# RECENT DEVELOPMENTS IN MEMBRANE TECHNOLOGY FOR WASTEWATER REUSE

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## ABSTRACT

Ever growing water scarcity problems combined with capacity limitations of the water and wastewater conveyance systems in many city centers lead to reuse of wastewater for secondary purposes. Progress in membrane manufacturing technology and application of membrane technology paved the ways to apply this technology for wastewater treatment and reclamation. Both direct membrane separation (physical treatment) as well membrane coupled biological reactors have their own merits in the wastewater treatment point of view. In this paper, recent studies on both direct membrane separation as well as membrane coupled bioreactors are discussed. Finally the potentials of membrane as an air diffuser and solid/liquid separator are reported with experimental results. This experimental results indicate, a system with membrane as air diffuser and solid/liquid separator can be a competitive system in terms of capital, operation and maintenance cost while offering a superior quality water for reuse, than a conventional systems.

## KEYWORDS

Air diffuser, membrane bioreactors (MBR), reuse, solid/liquid separation, wastewater reclamation.

## INTRODUCTION

Rapid urbanization, ever growing population, desire for raised level of living and industrialization have produced increasing demands for potable water and consequent increase in volumes of wastewater. Since the distribution of water resources is uneven, excessive withdrawal of water from existing water resources is inevitable to meet the demand, and this lead to unsustainability of the water resources and other associated problems. One of the best example to reflect these associated problems is land subsidence as much as 150 mm per year due to excessive pumping of ground water in Bangkok (Department of Mineral Resources, 1995), a metropolitan with the population of nearly 10 million. On the other hand this increase in potable water demand and sewage volume also put pressure on existing potable water supply networks as well as the sewer systems and it is not that easy to implement any expansion to existing systems in densely built-up cities.

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Construction of additional storage and conveyance facilities can alleviate the water shortage problem in certain circumstances but even it is to be accomplished at a substantial economic and environmental expenditure. So finding out a sustainable and affordable alternative is imperative. In the case of urban centers major portion of the water supply is consumed by office buildings and residential apartments. The average water consumption for an office building in Tokyo was reported as 10 L/m$^2$.d and out of this 40 % is used for toilet flushing (Asano et al., 1996) for which non potable water also can be used. In this context reuse of wastewater for secondary purposes will reduce the potable water demand significantly. Installing water reuse systems in large office buildings and apartment complexes itself can not only reduce the pressure on water resources, and water and sewage conveyance systems but also can reveal economic benefits by reducing the cost of potable water and disposal of sewage charges. In addition, the reuse of wastewater also have the other benefits such as pollution abatement in the receiving bodies and a reliable water source even during the drought years.

The conventional approach to accomplish the reuse of wastewater is by treatment schemes such as multimedia filtration, carbon adsorption, ozonation etc. on secondary effluents. However these conventional technologies face certain difficulties like cost, area requirement, operational problems, unstable product water quality due to load fluctuations etc. The progress of membrane manufacture technology and application of membrane technology made membrane technology as an attractive alternative to extend the wastewater reuse applications. Both direct membrane filtration and membrane filtration coupled with biological treatment have their own merits in the wastewater reuse point of view. However considering the residue disposal, membrane coupled biological treatment is preferred over the direct membrane filtration. Here biomass separation is effected by cross flow membrane filtration instead of secondary sedimentation. Such membrane coupled activated sludge treatment is the most popular system used in the Japanese buildings for reuse of wastewater (Aya, 1994).

The disadvantage associated with the membrane coupled bioreactors was the higher energy cost needed for the crossflow filtration, a method used to reduce the membrane fouling. However in recent years different energy saving alternatives were studied. Yamamoto et al. (1989) have discarded the crosflow filtration and used the submerged membrane modules in the aeration tanks to filter the treated water. On the other hand Yamgiwa et al. (1991) used the high pressure retanate from cross flow filtration for aeration by a plunging liquid jet thus the energy spent for aeration unit could be saved. Visvanathan et al. (1997) studied the application of air back flushing technique to submerged membrane modules and demonstrated the stable flux in a long term operation.

This paper briefly describes potential membrane technologies available for wastewater reuse and a case of direct membrane filtration developed recently. Finally developments in membrane coupled biological wastewater treatment are described with some experimental results.

## POTENTIAL MEMBRANE TECHNOLOGIES

Pollutants from wastewater can be removed to a reusable standard either by direct membrane filtration or membrane separation coupled with biological wastewater treatment. Each options have their own merits in the wastewater reuse point of view. To attain reusable quality by direct membrane filtration the general approach involves the pretreatment by microfiltration (for colloids/suspended solids removal) to screened wastewater followed by nanofiltration/reverse osmosis (for organic matter/salt removal). Whereas in the case of membrane coupled biological treatment, membrane filtration in the range of micro/ultra filtration for biosolids/macromolecules separation can provide the desired quality for reuse. The advantages of direct membrane separation alone are described bellow.

- Since there are no biological systems involved, the operation can be shutdown readily and restarted when required without loss in water quality.
- Since membrane processes are closed systems, breakthrough of odors and obnoxious smell can be eliminated.

- Since the process involve with the membrane separation, process automation is easy thus the process control is much better.
- Product water quality does not suffer from feed water quality.
- Unlike the conventional treatment systems such as multimedia filtration, adsorption where comparatively larger space is needed for the media which effect the treatment, membrane technologies are very space efficient. A typical water reclamation facility consist of micrfiltration and reverse osmosis could occupy as little as 400 $m^2$ area for a capacity of 2,400 $m^3$/d (Johnson et al., 1996)

As mentioned above, use of membrane separation alone to get reuse quality necessitates two stages, namely microfiltration and reverse osmosis/nanofiltration. Here the latter is high pressure operation than the previous, so the energy consumption. The main objective of incorporating the second stage in the case of municipal wastewater is, removal of soluble organic matters. If there is an alternative to flocculate these soluble organic matters, the first stage alone can attain the required quality, thus significant energy could be saved. The cheapest, probably effective and environmental friendly way to accomplish this is biological means (activated sludge process). Therefore coupling biological process with membrane separation offers a suitable combination for the objective. The benefits could be attained by this combination are stated bellow.

- Since suspended solid are totally eliminated through membrane separation, the settleability of the sludge, which is the problem in conventional activated sludge, has absolutely no effect on the quality of the treated effluent. Consequently the system is easy to operate and maintain.
- Sludge retention time (SRT) is independent of hydraulic retention time (HRT). Therefore a very long SRT can be maintained resulting in complete retention of slowly growing microorganisms, such as nitrifying bacteria, in the system.
- The overall activity level can be raised, since it is possible to maintain high concentration in bioreactors while keeping the microorganisms dispersed as long as desired and as a result reactor volume will be less. In addition the system requires neither sedimentation nor any post treatment equipment to achieve reusable quality, so the space saving is enormous.
- Treatment efficiency is also improved by preventing leakage of undecomposed polymer substances. If these polymer substances are biodegradable, they can be broken down, which means that there will be no endless accumulation of substances within the treatment process. On the other hand dissolved organic substance with low molecular weights, which cannot be eliminated by membrane separation alone, can be taken up, broken down and gasified by microorganisms or converted into polymers as constituents of bacterial cells, thereby raising the quality of treated water.
- Removal of bacteria and viruses can be expected, so the disinfection process is ecologically sound.
- Maintaining low F/M ratio will produce less excess sludge to be handled and treated.
- Since all the process equipments can be tightly closed no odor dispersion can occur.

## DIRECT MEMBRANE FILTRATION

In western Sydney, Australia, pilot studies have been conducted in large scale over a period of 12 months to reclaim the municipal wastewater for reuse (Johnson et al., 1996). The process being developed are designed to cover a wide range of treated water qualities. The most basic treatment is achieved by combining screening and cross flow microfiltration (CMF) to produce an effluent free of suspended solids and the bulk of bacteria and viruses, but still containing the dissolved nutrients and organics. This effluent may be suitable for low grade industrial reuse applications and some irrigation applications. The addition of reverse osmosis (RO) to the process provides the capability to remove dissolved salts and organics, producing water of very high quality without the need for biological treatment. Then the water from this process is suitable for a wide range of reuse applications such as feed to demineralizing plants for boiler water makeup, for non-potable reuse, for cooling or process water, and for irrigation. The microfiltration removes essentially all suspended solids (99%) and the bulk of bacteria and viruses (5.8 log removal of fecal coliforms). However the filtrate represents the soluble portion of the feed and has average BOD of 93 mg/L. Only minor nutrient removal is achieved by CMF with approximately 19% of phosphorus and no significant change in total nitrogen. After reverse osmosis the permeate quality achieved is excellent and noticeably better than that achievable by conventional biological treatment and filtration. BOD removal is essentially complete and nutrients are reduced to < 5 mg/L of total nitrogen and 0.1 mg/L of total phosphorus. Treated water appearance is as for typical potable water with color of 3 PCU and turbidity of < 0.1 NTU. Preliminary capital and operating costs for the screen/CMF/RO process are around Aus$ 1,150/$m^3$.d (excluding civil works) of installed capacity with operating costs around Aus$ 0.57/$m^3$. Depending on the allowance for civil works, storage, sewage extraction etc., the total cost would be Aus$ 0.8 to 1.05 per cubic meter. Low grade reuse water using the screen/CMF process alone could be produced for a total cost of Aus$ 0.3 to 0.4 per cubic meter.

## DEVELOPMENTS IN MEMBRANE COUPLED BIOLOGICAL WASTEWATER TREATMENT

Membrane in the ultra- or microfiltration range can prevent the escape of solids (biological) and higher molecular weight solutes with treated effluent. Developments in membrane separation technology in biological wastewater treatment are schematically represented in Figure 1. The conventional approach to get reusable quality water is by applying tertiary treatment techniques such as multimedia filtration, carbon adsorption, etc., on biologically treated secondary effluents. As a first step, these tertiary treatment methods were replaced with membrane (ultra/micro) filtration, which ensures almost bacterial and viral free effluent in addition to colloids and solid removal (Pouet et al., 1994; Langlais et al., 1992; Kolega et al., 1991). Here the coupling of membrane technology is solely for the purpose of getting extremely good quality effluent and this stage of development still has its own way where preference is to get a high quality effluent without modifying the existing treatment facilities. In the effort of utilizing membrane technology more effectively, the secondary sedimentation tanks were replaced with cross flow membrane filtration. However higher energy cost to maintain the cross flow velocity led to the next development of submerging membranes in the reactor itself and withdrawing the treated water through membranes (Yamamoto et al., 1989). As an another attempt to energy saving in membrane coupled bioreactors the possibility of using jet aeration in the bioreactor was studied (Yamagiwa et al., 1991). The main feature of this bioreactor is that, the membrane module is incorporated into the liquid circulation line for the formation of the liquid jet so that both the operation of aeration and membrane separation could be accomplished using only one pump. The jet aeration works on the principle that, a liquid jet after passing through a gas layer plunges into a liquid bath, entrain considerable amount of air. Invention of air back washing technique for membrane de-clogging led to the new development of using membrane itself as a clarifier as well as air diffuser.

## APPLICATION OF SUBMERGED MEMBRANES

Direct membrane separation using hollow fiber membranes in activated sludge was reported by Yamamoto et al. (1989). A membrane module with a pore size of 0.1 μm was immersed in the aeration tank and treated water was filtered through the membrane by suction. The results of the short term experiments with no substrate feed revealed that the flux declined considerably in a short time at a high suction pressure of 80 kPa. Further it was noticed on viewing the long term experimental results that the continuous suction caused severe clogging of the membrane module with an increasing pressure difference till a highest value of 100 kPa. Intermittent suction enabled a stable flux to be maintained for about 120 days with a volumetric organic loading of 1.5 kg COD/$m^3$.d and low pressure difference of 13 kPa. The COD removal was observed to be more than 95%. Comparison of COD concentration in the supernatant of the mixed liquor and effluent showed the effluent always had lower values. This phenomenon leads to the conclusion that the membrane could partially cut off the dissolved/colloidal organic materials resulting in a high degree of treatment. In addition by applying intermittent aeration up to 60 % of nitrogen could be completely removed. The energy consumption by suction pump was calculated to be 0.007 kWh/$m^3$, which is quite low.

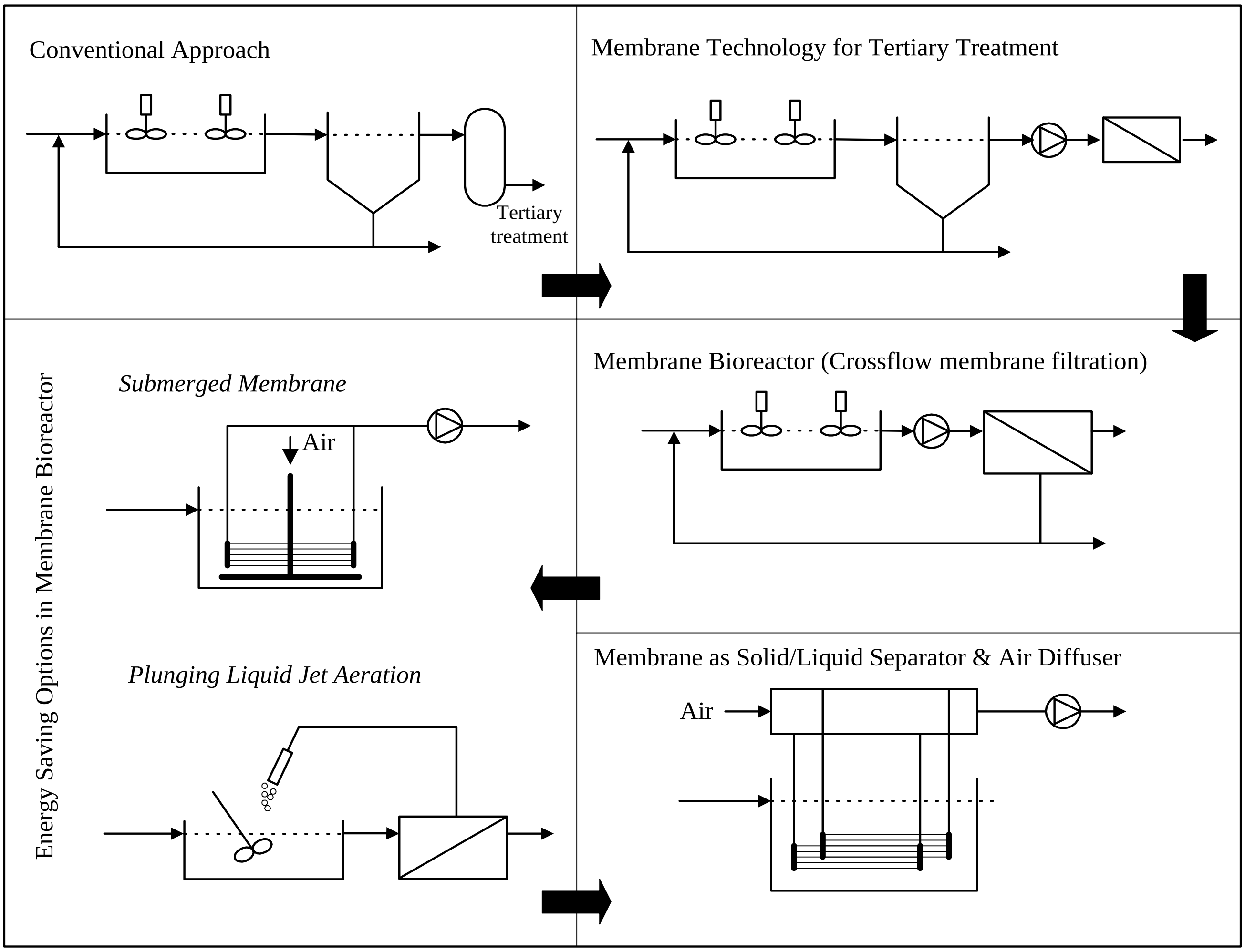


**Fig. 1. Developments in membrane coupled biological wastewater treatment for water reuse**

Air back flushing technique and filtration in an alternative cycle was studied (Visvanathan et al., 1997). Two similar membrane modules as used in the above study were immersed in an activated sludge aeration tank. Filtration and air back flushing to each module was affected in an alternate cycle with different time intervals. The time cycles studied were 60:60, 30:30, 15:15, 10:10 and 5:5 (here 5:5 indicates 5 min. filtration and 5 min. air back flushing). Trials were also carried out on continuous suction as well as intermittent suction without air back flushing. The results indicate, among the all modes investigated the 15:15 operation mode gave the best results in terms of flux stability and net cumulative volume. From these observations it can be conclusively said that although this cyclic operation could not completely remove the clogging, this process improved the flux by up to 370% compared to the continuous operation. The long term experiments revealed that the COD and TKN reduction of more than 90% could be achieved. In terms of operational stability, HRT of 12 hours gave the satisfactory results, whereas the decrease in HRT led to rapid formation of a compact cake layer on the membrane surface thus increasing the transmembrane pressure. However in this study backwash pressure was limited to 100 kPa due to membrane instability and supplementary aeration by stone diffusers was provided for mixed liquor. Further experiments carried out as the continuation of this study is described bellow. In this study, the membrane modules with the pore size of 0.2 μm capable of air back washing (so higher backwash air pressure could be used) were used with the aim of achieving higher flux rate as well as complete aeration of mixed liquor by backwash air only.

## EXPERIMENTAL STUDIES

The experimental investigation shows a promising application of membrane as solid/liquid separator as well as air diffuser simultaneously. In this study two hollow fiber microfiltration modules with the pore size of 0.2 μm were immersed in a 80 L aeration tank to effect the direct treated water extraction. Filtration for 15 min. and high pressure back washing for 15 min. were employed in an alternate cycle to obtain improved flux rate.

The domestic wastewater (adjusted with septage to reflect the typical domestic wastewater characteristics) fed to the aeration tank, was passed through an anoxic tank. Contents of the aeration tank was recycled to anoxic tank in such a way that the mixed liquor had a retention time of 90 min. in anoxic to enhance the nitrogen removal. The experiments were carried out for more than 20 days at each trials with the HRTs of 15, 10, 6 and 3 h while the SRT was kept unchanged (50 days). Due to the limitation of membrane modules, during the last trial experiments could not be carried out at the target HRT of 3 h, instead, the HRT tend to increase progressively with a sharp increase in transmembrane pressure to 96 kPa within two days of start up.

The study proved that the filtration through membrane in cyclic operation with air back washing plays an important role in the improvement of permeate flux stability by removing external deposits on the membrane surface, preventing the compaction of cake layer and reducing the internal pore clogging of the membranes. After 26 hours of operation in cyclic mode of 15:15 (15 minutes filtration and 15 minutes air back washing) with 150 kPa backwash air pressure, it was observed that the flux was improved by 90 % compared to continuos suction flux. Study with various backwash air pressure reveals, increase in backwash pressure will have a better improvement of flux in a long run. The major break through of the study was the utilization of backwash air for the aeration of mixed liquor in the aeration tank. Backwash air at 250 kPa is alone sufficient to aerate the mixed liquor (MLSS of 13,000 mg/L) to a DO level of 3.5 mg/L when system is loaded with 0.19 kg BOD/kg MLVSS.d. Thus in reality considerable portion if not whole of the investment, operation and maintenance cost for membrane modules and the air compressor could be counter balanced by the elimination of conventional air diffusers.

In terms of process efficiency the MBR performance was very much satisfactory. The overall performance in terms of influent and effluent concentrations is reported in Table 1. Considering the guidelines and criteria for reclaimed water use for various purpose in Japan (this also included in Table 1) the effluent of MBR comply with every aspects of the reported values. Fig. 2 shows the color and turbidity of the effluent, and COD, nitrogen and total phosphate removal in MBR through out the study and form which it can be noted that the reactor performance was not affected at various operating conditions. This indicates, if the membrane flux could be further improved, an undisturbed water quality can be obtained even at a HRT of 3h thus the treatment unit becomes further small. On the other hand the effluent turbidity was good with a maximum value of 0.3 NTU which is below the drinking water standard (0.5 to 1 NTU) set by USEPA (Sawyer et al., 1994). No pathogen indicator observed in the effluent of MBR means, the coupling of membranes offer a ecologically sound disinfection opportunity and if necessary a small dosage of chlorine cold be added, to have residual chlorine during the conveyance thus the reclaimed water is even safer for the last consumer.

## CONCLUSION

The recent works on both direct membrane separation as well as the membrane coupled bioreactors show the feasibility of the application of membrane technology for water reclamation. Depending on the circumstances and need, either direct membrane separation or membrane coupled bioreactor could be used for water reclamation. Since direct membrane separation always involve with cross flow filtration or back washing technique where backwash liquid/gas remains unutilized, it is attributed to be an expensive option in that sense. On the other hand, application of air back washing technique to submerged membrane exhibits a better flux rate. The added advantage of this technique is, the utilization of backwash air for the aeration of mixed liquor, thus conventional aeration equipment can be eliminated. This lead to a situation of very competitive system in terms of capital as well as operation and maintenance costs compared to conventional system while offering the treated water to a reusable quality. This new developments in MBR creates the prospects for more widespread application of bioreactors thus the potentials for reuse of wastewater with decreased sludge production and small footprint plant.

Table 1 Comparison of reclaimed water quality of the MBR with reuse guidelines

| Parameters | Concentration | | Criteria/Guidelines [a] | | |
|---|---|---|---|---|---|
| | Influent | Effluent | Toilet Flush Water | Landscape Irrigation | Environmental Water |
| Total coliform/(Count/mL) | > $10^7$ | ND | ≤ 10 | ND | ND |
| Fecal coliform/(Count/mL) | > $10^5$ | ND | - | - | - |
| Chlorine residual combined/(mg/L) | - | - | TA | ≤ 0.4 | - |
| Appearance | NP | NU | NU | NU | NU |
| Turbidity /(NTU) | > 1000 | < 0.3 | - | - | ≤ 10 |
| Biological Oxygen Demand (BOD)/(mg/L) | 295-375 | < 4 | - | - | ≤ 10 |
| Odor | NP | NU | NU | NU | NU |
| pH | 7.6-8.5 | 7.3-8.4 | 5.8-8.6 | 5.8-8.6 | 5.8-8.6 |
| Chemical Oxygen Demand (COD)/(mg/L) | 530-625 | < 25 | - | - | - |
| Total Kjedahl Nitrogen (TKN)/(mg/L) | 26-165 | < 3 | - | - | - |
| Total Nitrogen (TN)/(mg/L) | 26-165 | < 6 | - | - | - |
| Total Phosphate (TP)/(mg/L) | 2.2-9.0 | 0.2-4 | - | - | - |
| Color/(Hazen color unit) | > 5000 | <30 | - | - | - |

NP - Not pleasant NU - Not Unpleasant ND - Not Detected TA - Trace Amount

[a] adopted from Japan Sewage Work Association, 1993.

**Fig. 2 Treated Water Quality of MBR**

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