Table Of Contents Search Author Index

MEMBRANE BIOREACTORS FOR THE TREATMENT OF MUNICIPAL WASTEWATER: A CRITICAL REVIEW

K. Iqbal Basha[1] **and Muhammad H. Al-Malack**[2]

1: Lecturer-B, Department of Civil Engineering, KFUPM, Dhahran
2: Associate Professor, Department of Civil Engineering, KFUPM, Dhahran

E-mail: iqbal@kfupm.edu.sa

ABSTRACT

A membrane bioreactor (MBR) is one of the modifications to the conventional activated sludge process. An MBR is the combination of a membrane module and a bioreactor. This MBR process can retain a high concentration of mixed liquor suspended solids (MLSS) in the aeration tank, giving a number of benefits, such as, lower sludge wastage rate, smaller aeration tank volume and higher ability to withstand shock loadings. A high quality effluent, independent of the MLSS concentration and characteristics of the flock settliability can be achieved.

Basically there are two types of membrane bioreactors, crossflow MBR and immersed MBR. In a crossflow MBR, the membrane module is allocated outside the bioreactor and the mixed liquor is driven into the membrane module. In an immersed MBR, the membrane module is immersed into the aeration tank and the mixed liquor is generally suctioned from the effluent side.

With the recent advancement in the membrane technology, especially in microfiltration, has given an impetus to the development of membrane bioreactors for the treatment of various wastewaters especially for the treatment of municipal wastewater. In this paper, the trends in the municipal wastewater treatment with the application of both crossflow and immersed MBRs are reviewed critically.

Keywords: *Wastewater, Membrane Bioreactor, Crossflow, Submerged Membrane, Activated Sludge*

الملخص

يعتبر المفاعل الحيوي الغشائي أحد نتائج تطوير عملية معالجة الحمأة التقليدية ، ويتكون من مفاعل حيوي وغشاء ، وهناك عدة إيجابيات لعملية المعالجة بهذا المفاعل ، منها إمكانية الاحتفاظ بتركيز عال من المواد الصلبة العالقة في الحمأة المنشطة في خزان التهوية ، وينتج من ذلك خفض معدل فقدان الحمأة، والقدرة على استعمال خزان تهوية أصغر حجما، وقدرة نظام المعالجة على تحمل الأعباء التشغيلية المفاجئة، كما يمكن باستعمال المفاعل الحيوي الغشائي إنتاج مياه ذات نوعية أفضل مهما كان تركيز المواد الصلبة العالقة في الحمأة المنشطة ، ومدى ترسب المواد الصلبة العالقة.

وهناك أنواع مختلفة من المفاعلات الحيوية الغشائية، منها المفاعل الحيوي الغشائي ذي الدفق المتعامد ، حيث توضع وحدة الغشاء خارج المفاعل الحيوي ويتم ضخ الحمأة المنشطة إلى داخل الوحدة ، أما في حالة المفاعل الحيوي الغشائي المغمور فتكون وحدة الغشاء مغمورة في خزان التهوية ويتم ضخ الحمأة المنشطة من جهة المياه العادمة.

وقد ساهم التقدم في تقنيات الأغشية ، وبالتحديد في عمليات الترشيح الدقيق ، في دفع عمليات تطوير المفاعلات الحيوية الغشائية لمعالجة أنواع مختلفة من المياه العادمة ، وبالذات مياه الصرف الصحي . وفي هذا البحث تتم مناقشة اتجاهات استعمال كل من المفاعلات الحيوية الغشائية المغمورة وذات الدفق المتعامد في معالجة مياه الصرف الصحي.

1. INTRODUCTION

Biological treatment is an important aspect of municipal wastewater treatment processes. Standards for effluent discharge are becoming increasingly stringent to satisfy the constraints of the receiving bodies. Also, the use of treated municipal wastewater for secondary purposes in densely populated urban areas is also increasing due to the scarcity of available potable water. Thus achieving a high level of treatment is imperative.

Biological processes can be defined as an engineered system, designed to accumulate microorganisms which oxidize organic (Chemical Oxygen Demand, COD) and mineral (NH_3, Fe^{2+}, etc.) pollutants that are electron donors and reduce O_2, NO_3, SO_4 or CO_2 that are electron acceptors (Rittmann, 1987). In the conventional activated sludge process, organic waste is introduced into an aeration tank, which contains a large population of microorganisms, where the substrate is utilized to yield more biomass and to produce energy needed for growth. After a specified period of time, the mixture of cells is passed into a settling tank, where the cells are separated from the treated wastewater. A proportion of the settled biomass is recycled to the inlet of the aeration tank to maintain the desired level of microorganisms in contact with organic waste. The remainder is wasted as concentrated sludge.

Conventional activated sludge process (ASP) is restricted to a fairly low biomass concentration ranging from 1500 mg/l to 5000 mg/l (Mynhier et al., 1975 and White, 1975). At high mixed liquor suspended solid (MLSS) concentrations, more power will be needed for oxygen transfer, thereby increasing the turbulence in the reactor. A point will be reached at which fluid shear will destroy the biological floc, which makes biomass settling quite difficult if not impossible. However, when activated sludge process is operated at an MLSS concentration lower than 1500 mg/l, a larger volume will be required which requires more power for mixing and is much larger than that for oxygen transfer and intern the process will not be economically feasible. Moreover, low concentrations of MLSS result in a greater development of dispersed biological cells, which are difficult to settle (Gardy and Lim, 1980).

Top

Although quiescent sedimentation of biological solids is economical, the increase of public awareness concerning the environmental pollution is forcing the pollution control agencies to adopt other positive ways of controlling pollution. With its versatile separation capability, membrane technology is making an impact on a number of wastewater treatment areas. The recent development of new generation of more productive and less expensive ultrafiltration (UF) and microfiltration (MF) membranes has prompted emergence of a new concept in biological treatment, the membrane bioreactor (MBR).

This new technology offers a reliable high rate filtration process with an added advantage of consistently producing an effluent almost free from suspended solids (Al-Malack et al., 1998) and with less operation problems (Vera et al., 1998). The resulting high quality and perfectly disinfected effluent means that MBR processes can be used for many purposes such as drinking water, industrial and municipal wastewater treatment and reuse, recycling in buildings and landfill leachate treatment. Their low foot print ensures minimum land space requirement and provides excellent scope for retrofitting existing wastewater works.

2. MEMBRANE BIOREACTOR

Membrane Bioreactor (MBR) can be defined as the combination of two basic processes – biodegradation and membrane separation – into a single process where suspended solids and microorganisms responsible for biological degradation are separated from the treated water by a membrane unit. As a result of membrane separation, solids retention time (SRT) is independent of hydraulic retention time (HRT). In addition to energy for biosynthesis and cell growth, microbes require some amount of energy to maintain cell structure and integrity. Due to high biomass concentrations in MBRs, this amount of energy need to maintain cell structure and integrity is high, in addition to energy for biosynthesis and growth. Maintaining a low Food to Microorganisms (F/M) ratio in the reactor, results in minimum sludge wastage, reduced plant size and development and retention of waste-specific microorganisms (Chiemchaisri et al., 1992).

A membrane is a thin film, which has small pores or pore like structures. It is a novel filtration device, which replaces gravity settling of activated sludge flocks in biological wastewater treatment plant. Microfiltration (MF) and Ultrafiltration (UF) membranes are most commonly used membranes for this purpose. The driving force for the process is the pressure difference applied across the membrane. Membranes are categorized according to the size, number and distribution of their pores and the size of particles they can retain. Typical element configurations available include plate and frame, spiral wound, hollow fiber and tubular membranes (Mulder, 1991). Microporous membranes for microfiltration have been prepared from variety of materials, including ceramic, glass, graphite, metal or metal oxide and polymers (Gregor, 1988).

Top

Because of membrane filtration, the retention of organic particulate or soluble compounds, keeps slowly biodegradable molecules in the bioreactor and non biodegradable constituents are discharged with the sludge, rather than with the treated water. The high biomass concentration in the MBRs allows the system to treat high strength wastewater and, therefore, the system can be very compact (Chaize and Huyard, 1991).

3. CROSSFLOW MEMBRANE BIOREACTOR

The crossflow (also called tangential flow) membrane bioreactor is a modification of the conventional activated sludge process, where the secondary clarifier is replaced by a membrane system for the separation between the mixed liquor and the effluent. With the crossflow it is intended to eliminate or minimize the filter cake from being built up, by creating a shearing force, mainly by the flow at high velocity tangentially across the surface of the membrane. The mixed liquor from the aeration tank flows under pressure across the membrane, with a portion of the feed permeating the membrane and the balance of the feed sweeping tangentially along the membrane to exit the system without being filtered, and is returned to the aeration tank (Fig 1).

Use of crossflow membranes for biomass separation was investigated in the early seventies by Washington et al. (1969) and Hardt et al. (1970). Membranes have been used for biomass separation in treating municipal wastewaters in aerobic systems ranging from laboratory scale bioreactors of 8 liters capacity (Chaize and Huyard, 1991) to commercial treatment plants of 68,000 m^3/day in California, USA.

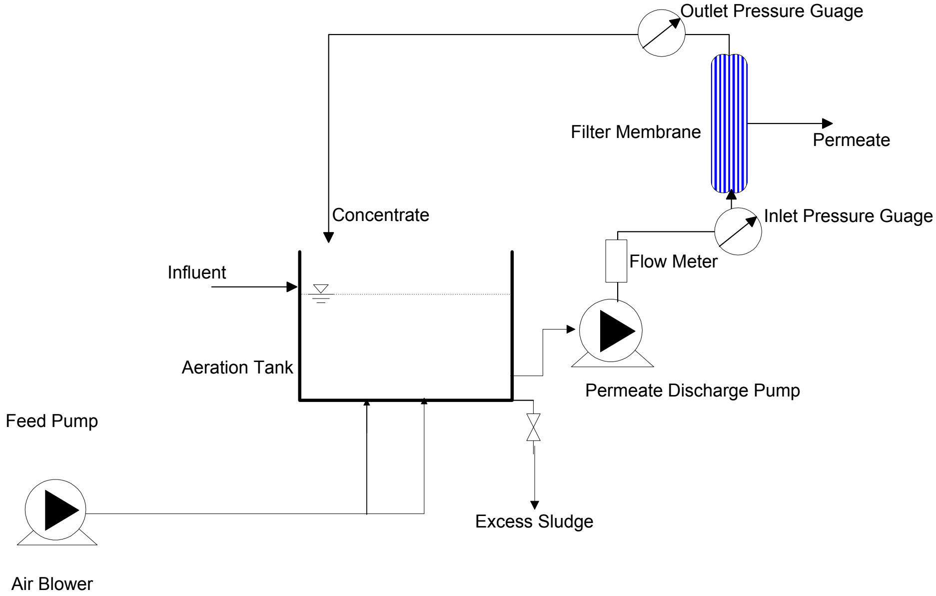

Figure 1. Schematic diagram of Crossflow Membrane Bioreactor

Top

The most common membrane module arrangements employed in crossflow MBRs treating municipal wastewater is the tubular module. A tubular membrane module essentially is a membrane installed inside a porous tube. Although configurations vary, pressurized feed water usually enters the inside of the tube and exits perpendicularly through the membrane (Conlon, 1990). Tubular membranes have low surface area to volume ratio, and are considered to be excellent for high solids – bearing wastewater because of their resistance to plugging (Monat, 1997).

Table 1 shows the characteristics and performance of some crossflow membrane filtration units in MBR process. At steady state, these systems can remove organic pollutants over a wide range of conditions producing a high quality permeate at high organic loading rates. The percentage removal of organics is generally greater than 90% of the influent COD (Muller et al., 1995), though removal performances as low as 62% COD have been reported (Vera et al., 1998).

Several researchers have studied the factors such as crossflow velocity, membrane pore size and concentration of the suspension that affect crossflow MBR. Stamatakis (1990) reported that the permeate flux will increase with increasing crossflow velocity until a certain value, beyond which flux was noticed to decrease. Flux increases with an increase in transmembrane pressure up to threshold pressure. Beyond the threshold pressure, the flux becomes independent of the transmembrane pressure due to concentration polarization (Ripperger, 1988). Higher pore sizes produce a minimum flux rate due to the clogging of the pores, while higher flux rates can be achieved with smaller pore sizes, which was due to the dominance of the cake filtration mechanism (Vigneswaran et al., 2000). A decrease in flux values was reported with increasing feed concentration (Sansome-Smith et al., 1989).

One of the disadvantages of this process is the possibility of shear lysis of microbial flocs because of high shear forces induced by the crossflow velocity, resulting in loss of viable microbial mass in the aeration tank (Jae-Seok et al., 2001). The microbial cell lysis also resulted in reduction of filtration flux because of the increase of the hydraulic resistance of the particle packed layer, which was formed on the membrane during filtration (Yasutoshi et al., 1994). Also separate chamber for membrane module and high energy costs are the other important factors that led to the modification of this membrane process leading to the submerged membrane bioreactor.

4. SUBMERGED MEMBRANE BIOREACTOR

A more recent configuration places the membrane within the activated sludge reactor. This configuration has been referred to as “direct solid/liquid separation”, immersed membrane bioreactor or submerged membrane bioreactor (Yamamoto et al., 1989, Pound et al., 1997, and Rui Liu et al., 2000). The use of this process has been increasing gradually in Japan, Europe and in North America.

Top

In a submerged MBR, the membrane module is immersed into the aeration tank and the mixed liquor is generally suctioned from the effluent side (Fig 2). The pressure across the membrane can be applied by suction through the membrane (Ishida et al., 1993) or by pressurizing the bioreactor. This process requires no circulation pumps thereby making it an energy conserving system. Hollow fiber membrane module is the most commonly employed membrane module for municipal wastewater treatment (Benitez et al. 1995). A hollow fiber membrane is compact bundle of flexible fibers aligned parallel to the bulk flow stream. These membranes have higher surface area to volume ratios and provide good resistance to clogging. In addition, the flexible membranes are capable of being “back pulsed”, or back washed, without membrane damage (Monat, 1997).

The use of submerged MBRs for municipal wastewater treatment was first developed by Yamamoto et al. (1989). Since then, considerable work has been done for using this technology for treatment of municipal wastewater, ranging from laboratory scale bioreactors of volume 20 lit (El Hani et al. 1998) to commercial treatment plants of capacity 106,000 m^3/day at Del Rio, Texas. Table 2 shows the characteristics and performance of some submerged membrane filtration units in MBR process. COD removals of greater than 97 % were achieved (Gander et al., 2000) and mixed liquor suspended solids concentrations were as high as 39,000 mg/l (Davies et al., 1998). Because of higher MLSS concentrations, dissolved oxygen concentrations were lower than the conventional activated sludge process plants. Hence the enhanced activity of denitrification microorganisms resulted in higher removal of total nitrogen than the conventional process (Yoon et al. 2000).

The main problem of membrane filtration is pore clogging. In submerged membrane MBR process, this problem is overcome by using air diffusers at the bottom of the membranes, which serve the dual purpose of keeping the membrane clean from clogging as well as aerating the contents of the reactor. Retardation in rate of clogging of the membrane is also partly achieved by intermittent suction of the permeate (Kishino et al., 1995).

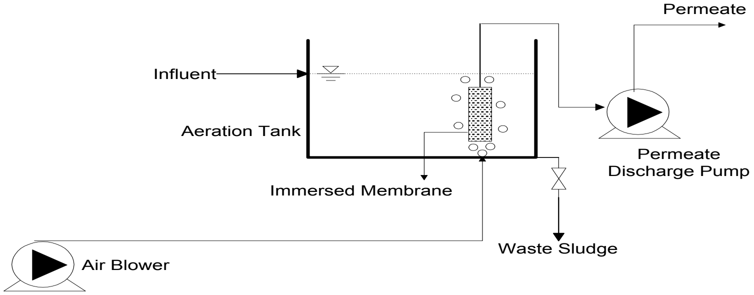

Figure 2. Schematic diagram of Immersed Membrane Bioreactor

Top

The immersed MBR can also be an effective process for tertiary treatment of municipal sewage. In a one step process, the combined bioreactor/filtration tank generates an effluent free of solids, Coliforms, Giardia, Cryptosporidium and with very low residual levels of BOD, Ammonia and Phosphorous (Hadi and Diana, 1996). Because of the high MLSS concentrations the bioreactor is designed at organic loadings five times higher than the conventional ASP systems. This means any existing submerged membrane aeration tank can be retrofitted into a highly effective MBR, which can treat high strength sewage without any additional infrastructure construction. This process becomes even more cost-effective when the municipality requires that the clarified effluent be further treated by a microfilter to remove solids, so as to make the effluent suitable for water recharge projects or disinfection.

In the kingdom of Saudi Arabia, where most of the existing wastewater treatment plants are operating to their full treatment capacities, if not exceeding, this process can be very useful to enhance the existing capacity of the treatment plants, without any space constraints, as MBR process has very low foot print. Also, the membrane bioreactor effluent is ideally suited for further purification by reverse osmosis or nano filtration, thus conserving scarce water resources in this region.

Two inherent problems can exist with MBRs, first a long biomass retention results in decreased biomass viability as the reactor is operated for a longer period of time. Second, retention and accumulation of non-reactive compounds in the bioreactor by the membrane could lead to microbial inhibition or toxicity, fouling of the membrane surface, and a limit in the alternatives available for excess sludge disposal (Chaize and Huyard, 1990).

5. CONCLUSION

The recent emergence of a new concept, the membrane bioreactor, should greatly enhance the performance and reliability of biological treatment of municipal wastewater. Its main advantages are the production of high quality effluent in terms of COD and a perfect disinfection meeting recharge standards, the maintenance of higher biomass concentrations that lead to a small foot print, lower sludge production rate, and ability to withstand high organic loadings. The submerged MBRs are more suitable for municipal wastewater treatment when compared with crossflow MBRs. Biomass viability and accumulation of toxic compounds in the reactor and fouling of the membrane surface are some of the disadvantages of the MBRs.

Top

REFERENCES

1. Al-Malack, Muhammad H., Anderson, G.K. and Ali Almasi, 1998, "Treatment of Anoxic Pond Effluent using Crossflow Microfiltration," *Water Research,* 32(12) pp 3738-3846.
2. Benitez, J., Rodriguez, A., Malaver, R., 1995, "Stabilization and Dewatering of Wastewater Using Hollow Fiber Membranes," *Water Research,* 29(10), pp 2281-2286.
3. Bodzek Michal, Debkowska Zuzanna, Lobos Ewa and Konieczny Krystyna, 1996, "Biomembrane Wastewater Treatment by Activated Sludge Method," *Desalination*, 107, pp 83-95.
4. Chaize, S and Huyard, A, 1991, "Membrane Bioreactor on Domestic Wastewater Treatment Sludge Production and Modelling Approach," *Water Science and Technology*, 23, pp 1591-1600.
5. Cheyran, M. and Mehala, M.A., 1986, "Membrane Bioreactors," *Chemtech,* pp 676.
6. Chiemchaisri, C., Wong, Y.K., Urase, T. and Yamamoto, K., 1992, "Organic Stabilization and Nitrogen Removal in Membrane Separation Bioreactor for Domestic Wastewater Treatment," *Water Science and Technology,* 25(10), pp 231-240.
7. Conlon, W.J., 1990, "Membrane Processes," Water Quality and Treatment, American Water Works Association, McGraw Hill Co., pp 709-746.
8. Davies, W.J., Le, M.S. and Heath, C.R., 1998, "Intensified Activated Sludge Process with Submerged Membrane Microfiltration," *Proceedings, IAWQ 19th International Conference,* Vancouver, Canada, pp 182-189.
9. El Hani Bouhabila, Ben Aim Roger, Buisson Herve, 1998, "Microfiltration of Activated Sludge using Submerged Membrane with Air Bubbling (Application to Wastewater Treatment)," *Desalination,* 118, pp 315-322.
10. Gander, M.A., Jefferson B. and Judd S.J., 2000, "Membrane Bioreactors for use in small Wastewater Treatment Plants: Membrane Materials and Effluent Quality," *Water Science and Technology,* 41(1), pp 205-211.
11. Grady, C.P.L. and Lim, H.C., 1980, Biological Wastewater Treatment, Marcel Dekker Inc., New York.
12. Gregor, E.C., 1988, "The State of the Art of Microfiltration: Current and Future Application," *Tappi Journal,* 71(4), pp 123-128.
13. Hardt, F.W., Clesceri, L.S., Nemerow, N.L. and Washigton, D.R., 1970, "Solids Separation by Ultrafiltration for Concentrated Activated Sludge," *Journal of the Water Pollution Control Federation*, 42, pp 2135-2148.
14. Ishida, H., Yamada, Y., Tsuboi, M and Matsumura, S., 1993, "Submerged Membrane Activated Sludge Process (SMASP) – Its Application into Activated Sludge Process with High Concentration of MLSS," *Proceedings of the 2nd International Conference on Advances in Water and Effluent Treatment,* pp 321-330.
15. Jae-Seok Kim, Chung-Hak Lee and In-Soung Chang, 2001, "Effect of Pump Shear on the Performance of a Crossflow Membrane Bioreactor," *Water Research*, 35(9), pp 2137-2144.
16. Kishino, H., Ishida, H., Iwabu, H. and I. Nakano, I., 1995, "Domestic Wastewater Reuse using a Submerged Membrane Bioreactor," *Desalination*, 106, pp 115-119.

Top

17. Monat, J.P., 1997, “Separation Systems: The Synergies Between Ultrafiltration and Ion Exchange,” *Ultrapure Water,* 14(6), pp 33-38.
18. Mulder, M., 1991, Basic Principles of Membrane Technology, Kluwer Academic Publishers, Dordrecht, The Netherlands.
19. Muller, E.B., Stouthamber, A.H., Verseveld, H.W. and Eikelboom, D.H., 1995, “Aerobic Domestic Wastewater Treatment in a Pilot Plant with Complete Sludge Retention by Crossflow Filtration,” *Water Resources,* 29(4), pp 1179-1189.
20. Mynhier, M.D. and Grady Jr. C.P.L., 1975, “Design Graphs for activated sludge process,” *Journal of the sanitary engineering division, ASCE,* 101, pp 829-846.
21. Pound, C., Sharp, R.W. and Harvey, R.C., 1997, “Immersed Membrane Bioreactor Provides Reclamation Quality Effluent,” *Water Environment Federation's Technical Exhibition and Conference Proceedings,* 1, pp 701-712.
22. Ripperger, S., 1988, “Engineering Aspects and Application of Crossflow Microfiltration,” *Chemical Engineering Technology,* 11(1), pp 17-25.
23. Rittmann, B.E., 1987, “Aerobic Biological Treatment,” *Environmental Sciences Technology,* 21(2), pp 128-136.
24. Rui Liu, Xia Huang, Lujun Chen, Chengwen Wang and Yi Qian, 2000, “A Pilot Study on a Submerged Membrane Bioreactor for Domestic Wastewater Treatment,” *Journal of Environmental Science and Health,* A35(10), pp 1761-1772.
25. Sansome-Smith, A., Huddleston, J., Young, T. and Lyddiatt, A., 1989, “Solid Liquid Separation in Productive Biotechnology: Sequential Integration with Other Unit Operations,” *Proceedings of International Chemical Engineering Symposium,* 113, pp 209-225.
26. Stamatakis, K.P., 1990, “Analysis of Cake Formation and Growth in Liquid – Solid Separation,” Ph.D. thesis, Syracuse University, U.S.A.
27. Suidan M.T., 2000, “Use of membrane reactors for the effective treatment and reuse of wastewater”, *3rd Annual workshop on water conservation in the kingdom,* pp B7.1-B7.6, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia.
28. Vera, L., Villarroel, R., Delgado, S. and Elmaleh, S., 1998, “Microfiltraion as a Tertiary Treatment,” *Proceedings, IAWQ 19th International Conference,* pp 152-159, Vancouver, Canada.
29. Vigneswaran, S., Kwon, D.Y., Ngo, H.H. and Hu, J.Y., 2000, “Improvement of Microfiltration Performance in Water treatment: Is Critical Flux a Viable Solution?” *Water Science and Technology,* 41(10-11), pp 309-315.
30. Washington, D.R., Clesceri, L.S., Hardt, F.W. and Young, J.C., 1969, “Ultrafiltration for the Control of Recycled Solids in a Biological System”, *Division of Water, Air and Waste Chemistry, American Chemical Society,* pp 196-204.
31. White, M.J.D., 1975, “Settling of Activated Sludge”, Technical report, TR11, WRC, Stevenage, England.
32. Yamamoto, K., Hiasa, M., Mahmood, T. and Matsuo, T., 1989, “Direct Solid – Liquid Separation Using Hollow Fiber Membrane in an Activated Sludge Aeration Tank,” *Water Science and Technology,* 21, pp 43-54.

Top

33. Yasutoshi Shimizu, Kohnosuke Matsushita and Atsno Watanabe, 1994, "Influence of Shear Breakage of Microbial Cells on Crossflow Microfiltration Flux", *Journal of Fermentation and Bioengineering,* 78(2), pp 170-174.
34. Yoon, S.H., Kim, H.S., Park, J.K., Kim, H. and Sung, J.Y., 2000, "Influence of Important Operational Parameters on Performance of a Membrane Biological Reactor," *Water Science and Technology,* 41(10-11), pp 235-242.
35. Zhang, B., Yamamoto, K., Ohgaki, S. and Kamiko, N., 1996, "Floc Size Distribution and Bacterial Activities in Hollow Fiber Microfiltration Membrane Used in Membrane Bioreactor for Domestic Wastewater Treatment," *Water Research,* 30, pp 2385.

Top

Table 1. Characteristics of Crossflow Membrane Bioreactors for Treatment of Municipal Wastewaters.

Membrane Configuration	Volume Lit	HRT (h)	MLSS Kg m^{-3}	Influent COD Kg m^{-3}	COD Loading Rate Kg m^{-3}d^{-1}	COD Removal %	Membrane Area m^{2}	Membrane Flux L m^{-2} h^{-1}	Reference
Plate & Frame	8.0	8	9	0.42	0.45 - 1.5	92	0.42	30	Chaize and Huyard, 1991
Tubular	600	10	3.0	0.64	0.9 – 2.0	> 90	-	15 - 35	Muller et al. 1995
Tubular	25	14.3	5.3	0.86	-	99	0.05	34	Michal et al. 1996
Tubular	40	6	10.8	0.325	-	97	0.085	-	Suidan, 2000

Table 2. Characteristics of Submerged Membrane Bioreactors for Treatment of Municipal Wastewaters

Membrane Material	Volume Lit	HRT (h)	MLSS Kg m^{-3}	Influent COD Kg m^{-3}	COD Loading Rate Kg m^{-3}d^{-1}	COD Removal %	Membrane Area m^{2}	Membrane Flux L m^{-2} h^{-1}	Reference
Polyethylene	34.5	4.0	20	-	-	80	-	20.8	Kishino et al. 1995
Polysulfone	2.5	3.3	-	-	3.2	89	0.016	30	El Hani et al. 1998
Polyolefin	15,500	4.5	39	0.7	-	87	160	20	Davies et al. 1998
Polusulfone	35	-	5	-	0.269[a]	97	0.24	15	Gander et al. 2000

[a] BOD loading rate, Kg m^{-3}d^{-1}

Top