1

Membrane Bioreactors

1.1. Introduction

Membrane bioreactors (MBRs) provide biological treatment using activated sludge and membrane filtration. Due to membrane integration, treatment can be carried out without a clarifier. The presence of membranes in the process helps to avoid all the problems related to final clarification and increases the compactness of the treatment system.

The joint use of membranes and activated sludge emerged in the late 1960s. The technique has significantly evolved with the nature of the membranes used, and its application has considerably increased in the past 10 years. In terms of design, the MBR process is equivalent to the standard activated sludge process, but the secondary settling tank (clarification tank) is replaced by membrane filtration. Indeed, in the MBR process, membranes are barriers that retain all micro-particles, large molecules, viruses and bacteria but, at the same time, organic matter is biodegraded in a bioreactor. Compared to other standard biological systems, MBRs provide higher quality effluent thanks to higher particle retention (total liquid/solid separation) and a high biomass content (controlled by the sludge retention time independently of the hydraulic retention time) adapted to the pollutant load. However, the factors that influence MBR purification performances remain the properties of membranes, the membrane module structure, the operating conditions and the bioreactor parameters.

Therefore, biological treatment is possible at high sludge concentrations (MES concentration between 8 and 15 $g.L^{-1}$), which enables work with high volume loading with low mass loading.

Membrane treatment provides high reliability due to the physical barrier represented by the membrane: no sludge loss and very high quality treated water. This is why MBRs have many advantages compared to the conventional wastewater treatment processes. The result is small dimensions, high quality filtered water, good disinfection capacity, higher volume loading and less sludge production. Consequently, the MBR process became an interesting option for the treatment and reuse of industrial and municipal wastewaters.

The range of membrane filtration adapted to membrane bioreactors extends from microfiltration to ultrafiltration (between 0.1 and 0.02 µm).

The MBR process is more resilient to loading variations and ensures constant quality for the effluent exiting the treatment line. MBRs provide a purification installation performing two functions on an ongoing basis: a biological purification function and a clarification function. Hence, the removal of dissolved and particulate pollutants leads to obtaining treated water of excellent quality that can be used for a wide range of applications. MBRs are therefore a hybrid technology that combine a biological system and a stage of separation on a porous membrane. This technology is an improvement of the biological system with activated sludge dating back to 1905, characterized by the replacement of the standard secondary settling tank by a membrane filtration unit, whose remarkable selectivity represents a barrier that cannot be crossed by purifying species, irrespective of their flocculation state. The metabolization process with its two aspects (anabolism and catabolism) observed in a system of activated sludge is similar to the one involved in MBR.

The modules containing membranes can be placed either on the external loop with activated sludge or directly in the reaction tank.

An MBR operation involves several automatically unfolding stages, mainly linked to membrane filtration, whose result is treated water and membrane cleaning.

MBR performances are the result of a combination of three factors:

– characteristics of activated sludge;

– membrane properties;

– membrane operating conditions.

1.2. MBR configurations

The use of membranes instead of a clarifier changes the definition of the "soluble" part of pollution as, depending on the membrane retention threshold, membrane walls remain impenetrable for a fraction of – or even all – colloids, which leads to a significant increase in the COD reduction in the case of high COD in raw water compared to the conventional activated sludge process.

Furthermore, the surface of the membrane is calculated based on the hydraulic loading of the plant. The higher the latter, the wider the membrane surface should be.

Due to these two aspects, the MBR process is a highly competitive system for the treatment of highly concentrated wastewater.

However, the MBR filtration performances inevitably decrease with filtration time. This is due to the deposit of soluble and particulate materials on and in the membrane, resulting from the interactions between the activated sludge components and the membrane.

MBR implementation includes pretreatments and activated sludge-based biological treatment, with sludge extraction towards a treatment workshop in a membrane filtration facility with an associated reactive facility for membrane cleaning.

Main treatment domains	MBR application domains
Treatment of carbon pollution	Concentrated effluents
Nitrification	Industrial effluents: particularly competitive for effluents with a very high COD concentration ($\geq$ 2,000 mg.L^{-1})
Nitrification/denitrification	Rehabilitation of existing plants
Treatment of carbon, nitrogen and phosphorus	Severe implementation constraints
Disinfection, mainly related to bacteria, protozoa	Very high quality water is needed: in situ recycling of treated water, reuse of water for irrigation or industrial needs, infiltration of treated water, discharge in sensitive area
Removal of ions and micropollutants	Pretreatment for secondary filtration of the reverse osmosis type

Table 1.1. *Main fields of treatment and application of the MBR process*

Membranes are often arranged into “rows” or “series”, sets using shared equipment (permeate piping, cleaning, concentrate piping). The module configuration strongly influences the global performances of the MBR processes. This configuration must facilitate a homogeneous distribution of the flow rate, high turbulences at the surface of the membrane, low energy cost, a strategy for easy cleaning and easy maintenance.

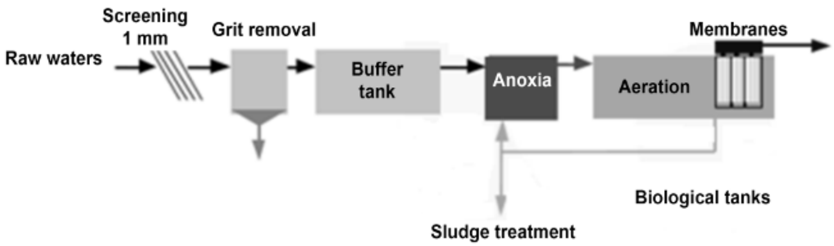


Figure 1.1. *Standard MBR wastewater treatment chain*

Considering these aspects, two general trends are manifest in practice.

Immersed membrane systems initially operated under cross-flow conditions. Depending on the concept, activated sludge could be pumped in the membrane modules placed next to the biological tank, leading to high performances and fluxes, but with high energy consumption.

Consequently, this was the preferred solution for the difficult cases of wastewater and for low flow rates. But due to airlift development and energy saving processes, it was extended to large volumes to be treated.

Two solutions are therefore implemented depending on membrane arrangement and insertion:

– a configuration known as immersed in a single tank (membranes immersed in the aerobic tank) (see Figure 1.2);

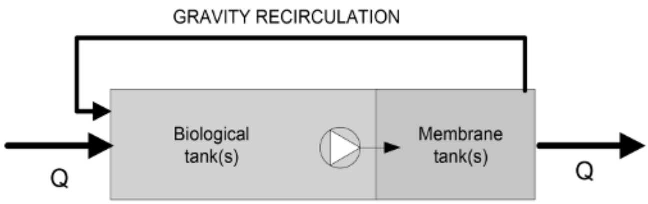


Figure 1.2. *Configuration known as immersed in a single tank*

– a configuration known as immersed in a separate tank (membranes immersed in tanks designed for filtration) (see Figure 1.3).

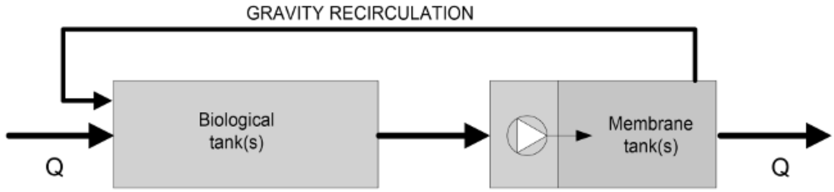


Figure 1.3. *Configuration known as immersed in a separate tank*

The membranes immersed in a single tank with the biological sludge are generally designed with hollow fiber or flat sheet membranes. A part of the air used to maintain aerobic conditions in the tank is then also used to support turbulences and proper circulation around membrane modules.

Due to the low turbulence facilitated around immersed membranes, they are preferred for the treatment of municipal wastewater.

Given their lower energy consumption, they are preferred by manufacturers. This system requires, however, intensive pretreatment and regular maintenance cleaning to maintain stable performances and avoid operational difficulties such as fiber clogging caused by hair or a poor distribution of turbulences.

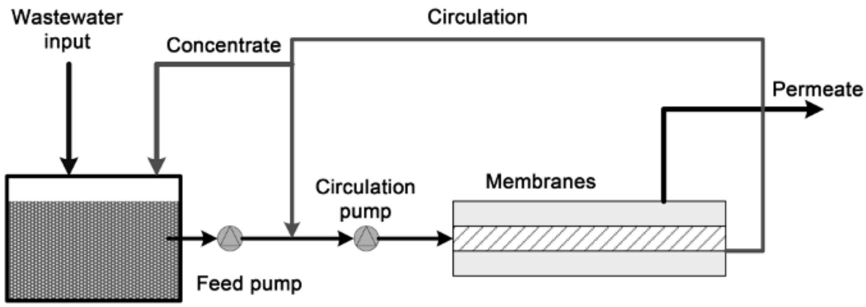


Figure 1.4. *Configuration in a separate tank with an external loop*

1.3. Types of membranes

Many suppliers on the market propose a wide range of products (Table 1.3). These membranes can be organic or inorganic. Organic membranes are generally made from hydrophobic polymer materials (polytetrafluoroethylene (PTFE), polypropylene (PP), etc.) or from hydrophilic polymer materials (polyethersulfone

(PES), polysulfone (PS), polyacrilonitrile (PAN), difluoride polyvinylidene (PVdF)). Membranes are therefore made by depositing material on a backing layer, and many variants exist. Manufacturers are currently offering various membrane structures, various membrane porosities and various types of materials.

The MBR market is dominated by the following membrane suppliers:

– flat sheet membranes: Kubota, A3, Toray, Martin System, Microdyn-Nadir, Huber;

– hollow fiber membranes: KMS-Puron, Zenon-GE, Mitsubishi Rayon, Memcor, Asahi Kasei, Polymem, Dow Chemical, Siemens, LG-Samsung, Tianjin Motimo;

– external loop membranes: Rhodia-Orelis, Norit X-Flow, Wehrle Environmental.

In France, large groups offer turnkey systems: Biosep® from Veolia, Aqua-RM® and Compact-RM® from Stereau and Ultrafor™ from Degrémont.

Membranes often consist of hollow fibers shaped as narrow porous tubes. Porous fibers are either grouped in a cylinder, thus making a tubular module, or in a bundle (hollow fiber module). In the tubular module, water to be treated enters at one end of the tubes and excess polluted water exits at the other end, while filtered water is recovered on the sides. The active part of the membrane is inside these tubes, and the water to be treated flows inside.

Two types of possible configurations of hollow fiber modules can be identified. In the first case, water flows inside the fibers and permeate is recovered outside the fibers (internal–external configuration). In the second case, water flows outside the fibers and permeate is recovered inside the fibers (external–internal configuration). Organic membranes can also be either stacked in layers separated by intermediate structures that ensure water circulation (flat modules), or self-rolled around a porous tube (spiral modules) (Berland and Juery 2002).

Among these organic membranes, there are membranes with symmetric, asymmetric and composite structures. Asymmetric membranes are composed of a thin layer known as “skin” deposited on a coarser porous backing of similar chemical nature, and whose role is to confer proper mechanical properties to the entire structure. Composite membranes differ from the previous ones as they are obtained by depositing the selective “skin” on a preexisting backing layer of different chemical nature. Symmetric membranes have a regular and uniform distribution of pores throughout their thickness (used only in microfiltration).

The materials used in membrane manufacturing must be resistant to the chemical products used for cleaning membranes, such as chlorine and certain acids or bases. Polypropylene membranes are sensitive to chlorine and must therefore be avoided.

There are advantages and disadvantages for each material used, as shown in Table 1.2.

Material	Advantages	Disadvantages
Polyvinylidene fluoride (PVdF)	Excellent flexibility Very high resistance Reasonable permeability	Difficult to modify its properties
Polyethylsulfone (PES)	Good chemical and thermal stability Easy to manufacture	Limited low pressures Low chemical resistance to aromatic compounds
Polyethylene (PE)	Inexpensive Good flexibility	Sensitive to oxidizing reactions
Polypropylene (PP)	Resistant to high temperatures	Moderate resistance to chemical agents Sensitive to chlorine

Table 1.2. *The main materials used for membrane manufacturing*

The main types of membranes used are microfiltration (MF) and ultrafiltration (UF). The nominal porosity for this type of application ranges between 0.01 and 1 µm.

Membranes can be layered or tubular. Filtration systems can operate under positive or negative pressure, depending on the manufacturer and on the intended application. For household wastewater applications, an immersed membrane filtration works under negative pressure in the biological tank. The membrane system works under positive pressure when it is implemented outside the biological tank. Microfiltration membranes are generally used for biological treatment of urban wastewater. Some manufacturers, however, propose ultrafiltration membranes that can remove viruses.

	Zenon	Puron	Mitsubishi	Kubota	Toray	Alfa Laval
Membrane type	HF	HF	HF	FS	FS	FS
Material	PVDF	PVDF	PVDF	PE + Cl	PVDF	PVDF
Pore size (µm)	0.04	0.03	0.4	0.4	0.08	0.2

Table 1.3. *Characteristics of membranes for six suppliers (HF = hollow fibers, FS = flat sheet membranes)*

According to its experience, each supplier has its own design recommendations (flux, membrane aeration, clogging control, chemical cleaning) and installation, implementation and operation procedures.

1.4. Description of general configurations of MBRs

Two large categories of membranes are present on the market:

– immersed membranes: filtration is achieved by imposing a transmembrane pressure (TMP) (between 0.1 and 1 bar) from outside the membrane towards the inside. Filtration is achieved by aspiration of the permeate, and membranes operate under vacuum;

– external membranes: activated sludge is pumped and recirculated at a tangential velocity (> 2 m/s) in the circulation loop. Filtration is tangential and is conducted by imposing a TMP (between 0.5 and 4 bars), from inside the membrane to the outside. The extracted permeate is evacuated to the exit/output channel and/or stored for cleaning membranes.

1.4.1. *Immersed membranes*

Immersed MBRs are a more recent configuration of MBRs with an external loop, aimed at reducing operation costs. The principle of this configuration consists of immersing the membranes in the bioreactor (activated sludge). The modules used are generally hollow fibers or flat sheet membranes. (Pseudo-frontal) filtration is achieved by applying negative pressure on the side of the permeate and by directly injecting air under the membrane module and inside the membrane module in order to maintain the particles in suspension and clean the external surface of the membrane. Given their low operating fluxes (15–30 $L.h^{-1}.m^{-2}$ compared to 50–120 $L.h^{-1}.m^{-2}$ for the MBR with external loop), several membranes must be simultaneously used in order to have a high membrane surface, which requires higher installation costs. Immersed membranes significantly reduce operating costs. This configuration has advantages in technical-economic terms where air injection has lower costs than a circulation of the suspension under turbulent conditions for the membranes with external loop. For a good transfer of oxygen, the MBR requires small bubbles of oxygen, while the membrane requires larger bubbles to maintain good permeability and reduce clogging phenomena. The appearance of immersed MBRs opened the municipal market of water treatment by membrane techniques. Immersed membranes therefore require higher installation capital, but they bring a significant reduction in operating costs compared to the external loop MBR. In order to improve the operating conditions, a third configuration is also used: the externally immersed MBR. In this configuration, the membrane is immersed in a tank outside the bioreactor. This has the advantage of maximizing the shearing stress in the vicinity of the membrane by the circulation of the sludge, on the one hand, and by the aeration of membranes, on the other hand. Consequently, clogging phenomena are reduced. This configuration allows decoupling the aeration dedicated to shearing from that dedicated to biological treatment and also facilitates the chemical cleaning phases. However, while the bioreactor requires good transfer of oxygen (requires small bubbles of oxygen), the membrane requires bubbles of larger dimensions, in order to maintain good permeability and reduce its clogging. For maintenance reasons, most manufacturers are now immersing membranes in a tank dedicated to filtration, which imposes significant recirculations (300–400% of the flow rate of permeate) in order to limit the increase in concentration in the membrane tank. The presence of the filtration tank increases investment costs (construction of the filtration tank) and operation costs (recirculation pump, additional aeration of the membrane in the filtration tank) and may call into question one of the key factors supporting the choice of MBRs at municipal scale.

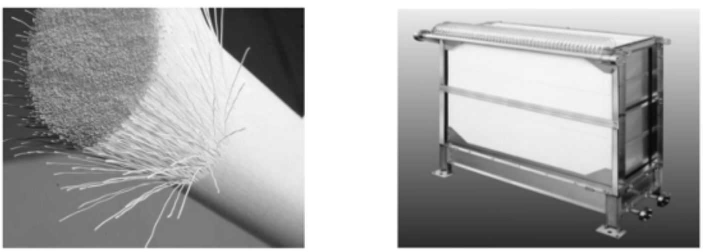
The following categories can be identified:

– membranes immersed in a single tank: membranes are directly immersed in the biological tank;

– membranes immersed in a separate tank: the membranes are installed in another tank referred to as “membrane tank”.

Membranes may consist of hollow fibers or flat surfaces.

Table 1.4 presents the advantages of both configurations. The separate tank configuration is generally preferred as it allows better control of the denitrification phase and facilitates the implementation of automated membrane cleaning operations. Indeed, the configurations in a single tank may yield poor denitrification performances because of the continuous aeration of membranes. Nevertheless, in the absence of strict requirements referring to nitrogen, and also for small plants, a single tank configuration reduces investment costs.



a) *b)*

Figure 1.5. *a) Hollow fibers. b) Flat sheet membranes (Toray)*

Single tank	Separate tank
No pumping required for recirculating the mixed liquor or feeding the membrane tank	Better control of the denitrification phase
Less costly implementation	Possibility to drain the tanks for exceptional cleaning (in terms of process and operation, prefer several small membrane tanks rather than a small number of large membrane tanks, in order to fully drain each tank and use the separate tank as a cleaning tank, while reducing the downtime of the station caused by these cleaning interventions)
For hollow fiber membranes, a separate immersion tank is needed to clean the membranes	The MES in the membrane system and in biology can be adjusted independently
Manual handling of hollow fiber membrane cassettes required for exceptional cleaning	The exceptional cleaning procedure can be readily automated
	No risk of hydraulic short circuit that may cause a biological clogging

Table 1.4. *Advantages of each configuration*

Certain systems with flat sheet membranes require a minimum MES concentration of about 12 $g.L^{-1}$ on the membranes. In the case of a separate membrane tank, the MES in the biological tank can be reduced to 5 $g.L^{-1}$ (e.g. off season, in a situation of temporary low load) while the membrane system can still operate with an MES concentration of 12 $g.L^{-1}$.

All the parameters involved in the design and operation of the MBR process influence membrane fouling. Three categories of factors are defined (see Figure 1.6):

– the characteristics of membranes and modules;

– the supply/feeding and biomass parameters;

– the operating conditions.

For some of them, the parameters have a direct influence on the fouling of MBR. Others lead to further effects on phenomena contributing to the development of clogging. The complex interactions between these parameters impact the perception and comprehension of clogging, and it is therefore important to have a proper understanding of the phenomena unfolding in MBRs in order to master the operation of this process and the means to implement in order to stop or reduce it.

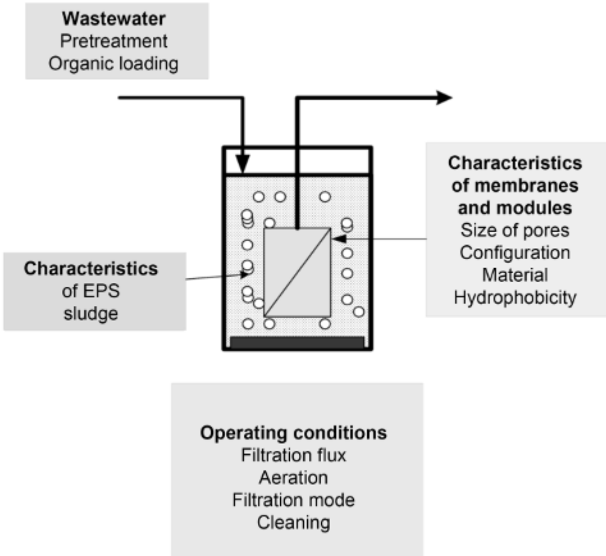


Figure 1.6. *Parameters affecting membrane clogging*

1.4.1.1. *Separate membrane tank*

In this configuration, the membrane tank is fed by the mixed liquor from the activated sludge tank. Figure 1.7 shows two cases of possible implantation of the membrane tank depending on the elevation of the biological tank.

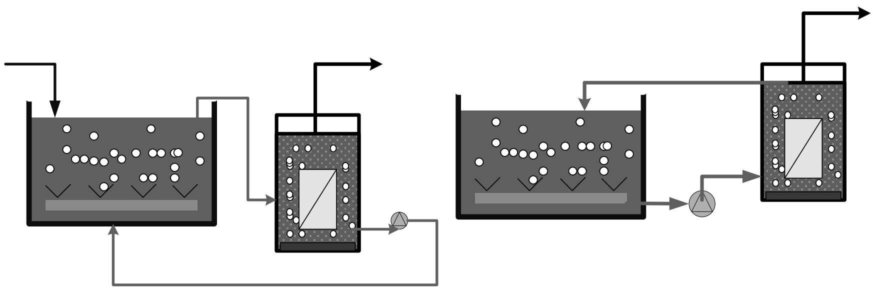


Figure 1.7. *Implementations of the configuration in a separate tank*

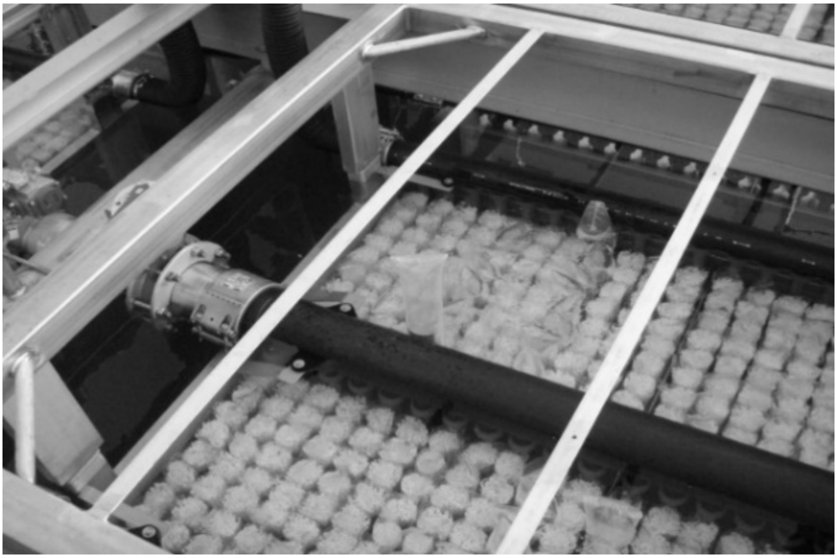


Figure 1.8. *MBR separate tank*

In case no. 1, there is gravity feeding of the membrane tank and pumped return. This configuration is often found in industrial units where the bioreactor is, for example, a 6 m high tank installed at height and the membrane system is enclosed in containers of about 3 m height.

In case no. 2, there is a pump feeding the membrane tank and a gravity return. This is the solution of choice for municipal stations, which is explained by the following reasons:

– The flux to the membrane system is easier (less costly) to control.

– In the configurations with several rows, all the filtration units are controlled exactly at the same water level (thanks to the overflow), which allows using the same boosters to aerate all membranes.

– In the case of foam formation in the membrane unit (due to intensive aeration), the foam may overflow to the bioreactor where it will be easier to manage than in a narrow membrane tank.

– This configuration makes it possible to establish a buffer capacity in the biological tank, which may be advantageous to control the peak flow.

In practice, since the permeate is only extracted from the membrane tank, it is necessary to recirculate the mixed liquor three to five times faster than the net filtration flow rate in order to stabilize the MES concentration to a reasonable value in the membrane tank.

The energy consumption of the recirculation pump may be significant. It is therefore important to minimize the water level difference between the bioreactor and the membrane unit(s), especially in the presence of high flow rates.

Activated sludge is sent to the membrane tank through pipes installed at the base of the tank and having holes on their lower or lateral side, in order to avoid damaging the membranes. This piping setup allows a better distribution of the mixed liquor exiting the biological tank.

It is interesting to place the membranes in compartments specific to each row of cassettes or modules. If the membrane tank is crossed by a significant recirculation flow (typically five times the flow rate of the station), there is a risk of "leaching" the chemical products when cleaning operations take place, and therefore limiting the efficiency of maintenance cleaning. A membrane tank whose rows are not separated by waterproof linings does not allow advanced cleaning in place without using an external tank.

1.4.1.2. *Single tank*

In this configuration, membranes are directly immersed in the biological tank (see Figure 1.9). This is the simplest configuration as it does not require a membrane tank or a recirculation circuit.

Exceptional cleaning is conducted in a dedicated cleaning tank placed outside the biological tank with modules of the same row aligned; it is therefore necessary to have a means of lifting modules to place them in this tank, either a mobile one (e.g. a lifting crane) or a fixed one (pillar crane, portal, etc.).

To avoid compromising the effectiveness of maintenance cleaning (with the use of chemical products), membranes should not be placed on top of or too close to air process diffusers in the bio tank.

Indeed, the airlift and the spiral flow induced by the diffusers can "wash" the chemical products, and limit their time of contact with the outside of membranes. If this is the case, it is imperative to be able to stop the air process under the membranes during cleaning.

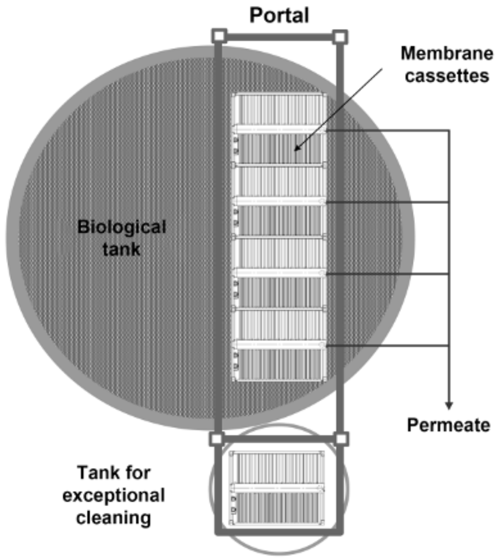


Figure 1.9. *Example of implementation of a single tank configuration with a tank reserved for potential exceptional cleaning*

Permeate can be extracted by pumping, gravity or siphon (see Figure 1.10).

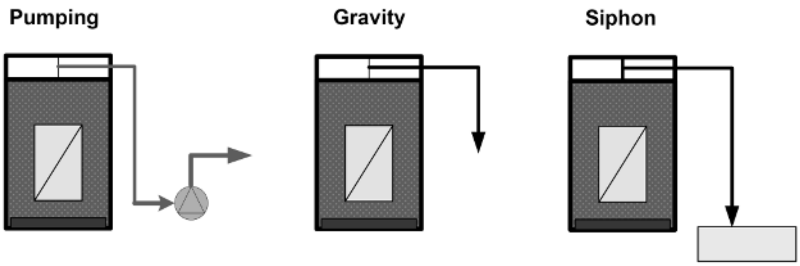


Figure 1.10. *Three configurations for the extraction of permeate*

1.4.2. *MBR with external loop*

The MBR with an external loop is the first generation of MBRs with tubular membranes implemented in the external loops. The biomass circulates at high speed in these loops in order to limit membrane clogging and reduce the frequency of chemical cleaning. The biomass retained by membrane filtration is recycled in order to maintain a much higher concentration in the bioreactor. The MBR with an external loop is generally used for the treatment of wastewater characterized by relatively high temperatures (e.g. 40°C), high organic loads (e.g. 10,500 mg DCO.L^{-1}) or high pH.

Several treatment stations are equipped with (generally tubular) membranes assembled on structures installed outside biological tanks (these membrane systems are referred to as "with external loop") for fluxes > 1,000 $m^3.d^{-1}$ as the operating costs of these units (energy consumption for the membrane operation) are much higher than in the presence of a configuration in which membranes are directly immersed (energy consumption for the operation of the membrane typically < 0.5 kWh.m^{-3} of permeate). Their disadvantages are essentially related to the significant rates of shear undergone by the biomass and also the relatively high energy consumption (of about 10–50 kWh.m^{-3}). The MBR with an external loop generates significant operating costs. However, these costs can be justified under specific conditions, such as the treatment of wastewater characterized by very high loads and the implementation of intensive systems.

Two configurations are possible and presented in Table 1.5. The systems withn external loop are relatively simple to implement and are less sensitive to clogging in the case of limited filterability of the biomass. Constructors often justify their choice by explaining that membranes combine a small size of pores with high permeability to provide a high quality effluent at low operational cost.

The main characteristics of membranes associated with this type of MBR are:

– PVDF(polyvinylidene difluoride)/PES (polyethylsulfone) membranes;

– small size of pores;

– high permeability;

– pressurized and closed systems;

– robustness;

– small dimensions;

– pore size of 30 nm;

– high quality instantaneous effluent;

– MS2 bacteriophage 4-Log tested.

Inserted in a protective tube, the membrane is optimally protected and does not risk abrasive wear of fibers during operation. The separation layer is entirely isolated from external influences.

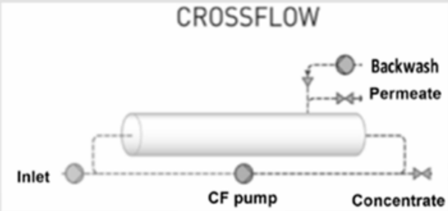
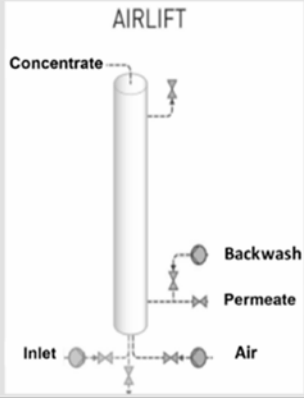
	Crossflow	*Air lift*
Diagram		
Specifications	MES: 12–30 g.L^{-1} Flux: 80–200 l.m^{-2}.h^{-1} Reduced overall size Energy consumption: 1.5–4 kwh.m^{-3} Continuous operation PTM: 1–5 bar Membrane: 1.5 mm diameter Length: 3 m	MES: 8–12 g.L^{-1} Flux: 45–65 l.m^{-2}.h^{-1} Reduced overall size Energy consumption: 0.25 kwh.m^{3} Discontinuous operation PTM: 0.05–0.3 bar

Table 1.5. *Characteristics of MBR with external loop*

MBR membranes are distinguished by their structure and their manufacturing process. Fiber protection differs depending on whether they are potted in tubes or in free air. It may consist of a thin protective layer relative to the solid materials that may degrade the external surface, or the membranes may be without protection when they are potted in tubes.

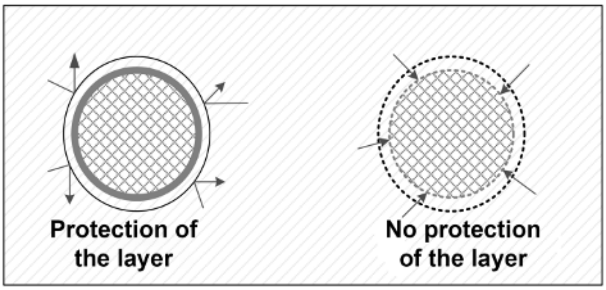


Figure 1.11. *Protection of fibers in tubular membranes*

Systems with tubular membranes can be used for:

– easy drainage of the system to remove the retained particles and sludge;

– safe, effective and efficient chemical cleaning;

– easy handling.

a) b)

Figure 1.12. *X-flow tubular membranes: a) vertical; b) horizontal*

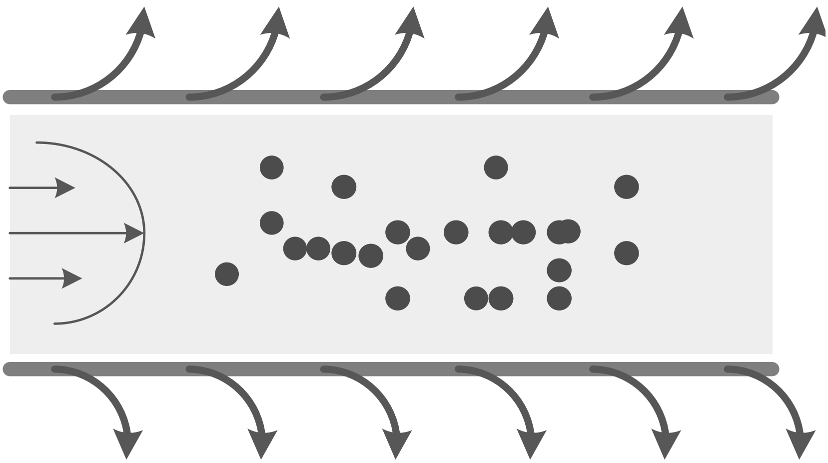


Figure 1.13. *X-flow tubular membranes: filtration direction*

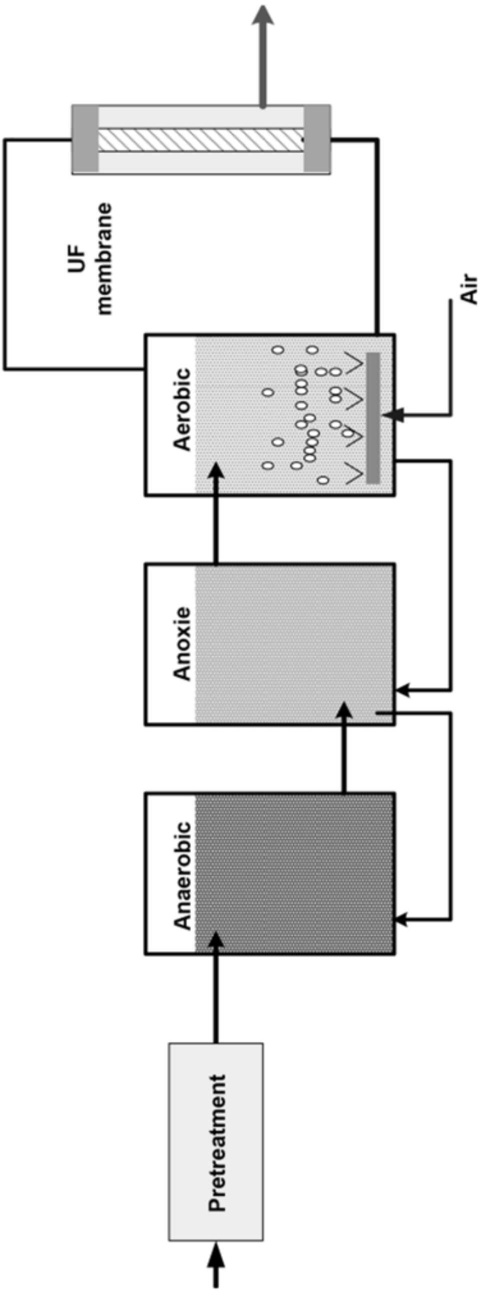


Figure 1.14. *Diagram of a biological treatment system with external membranes*

These membranes operate based on a cross flow inside the tubes. Filtration in the fibers has an internal–external direction. A continuous airlift avoids the accumulation of solids on the membranes and allows the recycling of sludge in the biological tank.

In a system with an external loop (see Figure 1.14), the acceptable concentration of sludge in the biological tank ranges between 10 and 20 $g.L^{-1}$. The quality of the output effluent gives an MES concentration < 3 $mg.L^{-1}$.

The operating flux is 50 lmh, PTM varies between 0.1 and 0.3 bar and permeability is 500 lmh.bar. The term lmh is an abbreviation of $L.m^{-2}.h^{-1}$.

a) *b)*

Figure 1.15. *Examples of membrane modules operating: a) in cross flow; b) helped by an airlift*

1.5. MBR dimensioning parameters

1.5.1. *Mechanical pretreatments*

Membrane filtration requires advanced pretreatment of raw waters in order to limit the obstruction of physical clogging of membranes. The recommended pretreatment involves the following stages:

– coarse screening (10–25 mm);

– grit removal (up to 200 µm);

– very fine screening.

The screening stage is very important and has a direct consequence on the lifetime of membranes, as it allows retaining the fibers that are an aggravating factor for the risk of membrane solidifying (solidifying being an accumulation of very dense sludge between the fibers leading to a significant loss of filtration surface).

The hollow fiber membranes are more sensitive to the accumulation of fibers than flat sheet membranes and therefore require a finer mesh opening.

In urban wastewater, we can systematize the use of rotary screens, with round meshes of (maximum) 1 mm for hollow fiber membranes, while round meshes ≤ 3 mm must be sufficient for flat sheet membranes.

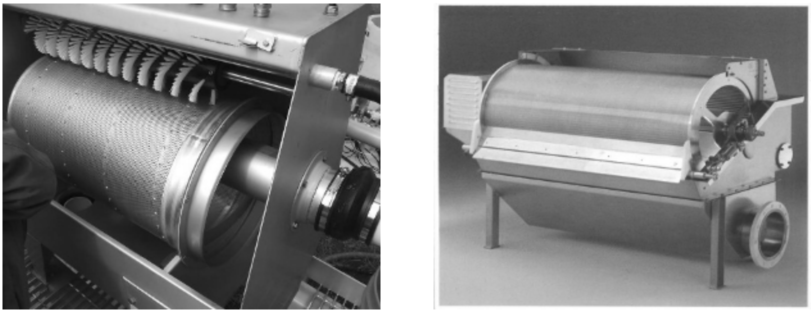


Figure 1.16. *Rotary screens (1 mm)*

1.5.2. *Buffer tank*

a) *b)*

Figure 1.17. *Clogging generated by a) poor screening; b) good screening*

The implementation of a buffer tank is a good solution for reducing the filtration surface required for the treatment of incoming effluents. The buffer tank is dimensioned to store, during the peak hours, the volumes of raw water that the MBR cannot take in. Its volume is calculated by multiplying the difference between the peak flow rate and the average flow rate by the total duration of these peak periods:

Buffer tank volume = $(Q_{peak\ flux} - Q_{net}) \times$ peak duration

For example, if the daily average maximum flow rate is 1,440 $m^3.d^{-1}$, the flow rate to be taken into account for the calculation of the filtration surface will be 1,440/24 or 60 $m^3.h^{-1}$. The net permeate flux is therefore 60 $m^3.h^{-1}$. If the peak flow rate is equal to 140 $m^3.h^{-1}$ and the peak duration to hours, the volume of the tank is calculated as follows (see Figure 1.18):

Buffer tank volume = (140 – 60) × 3 = 240 m^3

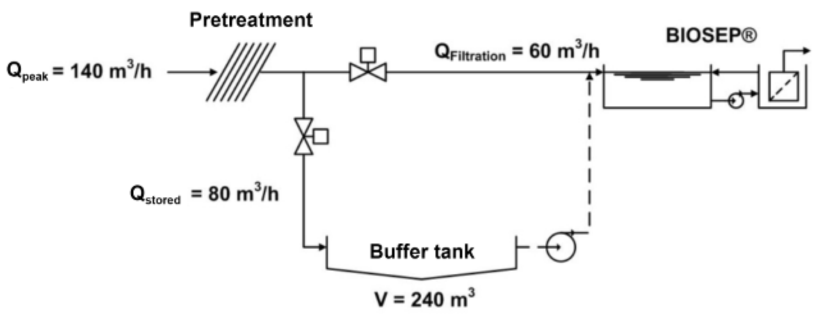


Figure 1.18. *Example of calculation of the buffer tank volume*

1.5.3. *Other factors to be taken into account*

1.5.3.1. *Silicone*

Silicone is a highly clogging product. It is encountered in effluents resulting from textile or cosmetic industries. It is not degraded by biology and accumulates in the tank, depositing on all equipment and primarily on membranes. Filtration then proves to be very difficult with a rapid drift of filtration performances (down to losing the treatment capacity).

On this type of effluent, it is not conceivable to propose an MBR without a physico-chemical pretreatment (coagulation–flocculation + decantation or flotation).

The dimensioning of pretreatment, and particularly the determination of the reagent dosage, can only be done based on tests (Jar Test/Flotation test).

1.5.3.2. *Grease/oils/hydrocarbons*

When the grease or oil content exceeds a value of 100 $mg.L^{-1}$ before pretreatment, there should be a flotation stage upstream of the MBR.

In the presence of hydrocarbons, a pretreatment by adsorption by flotation is required to reach a target value of 20 ppm at the inlet of the biological tank.

1.5.3.3. *Hardness*

Hard effluents are problematic because of the chlorine-based maintenance cleaning. These are conducted with a solution of sodium hypochlorite. Ca^{2+} and CO_3^{2-} ions precipitate. If alkalinity ($CaCO_3$) is high, the formation of these precipitates is all the more significant and is reflected by a loss of filtration of membranes and their calcification. This precipitation phenomenon can occur even at low alkalinities (alkalinity < 200 $mg.L^{-1}$ $CaCO_3$), but frequent maintenance cleanings with acid can stabilize filtration performances.

On the other hand, for higher values (TH > 500 $mg.L^{-1}$ $CaCO_3$), the maintenance cleanings with acid are not sufficient: raw water pretreatment by softening should be conducted.

1.6. Tank–membrane association

1.6.1. *Parameters linked to the biological tank*

MBR implementation requires taking into account a number of factors that govern each basic operation, particularly MBR dimensioning, hydrodynamic operating conditions, membrane structure, membrane module configuration, membrane cost, etc. The hydraulic retention time (HRT) will determine the time available for degrading soluble compounds, and therefore the volume of the bioreactor. The solid retention time (SRT, or sludge age: θ) corresponds to the time required to degrade particulate compounds and allow renewal/lysis of the purifying biomass. It will therefore directly influence the MES content of the tank.

MBR is a discontinuous treatment process whose operation is automated. It alternates:

– sequences of permeate production (filtration);

– sequences that do not produce and even consume permeate (backwashing, relaxation, degasification, chemical cleaning, etc.).

The sequences required for the proper operation of membranes are generally defined by the suppliers. Backwashing, relaxation, degasification and cleaning sequences are aimed to maintain or recover the filtration performances. The phases of backwashing, cleaning and possibly of degasification, depending on the technique used, consume permeate. When the solid–liquid separation is conducted by membrane filtration, all materials in suspension are retained by the membranes. In this case, the decantation capacity of the sludge has no impact on the efficiency of the solid–liquid separation. Unlike decanters, biopolymers can induce clogging of membranes, reduce the filtration capacity or have an impact on the frequency of cleanings. However, to the extent that sludge retention time is sufficient to induce good nitrification, biopolymers do not seem to cause significant clogging. Hence, in the case of MBR, the age of sludge can be maintained between 20 and 70 days and the MES concentration can reach 20,000 $mg.L^{-1}$, depending on the documentation. However, at concentrations of this order, sludge density limits the filtration rate of membranes and also the oxygen transfer due to viscosity phenomena. For these reasons, the MES concentration in MBRs is limited to 10,000 or 12,000 $mg.L^{-1}$ (Atasi 2006).

Since the capacity of sludge to decant is not an important factor during the design or operation of this type of treatment system, the factors that have an influence on sludge settling are not considered. This type of system is far simpler to operate. The intensity of stirring required in the biological reactor increases with the concentration of MES that must be maintained in suspension. Hence, in an MBR, the installed stirring capacity must be sufficient to maintain in suspension over 12,000 $mg.L^{-1}$. When denitrification precedes the treatment (in order to save aeration energy), the volume of the pre-anoxic zone must be increased in order to compensate the supplies of oxygen by the sludge recycling system.

Sludge properties and their impact on membrane fouling are explained through the particle size distribution and the major constituents considered as being involved in the fouling process, namely the extracellular polymer substances and the soluble products resulting from microbial activities.

The constituents of activated sludge are generally classified into three groups: materials in suspension (> 1 μm); colloids (0.1–1 μm); soluble constituents (< 0.1 μm).

The size of the physical characteristics of activated sludge has a major role in the fouling process. However, it is currently admitted that the size of flocs of activated sludge has no direct correlation with fouling. This is mainly due to the fact that the turbulence promoted in the proximity of the membrane surface by the aeration prevents large deposits of particles. Colloids are considered today as the main contributor to fouling given their size (0.1 and 0.5 μm), near the size of pores of the membrane.

Extracellular polymeric substances (EPSs) provide the cement that keeps together the microbial aggregates. They form a layer that protects microorganisms from external influences.

The biology–membrane association requires parameters identical to those of a classical activated sludge for the biological tank part.

1.6.1.1. *Hydraulics*

Hydraulic parameters to be considered are the daily average flow rate during the rainy season (unit network) and the daily average flow rate during the dry season (separate system). The peak hour coefficient is also taken into consideration.

This is why the biological tank is often preceded by a tank that stores the peak hour surplus, which allows the optimization of the membrane surface.

1.6.1.2. *Nature of pollution: characteristics of water to be treated*

1.6.1.2.1. Activated sludge tank

Hydraulic parameters to be considered are the volume of the biological tank, concentration of oxygen dissolved in the biological tank, rate of recirculation of the mixed liquor and also the age of sludge.

The biological reactor is modeled as a classical tank of activated sludge except that the higher mixed liquor suspended solid (MLSS) concentration (< 12 $g.L^{-1}$) allows the reduction of dimensions of biological tanks. The shape of the tank (single tank, anoxic + aerobic tanks, channel) is independent of the membrane filtration.

In the case of a “separate tank” configuration, the activated sludge is recirculated between the biological tank and the membrane tank, thus forming an additional tank that should be considered as an aerated volume (oxygen concentration about 4 $mg.L^{-1}$). The system will be chosen depending on the efficiency and quality of discharge.

1.6.1.2.2. Non-constraining level of total nitrogen (TN) (15 $mg.L^{-1}$) and 75% efficiency

A complete mixing solution is sufficient. Aeration is controlled by a redox probe or directly by NH_4^+/NO_3^- concentrations.

Figure 1.19. *Clogging of immersed membranes*

1.6.1.2.3. Constraining level of TN (10 mg.L^{-1}) and efficiency above 85%

Applying these operating conditions requires a solution in two (anoxic and aerobic) tanks to allow better control of denitrification. The process using an oxidation channel is also possible by controlling aeration and anoxic periods.

Figure 1.20 shows an example of the MBR configuration.

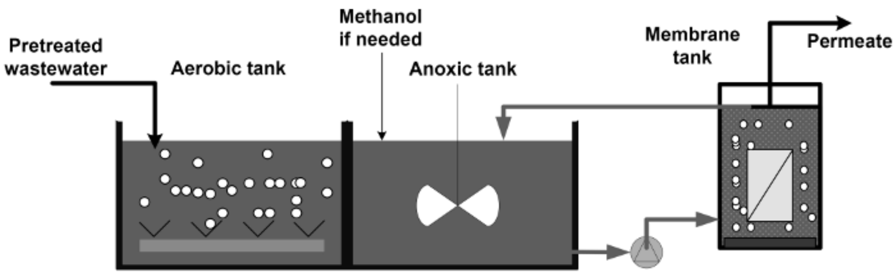


Figure 1.20. *Aerobic–anoxic configuration of MBR*

The membrane system does not instantly adjust to the variations of input flux/flow (there is no overflow as in the classical activated sludge plants). At least

15 minutes are required to make the permeate extraction system pass from the minimum flux to the maximum flux. The biological tank should therefore have the available sufficient buffer capacity. In general, a 25 cm level difference in the bioreactor is appropriate.

1.6.1.3. *Hydraulic retention time (HRT)*

This parameter determines the time available to degrade soluble compounds, and therefore the volume of the bioreactor. Besides the abovementioned factors, the choice of characteristics of the filtration system must also integrate the specific nature of suspensions present in the MBR, and particularly their significant concentration in cell biomass (10–15 $g.L^{-1}$), as well as their evolving nature depending on the imposed hydrodynamic and biological constraints. Indeed, the biomass concentration in MBRs is not limited to a critical value close to 4–5 $g.L^{-1}$, beyond which the separation by gravity decantation/settling appears as strongly slowed down, even perturbed, in the conventional systems with activated sludge. MBRs are thus susceptible to operate with concentrations that are two to five times higher (between 8 and 25 $g.L^{-1}$) depending on the configuration.

1.6.1.4. *Sludge age*

Similar to other biological processes, the age of sludge in MBRs determines the quality of treatment, but it also influences the filtration parameters. It is thus important to stick to a minimum sludge age (independent of temperature): it is the solid retention time (SRT, or sludge age) that corresponds to the time required to degrade the particulate components and allow the renewal/lysis of the purifying biomass. It will therefore directly influence the MLSS content of the tank. Furthermore, a proper biological operation requires making sure there is no limiting oxygen.

– Minimum sludge age: 15 days. This parameter must allow the complete oxidation of organic matter, in order to avoid the rapid clogging of the membrane. This is verified by measuring the ammonia concentration at the inlet of the membrane tank, which must be below 2 $mg.L^{-1}$. In practice, this is typically reflected by a sludge age above 15 days. Moreover, an operation at high sludge age (> 15 days) offers better filtration performances, while too low a sludge age (< 15 days) generally produces a heavily clogging sludge.

– Maximum sludge age: 80 days. Beyond this sludge age and according to the influent load variations, there will be an increase in the risk of appearance of extracellular polymer substances (EPSs) that contribute to membrane clogging.

Figure 1.21 shows the evolution of the correction factor allowing the calculation of the sludge age equivalent to various temperatures based on the sludge age at 12°C:

$$G(T\ °C)/G(12°C) = 2.3333\ e^{-0.0705 \times T}$$

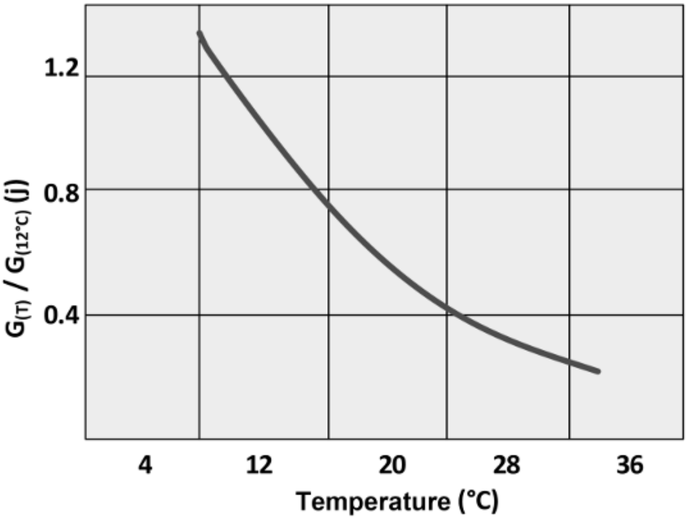


Figure 1.21. *Sludge age correction factor depending on temperature*

Stirring is required for:

– ensuring sludge homogenization;

– avoiding sludge decantation;

– limiting the risks of sludge overconcentration at the level of modules.

The stirring equipment depends on the type of equipment chosen for the oxygen transfer function in the process air supply.

The recirculation loop permanently ensures the supply of the membrane tank with mixed liquor from the biological tank. This recirculation allows the minimization of sludge overconcentration occurring in the membrane tank during filtration. The calculation of the concentration in the membrane tank and in the biological tanks relies on a simple principle: membranes remove interstitial water between SS and therefore the MLSS concentration in the mixed liquor. A mass balance on the membrane tank makes it possible to find the various input/output concentrations depending on the recirculation rate.

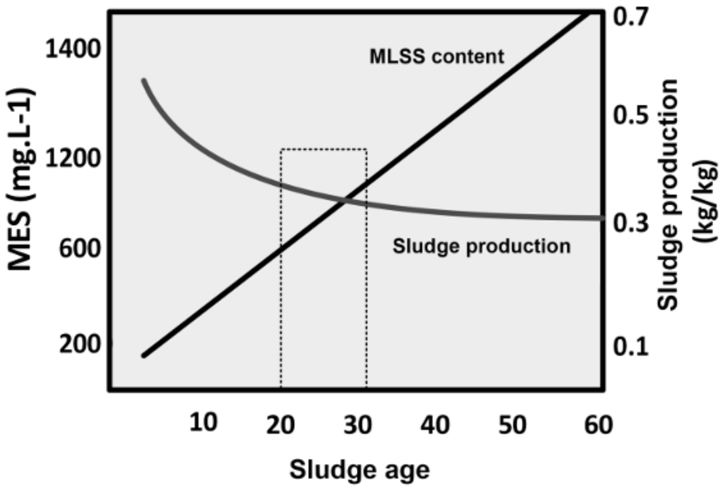


Figure 1.22. *Influence of operating parameters on a membrane bioreactor operation (Lobos 2009)*

The typical recirculation flow rates of the mixed liquor at the inlet of the membrane tank are four to five times the net flow rate. A high recirculation rate must be maintained between the biological reactor and the filtration tank. A 200–400% recirculation is recommended to prevent a significant increase in the MLSS concentration in the filtration tank, which might cause a decrease in the filtration rate and the system failure. When membranes are directly placed in the biological reactor, recirculation is not required, but a tank for cleaning membranes is required.

EXAMPLE.–

The daily flow rate (daily Q) is 384 $m^3.d^{-1}$. As the recirculation flow rate is dimensioned on the net flow rate to be treated (Qnet), the recirculation flow rate is calculated as follows:

Qnet to be treated = Q daily/24 = 16 $m^3.h^{-1}$

For domestic wastewater, we consider five times the net flow rate to be treated:

Q recirculation = Qnet to be treated × 5 = 16 × 5 = 80 $m^3.h^{-1}$

The choice of recirculation pumps is based on the following aspects:

– Recirculation pumps may represent a significant part of the total energy consumption of the plant. Therefore, good efficiency for the pump presents a specific interest in this case. If the water level in the aeration tank is close to the one in the membrane tank, propeller pumps can be used.

– The mixed liquor to be pumped (particularly during the transfer of the filtration tank to the biological tank) may contain a significant quantity of air. It is essential that recirculation pumps tolerate these conditions.

During exceptional cleanings, the sludge activated in the membrane tank must be drained and returned in the biological tank or in the adjacent membrane tank, or sent to the sludge treatment. As for the chlorine solution drainage, it can be moved under gravity to the all-water station by means of a manual valve or by pumping using a special mesh with the pump backflow. The acid solution is drained similarly to the chlorine solution except that the solution is neutralized with soda before discharge. The overflow of the mixed liquor of the biological tank to the membrane tank must be closed during cleaning to allow this same tank to store the excess mixed liquor.

It is essential to verify that no residual BOD ever remains in contact with membranes to avoid biological clogging at the surface of membranes.

In a single-tank immersed configuration, the risk of hydraulic bypass of one part of the effluent, or of solutions with methanol addition for denitrification, must be studied very carefully to ensure the quality of the treated water.

In a separate-tank immersed configuration, the fraction of hard COD should not exceed 2–3 $mg.L^{-1}$ in the membrane tank (total soluble COD < 20–40 $mg.L^{-1}$). The addition of an aerated tank upstream of the membrane tank can be considered to obtain these values.

Because of a higher sludge age, the sludge production of MBRs is theoretically lower than that of classical activated sludge, but the physical barrier of membranes retains more SS, which increases the sludge production. The sludge production by an MBR process compared to that of a classical activated sludge process shows a 5–8% increase in the quantity of sludge to be extracted for the membrane process. This corresponds to a drop by 12–20 $mg.L^{-1}$ of total SS in the effluent of MBR with respect to the classical activated sludge. With a domestic effluent, sludge production is close to 0.45 kg SS/kg $COD_{removed.}d^{-1}$.

In an MBR, the relatively high content of suspended solids in the biological tank drives higher viscosity values compared to conventional systems. Activated sludge is considered a non-Newtonian fluid behaving as a pseudo-plastic fluid (Rosenberger et al. 2002; Le-Clech et al. 2006).

A model based on the Ostwald model is proposed to determine the apparent viscosity as a function of the MLSS content:

$$\eta = \exp (0.882.\ MLSS\ 0.494) - (\kappa) - 0.050.\ MLSS\ 0.631$$

with:

– η: apparent viscosity of activated sludge (Pa.s);

– MLSS: mixed liquor suspended solid concentration in the biological tank ($g.L^{-1}$);

– κ: shearing rate at the level of the membrane (s^{-1}).

Aeration is used in the immersed MBR configurations to provide oxygen to the biomass, to maintain activated sludge in suspension and to reduce the clogging by turbulences and the cleaning of the membrane surface, that is, avoid membrane clogging and limit as much as possible the appearance of fouling.

Optimal aeration improves the filtration conditions up to an ideal theoretical value without, however, leading to an improvement in the membrane treatment performances.

The actual oxygen needs are calculated in the same manner as for classical activated sludge. They are slightly higher because of the higher sludge age. The specificity of MBR comes from the strong MLSS concentration in the tank, which impacts the calculation of the alpha factor. The global factor is calculated by taking into account MLSS concentration and the temperature of the effluent. Aeration can thus become a limiting parameter for reducing the dimension of the biological tank. Measures should be taken to make sure that the biological tank is sufficiently large to receive the aeration system.

Figure 1.23 presents data recorded for one year of evolution of permeability observed for a municipal MBR. The problems inherent to aeration during the first months result in a clear drop in permeability and in the flow rate of filtered water.

The MBR process relies on two aeration systems: the air process that provides the oxygen needed by the active biomass to ensure a proper biological treatment, and the air membrane whose function is to avoid membrane clogging.

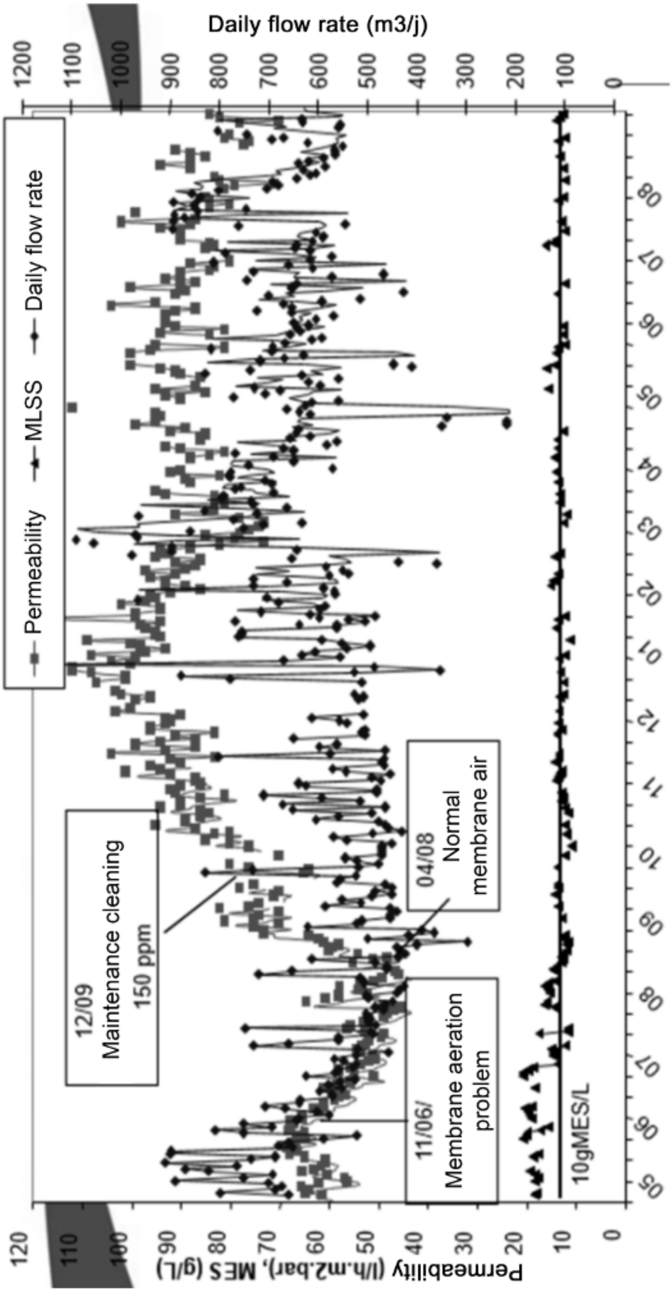


Figure 1.23. *Problems inherent to aeration. For a color version of this figure, seewww.iste.co.uk/gaid/wastewaterengineering2.zip*

Membrane aeration can be based on continuous or sequential operation according to recommendations of the membrane supplier. It generally involves large bubble diffusers, and more recently fine bubble diffusers. The operation of the membrane aeration is related to the performances of membranes and to the operation cycle, but it is independent of the biological process, which is susceptible to perturbing the efficiency of the treatment as the membrane air can, for example, introduce an additional quantity of oxygen in the biomass during denitrification.

In the separate-tank immersed configuration, the low volume of the membrane tank compared to the significant injected quantities of air leads to an oxygen concentration in the membrane tank from 2 to 4 $mg.L^{-1}$.

In the single-tank immersed configuration, the major disadvantage is the impossibility of reducing the oxygen concentration in the tank, and consequently the absence of actual ranges of denitrification. In a period of underload, membrane aeration may be sufficient to meet and even exceed the air process needs. When process aerators operate, the oxygenation capacity produced by the membrane air is generally considered negligible. However, during denitrification phases, when the oxygen concentration is low, the membrane air is no longer negligible.

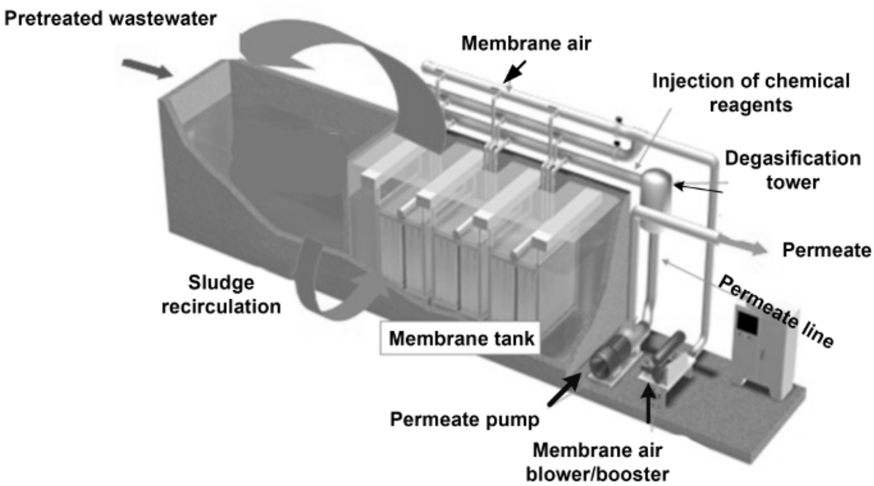


Figure 1.24. *Devices of the tank–membrane pair in a single tank*

Sludge can be extracted in two different places:

– Sludge can be extracted directly from a biological tank near an aeration zone using a volumetric pump. In fact, extraction must be conducted during an aeration phase to allow the proper homogeneity of extracted sludge. If a centrifugal pump is used for sludge extraction, we should make sure there are no risks of air pumping, either by placing a deflector at the level of the suction point during design, or by placing a suction point at more than one meter from the aeration zone.

– In the case of the immersed configuration with a separate tank, it is preferable to remove excess sludge at the outlet of the membrane tank. This way, it is more concentrated and properly aerated (therefore compatible also with the biological removal of phosphorus).

Extraction must be conducted as continuously as possible in order to minimize the potential abrupt changes of concentration in the biological tank. For this purpose, one continuous extraction of a small volume of sludge over a long period is recommended more than a rapid extraction of a significant volume only once a day.

Sludge coming from the biological tank can be sent directly to a centrifuge due to the high concentration (10 $g.L^{-1}$). It should be noted that sludge coming from MBR is generally difficult to decant, rendering densification more difficult.

1.6.2. *Parameters related to the membrane*

Due to the physical barrier formed by the membrane and the size of pores, a fraction of the soluble pollution (large size molecules) is retained by the membrane, while in the case of classical activated sludge, they exit the system with the treated water. Hence, this pollution, considered soluble, becomes particulate in the case of MBRs. The implementation of membranes requires taking into consideration a certain number of factors that govern this essential phase, particularly the hydrodynamic operating conditions, the structure of the membrane, the configuration of the membrane module, the cost of the membrane, etc.

The optimization of the MBR design and operation requires perfect knowledge of the relations between operating parameters and biological parameters (hydraulic retention time, sludge age, TMP, critical flux, efficiency, biomass activity, biomass concentration, etc.), as well as the physical parameters (filtration, durability, clogging of membranes, backwashing, etc.). The implementation of biological processes involved in the biodegradation of recalcitrant compounds requires an acclimation of the cell biomass to the degradation of pollution.

One of the major challenges of the industrial implementation of MBRs is maintaining during operation the membrane permeability at economically acceptable values, and therefore minimizing clogging. In general, the parameters monitored during operation are TMP, the water flow velocity (v), the concentrations of SS in the water to be treated and in the bioreactor, the hydraulic retention time (HRT), the concentration of dissolved oxygen, the specific consumption of oxygen, etc.

Ratios concerning the transfer of the soluble compartment to the particulate compartment for this application are used by the constructors in this fraction at the level of COD, BOD_5 and NK.

For the SS parameter, the concentration in conventional SS is increased to take into consideration the retention of dissolved materials (> 0.1 µm), which in a conventional activated sludge treatment undergo clarification.

The applied flows/flux must be carefully chosen to avoid the risk of rapidly driving a drop in permeability and too frequent cleaning, leading to a reduction of membrane lifetime. The velocity of the cross flow or of the transmembrane flow influences clogging and the nature of membrane clogging. When the MBR with an external loop operates at a low cross-flow velocity, between 1 and 2 $m.s^{-1}$ for an ultrafiltration membrane and between 1 and 3 $m.s^{-1}$ for a microfiltration membrane, the unfolding clogging is reversible. On the other hand, for velocities ≥ 3 $m.s^{-1}$, clogging becomes irreversible. A stable flow can be maintained during a long filtration period, when the MBR operates at a reasonably adjusted TMP.

Many studies indicate that the flow through the membrane or the cross flow and the TMP must be maintained below respective critical values. These critical values must be determined for each type of effluent, membrane and configuration of the membrane module (Cicek et al. 1998; Defrance 1999b).

Figure 1.25 shows the safe dimensioning zone for an MBR with immersed membranes with flows/flux depending on the peak frequency. The determination of the filtration surface is based on the flux/flow criterion (acceptable flow rate per m^2 of membranes) at a given temperature, the temperature affecting the filtered flow rate through the modification of water viscosity. The dimensioning fluxes considered for calculating the filtration surface are net fluxes. They must be chosen as a function of the:

– membrane supplier (each supplier has its own design recommendations);

– temperature of the mixed liquor;

– peak frequency (the higher the frequency, the more conservative the flux should be).

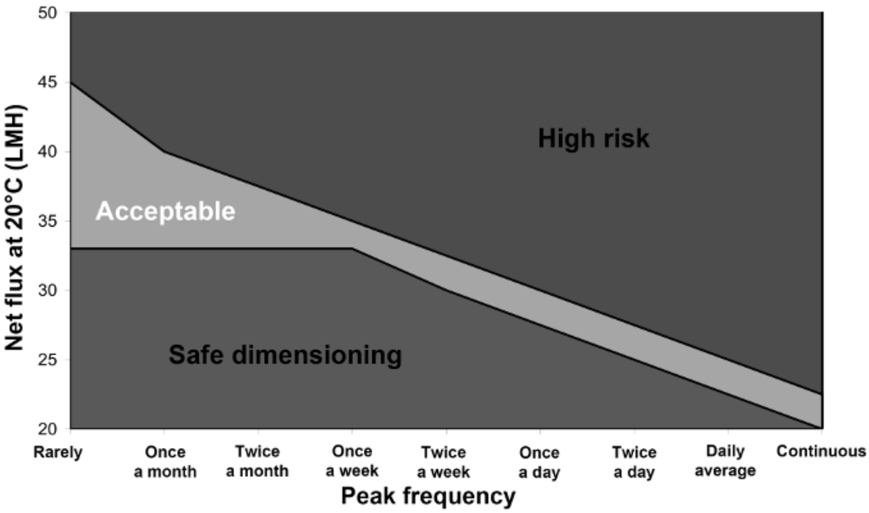


Figure 1.25. *Choice of fluxes applied to immersed membranes*

At 20°C and for standard projects, dimensioning fluxes may go from 10 to 40 $L.m^{-2}.h^{-1}$, according to the abovementioned conditions.

The filtration surface is calculated based on the limiting net flux. The hourly flow rates higher than the flow rate admitted on the membranes lead to one part of the influent being stored in a buffer structure upstream of the biological tank.

The hydraulic parameters used for the dimensioning of members are:

– the instantaneous filtration flow rate (Qi) or raw flow rate, expressed in $m^3.h^{-1}$, which denotes the instantaneous flow rate sucked by a row during the filtration phase. It is the set point of the flow rate applied to the pump or to the control valve;

– the net flow rate of the MBR system (set of rows/files, generally operating under the same conditions) which represents the average hourly flow rate actually treated by the membranes, which is the average flow rate discharged or available having subtracted all the permeate needs that are essential to the system operation (e.g. backwashing, cleaning, degasification). It is calculated by means of a balance of volumes on the tank permeate over 24 h;

– the net flow rate and the instantaneous flow rate, which are linked by the hydraulic efficiency, also representing the ratio between the quantity of water exiting the system per unit time and the quantity of filtered water per unit time. This corresponds to the production efficiency of the system:

$$Rh = \frac{Qnet}{Qi} = \frac{Fluxnet}{Flux\ i}$$

Qnet ($m^3.h^{-1}$) = Qj produced by the membranes – Qj consumed by the membranes

In general:

Qj net = Qj discharge/reuse + Q industrial water

A temperature correction should be applied to the flow rates similarly to the flux.

The permeate flux corresponds to the through flow per m^2 of membranes. Similarly to how the net flow rate is distinguished from the instantaneous or raw flow rate, the net flux (Fnet) is distinguished from the instantaneous flux in filtration (Fi) or to the raw flux. The value of a flux is significant only if brought at a given temperature, as the temperature of the fluid influences its filterability, through the modification of its viscosity. The common approach to comparing the hydraulic performances obtained at various temperatures is to normalize the operating flux at a reference temperature (often 20°C). This might be done by applying a temperature correction factor. To avoid the interference of temperature effects on MBR fouling, a nonlinear regression between the critical flux and temperature is proposed:

$$Fi,T = Fi,20 \times 1.025^{(T-20)}$$

$$Fnet(T) = \frac{Qnet(T) \times 1000}{Sf}$$

$$Fnet(20) = \frac{Fnet(T) \times \eta(T)}{\eta(20)}$$

$$Fi(T) = \frac{Qi(T) \times 1000}{Sf}$$

$$Fi(20) = \frac{Fi(T) \times \eta(T)}{\eta(20)}$$

In Europe, the flux is expressed in liters of permeate produced per m^2 of membrane and per hour (or $L.m^{-2}.h^{-1}$ or lmh). There is another international unit, the "m/j", which corresponds physically to the water approach velocity at the contact with membranes. It is therefore essential to always specify the temperature associated with the flux.

The design of the required filtration surface of the membrane systems is mainly based on the filtration rates. In an MBR, the net filtration flux can range between 14 and 25 $L.m^{-2}.h^{-1}$ if the concentration of MLSS in the reactor remains below 12,000 $mg.L^{-1}$ at 20°C. This flux must be reduced by 3% per °C below 20°C. Because of periodical backwashes, the net filtration flux is below the instantaneous flux according to a ratio that can vary between 1.1 and 1.2 depending on the programmed washing sequences.

As the membrane system is limiting equipment in terms of hydraulic capacity, the filtration capacity at the design temperature must be higher than the maximal instantaneous flow rate of water to be treated. Special attention should be paid to the peak factor and also to the parasite water flow rate that will be admitted at the treatment station.

Table 1.6 presents the usual values observed in MBR stations by various suppliers of membranes.

	Hollow fibers	**Flat sheet membranes**
Instantaneous flux at 20°C ($L.m^{-2}.h^{-1}$)	20	30
TMP (bar)	0.1–0.4	0.04–0.15
Permeability ($L.m^{-2}.h^{-1}.bar^{-1}$)	80–150	200–800
Specific membrane aeration demand ($Nm^3.h^{-1}.m^{-2}$)	0.2–0.5	0.2–1

Table 1.6. *Operating parameters*

Membrane technology was implemented in the treatment of wastewater due to its high separation properties. Acting as a physical barrier between two phases, a motive force is needed to obtain a flux. The transmembrane flux can be caused by a temperature gradient, a concentration gradient or a hydraulic pressure gradient. The motive force in the membrane processes of water treatment is generally the hydraulic pressure gradient, also known as TMP. It is equal to the difference between the supply pressure and the permeate pressure. It is therefore the head loss through membranes.

TMP is an indicator of membrane clogging at a given moment and it is highly dependent on the permeate flux, on temperature, on the filterability of biomass and on concentration. A too high TMP accelerates the clogging and can damage membranes. Its value is determined by calculating the absolute value of the difference between the pressure read upon the shutdown of the installation (the circuit being initiated) and the dynamic pressure. As an example, TMP in the filtration phase ranges between 100 and 300 mbar for the hollow fiber membranes and between 50 and 100 mbar for the flat sheet membranes.

By convention, it is negative in the filtration phase (permeate suction in the membranes) and positive in the backwashing phase (permeate backflow in the membranes):

$$\text{TMP} = \text{Abs (P inlet} - \text{P outlet)}$$

In the MBR with external loop, the TMP is obtained by the equation (Cardot 1999):

$$\text{TMP} = \frac{\text{Pa} + \text{Pc}}{2} - \text{Pp}$$

In this equation, Pa is the supply pressure, Pp is the permeate pressure and Pc is the concentrate pressure. Filtration operations can be conducted either by imposing a pressure gradient or a permeation flux. MBRs must always be operated below a certain TMP known as the critical pressure. The value of the critical pressure depends on the chemical nature of the membrane and is often provided by the supplier. Most installations operate at a constant flow rate, and a suction pump is used for immersed membranes, even though TMPs of several tenths of a bar are already ensured by the levels of water present in the tanks or by the level of discharge of the permeate. The flux is a crucial parameter in the evolution of TMP. Even though filtration is conducted below critical conditions, a change in TMP is observed.

Permeability (Lp20) is an indicator of long-term stability of filtration performances. It corresponds to the filtration capacity per m^2 and per bar. A high permeability indicates a good general state of membranes and corresponds to a lower TMP. It is always calculated at 20°C, on the basis of the instantaneous flux:

$$\text{Lp20} = \frac{\text{Flux}}{\text{TMPfiltration}} e^{-0.0239(\text{T}-20)}$$

With the temperature correction:

$$\text{Lp20} = \frac{\text{Ji(20)}}{\text{TMPfiltration}} = \frac{\text{Ji(20)}}{\Delta\text{Pf}}$$

Permeability is expressed in $L.m^{-2}.h^{-1}.bar^{-1}$ and more rarely in $m.d^{-1}.bar^{-1}$. As an example, a new membrane with hollow fibers has a sludge permeability ≥ 500 lmh/bar at 20°C.

Nevertheless, clean water permeability is not as significant in MBR processes as in conventional processes, as the accumulation of clogging particles at the level of the surface will strongly impact the properties of membrane filtration.

Permeability is mainly governed by the cross-flow velocity of the flux in the MBR with an external loop and by aeration in the immersed MBR. In the latter, air injection under and inside the membrane attenuates the formation of a cake on the external surface of the membrane (Pellegrin et al. 2002; Matosic et al. 2008). Aeration produces the oxygen needed for the biological activity and creates turbulence around the membrane which removes the large particles/grosses and dislodges the cake formed under the effect of suction required for filtration. However, aeration may have negative impacts on the bioreactor performances. Alternating aeration may limit clogging.

While membrane performances are a critical factor in this process, the configuration of membrane modules, the design of processes, the operating conditions and the biological performances are even more essential.

However, membrane performances are sensitive to certain factors:

– dependence on flux and pressure when a cake is formed around the membrane;

– lack of differentiation between the resistance of the membrane and the resistance to fouling after a certain operating time;

– calculations based on the total surface of the membrane and not on the effective surface of the membrane.

Consequently, the measures of the fouling rate and of the drop in permeability can be considered a consequence of the degradation of the filtration process but their causes are difficult to explain.

The maximal temperature admitted around the membranes is 35°C. Beyond this value, membranes and potting (material that maintains fibers) may suffer serious damage.

The membrane tank is designed to receive chemical reagents for membrane cleaning. It must be able to bear/supporter the acidic, basic and oxidizing character. A 1% slope of the bottom of the tank allows its full drainage during cleaning operations. A vessel/caisson or a cesspit will be installed at the lowest point of the tank to allow complete drainage of the membrane tank. The membrane tank is designed to allow jet cleaning of aerators and of the bottom of the tank when lifting modules would not be possible.

The distribution of the mixed liquor in the membrane tank is an important parameter to be taken into consideration to avoid the differences of concentration in the tank, which would lead to a clogging disparity in the modules. Membrane aeration creates a strong turbulence around the membranes and contributes to a good homogenization of the sludge. However, dead zones in the membrane tank can lead to excessive accumulation of sludge on the elements and on the bottom, which is difficult to remove during exceptional cleanings.

In the presence of large membrane tanks, several inlet points of the mixed liquor are necessary to allow good homogenization of the MLSS concentration in the membrane tank. A pipeline is then installed on the bottom of the membrane tank to distribute the mixed liquor throughout the length of the tank. This pipeline having holes directed downwards also allows avoiding an accumulation of sludge at the bottom of the membrane tank.

Membrane aeration has a double objective:

– avoid any sludge overconcentration at the level of membranes, by creating an airlift;

– limit the physical clogging of membranes by preventing sludge adherence to membranes.

It is implemented using a forced draught of air at the base of the membrane modules through aerators more or less integrated with each element, depending on suppliers, in order to create turbulence that puts into suspension the SS accumulated at the surface of membranes. In such cases, an aeration rate of 0.2–0.9 $Nm^3.h^{-1}$ per square meter of membrane surface is generally recommended (Krause et al. 2010). Membrane relaxation periods can also be scheduled. Despite these measures, membranes must be periodically cleaned by backwashing with filtered water or chemical products, or by immersion in a bath of chemical products.

Membrane aeration is essential for obtaining good filtration performances. Membrane air production is ensured by one or several boosters, backflowing into one or several collectors shared by the set of modules of a row/file.

Membrane aeration can be applied between several modules or several groups of modules and can be either cyclic or continuous, depending on the supplier. In case of cyclic aeration, the choice of automatic valves should be properly studied. The number of times these valves are used should also be clearly stated in the specification.

During night time, MBRs can be shut down because of lack of water. Membrane aeration can be reduced to save energy for this station.

A permeate storage tank is necessary for the industrial water needs of the plant (screens, sludge treatment equipment). This tank can also be used for storing the permeate used during backwashing, degasification and maintenance cleaning.

Figure 1.26. *Non-aerated membrane tank*

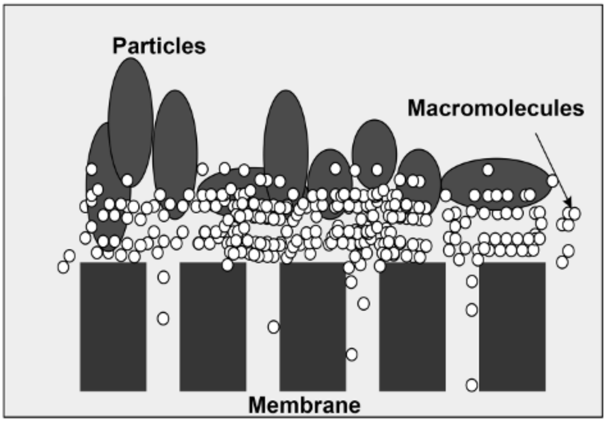
The MLSS concentration around membranes must be limited at 12–14 $g.L^{-1}$ for hollow fiber membranes and at 18 $g.L^{-1}$ for flat sheet membranes, in order to limit the risks of membrane solidification. In case of configuration immersed in a separate tank, the MLSS concentration in the biological tank must be approximately 10 $g.L^{-1}$ for hollow fibers and 14 $g.L^{-1}$ for flat sheet membranes.

In the case of seasonal loading variations, sludge age must be limited to 80 days in the low season. One method to limit sludge age involves using a tank whose volume depends on the season. To control sludge age, the station can be operated at various MES concentrations depending on actual needs.

1.6.3. *Management of membrane filtration*

MBR stations rely on a management system based on the control of operating conditions throughout the system. Flux demands are defined by the ingoing flux, and each downstream treatment phase must comply with the demands defined by the previous phase. In classical stations, control is generally facilitated by the process of overflow to the next phase. On the other hand, the adaptation of performances of the membrane system requires time. This is why a buffer work should be considered.

For urban applications, a 15 minutes buffer is recommended to allow the filtration unit to pass from minimum flux to maximum flux.



a)

b)

Figure 1.27. *Membrane clogging: a) simplified diagram; b) in station*

Beyond the membrane filtration, an MBR station is monitored similarly to a classical activated sludge station. But it is essential to implement a tool aiding efficient decision-making to simplify the operation in terms of filtration performances, particularly in the presence of several filtration rows/files of filtration. Data analysis requires a high-performance system to ensure a proper monitoring of the membrane performances.

To avoid excessive clogging of membranes, the pressure differential between upstream and downstream of the membrane must be continuously monitored and connected to alarms. Membranes can also be subjected to a loss of integrity. If needed, a device may be installed to allow leakage detection. All mechanical equipment and accessories required for membrane cleaning, MBR monitoring and maintenance must be included in the project.

Veolia developed its own software for data acquisition and processing. As part of the Veolink Care package, it is very simple to implement on site and is used in most Biosep® projects (Veolia MBR).

The control of MLSS leakage in the permeate circuit is essential for the efficiency of the treatment. The procedure consists of installing on the permeate circuit either a prefilter (control and prevention function) or an online turbidimeter (only control function). The objective of the prefilter is to prevent membranes from being clogged by SS that could have been sucked in filtration, such as, for example, in the case of breakage at the level of permeate connections.

It is recommended to install a prefilter with a cutoff of 80 µm, associated with a system of detection of high differential pressure connected to the optional automatic control system along the permeate circuit. In case of detection, filtration cycles are stopped. The prefilter is installed downstream of the membranes in order to detect any SS leakage and prevent the SS pumped return to the membranes during backwashing.

The online turbidimeter should be of the latest generation with a good resolution to be able to detect very fine particles. It is essential to install the turbidimeter with a bubble trap upstream to avoid signal perturbations due to microbubbles.

1.7. Membrane clogging

Nowadays, the main factor limiting the long-term application of MBRs is the clogging of membranes. Seyhi (2011) reports that by splitting clogging according to three observation scales – macroclogging (SS accumulation on the membrane), microclogging (development of biofilm on the membrane) and nanoclogging (adsorption of molecules) – the classification includes:

– macroclogging, underlining the importance of activated sludge and its role in clogging (Li et al. 2005), with SS considered as the main cause of membrane clogging (Yamamoto et al. 1989; Brindle and Stephenson 1996). The interest of this cake, as a selective dynamic layer, is that it can improve the retention capacity of the membrane (Tardieu et al. 1999; Ognier et al. 2004), but will rapidly become limiting depending on the permeate flux (> 10 lmh);

– microclogging, highlighting the importance of soluble microbial products (SMPs) generated during biological reactions and extracellular polymeric substances (EPSs) (Defrance 2000; Lee et al. 2003);

– nanoclogging, with a significant contribution of dissolved compounds. According to Fane et al. (1980), dissolved substances contribute up to 60% to clogging. This membrane clogging must be managed and controlled in order to maintain the permeability conditions required for membrane longevity and system productivity. Customized operating conditions and design can actually minimize macroclogging (Lebegue et al. 2009). Among other results, clogging management leads to reducing the costs related to membrane cleaning operations.

1.7.1. *Parameters influencing membrane clogging*

Several studies tried to clarify the mechanisms and factors that influence and govern membrane clogging. Even though clogging is the result of complex phenomena, it is significantly influenced by the operating and hydrodynamic conditions, the membrane type and configuration and the sludge characteristics (SS, physiological state of biomass, viscosity, etc.) (Cicek et al. 1998; Choi et al. 2005; Kaam et al. 2006). It is therefore a complex phenomenon. It can be described as being a continuous decrease of the permeate flux (under constant pressure) or an increase of TMP, caused by the accumulation or adhesion and/or adsorption of soluble or colloidal (organic, inorganic and microbial cells) particles or particles in suspension at the surface of the membrane and on the pores of the membrane (Choo and Lee 1996). It is possible to quantify clogging depending on its reversibility: reversible clogging (of a physical nature) and the irreversible clogging (of a chemical nature). Several factors can contribute to membrane clogging, and the description of this clogging varies from one author to the other, but it is rather the reflection of operating conditions and of the membrane configuration used.

The wide majority of membranes used in MBRs are based on polymer. A direct comparison between polyethylene (PE) and PVdF membranes clearly shows that PVdF membranes are less sensitive to irreversible clogging.

The type of material of organic membranes must be:

– sufficiently mechanically and chemically robust to bear the constraints imposed during filtration and cleaning cycles;

– easily modifiable to provide a hydrophilic surface, which then renders it more resistant to fouling, especially by exopolysaccharides (EPSs), and it is easily linked to a substrate to provide sufficient mechanical integrity.

Concentration polarization as well as clogging are considered major limits that tend to reduce membrane performances. The concentration polarization phenomenon is the consequence of the accumulation of compounds in the vicinity of the membrane. A decrease in the TMP or a filtration shutdown allows the instantaneous removal of the concentration polarization layer: the phenomenon is therefore reversible. As for the clogging, there are three ways in which it can occur. It may be from the adsorption of compounds on the membrane material with which there are strong interactions. Deep clogging may also occur when the size of compounds on the filter is smaller than that of the membrane pores (case of macromolecules present in the MBR). The third form of clogging is the deposit of particles at the surface of the membrane, which may generate a more or less compact cake (Le-Clech et al. 2006). The clogging of MBRs is generally a combination of these three forms. It depends on the physical characteristics of membranes, on those of used water and on the operating conditions.

The pore diameter makes it possible to distinguish between a microfiltration membrane and an ultrafiltration membrane and addresses the importance of discharge and the control potential of the organic and bacterial clogging. Indeed, the effects of the diameter of pores and of their distribution are strongly related to the characteristics of the effluent to be treated and of the bacterial populations present in the bioreactor. If the size of particles is smaller than the diameter of pores, obstruction of pores and limitation of the treatment flux will be rapidly observed. For this reason, some providers of membranes prefer to use a microfiltration membrane rather than an ultrafiltration membrane.

This parameter remains, however, insufficient to predict the hydraulic performances given the complexity of the biological and particulate matrix in the reactor. Other factors are involved, such as the hydraulic resistance of the membrane, the transmembrane velocity, the applied pressure and flux. Fortunately, a part of the clogging is reversible and is easily removed during the maintenance cleaning.

Membrane roughness and porosity are involved in the membrane clogging mechanisms. A membrane with dense structure and low porosity is more sensitive to clogging. For example, polyvinylidene fluoride (PVdF) and polyethersulfone (PES) membranes with pores of similar diameters may have different fouling behaviors. While fouling is mainly due to the cake surrounding PVdF and AC membranes, the blocking of pores is responsible for over 80% of the total hydraulic resistance of the PES membrane. Moreover, less fouling is observed with membranes having elliptical pores rather than circular pores.

The effect of roughness with respect to fouling of membranes shows that the higher the roughness, the more significant is the potential to accumulate fouling layers.

Due to hydrophobic interactions between the effluent, the bacterial biomass and the material of the membrane, membrane fouling is more serious with hydrophobic than with hydrophilic membranes. For example, the measurement of the contact angle showed that the apparent hydrophobicity of polyethersulfone (PES) decreased (from 55° to 47°) with the increase in the molecular weight cut-off (MWCO) parameter of organic materials passing from 20 to 70 kDa.

The loss of permeability can be explained by the dynamic layer formed in the cake deposited on the membrane, and, to a lesser extent, by the direct adsorption in the pores of the membrane and on its surface.

In MBRs, depending on the sludge age, activated sludge may contain significant quantities of hydrophilic EPSs (exopolysaccharides), which are known for their significant contribution to membrane clogging.

The TMP that measures the difference in pressure between the two compartments of the membrane is an important parameter for the evaluation of performances of MBR systems as it allows preventing membrane clogging. Indeed, this clogging phenomenon leads to an increase in hydraulic resistance and, at the same time, to an increase in TMP and to a decrease in the permeate flux when the system operates, respectively, under constant PTM or flux. The drop in flux or the increase in TMP requires the membrane to be hydraulically or chemically regenerated at regular intervals. For example, with a sludge concentration (MLSS) in the biological tank of 10 $g.L^{-1}$, TMP increases progressively to reach, at the end of 20–40 days, the limit value of clogging fixed at 500 mbar. At this moment, the activity of biomass is intense and results in the formation of a sludge cake that adheres to the membrane pores, blocks the filtration operation and drives an increase in TMP. Clogging is the vulnerability of membrane technology and can be defined as an undesirable deposit and an accumulation of microorganisms, colloids, cell debris and other solutes either inside the pores or at the surface of membranes.

The presence of an airlift may delay clogging. TMP becomes maximal after 50–60 days of operation.

In MBRs, it is important to anticipate the prediction of the resistance to fouling for the optimization of the operating conditions. Among these strategies, the membrane geometry and the modification of the surface to reduce the biological fouling are the object of special attention. In particular, the characteristics of the membrane, such as the material of the membrane, the size of pores and the hydrophilic character, are important factors for membrane fouling, as they affect the interactions between the surface of the membrane and the mixed liquor in the bioreactor. Hydrophilic membranes allow a higher attenuation of the membrane fouling than hydrophobic membranes.

Once clogging starts, membranes must undergo a chemical cleaning that is essential to prevent the irreversible clogging of membranes.

1.8. Membrane cleaning

The major problem of the membrane process is related to the continuous clogging of membranes in the filtration phase. While the purpose of membrane aeration is to avoid this clogging process, regular cleaning must be practiced in order to recover a part of the membrane performances. Adsorption-based clogging requires chemical cleaning to regenerate the filtration performances of the membrane. Pore blockage and the deposit of particles can be removed by the backwashing when membrane technology allows it (the case of hollow fiber membranes). For the other membrane technologies, chemical cleaning is required. Chemical washing involves using an acidic solution (e.g. citric acid) to remove the clogging due to inorganic material and an oxidizer (e.g. a NaOCl solution) to oxidize the organic material.

Permeability corresponds to the treatment capacity of an MBR brought to identical conditions of TMP and temperature. TMP is related to the quality of the membrane and to the quality of sludge. This is why, at equal flux, permeability evolves depending on the sludge age and on the clogging of membranes along the filtration cycles (see Figure 1.28).

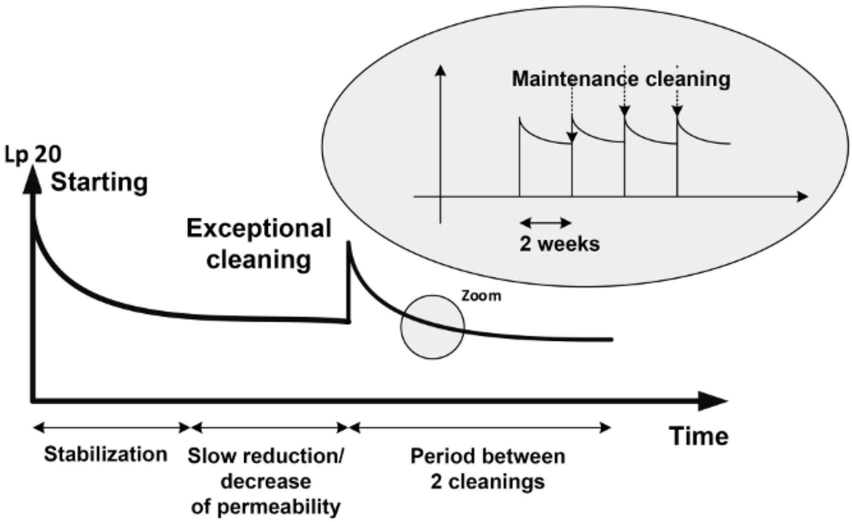


Figure 1.28. *Typical evolution of membrane permeability in time*

Membrane cleaning removes clogging and thus extends the life time. There are several techniques for cleaning membranes.

There are two ways to deal with fouling, which is the main obstacle to filtration:

– By mechanical and hydraulic action:

- Immersed membranes: fibers are permanently stirred by large air bubbles directly injected under the modules. Due to the resulting turbulences, the deposit formation is perturbed. It is also rinsed by backwashing with water, in the opposite direction to filtration.

- Tangential filtration: the effluent circulates at high velocity in the circulation loop and allows the evacuation of accumulated sludge.

– By backwashing and chemical washing, which are the most commonly used ways to remove fouling:

- Backwashing is conducted with water or with air. The larger the pores of the membrane, the less efficient is the backwashing. Several parameters influence the efficiency of backwashing, particularly the backwashing flow rate (in general, this flow rate is twice to three times higher than the filtration flow rate), the frequency and the duration of backwashing. The literature reveals that the shorter the backwashing, the more it contributes to reestablishing a better flux (Ramirez 1998; Barrios 2006). As only hollow fiber membranes can be backwashed (pull-out of adhesive lines and swelling of flat sheet membranes during backwashing), manufacturers are currently working to produce backwash flat sheet membranes.

- By chemical action: chemical cleaning can be used to attack the deposits fouling the membranes. Acidic solutions remove mineral deposits. Alkaline solutions remove organic materials, and chlorine prevents bacterial development.

1.8.1. *Chemical cleaning*

Two categories of chemical cleaning can be identified: maintenance cleaning and exceptional cleaning.

1.8.1.1. *Maintenance cleaning*

The maintenance cleaning procedure depends on the membrane provider. For the immersed membranes, maintenance cleaning involves backwashing with a chemical solution, generally with chlorine water or from time to time with citric acid (case of high hardness effluents). Maintenance cleaning is conducted in the opposite direction to filtration.

This cleaning is based on the injection of chemical products such as chlorine and/or acid in the membranes on the permeate side. The counter-pressure and the flow rate of the chemical injection vary depending on the supplier and on the membrane type. The frequency of the maintenance cleaning is a function of the type of influent. The current values are the following: 0.5–2 times/week for domestic wastewater.

The concentration of the chemical product depends on the membrane supplier. The pH specifications are also provided by the suppliers to enhance the efficiency of the chlorine cleaning. The pH limits specified by the membrane suppliers must be strictly observed.

A space should be dedicated to the on-site preparation of chemical products in order to host tanks for the storage of chemical products and the associated pumps. Chemical products must generally be diluted with a bit of permeate to reach the appropriate concentrations. The operation is conducted directly in the permeate storage tank. The chemical products are injected, by pumping or gravity, in the membranes on the permeate side. Flat sheet membranes do not bear the counter-pressure and therefore they generally need an intermediary storage tank that is slightly above the membrane modules, allowing the slow percolation of the chemical solution through the membrane.

After the chlorine cleaning, dechlorination and neutralization of residual waters are necessary in all cases, particularly if they are recycled at the head of the station ($6 < pH < 9$; free residual Cl < 0.05 $mg.L^{-1}$).

In all cases, the function of maintenance cleaning is to maintain the low permeability slope within an acceptable limit. Conversely, exceptional cleaning allows the recovery of a certain permeability when a low threshold of permeability was reached.

1.8.1.2. *Exceptional cleaning*

Some membrane suppliers recommend a more complete and deep cleaning. This cycle, referred to as exceptional cleaning or regenerative cleaning, involves submerging the membranes in a cleaning solution (chlorinated solution, acid or detergent). In general, this starts by a manual cleaning of membranes in order to remove the accumulation of sludge and fibers. Immersion periods can last up to 12 h, which explains the long duration of regenerative cleaning. The frequency of exceptional cleaning depends on the type of influent. Its common value is one or two times/year in urban wastewater.

Acidic solutions are mainly used to remove inorganic deposits, basic solutions and surfactants to remove organic materials and disinfectants to prevent the growth of microorganisms in the membrane system (Bouchard et al. 2000).

Chemical products are chosen depending on the nature of the membrane material, in order to respect the limits of pH and temperature as well as the tolerance to chlorine, other disinfectants and acids. Under normal conditions, the generally used solutions for chemical cleaning are sodium hypochlorite (NaOCl) to dislodge organic materials and citric acid ($C_6H_8O_7$) for inorganic materials (Lee et al. 2003; Chang and Kim 2005; Le-Clech et al. 2006).

Membrane manufacturers frequently propose scientific protocols specific to chemical cleaning. Most of these cleanings are operational without emptying the bioreactor where the cleaning solutions are sent during backwashing and have little impact on the biological process.

The concentration of the chemical product used depends on the membrane supplier and is generally higher than that related to maintenance cleaning. The procedures are, however, different for immersed membranes depending on whether it is a single tank or a separate tank.

1.8.2. *Implementation of cleaning*

1.8.2.1. *Single-tank configuration*

The membrane module is taken out of the tank by means of a cleaning device; the operator must wash it manually in order to clean it and remove the accumulated sludge. A low pressure water jet is used to prevent membrane damage. After the manual cleaning, the module is dived in a cleaning tank filled with a chemical solution at a given concentration for a given period of time (variable depending on the temperature of the cleaning solution).

1.8.2.2. *Separate-tank configuration*

For the separate-tank configuration, the exceptional cleaning protocol is, in principle, similar to the one for the single-tank design. It involves extended soaking of all membranes of the same tank in at least two cleaning solutions (chlorine, acid), for an in-depth removal of the elements that may clog the pores. The modules of the membrane tank are not displaced, the membrane tank playing the role of cleaning tank. The mixed liquor is evacuated from the membrane tank to the biological tank by pumping. A tidal range should be considered in the biological tank, as well as a pipeline system to allow sludge evacuation from the membrane tank to the biological tank.

The exceptional cleaning in a separate tank involves the following six phases:

1) *Drainage of the membrane tank*: the mixed liquor is evacuated by pumping to the biological tank.

2) *Rinsing*: before introducing the cleaning solution, membranes are rinsed. For this, membrane aeration is maintained during the sludge drainage up to an intermediary threshold (50 cm above aerators). The membrane tank is filled with permeate coming from another row/file in the case of a configuration with several rows/files (a meshing on the permeate collectors should be considered) or a permeate tank. Backwashing is conducted in order to again suspend the sludge stuck to the fibers (with the aeration). The rinsing solution is drained, by gravity or by pumping to the "all-water" station.

3) *Chlorine cleaning*: a chlorine solution at a given concentration is introduced in the membrane tank for a given duration (typically 12–24 h). The cleaning solution is then drained, to the all-water station or to the biological tank if the tidal range volume allows it, and if the chlorine quantities do not endanger the biology (total Cl_2 dose below 4 $gCl_2.kg^{-1}$ VSS $.d^{-1}$) (VSS: volatile suspended solids).

4) *Acid cleaning*: an acidic solution at a given pH is introduced in the membrane tank for a given duration (typically 3–6 h).

5) *Acid neutralization and drainage*: the acid solution is neutralized by the addition of caustic soda in the membrane tank before draining it to the "all-water" station. On the other hand, no neutralization is required if the solution is sufficiently dissolved in the biological tank (in other terms, the pH of the mixed liquor where the acid is injected should not be influenced by the acidic solution; the latter should therefore be injected where alkalinity is maximal in the treatment row).

6) *Restart*: when the drainage of the membrane tank is completed, the mixed liquor of the biological tank is sent to this tank up to the operating level corresponding to the restart of filtration.

Membranes with an external loop are cleaned by circulating through them an alkaline solution of sodium hypochlorite and an acidic solution, in the direction of filtration.

For urban wastewater, one or two exceptional cleanings are recommended per year. This figure can be increased depending on the operating conditions and on the quality of the wastewater to be treated.

1.9. Performances and warranties

The performances of MBRs are interesting both in relation to biodegradable and difficult to biodegrade pollutants and to particulate materials. MBRs also ensure an advanced disinfection whose intensity depends on the cutoff and on the distribution of the diameters of membrane pores. The treated effluent has excellent quality in terms of reduction of turbidity, SS, BOD, COD, disinfection and by-products of disinfection. This treated water is completely acceptable for direct reuse at the municipal level (toilet flush water, car washing, etc.) or for indirect use at the industrial level (cooling water, process water, etc.). It might also serve as feedwater for reverse osmosis (RO) units (Xing et al. 2000). The additional investment and operation cost of an MBR is then compensated by the minimization of its covered surface (by a factor of four with respect to a conventional activated sludge process) and the fact that the quality of water produced does not require a tertiary treatment such as oxidizing or infiltration/percolation.

1.9.1. *Physico-chemical and microbiological guarantees*

The synergistic filtration–biodegradation action allows the complete removal of SS. At the same time, the intense microbial activity at the level of the reactor allows a removal of organic material in terms of COD and BOD_5. The COD and BOD_5 residuals depend on soluble or biodegradable fractions of raw water. In general, the reduction rates of organic pollution in wastewater are very interesting. MBR is very robust to unexpected loading variations and may operate under significant volume and organic load. A 99% reduction of COD was observed on a wastewater of organic load of the order of 10 500 mg $COD.L^{-1}$ (Zhang et al. 2002). Several studies report COD reduction rates of up to 99%, depending on the type of treated water, organic compounds, membrane type and imposed treatment conditions (TMP, θ, etc.). The aeration, carbon availability and the pH of the medium facilitate nitrogen removal. However, the direct removal of phosphorus remains moderate and other techniques involving chemical reagents (iron salts) are used when the required residual phosphorus concentration is very low.

The guarantee for COD is based on the hard COD of raw water. A value of 30 $mg.L^{-1}$ is valid for standard French raw water. The efficiency of an MBR makes it possible to reach an annual or periodical average concentration below 5 mg $BOD_5.L^{-1}$ and below the detection limit of the SS method (3 $mg.L^{-1}$) or to ensure at least 97% and 99% removal, respectively, for these parameters.

MBRs are also used to remove nitrogen (N-NH_4 and N-NTK) and phosphorus (P-PO_4 and total P). It is then possible to use the recirculation flow rate of the membrane tank (300–400%) to return to the top the nitrates produced during the aerobic phase. Pt and N-NH_4 removal rates going up to 97% and 99% can be, respectively, obtained, depending on operating conditions and on the type of treated effluent. However, the application of MBRs with urban wastewaters requires a higher θ (> 20 days), taking into account the complexity of the effluent. In a conventional MBR, denitrification is due to the presence of anoxia zones caused by high concentrations of biomass. Indeed, at a low concentration of dissolved oxygen, the limits of diffusion can create, in the aerobic tank, anoxia zones between biological flocs, thus facilitating denitrification (Pochanna et al. 1999). However, the simultaneous nitrification and denitrification processes require taking into account certain operating and MBR configuration conditions. The type of aeration may have a significant effect on the growth and development of nitrifying and denitrifying bacteria. The concentration of dissolved oxygen required for carbon oxidation and simultaneous nitrification must be greater than or equal to 2 mg $O_2.L^{-1}$ (Sorensen and Jorgensen 1993). Intermittent aeration can be used to reach this concentration. Nitrogen removal can also be improved with the creation of an anoxia zone separated from the aerobic zone (Côté et al. 1997). N-NH_4 and NT reduction rates above 90% and 97% are obtained. It should be noted that during an underload period, it is very difficult to control denitrification because of the oxygen supplied by the membrane air, sometimes exceeding the needs of O_2.

In general, MBR performances in terms of biological removal of phosphorus are low. A 45–67% reduction rate of phosphorus, by biological means, is observed (Vera et al. 1997; Battistoni et al. 2006). The degree of P removal depends on the (physico-chemical or biological) type of station.

There is practically no SS in the effluents exiting MBR. Consequently, the particulate fraction of N and P encountered at the outlet of conventional activated sludge stations is not found in the effluent.

Though each membrane supplier can propose its own process warranties, Table 1.7 indicates the warranties that are generally easy to reach provided the activated sludge process is properly designed.

However, several factors are involved in ensuring the best efficiencies. Certain factors are intrinsic and related to the biological medium and to the operating conditions: pH, concentration of dry material, aeration rate, permeation flow rate/relaxation time and sludge content. Other factors are inherent to the nature and composition of membranes.

The optimization of the operation of an MBR is based on the optimization of these factors, and this is an essential step for achieving an optimal membrane filtration. However, the limiting factor for membrane filtration remains the clogging of membranes which causes a loss of MBR performances by influencing TMP and permeate flux.

Parameters	Concentrations in the effluent
COD	≤ 30 mg.L^{-1}
BOD_5	≤ 5 mg.L^{-1}
SS	≤ 5 mg.L^{-1}
NT (total nitrogen)	Comparable to a classical activated sludge
PT (total phosphorus)	Comparable to a classical activated sludge

Table 1.7. *Process warranties for the MBR*

The disinfecting effectiveness of MBRs has been evaluated. MBR application allows the efficient removal of pathogen indicators (total and fecal coliforms), viruses and aerobic heterotrophic bacteria (AHB). This process also removes a very large part of pathogens and can be followed by a complementary disinfecting stage according to local regulations. The membranes used in MBRs have a nominal porosity ranging between 0.01 and 0.2 µm. This type of membrane can therefore retain bacteria such as coliforms, but does not seem able to retain all viruses with a diameter ranging between 0.001 and 0.1 µm. It is important to pay special attention to warranties related to the removal of microorganisms. Indeed, even though the membrane barrier may achieve a 5 log reduction of bacteria and a 1–4 log reduction of viruses, the residual may be higher than the concentrations required by the local regulation.

The disinfecting effectiveness of MBR is highly dependent on the size of pores. As the size of pores is never uniform, the selected membrane must have a sufficient gap with respect to the smallest microorganisms to be retained. However, microclogging reduces the cut-off threshold of membranes and some membranes, with a cut-off threshold of 0.4 µm, present a total bacteriological reduction.

1.9.2. *Removal of endocrine disruptors (EDs)*

Many endocrine disruptors (EDs) escape classical wastewater treatment. There are few studies on ED removal in MBRs. Most of them concern phenolic compounds (e.g. nonylphenol, bisphenol A), hormones and hormone derivatives (17β-ethinylestradiol, estradiol), several pharmaceutical compounds, etc.

The reduction rate of bisphenol A in an MBR generally oscillates between 93 and 97%. Nonylphenols, estradiol and 17β-ethinylestradiol are removed at a rate of 55%, 64% and ≥ 71%, respectively. Over 93% of genistin is removed.

Pharmaceutical products and derivatives (drugs, drug metabolites, cosmetic products, food supplements and derived metabolites) have also been highlighted, particularly the lipid regulator benzafibrate, analgesics (ibuprofen), polycyclic compounds (galaxolide and tonalide) and the antiepileptic carbamazepine, to cite but a few (Clara et al. 2005a, 2005b; Lyko et al. 2005; Chen 2008; Lee et al. 2008; Seyhi 2011).

According to study results, benzafibrate and ibuprofen have high removal rates (≥ 95%). They are followed by polycyclic compounds (tonalide and galaxolide), which are removed at a rate of nearly 80%. Carbamazepine is not removed. Compounds such as phenazone and propyphenazone are partially (70%) removed in MBRs.

In tertiary treatment, aimed at reuse for industrial applications, MBR is often the treatment stage (Gaid 2025) before a final stage consisting of RO. The silt density index (SDI) must generally reach a value ≤ 3 upon entering RO, and this value can be normally reached after an MBR treatment.

1.9.3. *Hydraulic guarantees*

As the flux decreases with temperature, it is important to clearly specify the temperature ranges within which the hydraulic capacity can be guaranteed (the lowest temperature mentioned in the call for tender documentation). The filtration surface is dimensioned for the most penalizing case (peak duration and intensity, temperature). In a municipal context, the dimensioning case is most often the winter, when there are significant volumes and temperature is the lowest.

Moreover, the hypotheses considered for the dimensioning of the buffer tank (total peak duration) must be clarified in the guarantee specifications. A distinction should be made between a buffer tank and a storm water tank; the function of the first one is to store water reserves during maximum flux in the dry season and that of the second one is to store the over-flow of the water collected during rainy days.

As the flux decreases with membrane aging, design should take into consideration the customer guarantee duration.

1.9.4. *Membrane warranties*

Membrane lifetime is estimated between three and seven years depending on the system design and on the use of membranes, as the lifetime of membranes is directly related to their operating conditions. The warranty given by membrane suppliers may have various forms. It can be firmly offered for a reasonable duration (two years) by the supplier, and supplemented by a three-year *prorata temporis* warranty.

1.9.4.1. *Principles of* prorata temporis *warranty*

Under normal operating conditions as specified in the technical documentation (raw water quality, daily production, operating duration of the membrane system), and to the extent that the system is operated according to the manufacturer's recommendations, the customer will not need to replace the membranes for seven years, for example, if this is the period specified by the membrane supplier.

However, if a partial or total replacement of membranes is needed during the period of seven years, the costs are supported by the manufacturer and the customer according to the *prorata temporis* principle. This procedure is applicable if the manufacturing flow rate is not respected for a reason attributed to membranes (drop in permeability, abnormal breakage of fibers, etc.).

The *prorata temporis* warranty means that the warranty offered for the membranes is proportional to the operating time.

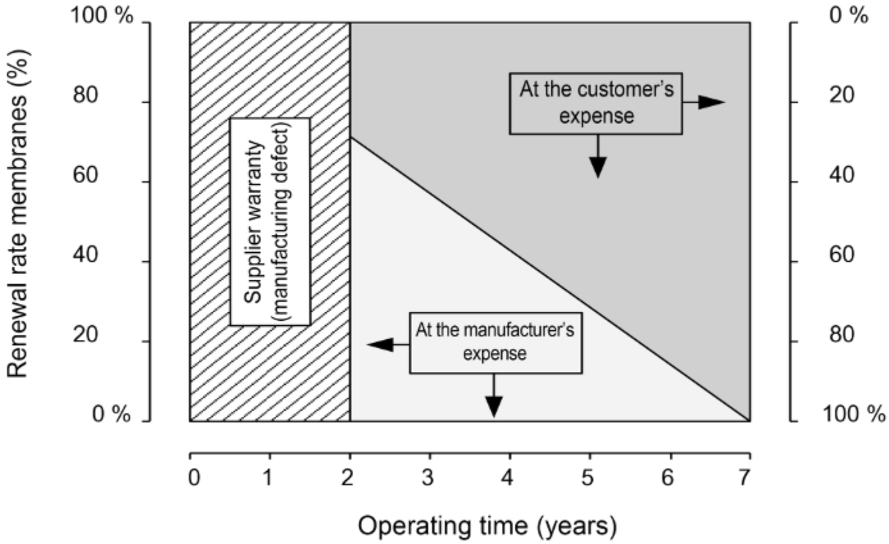


Figure 1.29. Prorata temporis *warranty operation*

The curve presented in Figure 1.29 shows the mechanism for prorating the membranes for the first operation cycle:

– The *prorata temporis* warranty comes into effect as soon as the plant starts operating, at the end of the period of observation.

– During the supplier warranty period which corresponds to the hatched area in Figure 1.29 (warranty against manufacturing defects), if the production flow rate is not reached because of defective membranes, the replacement of these membranes is at the supplier's expense. There are no charges for the customer.

– The *prorata temporis* calculation becomes applicable when the supplier warranty period expires. It involves customer participation in the replacement of membranes depending on their operating time (days, months, years). This procedure is implemented if the production flow rate of the plant is not met for a reason attributable to membranes (drop of permeability, abnormal breakage of fibers, etc.).

– After seven years of operation, the replacement of all membranes will be at the customer's expense. They will have benefited from drinking water production according to the technical specifications during this period.

– A new operating cycle is implemented according to the warranty procedure.

EXAMPLES.–

1) If at the beginning of the third year observations reveal that membranes are the permanent cause of a drop in production, the manufacturer (and the supplier) will be responsible for the replacement of 100 x (7 – 2)/7) = 71.4% of membranes, and the customer will be responsible for the remaining 28.6% because of satisfactory operation of the plant for two years and the customer's benefit of drinking water production according to the technical specifications during this period.

2) If these incidents occur at the end of the fifth year, the manufacturer (and supplier) will be responsible for 100 x (7 – 5)/7 = 28.6% of the replacement of membranes, and the customer will be responsible for the remaining 71.4% because of satisfactory operation of the plant for five years and the customer's benefit of drinking water production according to the technical specifications during this period.

1.10. Example of dimensioning of MBR with external loop

1.10.1. *Characteristics of supply water*

The treatment plant receives raw wastewater coming from domestic networks. The raw wastewater entering the plant is pretreated via screens and sand and grease removal before getting into the bioreactor. Wastewater characteristics are presented in Tables 1.8 and 1.9.

Given the high peak factor, the installation must buffer a part of the ingoing peak flow rate. The pretreatment is expected to take 1,770 $m^3.h^{-1}$ before the buffer tank (fine screening and grit removal-degreasing) and 1,070 $m^3.h^{-1}$ after the buffer tank (screening).

In order to comply with the specified maximal peak flow rate, a buffer tank of a net volume of 1,500 m^3 is integrated in the design.

The load considered for the design of the plant corresponds to a maximum daily flow rate of 20,500 $m^3.d^{-1}$ multiplied by the concentrations.

Hydraulic parameters	Average	Maximum	Notes
Daily average flow rate ($m^3.d^{-1}$)	17,000	20,500	–
Hourly average flow rate ($m^3.h^{-1}$)	708	854	
Peak flow rate factor	–	2.5	Peak for max. two hours/day two times/day
Feed flow rate ($m^3.h^{-1}$)	708	1,770	Maximum for max-two hours/day two times/day

Table 1.8. *Hydraulic parameters*

Wastewater parameters	Base	Pollutant load ($kg.d^{-1}$)
Temperature (°C)	22–35	–
Temperature air (°C)	10–60	–
pH	6–9	–
COD (mg $O_2.L^{-1}$)	500	10,250
BOD_5 (mg $O_2.L^{-1}$)	250	5,125
Total SS ($mg.L^{-1}$)	250	5,125
Total Kjeldahl nitrogen (mg $N.L^{-1}$)	55	1,127
Total phosphorus in P (mg $P.L^{-1}$)	8	164
Oil and grease ($mg.L^{-1}$)	40	820

Table 1.9. *Raw wastewater parameters*

1.10.2. *Pretreatment required for the MBR*

A 6 mm raw screening followed by a 1 mm fine screening are required.

Parameters	Average values Raw water	Maximal values Raw water
Temperature (°C)	22–36	22–36
MES concentration in the biological tank (g.L^{-1})	11.3–36ºC 12.7–22ºC	15
Filtrability	See the rest of the section	
%VSS in sludge	60–70%	–
Sludge age	Minimum 17 days	–

Table 1.10. *MBR operating conditions*

Operating conditions	Operating flow rates		
	At 636 m³.h^{-1}	**At 811 m³.h^{-1}**	**At 1 070 m³.h^{-1}**
Average permeate/skid flow rate (including washing)	31.8 m^3.h^{-1}	40.6 m^3.h^{-1}	53.5 m^3.h^{-1}
Applied flux (L.m^2.h^{-1})	40.7	52	68.6
Max permeate/skid flow rate	36 m^3.h^{-1}	46.9 m^3.h^{-1}	60 m^3.h^{-1}
TMP during filtration	0.10–0.19 bar	0.12–0.24 bar	0.15–0.30 bar
Recirculation/skid flow rate	390 m^3.h^{-1}	520 m^3.h^{-1}	520 m^3.h^{-1}
Pressure drop on skids	0.24 bar	0.26 bar	0.26 bar
Air/skid flow rate	115 Nm^3.h^{-1}	229 Nm^3.h^{-1}	229 Nm^3.h^{-1}
Applied air pressure	0.6 bar	0.6 bar	0.6 bar
Washing/skid flow rate	234 m^3.h^{-1}	234 m^3.h^{-1}	234 m^3.h^{-1}
Time between two washing processes	10 min	7 min	7 min
Washing/skid time	7 s	7 s	7 s
TMP on membranes during washing	0.5–0.8 bar	0.5–0.8 bar	0.5–0.8 bar

Table 1.11. *Operating conditions of membrane filtration*

Sludge filterability must be sufficient for the MBR process. Besides the sludge age, filterability will be evaluated by means of a laboratory test (C5 paper for 5 min) and should normally reach a reference value > 15 ml. Taking into account the peak flow rate of 1,770 m^3.h^{-1} two times and two hours per day, the permeate production of the membrane workshop consisting of 20 operating skids will be the following during the day:

– average case (17,000 m^3.d^{-1}):

- 2 h at 1070 $m^3.h^{-1}$,
- 10 h at 636 $m^3.h^{-1}$,
- 2 h at 1070 $m^3.h^{-1}$,
- 10 h at 636 $m^3.h^{-1}$;

– maximum case (20,500 $m^3.h^{-1}$):
- 2 h at 1070 $m^3.h^{-1}$,
- 10 h at 811 $m^3.h^{-1}$,
- 2 h at 1070 $m^3.h^{-1}$,
- 10 h at 811 $m^3.h^{-1}$.

The workshop is composed of 20 skids with an installed membrane surface of 780 m^2 (26 modules with a unit surface of 30 m^2 or a total surface of an installed membrane of 15,600 m^2).

Due to the aeration of membrane modules, the level of oxygen dissolved in the tank increases generally from 1.5 to 2.5 $mg.L^{-1}$ during the passage in the membrane installation.

Chemical cleaning must be conducted every 30–120 days (depending on the quality of the bioreactor sludge).

A chemical cleaning is conducted with citric acid followed by sodium hypochlorite (NaOCl) for each individual skid. This skid is taken out of service during this cleaning. It is recommended to conduct chemical cleaning when the flow rate is the lowest (during night).

Chemical agent	Contact time	Interval	Concentration of reagents
Citric acid	30–120 min	30–120 d	10 $g.L^{-1}$
Sodium hypochlorite			400–500 ppm free chlorine

Table 1.12. *Conditions for the chemical cleaning of membranes*

1.10.3. *Characteristics required for the treated water*

The membrane workshop will meet the required warranties provided that the bioreactor operates according to the characteristics indicated in Table 1.13.

Parameters	Maximal concentration
COD	≤ 50 $mg.L^{-1}$
BOD_5	≤ 10 $mg.L^{-1}$
SS ($mg.L^{-1}$)	≤ 2
Turbidity (NTU)	≤ 0.5
pH	6–9
$N\text{-}NH_4$	≤ 1 $mg.L^{-1}$
Total nitrogen (NGL)	≤ 30 $mg.L^{-1}$
Dissolved oxygen	≥ 2 $mg.L^{-1}$
Fecal coliforms	≤ 5 MNP/100 ml

Table 1.13. *Guaranteed quality of the effluent outgoing from the MBR*

Guarantees are given over 95 percentiles of a daily sample.

Figure 1.30. *Quality of the filtered water*

1.11. Conclusion

The MBR system is a revolutionary technology in the field of water treatment. It is characterized by interesting performances in terms of removal of biodegradable pollutants and pollutants considered difficult to biodegrade by the usual processes of wastewater treatment. Waters treated by MBR have excellent quality in terms of SS and disinfection. MBR technology is relatively more expensive than the standard active sludge systems, but enormous efforts have been undertaken (significant reduction of membrane costs and operation costs) to ensure its industrial and commercial development. The MBR operating range (sludge age and MLSS content) is rapidly limited as a consequence of stirring and mixing problems and (oxygen) mass transfer. Due to excessive energy consumption during MBR operation, MBR users have had to reexamine their objectives to finally adopt an SRT ranging between 20 and 30 days, and MLSS contents of 6–8 $g.L^{-1}$. However, so far the technology is mainly competitive for the treatment of industrial wastewater where effluents are highly loaded. For municipal wastewater, the high energy demand of 30–50% (compared to the conventional activated sludge system) may limit the use of this technology. This limitation is reduced when considering the compactness of an MBR installation (four times reduction of the covered surface) and the process performances (comparable to a tertiary treatment). Moreover, many research teams are working to develop and optimize the MBR technology, in order to increase its competitiveness and adapt it to municipal applications.

In recent years, the costs have been reduced thanks to the progress in the domain of membrane manufacturing. Progress also led to an increase in the life time of membranes, a reduction in the costs of their replacement, a reduction in energy consumption with respect to the obtained permeate flux and a decrease in the operating costs due to the possibilities to reuse treated waters.

Nowadays, water users agree on the fact that the use of membrane technologies has gained its place in the wastewater treatment field. Indeed, membrane modules have many advantages compared to a conventional activated sludge treatment process. These advantages can be divided into three major categories: installation, operation and process. They are therefore more compact and the ground surface can be five times smaller. Membranes can be implemented in small spaces. Moreover, MBRs have the advantage of being modular. Due to these characteristics, this process can be readily implemented in the existing installations that already have biological reactors such as, for example, during the rehabilitation of old treatment plants where settling tanks can be reconverted into buffer tanks. The treatment of wastewater by MBR has many advantages concerning the removal of biodegradable pollutants and also of micropollutants considered to be difficult to degrade in the conventional systems for wastewater treatment. Several studies reported very high rates of reduction of organic and inorganic pollution depending on the type of treated waters, on the type of organic compounds, on the type of membranes used and on the imposed treatment conditions.

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