A REVIEW OF MEMBRANE BIOREACTOR (MBR) TECHNOLOGY AND THEIR APPLICATIONS IN THE WASTEWATER TREATMENT SYSTEMS

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ABSTRACT

Membrane bioreactors (MBRs) can be broadly defined as systems integrating biological degradation of waste products with membrane filtration. They have proven quite effective in removing organic and inorganic contaminants as well as biological entities from wastewater. Advantages of the MBR include good control of biological activity, high quality effluent free of bacteria and pathogens, smaller plant size, and higher organic load rates. This article aims to review all the principles and potential applications of the MBR technology. Current applications include water recycling in buildings, wastewater treatment for small communities, industrial wastewater treatment, and landfill leachate treatment.

Keywords: Activated Sludge; Membrane Bioreactor; Cross-flow Membrane; Submerge Membrane; Water Reuse.

INTRODUCTION

The membrane bioreactor (MBR) concept is a combination of conventional biological wastewater treatment plant and membrane filtration. The concept is technically similar to that of a traditional wastewater treatment plant, except for the separation of activated sludge and treated wastewater. In an MBR installation, this separation is not done by sedimentation in a secondary clarification tank, but by membrane filtration.

The first generation of MBRs consisted of external cross-flow operated membranes, which were installed outside the activated sludge tank. The cross-flow principle, with its associated high flow velocity, was used to prevent the build up of solids on the membrane surface, so-called cake-layer formation. This method of cross-flow operation required large amounts of energy to generate the sludge velocity across the membrane surface to maintain both the high cross-flow velocity for membrane cleaning and the required pressure drop necessary for permeation. Owing to the energy requirements this concept was considered as non-viable for the applicability in municipal wastewater treatment. Furthermore the use of the cross-flow re-circulation pump with its associated high pressure and excessive shear was supposed to be detrimental to the floc size and stability within the system.

An important development for membranes came when it was proposed to submerge the membrane in the aeration tank. To achieve permeation the technique utilized a reduced pressure as opposed to an external installation in pressure tubes and the necessity for high over pressure. This type of submerged membrane filtration in a biological system was referred to as submerged MBR (SMBR). Energy consumption was significantly reduced. The reduced pressure applied in permeate extraction was considerably lower than that required for cross-flow permeation. Furthermore an essential part of the cross-flow technique, the recirculation pump, was absent in the SMBR configuration.

PRINCIPLES AND BACKGROUND

Membrane Filtration

Filtration is defined as the separation of two or more components from a fluid stream. In conventional usage, it usually refers to the separation of solid or insoluble particles from a liquid stream. Membrane filtration extends this application further to include the separation of dissolved solids in liquid streams, and hence membrane processes in water treatment are commonly used to remove various materials ranging from salts to microorganisms. Membranes processes can be categorized in various, related categories, three of which are: their pore size, their molecular weight cut-off; or the pressure at which they operated. As the pore size gets smaller or the molecular weight cut-off decreases, the pressure applied to the membrane for separation of water from other material generally increases.

In the Figure 1, pressure driven membrane processes from micro-filtration to reverse osmosis are specified with the respective pore size. The separation involved in the micro-filtration (MF) can deal with removal of particulate or suspended material ranged in size from 0.1 to 10 µm. On the other hand, ultra-filtration (UF) is usually used to recover macro-molecules in the 0.01 to 0.1 µm range. Whereas nano-filtration (NF) can deal with removal of particulate 0.001 to 0.01 µm. Reverse osmosis (RO) membranes are capable of separating materials less than 0.001 µm. The operation of RO requires very high pressure sometimes as high as 150 bar in order to overcome the osmotic pressure; whereas the hydrodynamic pressure required to include flow through micro-filtration and ultra-filtration membranes are generally in the region of o.1 to 10 bar.

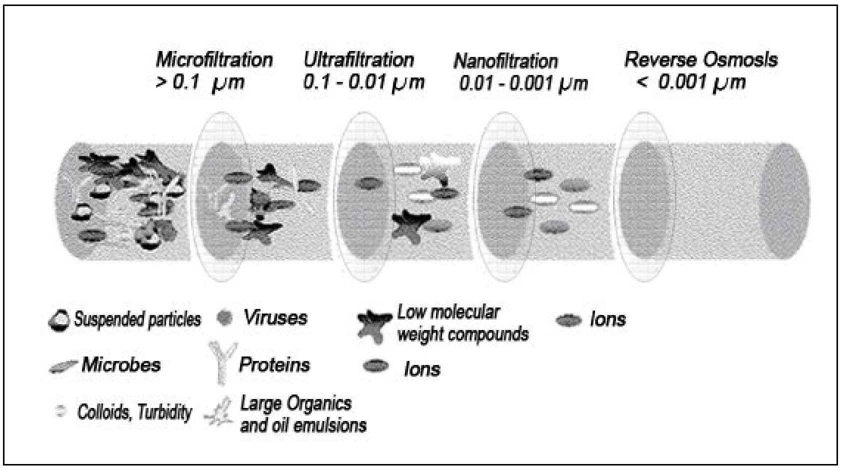

Figure 1 Membrane filtration types.

System Configurations

Membrane bioreactors are composed of two primary parts, the biological unit responsible for the biodegradation of the waste compounds and the membrane module for the physical separation of the treated water from mixed liquor. MBR systems can be classified into two major groups according to their configuration. The first group, commonly known as the submerged MBR system, involves outer skin membranes that are internal to the bioreactor (see Figure 2). The driving force across the membrane is achieved by pressurizing the bioreactor or creating negative pressure on the permeate side. Cleaning of the membrane is achieved through frequent permeate back pulsing and occasional chemical backwashing. A diffuser is usually placed directly beneath the membrane module to facilitate scouring of the filtration surface. Aeration and mixing are also achieved by the unit. Anoxic or anaerobic compartments can be incorporated to enable simultaneous biological nutrient removal.

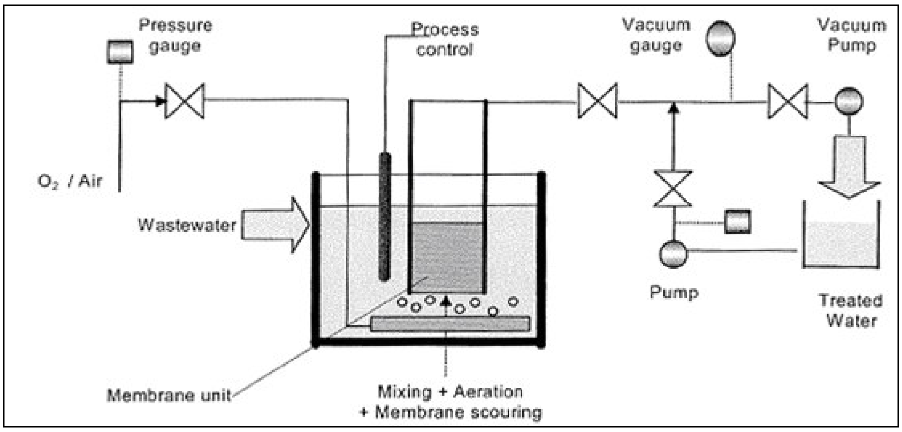

Figure 2 Submerged membrane filtration system.

The second configuration is the external MBR (Figure 2.b), which involves the recirculation of the mixed liquor through a membrane module that is outside the bioreactor. Both inter skin and outer skin membranes can be used in this application. The driven force is the pressure created by high cross flow velocity along the membrane surface. A schematic of the recirculated and more resilient polymeric membranes along with lower pressure requirements and higher permeate fluxes have accelerated the worldwide commercial use of submerged MBRs.

Several types and configurations of membranes have been used for MBR applications. These include tubular, plate and frame, rotary disk, hollow fiber, organic (polyethylene, polysulfone, etc.), metallic, and inorganic (ceramic) microfiltration and ultrafiltration membranes. The pore size of membranes used ranged from 0.01 to 0.4 µm. The fluxes obtained ranged from 0.05 to 10 m/d (m^3 m^{-2} d^{-1}), strongly depending on the configuration and membrane material. Typical values for inner skin membranes are reported as 0.5 to 2.0 m/d and for outer skin membranes as 0.2-0.6 m/d at 20 C^o. the applied trans-membranes pressure ranges from 20 to 500 kpa for inner skin membranes and from -10 to -80 kpa for outer skin membranes. The membranes used in MBR systems must satisfy various criteria. For a review on the selection of membrane material and configuration and on the impact of various operating parameters, a number of research articles and books can be accessed.

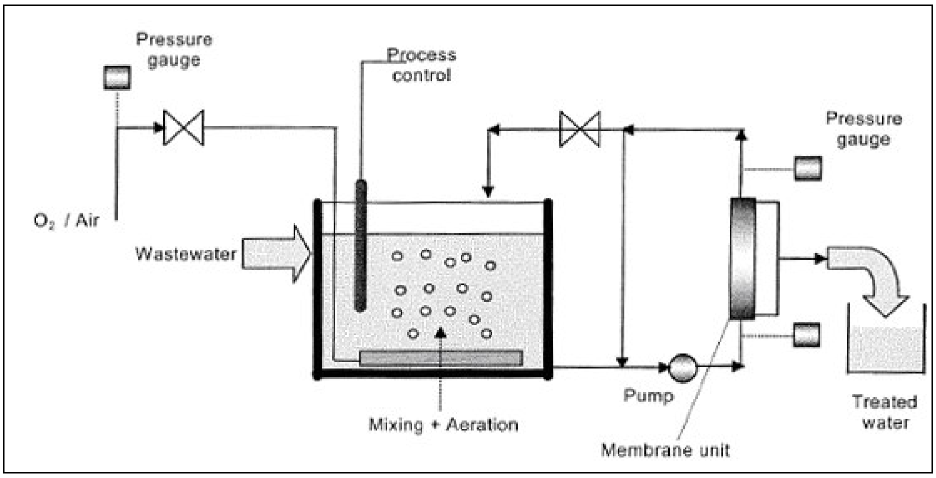

Figure 3 Cross-flow membrane filtration system.

Membrane Characteristics

MF and UF membrane can be made of an organic polymer, such as poly-ethylene or poly-sulphon or from ceramic material. In both cases the filtration principle is the same. The membrane can be manufactured on top of numerous support materials or be self supporting.

The MF or UF membrane is a device that allows the passage of certain components, but rejects others above a particular size or weight. This separation gives rise to two streams, the permeate or liquid stream which has passed through the membrane (clean side) and the concentrate stream which remains in the process tank (polluted side). The permeate is equivalent to the final effluent and is the product that is discharged after biological treatment.

The flow rate at which the permeate is made is dictated by the required throughput of the treatment process. This required flow must pass through the membrane barrier of a defined surface area. The flow of liquid through a specific membrane surface area is called Flux, and is expressed as:

$$Flux\ rate\ (l/(m^2.h) = \frac{Permeate\ flow\,(l/h)}{Membrane\ surface\ used\,(m^2)} \qquad (1)$$

The membranes are in process mode most of the time. Depending on the membrane type, a relaxation and/or a back-pulse mode is required for cleaning purposes. These procedures affect the next flux of the system, which is therefore lower than the gross flux.

During the relaxation mode (RLX) the membranes are recovered without extraction of permeate:

$$F_n.(l/(m^2.h) = F_g\,(l/(m^2.h) \times \left\{ \frac{PR(s)}{PR(s) + RLX(s)} \right\} \qquad (2)$$

During back-pulse mode permeate is pumped back through the membranes:

$$F_n.(l/(m^2.h) = F_g\,(l/(m^2.h) \times \left\{ \frac{[\ PR(s) \times Q_{PR}(l/s) - BP(s) \times Q_{BP}(l/s)\ ]}{[(PR(s) + RLX(s)) \times Q_{PR}(l/s))]} \right\} \qquad (3)$$

where:

F_n	Net flux	$l/m^2.h$
F_g	Gross flux	$l/m^2.h$
PR	Process mode	s
RLX	Relaxation mode	s
BP	Back pulse mode	s
Q_{PR}	Process flow	l/s
Q_{BP}	Back pulse flow	l/s

In generating a flow through the membrane the liquid must have an associated driving force, a pressure drop. The latter gives rise to two pressure points, the static pressure at zero permeate flow and the dynamic pressure with permeate flow. From these pressures the trans-membrane pressure (TMP) can be determined:

Trans-Membrane Pressure TMP (*bar*) = *static pressure* (*bar*) – *dynamic pressure* (*bar*)

The flux and TMP alone yield relatively little regarding the performance of the membrane, but define the operating range. If the flux is divided by the TMP the resultant is the specific flow rate through a specific surface area for a particular pressure drop. This is know as the permeability and is expressed as l/(m^2.h.bar).

$$Permeability\ (l/m^2.h.bar) = \frac{Flux\,(l/m^2.h)}{TMP\,(bar)} \quad \text{(at temperature T)} \qquad (4)$$

This parameter is used to assess the performance of the operating membrane system and must be related to the operating temperature. During operation the membrane must process flow variations according to the dry weather flow and rain weather flow conditions. The permeability at a given time defines the condition of the membrane in operation. Comparisons can be drawn between the operating permeability at different times and under different conditions. If the temperature is relatively constant, the effect of peak loads can be directly seen on the membrane performance and the associated recovery. In the long term, permeability from different periods of time can be correlated via a standard temperature (15°C) and the durability and longevity of the membrane can be interpreted. Permeability is also used to establish the effect of cleaning on the membrane, be it chemical based or time/process based. Through the latter membrane filtration process can be optimized. For a system operating at constant flow (constant flux) the permeability is used to establish the onset of required cleaning. The biological process as well as the processing conditions also reflects on the measured permeability. The permeability is a membrane characteristic and should not be confused with filterability which is sludge characteristic.

The temperature of the water also plays an important role in the assessment of the membrane performance because of the changes in the viscosity of the permeate and concentrate (biomass in the MBR). The pores of the membrane are very small and the viscosity of water increases with decreasing temperature, the driving force or TMP needed to achieve the required flux will increase, thus reducing the permeability. To avoid the confusion of relating data at different temperatures, all data should be corrected to a standard temperature of 20°C. It must be noted that the permeability depicted in all graphical representations measured on any MBR plant is the permeability at the operating process temperature at the time of the data sample.

A factor that has an effect on membrane performance is fouling. The fouling consists of two main types: surface fouling (macro) and pore fouling (micro). Surface fouling can be a build up of solids on the surface caused by a too high solids-flux toward the surface, thus blinding the pores and reducing the available surface are for filtration, or an inorganic scaling which forms a rigid non porous layer or scale over the surface. In both cases this fouling can lead to a substantial build-up of solid material around the membrane giving rise to the potential problem of sludge, i.e. the build up of biomass in between the membranes.

Pore fouling on the other hand occurs at microscopic level and involves the blinding of pores via soluble organic material such as surfactants, slime, extra-cellular polymeric substances and soluble microbiological products. Scaling can also occur at microscopic pore level with the result that the scaling uses the pore as an active site for further, prolonged precipitation. In both cases the pore will be blocked, thus eventually reducing the available surface area for filtration. In extreme cases the pore scaling can cause the membrane to become brittle.

Filtration Processes

The method of extracting permeate from the bioreactor is referred to as the 'process' mode, this mode is interrupted with in situ cleaning modes which vary depending on the membranes are often aerated with coarse bubbles to keep the solids from building up around the membrane.

Some membranes require a 'relaxation' mode to stabilize the surface solids' flux before being returned to the process mode. This relaxation mode is a simple stop of the permeate flow for a short period of time; the membranes, which are basically elastic in nature, then return to their original relaxed state. During relaxation the aeration of the membranes often remains on to assist the renewal of the biomass solids in the vicinity of the membrane surface, and also has the effect of scouring the surface of the membrane thus removing any solids build up. Other membranes utilize the so called 'back pulse' mode. After a process mode period of operation the permeate produced exits the system via clean in place tank. This tank stores enough permeate to allow the membrane to be flushed for a short period in the opposite direction of the process filtration. The latter has the effect of flushing the membrane surface of solids build up and fouling before being returned to process mode. The modes are summarized in Figure 4. Some membranes are running at continuous process (permeation) mode, others require a regular back flush and/or relaxation mode.

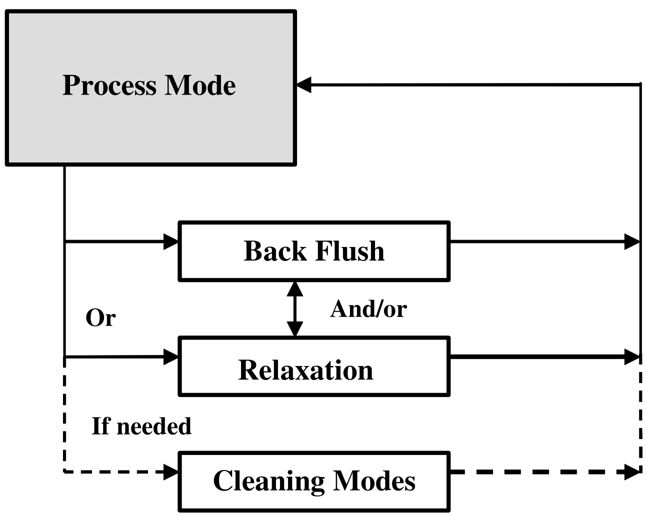

Figure 4 Filtration and cleaning modes.

All the membrane systems installed have the capacity to be cleaned with chemicals. The chemicals often used are: sodium hypochloride (NaOCl), sodium hydroxide (NaOH), citric acid, oxalic acid, hydrochloric acid (HCl), and detergents or combinations of these. The use of the chemicals depends strongly on the fouling and the type of membrane.

The cleaning processes can be split into two distinct categories: maintenance clean (MC) and intensive clean (IC). The MC is as suggested a preventative clean carried out with low chemical concentrations but a higher cleaning frequency, thus prolonging the time between IC. The IC is simply a cleaning procedure established to return the membrane back to its original permeability after a long period in operation. The chemical concentrations used and the contact time are higher and longer respectively, hence intensive.

All the above mentioned modes of operation are carried out automatically with the exception of the IC, where some manual supervision is needed. The combinations of the modes and the MC and/or IC vary greatly depending on the membrane supplier, the feed flow conditions, the season (summer or winter) and more so the performance of the bioreactor.

MBR APPLICATIONS ON WASTEWATER TREATMENT

Applications in Municipal Wastewater Treatment

MBR systems were initially used for municipal wastewater treatment, primarily in the area of water reuse and recycling. Compactness, production of reusable water, and trouble – free operation made the MBR an ideal process for recycling municipal wastewater in water and space limited environments. By the mid 1990s, the development of less expensive submerged membranes made MBRs a real alternative for high flow, large scale municipal wastewater applications. Over 1,500 MBRs are currently in operation around the world in Japan, Europe and North America. Table 1 summarizes MBR applications in municipal wastewater treatment with respect to type and configuration of the membrane, size of operation (bench, pilot, or full – scale), treatment success and country of application.

Table 1 MBR Applications in municipal wastewater treatment (Ref. Ciek, N. 2003)

Membrane type	Configuration	Size of operation	Treatment efficiency	Country of application
Ceramic Ultrafiltration	External membrane	Full scale 125 m^3/d	Effluent COD 5 mg/l	Japan
Polymeric Ultrafiltration	External membrane	Pilot scale 360-840 m^3/d	Effluent TC 12 mg/l	Netherlands
Ceramic Ultrafiltration	External membrane	Bench scale 0.16 m^3/d	COD removal 98%	USA
Polymeric Ultrafiltration	Submerged membrane	Pilot scale 6-9 m^3/d	COD removal 95%	Germany
Polymeric Ultrafiltration	Submerged membrane	Full scale 750 m^3/d	Effluent BOD 1 mg/l	USA
Polymeric Ultrafiltration	Submerged membrane	Pilot scale 9000 m^3/d	COD removal 95%	USA

Applications in Industrial Wastewater Treatment

High organic loadings and very specific and difficult to treat compounds are two major characteristics of industrial waste streams that render alternative treatment techniques such as the MBR desirable. Since, traditionally wastewater with high COD content applications for industrial wastewater was in the field of anaerobic treatment. Table 2 presents overviews of MBR applications in the industrial wastewater treatment area.

Applications in Fields of Landfill Leachate and Sludge Digestion

In addition to municipal and industrial wastewater treatment, MBRs have been utilized in a number of others areas. One such area is the treatment of landfill leachates. Landfill leachates usually contain high concentrations of organic and inorganic compounds. Conventionally, the treatment of leachates involves a physical, biological, or membrane filtration process. MBR systems have been successfully utilized with an additional treatment step for inorganics and heavy metal removal, such as reverse osmosis (RO).

Another application of the MBR is in the area of sludge treatment. Conventionally, sludge stabilization in wastewater treatment plants is achieved by a single pass, anaerobic digester. Since the HRT and the SRT are identical in these systems, the capacity is limited and long solid retention times are required for effective solids destruction. Pillary et al. (1994) showed that a microfiltration unit enhances the performance of the digester by decoupling the HRT and the SRT and, thereby, allowing higher volumetric throughput. Table 3 presents overviews of MBR applications in fields of landfill leachate and sludge digestion.

Table 2 MBR Applications in industrial wastewater treatment
(Ref. Ciek, N. 2003)

Wastewater source	Membrane configuration	Size of operation	Treatment efficiency	Country of application
Various sources	Ultrafiltration external	Pilot scale 0.2-24.6 m^3/d	COD removal 97 %	Germany
Paint industry	Ultrafiltration external	Full scale 113 m^3/d	COD removal 94 %	USA
Tannery industry	Ultrafiltration external	Full scale 500-600 m^3/d	COD removal 93 %	Germany
Cosmetic industry	Ultrafiltration external	Full scale	COD removal 98 %	France
Electrical industry	Ultrafiltration external	Full scale 10 m^3/d	COD removal 97 %	Germany
Food industry	Microfiltration	Full scale 600 m^3/d	Effluent TSS 9 mg/l	USA

Table 3 MBR Applications in the treatment of landfill leachate and sludge digestion
(Ref. Ciek, N. 2003)

Source of wastewater	Membrane configuration	Size of operation	Treatment efficiency	Country of application
Landfill leachate	Ultrafiltration external	Full scale 50 m^3/d	Not available	France
Landfill leachate	Ultrafiltration external	Full scale 264 m^3/d	COD removal 80%	Germany
Landfill leachate	Ultrafiltration external	Full scale 250 m^3/d	COD removal 90%	Germany
Sludge digestion (anaerobic)	Microfiltration external	Pilot scale 0.13 m^3/d	Not available	South Africa

CONCLUSION

The MBR concept is similar to conventional biological wastewater treatment except for the separation of the activated sludge and treated wastewater. In the MBR system this separation is done by membrane filtration whereas in the conventional system is done by secondary clarification. The treatment in the MBR system provides a high degree of treatment in terms of suspended solids and organic matter removal. Also the process can be run in a nitrification/ denitrification mode to remove nitrogen compounds, and can be combined with the use of a coagulant for phosphorus removal.

The MBR technology has great potential in wide ranging applications including municipal, industrial wastewater treatment and solid waste digestion. Full scale systems are operational in various parts of the world and substantial growth in the number and size of installations is anticipated as a viable alternative for many wastewater challenges like water quality issues.

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