IJABBR- 2014- eISSN: 2322-4827

International Journal of Advanced Biological and Biomedical Research

Journal homepage: www.ijabbr.com

Review Article

Membrane Biological Reactors (MBR) and Their Applications for Water Reuse

Farshad Golbabaei Kootenaei*1, Hasan Aminirad2

[1] Young Researchers and Elite Club; Islamic Azad University, Qaemshahr Branch, Qaemshahr, Iran
[2] Department of Civil Engineering, Babol Noshirvani University of Technology, Babol, Iran

ARTICLE INFO

Article history:
Received: 11 March, 2014
Revised: 24 March, 2014
Accepted: 12 June, 2014
ePublished: 30 July, 2014

Key words:
Membrane bioreactor
Activated sludge
Membrane fouling
Reuse
Wastewater treatment

ABSTRACT

Know days, pollution made by the wastewater in rivers and other water body's is one of the main concerns of environmental engineers. Membrane bioreactors are one of the earliest methods for treating swage and also to produce water that is acceptable for reuse purposes. The term membrane bioreactor expresses a combination of activated sludge and membrane separation processes. The need to processes like sedimentation and disinfection used in common methods is eliminated through MBR systems in a way that membranes are placed into or out of an aeration tank and the vacuumed wastewater created by the suction pump is pulled up from inside the membranes and leaves the Mixed Liquid Suspended Solids (MLSS) inside the aeration tank. MBR allows biological processes to work in a long SRT (20 to 100 days generally) and therefore concentration of the MLSS can increase even higher than 10000 mg/l. 93-99% removal of BOD, COD and 85-97% nitrification performance has been proved by different experiments. Membrane filtration removes biological pollutants, particulate materials and colloid dilution, turbidity, microorganisms, suspension impurities and elements such as iron and manganese. Concerning the advantages of this system, smaller required space due to the omission of sedimentation tank, extra disposable sludge production reduction about 60-75 percent, constant effluent quality and its independence from influent can be mentioned. Membrane fouling and its periodic replacement are the main disadvantages of this system. Membrane bioreactor technology can be used as a technology to treat different types of wastewater and to produce effluent with a good and suitable quality for reusing.

INTRODUCTION

Nowadays, because of the shortage of water resources and continuous quality degradation, it is clearly essential that new generations of treatment processes have to be defined to achieve:

- Disinfection without any oxidation step that induces carcinogen molecule formation,
- Possibility of compactness to optimize aesthetics, environmental impact (odor and noise),
- Reliability notwithstanding the influent characteristic variation,
- Standards regarding sustainability (energy, chemicals and waste production) (Wisniewski, 2007).

The membrane bioreactor (MBR) holds the potential to become one of the new generation treatment processes. This system is based on the combination of a suspended biomass reactor and a separation step on porous membrane filtration (Wisniewski, 2007; Stephenson et al., 2000). The first reported application of MBR

***Corresponding Author:** Golbabaei Kootenaei, Young Researchers and Elite Club; Islamic Azad University, Qaemshahr Branch, Qaemshahr, Iran, E-mail: farshadgolbabaei@yahoo.com

technology was in 1969, when an ultra filtration membrane was used to separate activated sludge from the final effluent of a biological wastewater treatment system and the sludge was recycled back into the aeration tank (Smith et al., 2009; Aileen and Kim, 2007). Since then, the MBR system has evolved, and research on MBR technology has increased significantly, particularly in the last 5 years (Aileen and Kim, 2007; Yang et al., 2006).

Table 1 shows the historical way of evaluation of MBR and the companies that developed and improved this system and the technology that they used (Buer and Cumin, 2010).

Table 1:

The evolution of MBR (Buer and Cumin, 2010)

Time	Event	Technology
Late 1960s	Dorr Oliver develops first MBR	Pressurized flat-sheet
Early 1970s	The fords-Systems (ZENON) commercialized Cycle-Let® for water reuse in USA.	Pressurized tubular membrane
Early 1980s	Tech Sep (Rhone-Poulence) commercializes PLEIADE for water reuse in Japan.	Pressurized flat-sheet
Mid 1990s	Nitto- Denko files a Japanese patent on a immersed MBR.	Immersed flat-sheet
	University of Tokyo experiments with hollow fiber MBR.	Immersed flat-sheet
Early 2000s	Kubota commercializes an MBR in Japan.	Immersed flat-sheet
	Mitsubishi Rayon commercializes an MBR in Japan.	Immersed unsupported.
	Zenon commercializes Zee Weed® in North America and Europe.	hollow fibers
		Immersed reinforced
		hollow fibers
Early 2010s	USF commercializes Memjet.	Immersed unsupported
		hollow fibers
	Puron (Germany) introduces a copy-like version of Zee Weed®.	Immersed reinforced
		hollow fibers
	Kolon and Para (Korea) introduce copies similar of Zee Weed®.	Immersed reinforced
		hollow fibers
	Toray introduces a copy-like version of Kubota module.	Immersed flat-sheet
	Mitsubishi Rayon replaces their fine hollow fiber with a braid based HF-membrane. Zee Weed®	
		Immersed reinforced
		hollow fibers

Membrane bioreactor (MBR) technology is a promising method for water and wastewater treatment because of its ability to produce high-quality effluent that meets water quality regulations (Aileen and Kim, 2007).

The advantages of the MBR system over conventional biological treatment processes such as less sludge production, longer SRT and better effluent quality spur the growing interest in MBR technology for water and wastewater treatment (Aileen and Kim, 2007; Judd, 2006).

1.2. Membrane and membrane module

There are broadly four categories of membrane types, with classification being dependent on the pore size of the membrane. These categories, from smallest to largest pore size, are reverse Osmosis (RO), Nan filtration (NF), Ultra filtration (UF) and Microfiltration (MF) (Judd, 2006; Till and Mallia, 2001; Metcalf & Eddy. 2004; Gander et al., 2014).

The effect of increasing the pore size of the membrane has a marked effect on the performance of the membrane and the quality of the filtered effluent. MF membranes will essentially reject particulate matter, whilst RO membranes are capable of rejecting macromolecular fractions, such as dissolved salts (Till and Mallia, 2001; Metcalf & Eddy. 2004; Gander et al., 2000). Historically, membranes have not been commonly used for the treatment of sewage effluents.

Today, however, there are several large-scale membrane treatment plants being used for sewage treatment. One of the most promising newer technologies is the membrane bioreactor (MBR), a process that couples membrane filtration with biological treatment to achieve excellent effluent quality with a small design footprint (Till and Mallia, 2001; Metcalf & Eddy. 2004; Gander et al., 2014).

The influent to the membrane is known as the feed stream, the liquid that passes through the semi permeable membrane is known as permeate and the liquid containing the retained constituents is known as the concentrate (also known as retentive) (Judd, 2006; Metcalf & Eddy. 2004).

In the membrane field, the term module [Figure 1] is used to describe a complete unit comprised of the membranes, the pressure support structure for the membranes, the feed inlet and outlet permeate and retentive ports, and an overall support structure. The principal types of membrane modules used for wastewater treatment are (1) tubular, (2) hollow fiber, and (3) spiral wound. Plate and frame and pleated cartridge filters are also available but are used more commonly in industrial applications. Two types of membrane modules are most commonly used in MBR:

Hollow Fiber. The hollow- fiber membrane module consists of a bundle of hundreds to thousands of hollow fibers. The entire assembly is inserted into a pressure vessel. The feed can be applied to the inside of the fiber (inside-out flow) or the outside of the fiber (outside- flow).

Plat and Frame. Plate and frame member modules are comprised of a series of flat membrane sheets and support plates. The water to be treated passes between the membranes of two adjacent membrane assemblies. The plate supports the membranes and provides a channel for the permeate to flow out of the unit. The plate and frame configuration is used most commonly for electro dialysis modules (Metcalf & Eddy. 2004).

1.3. Types of MBR

Basic MBR configurations are shown in Figure 2. The first is a recalculated configuration with an external membrane unit (Figure 2.b). Mixed liquor is circulated outside of the reactor to the membrane module, where pressure drives the separation of water from the sludge. The concentrated sludge is then recycled back into the reactor. The second is a submerged configuration with the membrane module immersed in the activated sludge (Figure 2.a).

A suction force is applied to draw the water through the membrane, while the sludge is retained on the membrane surface. A manifold at the base of the reactor diffuses compressed air within the reactor, providing oxygen to maintain aerobic conditions. The air bubbles also function to scour the membrane surface and clean the exterior of the membrane as they rise in the reactor. The submerged configuration is more commonly used than the recalculated configuration because it is less energy-intensive and provides a cleaning mechanism to reduce membrane fouling (Yang et al., 2006; Judd, 2006; Till and Mallia, 2001).

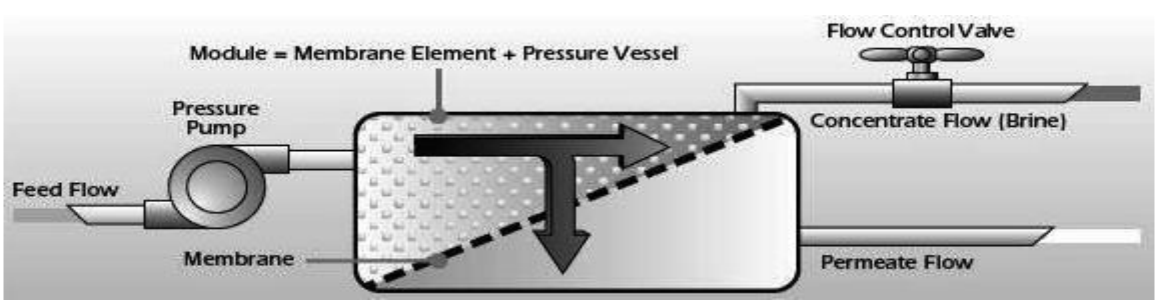

Figure 1:
A module configuration

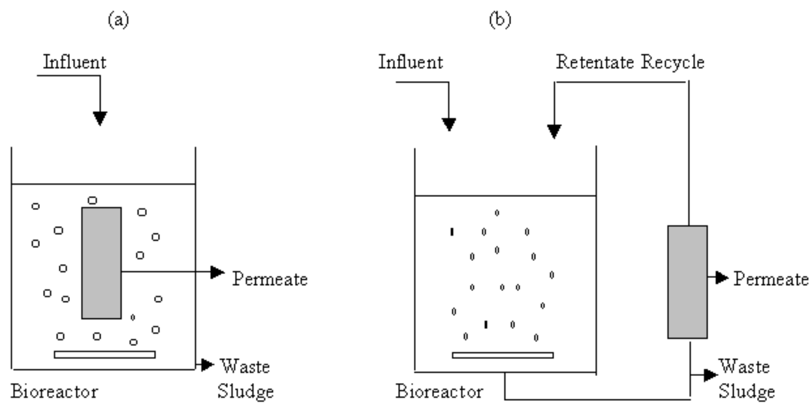

Figure2:
(a) Submerged MBR configuration (b) External MBR configuration [5]

1.4. Membrane Fouling

1.4.1. Major problem in MBR

In recent reviews covering membrane applications to bioreactors, it has been shown that, as with other membrane separation processes, membrane fouling is the most serious problem affecting system performance (Le-Clech, 2006). Fouling leads to a significant increase in hydraulic resistance, manifested as permeate flux decline or transmembrane pressure (TMP) increase when the process is operated under constant-TMP or constant-flux conditions respectively. Frequent membrane cleaning and replacement is therefore required, increasing significantly the operating costs (Judd, 2006). This membrane fouling is dependent on various parameters concerning the suspension characteristics, the membrane characteristics and the operating conditions (Figure 3) (Wisniewski, 2007; Massé, 2004; Ognier et al., 2002). Membrane fouling results from interaction between the membrane material and the components of the activated sludge liquor, which include biological flocs formed by a large range of living microorganisms along with soluble and colloidal compounds. The suspended biomass has no fixed composition and varies both with feed water composition and MBR operating conditions employed. Thus though many investigations of membrane fouling have been published, the diverse range of operating conditions and feed water matrices employed, and the limited information reported in most studies on the suspended biomass composition, has made it difficult to establish any generic behaviour pertaining to membrane fouling in MBRs specifically (Judd, 2006).

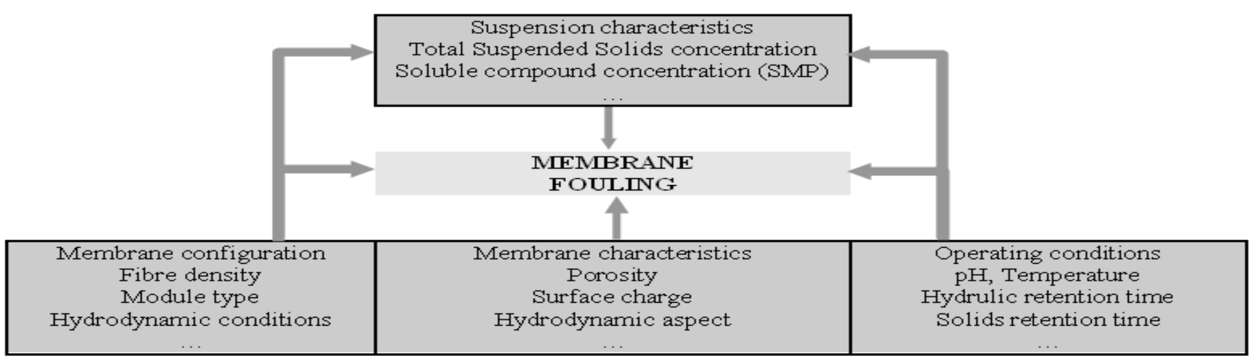

Figure 3:

Key parameters in membrane fouling

1.4.2. Fouling control

Three families of compounds (particular compounds, colloidal and soluble compounds) take part in membrane fouling that can be considered to be either reversible or irreversible (Figure 4). A long-term diminution in flux which is not recovered by simple hydro dynamical techniques is indicative of irreversible fouling, and this is often attributable to colloidal deposition or soluble adsorption onto the membrane (Massé, 2004; Ognier et al., 2002). Chemical cleanings are necessary to eliminate such fouling. The deposition of particular compounds is considered as reversible fouling and can be avoided by suitable filtration conditions. Indeed, this deposition of solids and high-molecular weight compounds can be controlled during the operation by achieving specific cleaning procedures by means of high shear stress at the membrane surface (Wisniewski, 2007).

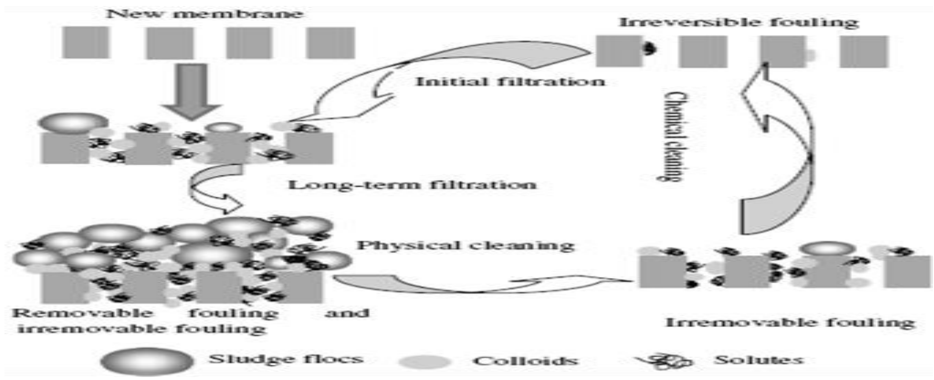

Figure 4:
Schematic illustration of the formation and removal of removable and irremovable fouling in MBRs

Many other anti-fouling strategies have been proposed for MBR applications. They comprise, for example, intermittent permeation, where the filtration is stopped at regular time interval for a couple of minutes before being resumed.

Particles deposited on the membrane surface tend to diffuse back to the reactor; this phenomena being increased by the continuous aeration applied during this resting period. Membrane backwashing is another common anti-fouling technique, where permeate water is pumped back to the membrane, and flow through the pores to the feed channel, dislodging internal and external foul ants.

A small amount of cleaning agents (like hypochloride) could be added to the permeate water to improve the removal efficiency. Because of the relative long time necessary to build up liquid back-pressure, the efficiency of the liquid backwash is somehow limited as the liquid prefers to go through open (not fouled) pores. This could be improved by using pressurized air in the permeate side of the membrane to build up and release a significant pressure within a very short period of time. Membrane modules therefore need to be in a pressurized vessel coupled to a vent system. Air usually does not go through the membrane. If it was, the air would dry the membrane and a rewet step would be necessary, by pressurizing the feed side of the membrane (Judd, 2006; Le-Clech, 2006).

1.5. Advantages and disadvantages of MBR

1.5.1. Advantages

• MBR produce extremely good quality filtered effluent with less than 1 NTU turbidity and less than 5 mg/L BOD consistently.

• MBR improves effectiveness of biological process by allowing it to operate at high solids concentration and eliminating problem such as sludge bulking, sludge rising, nocardia Foam, etc.

• When used before RO, MBR eliminates need for secondary and tertiary treatment equipment. In spite of this, the filtered water quality is acceptable to RO which operates smoothly.

• Single package unit with minimum civil construction.

• Low energy consumption.

• Filtration Up to 6 log (99.999%) removal of total coli form.

• No chemical required during treatment.

• MBRs typically operate at higher biomass concentrations than conventional biological treatment processes. The advantage that this provides is increased volumetric loading and less sludge production, which in turn lowers capital investment costs for civil works and reduces sludge disposal costs.

• Potential Reuse of effluent water.

• Higher rate of nitrification and gentrification.

• Greater control of longer SRT allow for retention and degradation of slowly biodegradable contaminant.

• Constant effluent quality and its independence from influent (Aileen and Kim, 2007; Till and Mallia, 2001; Metcalf & Eddy, 2004; Adema and Benson, 2001; Sharrer et al., 2007; Schwartz and Herring, 2001; Verberk and Vandijk, 2002; Bridle et al., 2009).

1.5.2. Disadvantages

• High investment and operation cost.

• Membrane lifetime and replacement.

• Membrane fouling problem (Aileen and Kim, 2007; Till and Mallia, 2001; Metcalf & Eddy, 2004; Adema and Benson, 2001; Crites and Tchobnanoglous, 2013; Eckenfelder, 2010).

1.6. MBR application in wastewater treatment

Today MBR systems are most widely used in treatment of wastewater (industrial and municipal) in many countries of the world like USA, England, Germany, Norway, Denmark, Netherland, Kuwait, UEA and specially countries from Fareast of Asia such as Japan, South Korea and china.

MBRs are used for the treatment of chemical wastewater, oily wastewater, Landfill Leach ate, Color Industry, Leather Industry, Dying Industry, Paper Industry, Dairy Industry, Hospitals and Lab waste water Liquid, hazardous waste water, Waste Oil Processing, Chemical-pharmaceutical waste water, Tank cleaning waste water, Groundwater redevelopment, Automobile Industry, Laundry waste water, municipal wastewater and gray water (Judd, 2006; Adema and Benson, 2001; Sharrer et al., 2007).

1.7. Process Capabilities

The treatment capability of MBR is evaluated in terms of BOD, TSS, coli form, and nitrogen removal based on laboratory, pilot-plant, and full- scale plant studies. Because the activated- sludge effluent from MBRs is treated by filtration through a nominal 0.10 - 0.40 μm membrane, very low concentrations of effluent suspended solids, turbidity, and BOD are produced that provide an effluent suitable for water reuse following disinfection. Reported operational and performance characteristics for MBR systems are summarized in Table (2, 3). Low effluent BOD and turbidity concentrations are possible for MBR systems with MLSS concentrations in the range of 6000 to 16,000 mg/L.

Full- scale and pilot- plant systems have been operated with the anoxic/aerobic MLE biological nitrogen- removal process with the result that effluent total nitrogen concentrations of <10 mg/L have been achieved (Mourato et al., 1999; ReVoir et al., 2000; and Giese et al., 2000). Influent recycles flow rate ratios of 4.0 to 6.0 have been used in those studies to feed nitrate to a separate preanoxic tank (Judd, 2006; Metcalf & Eddy, 2004). Table 3 gives the results of comparison of the MBR performances with the performances of conventional treatment processes (Wisniewski, 2007; Tardieu et al., 2012; Pouet et al., 2011).

Table 2:

Operational data (Metcalf & Eddy, 2004)

Parameter	Unit	range
COD loading	$Kg/m^3.d$	1.2-3.2
MLSS	mg/L	5000-20.000
MLVSS	mg/L	4000-16.000
F/M	g COD/g.MLVSS.d	0.1-0.4
SRT	d	5-20
τ	h	4-6
Flux	$L/m^2.d$	600-1100
Applied vacuum	kPa	4-35
DO	mg/L	0.5-1.0

Table 3:

Operational data (Metcalf & Eddy, 2004)

Parameter	Unit	range
Effluent BOD	mg/L	<5
Effluent COD	mg/L	<30
Effluent NH_3	mg/L	<1
Effluent TN	mg/L	<10
Effluent turbidity	NTU	<1

Table 4:

MBR performance vs. conventional processes

	Raw water				Treated water			
	TSS (kg/m^3)	COD (kg/m^3)	Turbidity (NTU)	Germs (/100ml)	TSS (kg/m^3)	COD (kg/m^3)	Turbidity (NTU)	Germs (/100ml)
Trickling bed	0.2	0.7	120	10^8	0.035	0.125	10	10^6
Activated sludge	0.2	0.7	120	10^8	0.030	0.080	5	10^6
Physico- chemical process	0.2	0.7	120	10^8	0.060	0.130	20	10^7
MBR	0.2	0.7	120	10^8	0	0.020	<2	$<10^2$

1.8. COMMERCIAL MBR SYSTEMS

The two main suppliers of MBR systems for wastewater treatment are Kubota (Japan) and Zenon (USA). Other suppliers are Degremont (France), X-Flow (Netherlands), Membratek (S. Africa), Orelis/Mitsuibishi (Japan), US Filter (USA), Wehrle Werk (Germany), etc (Yang et al., 2006; Buer and Cumin, 2010).

1.8.1. Kubota

Kubota uses a flat sheet membrane made of polyolefin with a non-woven cloth base giving a nominal pore size of 0.4 mm. Each membrane cartridge consists of solid acrylonitrile butadiene styrene (ABS) support plate with a spacer layer between it and an ultrasonically welded flat sheet membrane on both sides. The typical membrane cartridge (Type 510) has dimensions of 1.0 m (H) x 0.49 (W) x 6 mm thick- filtered water passes through to the interior of each membrane to an outlet nipple cast into the top of the support plate. Each cartridge provides an effective filtration area of 0.8 m^2.

The Kubota MBR operates with membrane treatment units submerged in the reactor in which the MLSS is maintained within the range of 15,000 to 20,000 mg/L.

The standard Kubota unit has a glass fibre reinforced plastic casing and consists of 2 sections. The upper section contains up to 150 membrane cartridges, each connected to a filtered effluent manifold with a gap of approximately 7 mm between cartridges. The lower section is a matching unit containing a coarse bubble diffuser. The lower section supports the upper section and directs the mixture of air bubbles and mixed liquor between the membrane cartridges in the upper section. This air-water mixture maintains an upward cross flow over the membrane surface of approximately 0.5 m/s, minimizing fouling of the membranes. The minimum air requirement is 10 L/minicartridge.

The Kubota system operates by gravity, with a head of 1-1.5m above the membranes sufficient to drive permeate through the membranes. Grit removal and fine (2-3 mm) screening are prerequisites prior to the MBR. The membrane flux for the Kubota system is approximately 20 L/m^2.h (submerged system at a TMP of ~0.1bar). Chemical cleaning of the membranes is required every 3-6 months using sodium hypochlorite and oxalic acid. Cleaning requires 3 L of chemical solution per cartridge and the cleaning cycle takes upto 2 hours. Kubota has a reference list of over 400 plants treating domestic and industrial wastewater, with most of the sites located in Japan. The Kubota plants range in size from systems to treat the equivalent of individual households to the 23,000 EP (5,800 m^3/d ADWF) plant at Swan age in the south of England. The Kubota technology is to be utilized at a new MBR plant (2,000 EP) to be built at Magnetic Island in Queensland (Judd, 2006; Till and Mallia, 2001; Gander et al., 2014).

1.8.2. Zenon

Zenon markets the Zeno Gem system, based on the Zee Weed membrane, which is a hollow fibre with an external diameter of 1.9 mm and a nominal pore size of 0.4 mm. The fibres are mounted on vertical frames into modules with filtered effluent passing into the centre of the fibre and extracted from both ends. The ZW-500 module is 2.0 m (H) x 0.7 m (W) x 0.2 m thick with 46 m^2 of filtration surface area. Cassettes are made up of 8 modules each. Air is supplied to the system by a combination of coarse bubble aerators integrated into the bottom header of modules, to gently agitate the membrane fibres and to keep the tank contents mixed, and by fine bubble aeration to supply the balance of the total biological oxygen demand. The filtration capacity is in the range of 40-70 L/m^{2}h under a driving transmembrane pressure of 10-50 kPa. This pressure is provided by the head of water over the membranes and by maintaining a negative pressure on the permeate side using conventional centrifugal pumps. Sludge wastage is claimed to be 1.5-2.0% of the influent flow.

ZenoGem biological design parameters are:

- MLSS 15,000-20,000 mg/L
- F: M< 0.2 kg BOD/kg MLSS.d
- Volumetric Loading 1.8-5.7 kg BOD/m^3.d
- HRT > 2 hours
- SRT > 15 days
- Flux 15-25 L/m^2.h (TMP of ~0.5 bar)

In addition to the scouring action of the coarse bubble aeration, cleaning of the membranes to control fouling is provided by automatic pulses of backwashing with stored permeate and periodic in-situ membrane cleaning with a hypochlorite solution or other chemicals. Zenon has a reference list of over 150 plants treating domestic and industrial wastewater (Judd, 2006; Till and Mallia, 2001; Gander et al., 2014).

Conclusion

MBR technology is widely accepted today as the key technology for wastewater treatment. Almost globally, the MBR approach is used for wastewater reuse or to provide superior effluent quality. The system showed a high robustness providing a fairly constant effluent with a large reduction of the entry pollutants and thus providing a highly reliable operation. High TSS, COD, BOD, NH^{+4} and TN removal efficiencies up to 97, 94, 95, 98 and 81% respectively where achieved. The implementation of MBR will also reduce the space required and provides room for future expansion. Recently, rapidly decreasing membrane costs is another important driving force for the widespread application of MBRs. Many regions in the world even south of Europe are suffering an acute lack of water. One way to solve this hydric deficit is to use membrane bioreactors (MBR) to reuse the treated wastewater in tasks where drinking water is not required, e.g. irrigation.

References

Adema, M., Benson, H., 2001. Membrane biological non-oily wastewater treatment systems for ships, Virginia.

Aileen, N.L., Kim, S., 2007. A mini-review of modeling studies on membrane bioreactor (MBR) treatment for municipal wastewaters, *Desalination.* 212, 261–281.

Bridle, K., Stephenson, T., Semmens, M.J., 2009. pilotplant treatment of a high-strength Bewery wastewater using a membrane-aeration bioreactor, 71, 1197-2004.

Buer, T., Cumin, J., 2010. MBR module design and operation, *Desalination.* 250, 1073–1077.

Crites, R., Tchobnanoglous, G., 2013. Small and decentralized wastewater management systems, McGraw Hill Inc.

Eckenfelder, W., 2010. Industrial water pollution control. McGraw Hill Inc..

Gander, M., Jefferson, B., Judd, S., 2014. Membrane bioreactors for use in small wastewater treatment plants: membrane materials and effluent quality, *Water. Sci. Technol.* (In press).

Gander, M., Jefferson, B., Judd, S., 2000. Aerobic MBRs for domestic wastewater treatment: a review with cost considerations, *Separation and Purification*. 18. 119-130.

Judd, S., 2006. *The MBR book:* Principles and applications of membrane bioreactors in water and wastewater treatment. *Elsevier, Oxford*.

Le-Clech, P., Chen, V., Fane, A.G., 2006. Fouling in membrane bioreactors used for wastewater treatment – A review, *J. Memb. Sci.* 284, 17-53.

Massé, A., 2004. Bioréacteurs à membranes immerges pour le traitement des eaux résiduaires urbaines spécificités physico-chimiques du milieu biologique et colmatage, Thèse INSA Tououse, N°ordre 759.

Metcalf & Eddy. 2004. Wastewater Engineering, Treatment and Reuse, Fourth Edition, McGraw-Hill, Inc.

Ognier, S., Wisniewski, C., Grasmick, A., 2002. Influence of macromolecule adsorption during filtration of a membrane bioreactor mixed liquor suspension, *J. Membr. Sci.* 209, 27–37.

Pouet, M.F., Grasmick, A., Homer, F., Nauleau, F., Cornier, J.C., 2011. Tertiary treatment of urban wastewater by cross-flow microfiltration, 17th Biennial Int. Conf., Budapest, 24–29 July.

Schwartz, T.C., Herring, B.R., 2001. The first year's performance of a membrane bioreactor compared with conventional wastewater treatment of domestic waste, Proceedings of WEFTEC.

Sharrer, M.J., Ferrier, Y., Tal, D., Hankins, J.A., Summerfelt, S.T., 2007. Membrane biological reactor treatment of a saline backwash flow from a recirculating aquaculture system, *Aquac. Eng.* 36, 159–176.

Smith, C.W., Gregorio, D., Taleott, R.M., 2009. The use of ultrafiltration membrane for activated sludge separation, Presented at the 24th Annual Purdue Industrial Waste Conference, 1300–1310.

Stephenson, T., Judd, S., Jefferson, B., Brindle, K., 2000. *Membrane Bioreactors for Wastewater Treatment*. IWA Publishing, London.

Tardieu, E., Grasmick, A., Geaugey, V., Manem, J., Xing, C.H., 2012. Pilot study of domestic wastewater tretment by ceramic membrane bioreactor. Treatment performances and fouling characterisation, Wefuec, Singapore, 8–11 March.

Till, S., Mallia, H., 2001. Membrane Bioreactors: Wastewater Treatment Applications to Achieve High Quality Effluent, Presented at the 64th Annual Water Industry Engineers and Operators Conference.

Verberk, J., Vandijk, H., 2002. Research on AirFlush: distribution of water and air in tubular and capillary membrane modules, Berichte aus dem IWW Rheinisch-Westfälisches Institut für Wasserforschung.

Wisniewski, C., 2007. Membrane bioreactor for water reuse, *Desalination*. 203, 15–19.

Yang, W., Cicek, N., Ilg, J., 2006. State-of-the-art of membrane bioreactors: Worldwide research and commercial applications in North America, *J. Membr. Sci.* 270, 201–211.