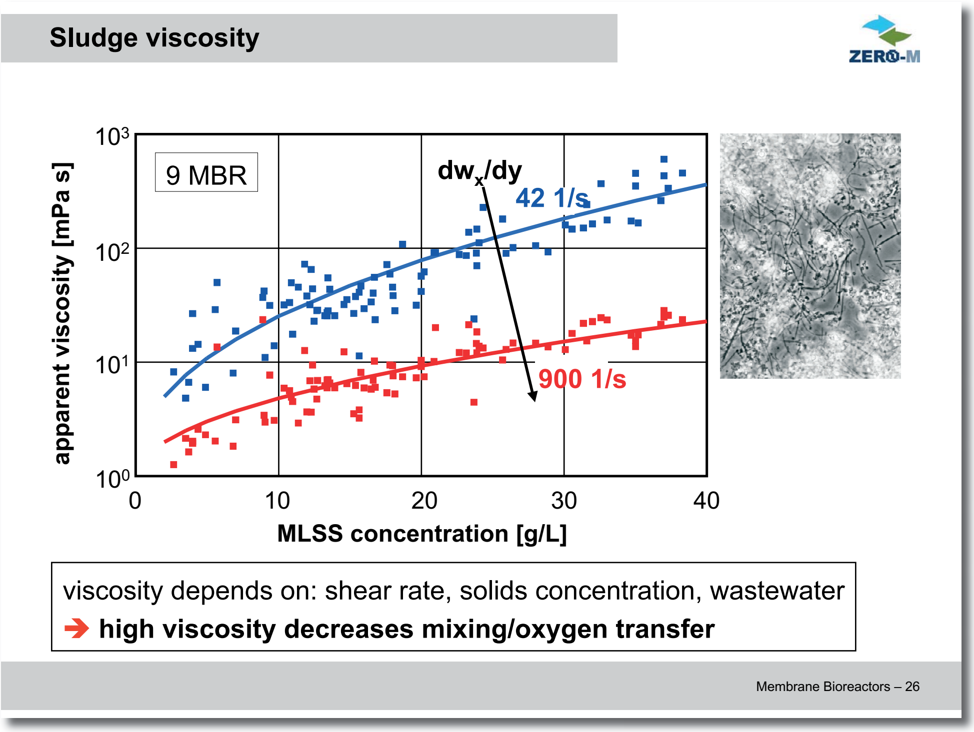
Membrane area required – permeate flux



Sludge yield

Of the many ways of reducing sludge yield in aerobic systems the most simple in suspended growth systems is to increase the sludge age, i.e. reduce the wastage rate. The organic substrate is used by micro-organisms for two things; synthesis of more biomass and for cell maintenance. The latter results in production of waste gases – methane and carbon dioxide if anaerobic, nitrogen and carbon dioxide if anoxic and carbon dioxide if aerobic. Therefore, the higher the yield coefficient, the more biomass and less carbon dioxide is produced from the degradation of the substrate.

At technical scale, no significant decrease in excess sludge production is reported for sludge ages < 30 d in the German WWTPs Markranstädt and Rödingen. In order to significantly reduce excess sludge formation, sludge age needs to be increased to > 100 d (Kraume and Bracklow, 2003). At the MBR plant on Magnetic Island (Australia), 0.48 kg MLSS (kg COD)$^{-1}$ are produced including precipitation solids. With 0.25 kg MLSS (kg COD)$^{-1}$, biological sludge yield is on the same line as for conventional ASP (de Haas et al., 2004).



Sludge viscosity

Rheological measurements of highly concentrated activated sludge show a strongly pseudoplastic behaviour indicating that MBR activated sludge has to be regarded as a non-Newtonian fluid. The value of apparent viscosity can vary up to factor 10 or even 100 between low and high shear rates (see table above). Activated sludge also shows a slightly time-dependent rheological behaviour. An explanation for pseudoplastic and thixotropic behaviour can be found in the bioparticulate structure of activated sludge. The particles tend to flocculate in a large-scale network. With increasing shear rate, this network is disrupted and aligned that results in a decrease in viscosity.

The non-Newtonian behaviour of highly concentrated activated sludge has a strong impact on the operation of membrane bioreactors: in areas with low convection viscosity increases by one or two orders of magnitude. This is likely to form dead zones and thus decrease the effective volume of the activated sludge compartment. In addition, clogging, especially of the membrane modules, is difficult to remove without additional energy supply.

Increasing viscosity is one of the limiting factors for economically reasonable MLSS concentrations in MBR. Energy consumption both for mixing and convection along the membrane surface and for oxygen mass transfer increase with higher viscosity (Rosenberger et al., 2002).

Aeration

Goals

- Oxygen supply for aerobic microbial activity
- Hydrodynamic mixing of activated sludge
- Generation of liquid velocity at submerged membrane surfaces

Oxygen transfer rate (OTR)

- Limitations due to high biomass concentrations (OTR_{sludge}/OTR_{water} <1)
- OTR increases with increased air flow rate (increasing energy demand)
- OTR increases with oxygen-enriched air (increased oxygen costs)

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Aeration

In conventional aerobic biological wastewater treatment processes oxygen is usually supplied as atmospheric air, either via submerged air-bubble diffusers or surface aeration. Diffused air bubbles are added to the bulk liquid (activated sludge) or oxygen transfer occurs from the surrounding air to the bulk liquid via the liquid/air interface. The oxygen required by a biological process to degrade a known amount of organic matter can be calculated from:

$$Q_o = OUE \cdot Q\,(S - S_e) + b \cdot VX$$

where Q_o is oxygen requirement (kg d^{-1}), OUE is oxygen utilisation efficiency (dimensionless) and b is the endogenous oxygen demand coefficient (d^{-1}). It can be seen from this equation that in addition to the substrate exerting an oxygen demand, a higher MLSS will increase demand.

In order to satisfy the oxygen requirement, the gas has to be transferred into the liquid at a fast enough rate; this can be calculated from:

$$OTR = K_L a \cdot (C^* - C)$$

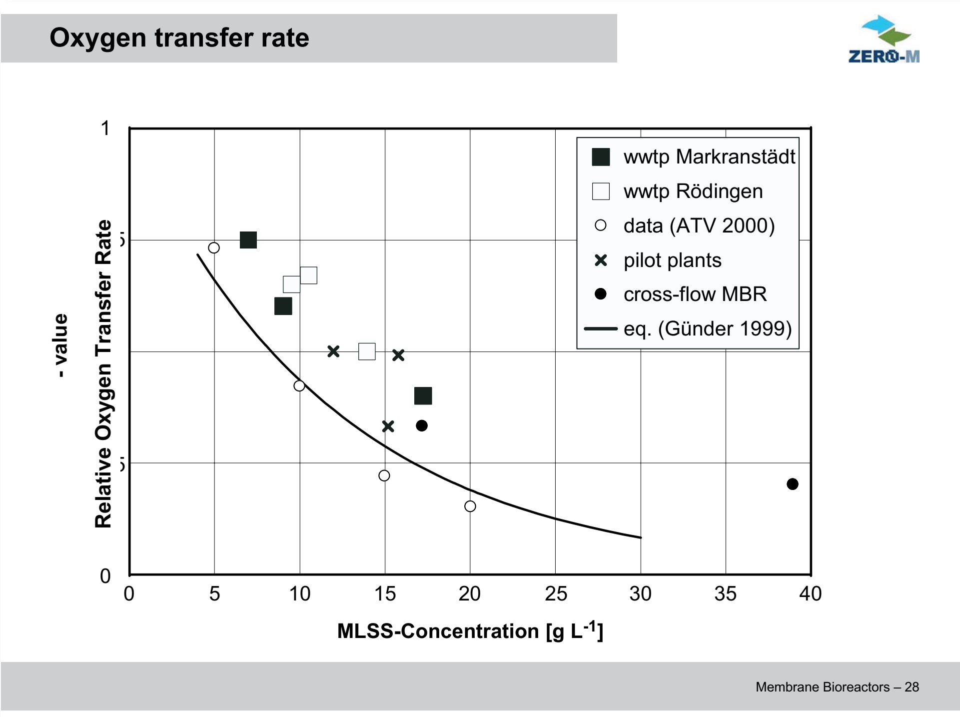
where OTR is oxygen transfer rate (kg m^{-3} d^{-1}), $K_L a$ is the overall mass transfer coefficient (d^{-1}), a is the gas-liquid interface surface area (m^2), C* is the oxygen saturation concentration ($kg \cdot m^{-3}$) and C is the dissolved oxygen concentration ($kg \cdot m^{-3}$). The dissolved oxygen concentration in equilibrium with the oxygen partial pressure can be calculated from Henry‘s Law:

$$C^* = P_T \cdot \text{mole fraction of } O_2 \text{ in gas} / H_C$$

where H_C is Henry‘s constant (bar m^3 kg^{-1}) and P_T is total gas pressure (bar).

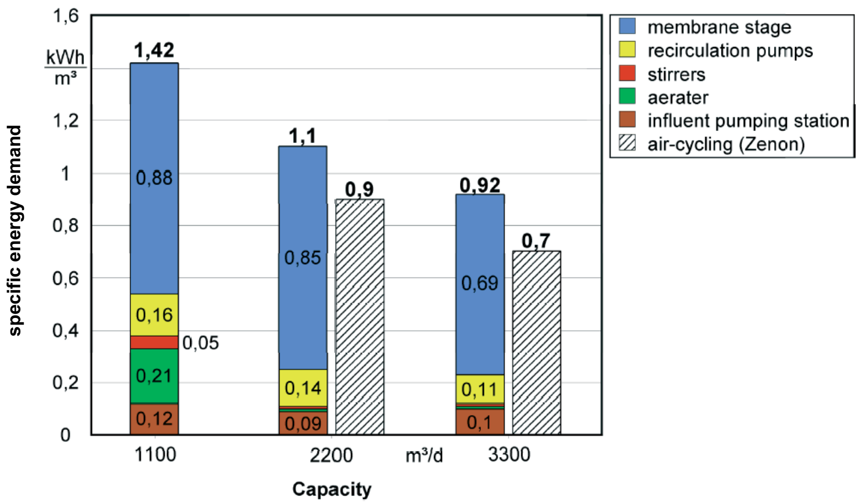
As well as providing the oxygen required for microbial activity, aeration is also used for hydrodynamic mixing to ensure high mass transfer rates. A compromise must be made regarding the amount of aeration and the ideal bubble size required to satisfy this dual role. Consequently, oxygen utilisation can be surprisingly low; typically 80 to 90 % of oxygen diffused as air in the activated sludge process is lost to atmosphere.

Air aeration limitations can be overcome by using oxygen-enriched air or high purity oxygen, the latter treatment increases the saturation concentration (C*) by approximately 4.7 times. Such processes have a greater volumetric degradation capacity compared to conventional air aeration processes. As a result of the high cost of oxygen, processes need to achieve high OUEs.



Oxygen transfer rate

Energy demand



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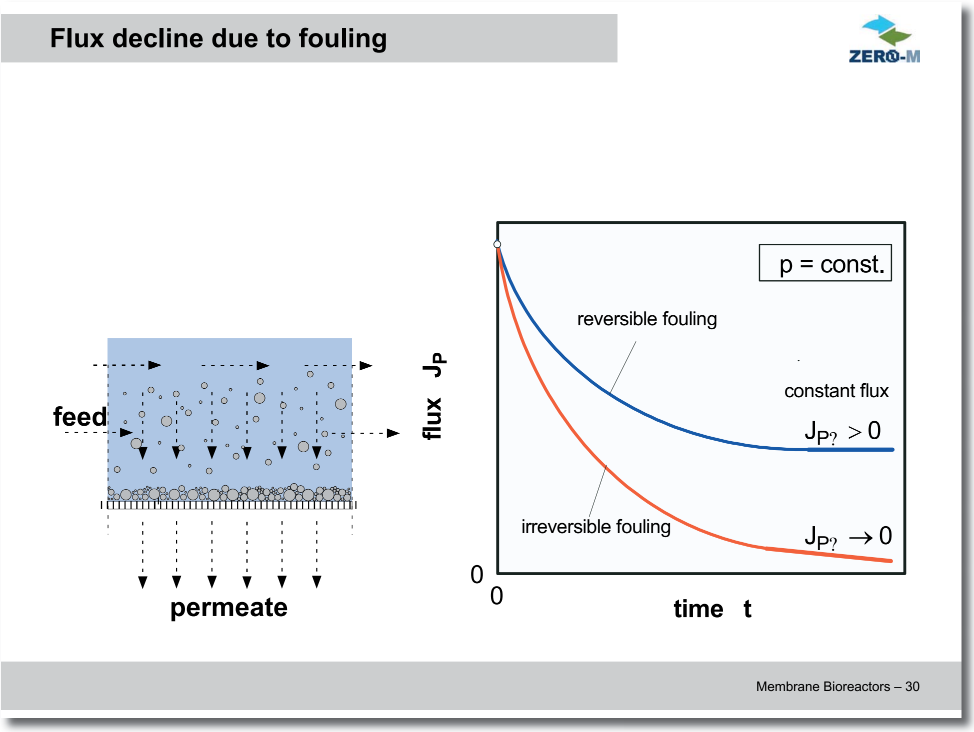
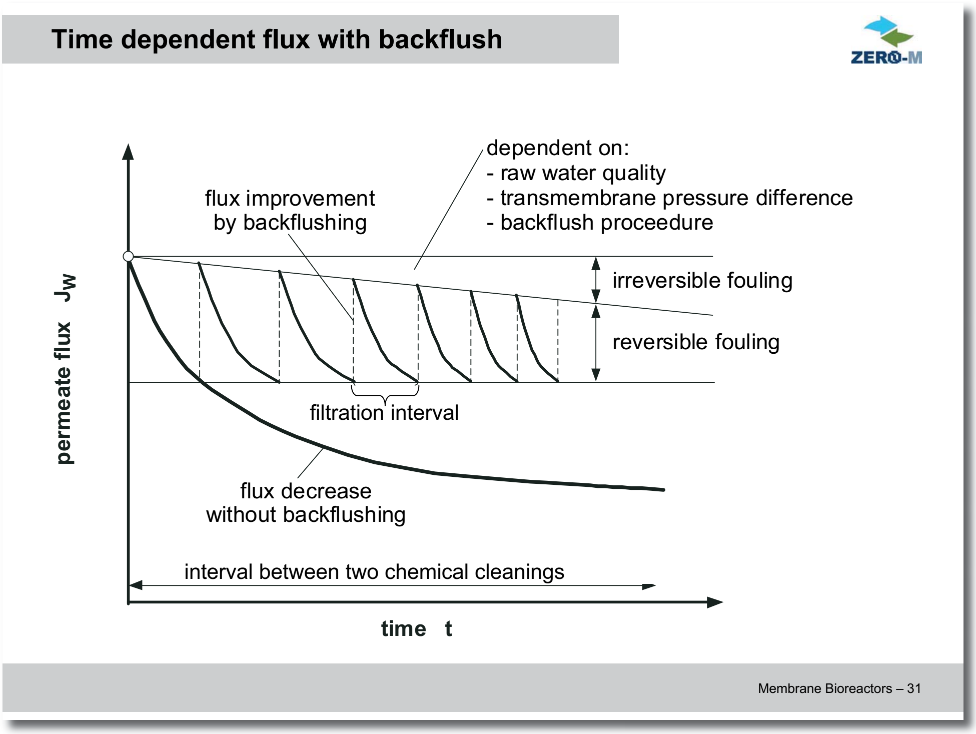
Energy demand

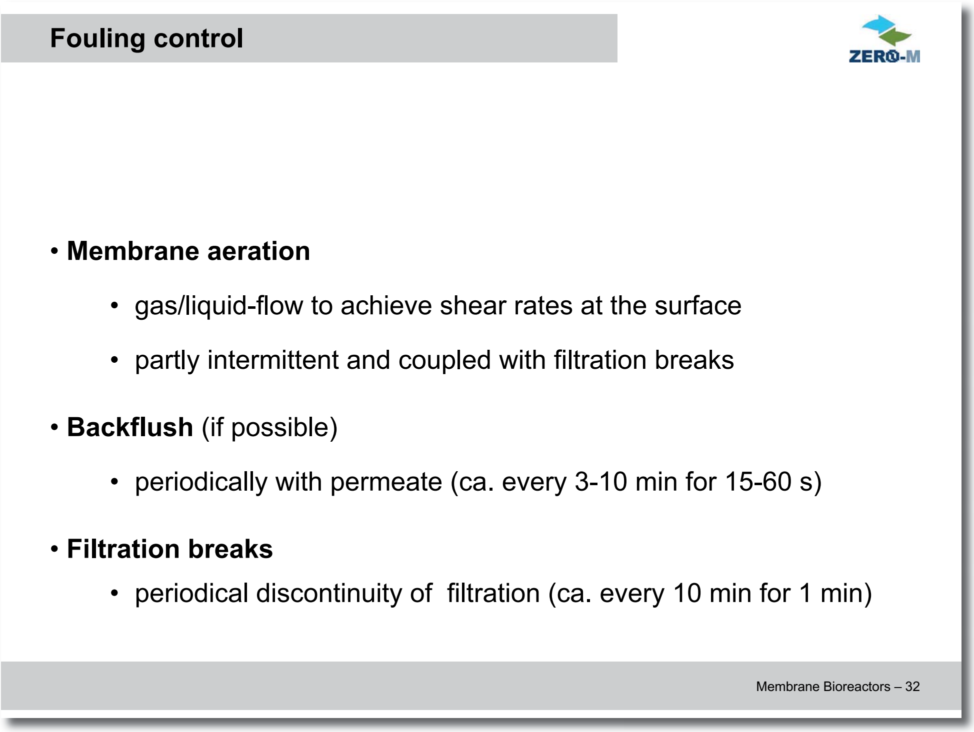


Flux decline due to fouling

Fouling is the general term given to the process by which a variety of species present in the water increase the membrane resistance, by adsorbing or depositing onto its´ surface, adsorption onto the pore surfaces within the bulk membrane material (pore restriction) or by complete pore-blocking. Fouling can occur through a number of physicochemical and biological mechanisms. Fouling by individual components tends to be specific to the membrane material and application, but in general physico-chemical fouling, i.e. fouling unrelated to biological growth, can be attributed to two key components in the feed: proteins and colloidal/particulate materials (Stephenson et al., 2000).



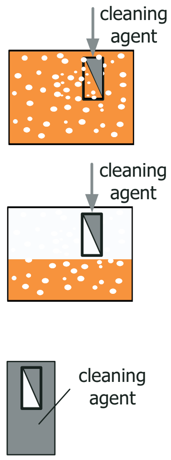
Time dependent flux with backflush



Fouling control

Fouling can be suppressed in three ways: (a) pretreatment or in-treatment (i.e. membrane cleaning) to remove foulants; (b) promotion of turbulence to limit the thickness of the hydrodynamic boundary layer and (c) reduction of the flux. Since all of these options add to the overall cost, for either ostensibly operational (b) or capital (a, c), it is essential to optimize the system so that it suppresses fouling or ameliorates problems introduced by it, in such a way without excessively adding to the cost. In MBRs it is not feasible to remove the foulants by pretreatment, since it is these constituents that form a large part of the organic load which the MBR treats. Of the two remaining options, turbulence promotion is achieved by operating in a relatively wide bore of channel membrane elements that are placed external to the bioreactor at high crossflow. Flux reduction is employed for MBR systems in which the membrane is submerged in the bioreactor itself thereby limiting the degree of possible turbulence promotion.

Chemical membrane cleaning



in-situ

- recirculation with cleaning agents
- addition to aerated tank

on-air

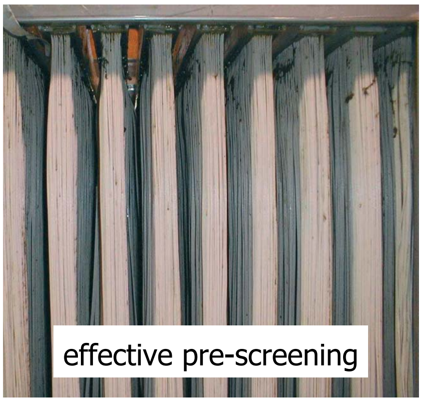
- undiluted application of cleaning agent

external cleaning

- dismounting of modules, separate cleaning tank

Chemical membrane cleaning

Pretreatment



- low concentrations of coarse/fabric material (min. 3 mm pre-screening)
- low conc. of greasy substances (aerated grit chamber and grease trap)

Source: Zenon Environmental

Membrane Bioreactors – 34

Pretreatment

WWTP Nordkanal (Germany) 80.000 PE

Capacity

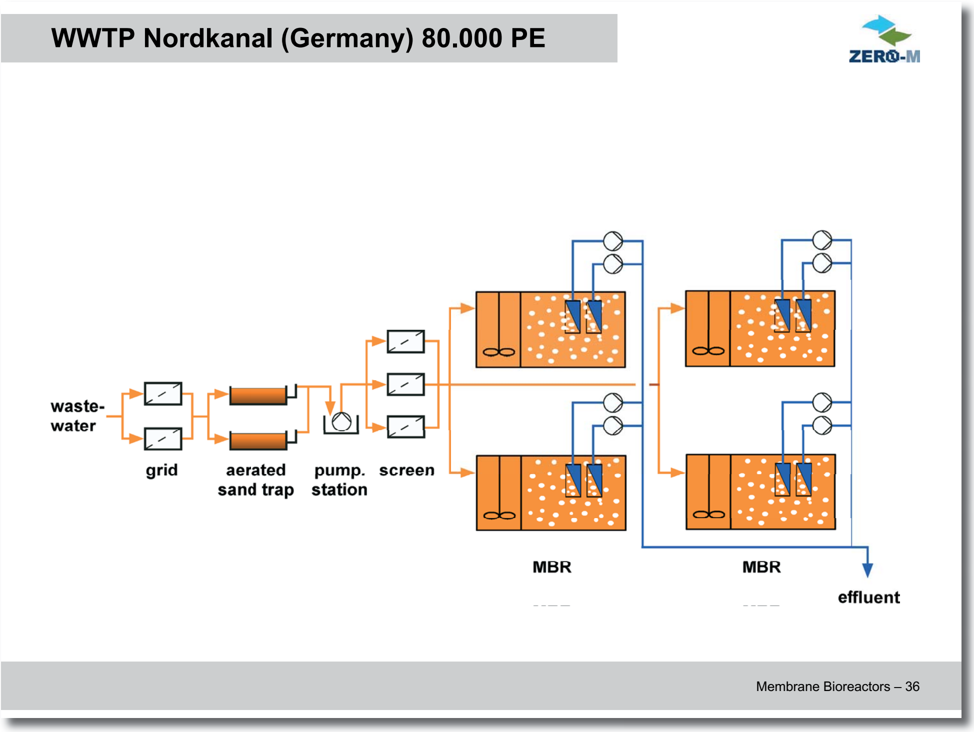
- 80,000 PE
- wastewater influent 16,000 m^3/d
- COD 9,600 kg/d
- BOD_5 5250 kg/d
- suspended solids 5,600 kg/d

Design

- total volume 9,200 m^3
- membrane surface area 88,000 m^2

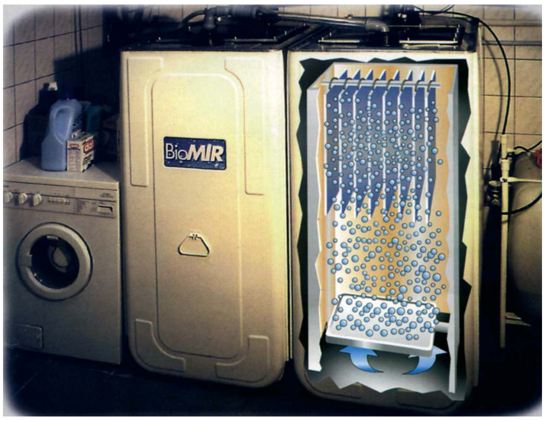
Membrane Bioreactors – 35

WWTP Nordkanal (Germany) 80.000 PE



WWTP Nordkanal (Germany) 80.000 PE

Domestic wastewater treatment



Small scale plant BioMIR©:

4 – 8 persons

2 - 3 m³ reactor volume

2,4 - 4,8 m² membrane area

➔ **small scale decentralized plants**

Membrane Bioreactors – 37

Domestic wastewater treatment

Conclusions

Membrane bioreactors
- several advantages compared to the conventional processes
- a modern and highly effective process
- treatment costs are approximately competitive

Drawbacks
- high energy consumption
- high cleaning effort due to intensive fouling
- reduced oxygen transfer rates for higher MLSS concentrations

Tasks and trends
- longer operation times without cleaning
- reduction of energy demand for aeration
- management of increased hydraulic loads

} **optimum MLSS concentration**

Membrane Bioreactors – 38

Conclusions

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