Reaktor, Vol. 13 No. 1, Juni 2010, Hal. 1-9

MEMBRANE BIOREACTOR FOR TREATMENT OF RECALCITRANT WASTEWATERS

Suprihatin*) and Muhammad Romli

Department of Agroindustrial Technology, Faculty of Agricultural Technology, IPB
Kampus IPB Darmaga, PO. Box 220, Bogor
*)Corresponding author: suprihatin@indo.net.id

Abstract

The low biodegradable wastewaters remain a challenge in wastewater treatment technology. The performance of membrane bioreactor systems with submerged hollow fiber micro- and ultrafiltration membrane modules were examined for purifying recalcitrant wastewaters of leachate of a municipal solid waste open dumping site and effluent of pulp and paper mill. The use of MF and UF membrane bioreactor systems showed an efficient treatment for both types wastewaters with COD reduction of 80-90%. The membrane process achieved the desirable effects of maintaining reasonably high biomass concentration and long sludge retention time, while producing a colloid or particle free effluent. For pulp and paper mill effluent a specific sludge production of 0.11 kg MLSS/kg COD removed was achieved. A permeate flux of about 5 L/m²h could be achieved with the submerged microfiltration membrane. Experiments using ultrafiltration membrane produced relatively low permeate fluxes of 2 L/m²h. By applying periodical backwash, the flux could be improved significantly. It was indicated that the particle or colloid deposition on membrane surface was suppressed by backwash, but reformation of deposit was not effectively be prevented by shear-rate effect of aeration. Particle and colloid started to accumulate soon after backwash. Construction of membrane module and operation mode played a critical role in achieving the effectiveness of aeration in minimizing deposit formation on the membrane surface.

Keywords: *leachate, microfiltration, pulp and paper mill effluent, recalcitrant wastewater, submerged membrane, ultrafilitration*

Abstrak

Bioreaktor membran digunakan untuk pengolahan air limbah sulit terdegradasi. Air limbah sulit terdegradasi hingga saat ini masih menjadi tantangan dalam teknologi pengolahan air limbah. Dalam penelitian ini kinerja sistem bioreaktor membran dengan modul membran mikro- dan ultrafiltrasi serat berlubang dikaji untuk mengolah dua jenis air limbah yang sulit terdegradasi yaitu air lindi dari tempat pembuangan sampah dan air limbah industri pulp dan kertas. Penggunaan bioreaktor membran mirko- dan ultrafiltrasi tercelup menunjukkan kinerja yang efisien baik untuk pengolahan air lindi maupun air limbah industri pulp dan kertas dengan tingkat reduksi COD antara 80-90%. Proses membran tersebut dapat mencapai efek-efek yang dikehendaki berupa konsentrasi biomassa dan umur lumpur yang rasional tinggi, serta menghasilkan keluaran yang bebas dari koloida atau partikel. Pada pengolahan air limbah industri pulp dan kertas dicapai produksi lumpur spesifik 0,11 kg MLSS/kg COD tereliminasi. Permeat fluks 5 L/m²h dapat dicapai oleh membran mikrofiltrasi. Percobaan dengan membran ultrafiltrasi menghasilkan fluks relatif lebih rendah yaitu sekitar 2 L/m²h. Dengan penerapan pencucian balik secara periodik, fluks dapat ditingkatkan secara signifikan. Hal ini mengindikasikan bahwa partikel-partikel atau endapan koloida pada permukaan membran dapat dikurangi dengan pencucian balik, tetapi pembentukan kembali endapan tidak dapat secara efektif dicegah dengan efek aliran silang akibat aerasi. Partikel dan koloida mulai terakumulasi segera setelah pencucian balik dihentikan. Konstruksi dan pengoperasian modul membran memegang peranan penting dalam pencapaian efektivitas aerasi dalam meminimumkan pembentukan endapan pada permukaan membran.

Kata kunci: *air lindi, mikrofiltrasi, air limbah industri pulp dan kertas, air limbah sulit terdegradasi, membran tercelup, ultrafiltrasi*

INTRODUCTION

A hardly degradable (recalcitrant) wastewater is that dominated by polymers (macromolecules), toxics, and synthetic organics (mostly chlorinated compound) types of pollutant and is generally characterized by low BOD_5/COD (less than 0.4). Such a type of wastewater can be generated by industrial activity, such as pulp and paper, leather tanning, and textile as well as domestic activity, such as landfill leachate. The recalcitrant wastewater cannot be treated effectively by a conventional wastewater treatment system, such as activated sludge system. Research works dealing specifically with such a type of wastewater are until recently relatively limited, regardless the high demand for such a technology because of the increased community awareness on environment and of the stricter governmental regulations on wastewater discharge.

The recalcitrant wastewater remains a particular challenge for wastewater treatment. In many cases such a wastewater cannot even be treated biologically. This is mainly because of the toxic effect of certain pollutants on the microorganisms. Therefore, for a biological degradation to take place some “specialists” microorganisms are required. The “specialists” have generally a very long generation time, so that the technology objectives are to strive for total retaining of the “specialists” in a suitable reactor system, increasing concentration of the “specialists” in the system, and achieving a high reaction rate through enrichment of hardly biodegradable substances.

By replacing the secondary clarification with membrane systems the requirements could be met. Results of past research work (Suprihatin *et al*, 1997) showed that the biomass concentration in the biological step could be increased up to 20-30 g/l, reactor volumes can therefore be reduced dramatically, and thus the volumetric treatment capacity. If ultrafiltration, instead of microfiltration, is used the large organic molecules are retained in the reactor. The increased residence time leads to further degradation. Under certain conditions, the ultrafiltration in tubular membranes can be applied for separation of activated sludge successfully over a long period without interruption or cleaning. Integrating a bioreactor with a membrane filtration can solve the limitations of the sedimentation for separation of biomass. It leads to improving effluent quality, reducing the space demand as well as specific sludge production through various mechanisms as shown schematically in Figure 1.

Since the permeate flux is one of the main parameters determining the economic viability of the process, it must be enhanced to minimize the used membrane surface or the capital costs. The flux can be increased by applying higher flow rate across the membrane surface (Liao *et al*, 2007). High flow rates, however, result in high energy consumption, because the energy consumption depends on the square of the flow rate. The low flux will prevent broader applications of membrane bioreactor (MBR) in full-scale wastewater treatment operations. Any improvement in membrane technology that increases the flux and/or reduces power requirement will, therefore, promote MBR application in wastewater treatments.

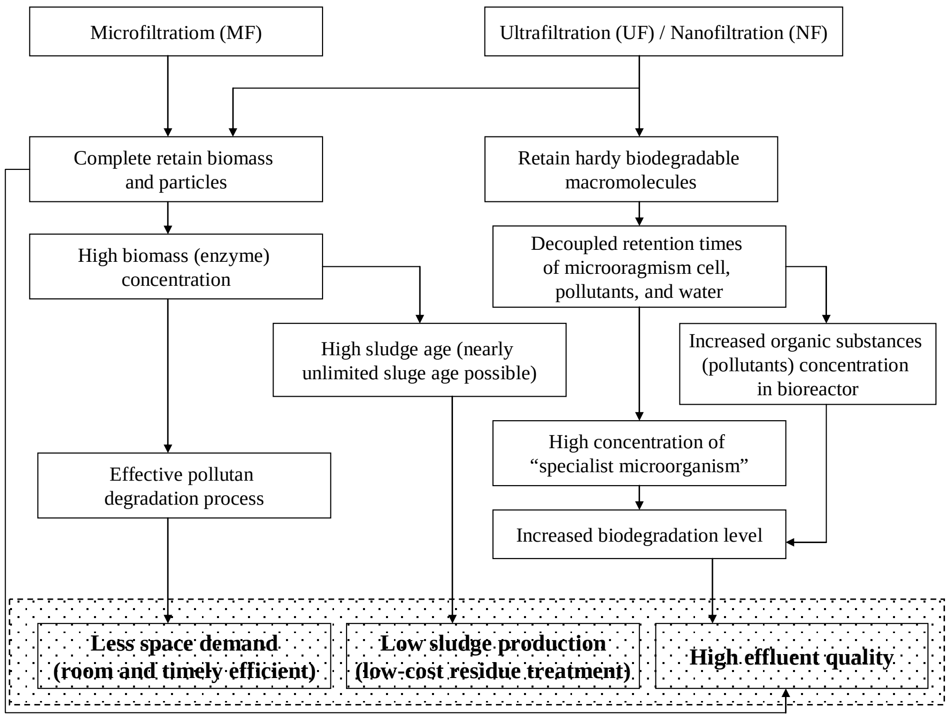

Figure 1. Effects of integration of a bioreactor with a membrane filtration in biological treatment system (Suprihatin, 1999)

A recent approach is the use of a membrane, which is submerged directly into the activated sludge tank. To control of the formation of a deposition layer, a cross flow stream over the membrane surface is created by air bubbling, which is generated by a diffuser installed underneath the membrane modules. The air bubbles flow upward over the membrane surface and induce turbulence and a shear rate on the membrane surface, which generate the back-transport of the retained particles from the membrane surface. The submerged system with aerated microfiltration tubular modules has also been subject of a number of investigations in the past years (e.g. Chimchaisri *et al*, 1992; Shimizu *et al*, 1996; Chang and Judd, 2002; Jin *et al*, 2005; Jin *et al*, 2006).

Despite of some advantages of the system, especially in the practical aspects and its low energy consumption, until now research works and experiments are concentrated on domestic wastewater treatment application, which is relatively easier to treat (Ghyoot *et al*, 1989; Chiemchaisri, 1993; Chang and Judd, 2002; Seo *et al*, 2004). For this reason, in this work, the performance of MBR systems for treating leachate of a municipal solid waste dumping site and pulp and paper mill effluent is evaluated. Performance of the membrane bioreactor system is determined based on organic load or hydraulic retention time, pollutants removal efficiency, achievable stable permeate rate (flux), sludge production, and effluent quality.

RESEARCH METHODOLOGY

Materials used for these experiments include leachate of a municipal open dumping site and effluent of pulp and paper mill. The characteristics of the wastewater are presented in Table 1. For executing the experiments, following apparatus were used: a set of microfiltration membrane bioreactor (MF-MBR), a set of ultrafiltration membrane bioreactor (UF-MBR), and analytical apparatus such as COD apparatus, TKN apparatus, and spectrophotometer.

Table 1. Wastewater characteristics (in mg/L)

Parameter	Leachate	Pulp and paper mill effluent
COD	400-4,500	570 – 1,210
TKN	300–635	16 – 20
NH_3-N	300-620	20 – 40
NO_3-N	7 – 24	1 – 6

The set-up of membrane bioreactor systems is shown schematically in Figures 2 and 3. The membrane systems consisted of reactor, membrane module, pumps for permeate extraction, pump for backwash, aerator, and manometer. Technical specification of the bioreactor systems is presented in Table 2. The hollow fiber MF and UF module used in this experiment were purchased from PT. GDP Filter, Bandung. The polypropylene MF membrane was chosen due to its durability against physical and biological harms. Polypropylene (PP) is known as hydrophobic material. To minimize hydrophobic fouling, the PP membrane was hydrophilized by immersing the module in isopropanol.

Two different types of hollow fiber membrane modules were used for the experiments, namely microfiltration membrane and ultrafiltration membrane. The hollow fiber microfiltration membrane has a nominal pore size of 0.2 μm, an inside diameter of 0.5 mm, outside diameter of 1.0 mm and an effective length of 22 cm. The module contains 75 membrane fibers. The ultrafiltration membrane with pore size of 0.01 μm allows a complete retention of suspended solids, supracolloidal materials and microorganisms. The module contains 500 membrane tubes fiber of 18 cm length, an outside diameter of 1.0 mm and an inside diameter of 0.5 mm. The total ultrafiltration membrane surface area is app. 0.5 m².

Table 2. Technical specification of both bioreactor systems

	MF-MBR	UF-MBR
Bioreactor:		
- Material	Plexiglas	Plexiglas
- Effective Volume (L)	11	11
- Accessories	Aerator, diffuser, vacuum pump, backwash pump, vacuum gauge, power supply, electrical regulators, regulator valves, product tank	Aerator, diffuser, vacuum pump, backwash pump, vacuum gauge, power supply, electrical regulators, regulator valves, product tank
Membrane:		
- Type of membrane module	Hollow fiber	Hollow fiber
- Material	Polypropylene (PP)	Polyacrylonitrile (PAN)
- Pore Diameter (μm)	0.2	0.01
- Diameter of fiber (mm):		
- Outside	1.0	1.0
- Inside	0.5	0.5
Number of fiber	75	500
Effective length of fiber (cm)	22	18

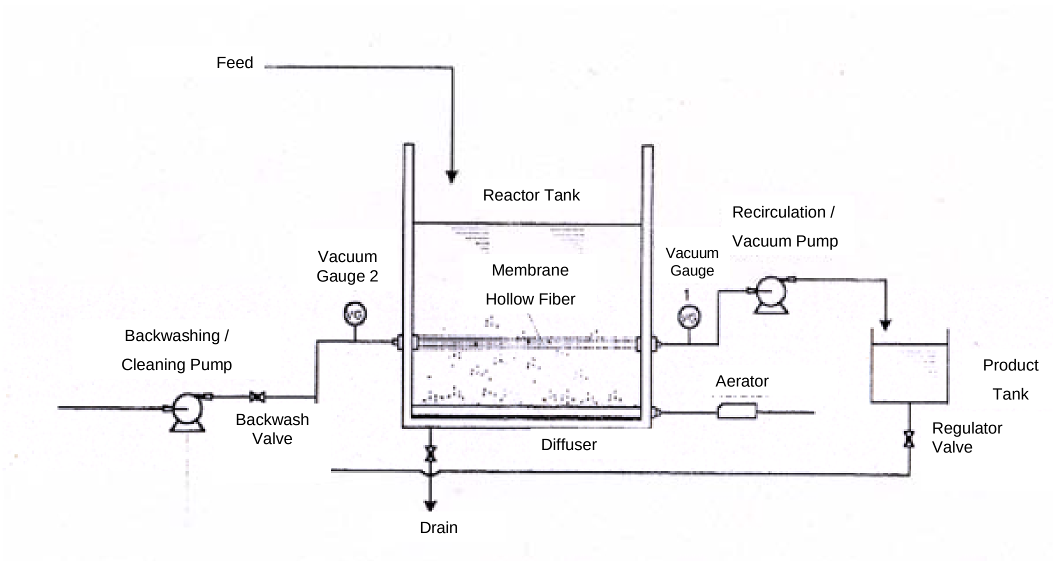

Figure 2. Schematic diagram of MF/UF-MBR for treatment of leachate

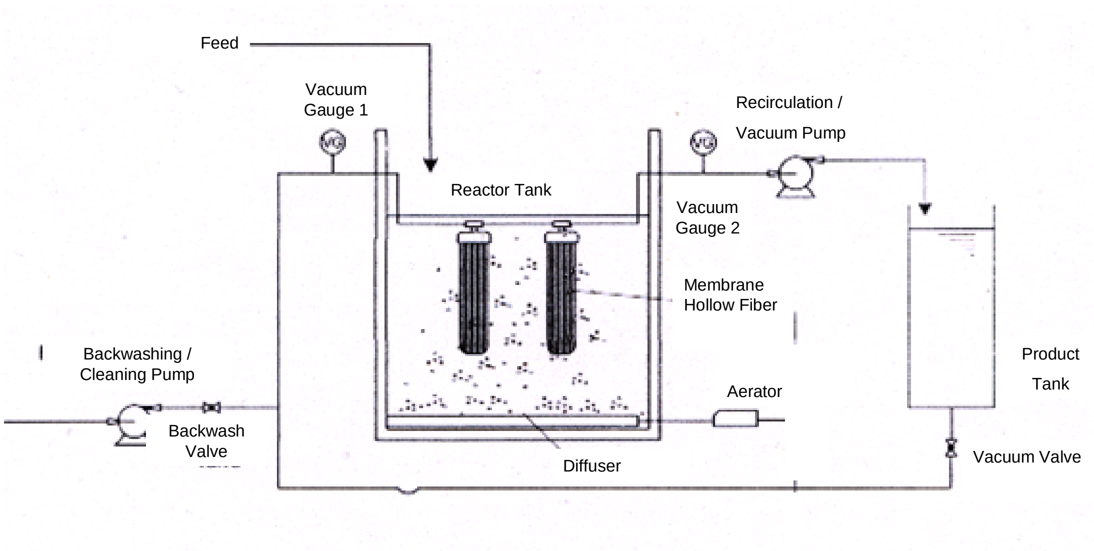

Figure 3. Schematic diagram of UF-MBR for treatment of pulp and paper mill effluent

The membrane modules were submerged directly in about 11 liter liquid upon a diffuser, which was installed, on the bottom of the reactor constructed from Plexiglas. In the experiments, a set of diffusers was used, by which air bubbling is generated. Because of the hydrostatic pressure difference between the riser and down comer, a cross-flow stream was effected (air-lift). Each bioreactor was operated for various operating conditions. Pollutants removal efficiency, permeate rate (flux), sludge production, and effluent quality were measured with respects to operation time and operating conditions. Samples of influent and effluent were analyzed for the chemical oxygen demand (COD), total suspended solids (TSS), ammonium (NH_4-N), nitrate (NO_3-N), and total Kjeldahl nitrogen (TKN). The laboratory analyses were carried out by following the Standard Methods for the Examination of Water and wastewater (APHA, 1998). Permeate flux was determined by measuring the permeate flow rate (unit volume per unit time) divided by outside membrane surface area for hollow fiber modules. To make direct comparison of membrane performance possible, permeate flux is presented in L/m^2h.

RESULTS AND DISCUSSION

Treatment of Leachate

Experiments with MF-MBR for treatment of leachate were conducted with hydraulic retention times (HRT) of 0.1-2 days. At HRT of 2 d COD was reduced from 474 to 154 mg/L, equivalent to a reduction of 69%. Lowering HRT to 1 d, did not change the COD elimination significantly, but further lowering to 0.75 d decreased the level of COD elimination to 56%. The low level of COD removal was attributed to hardly biodegradable substances in the leachate.

In further experiments, an ultrafiltration membrane bioreactor was used. The UF-MBR was operated at HRT of 0.1-2.0 d, equivalent to food-microorganism ratio (F/M) values of 0.1-0.3 kg COD/kg MLSS.d. Results of this experiment are presented in Figure 4. Eventhough influent COD concentration varied greatly, the system was able to accommodate the situation and resulting in relatively stable effluent COD of 180 mg/L. This confirmed the ability of MBR to accommodate the pollutant shock loading as reported by Melin *et al* (2006).

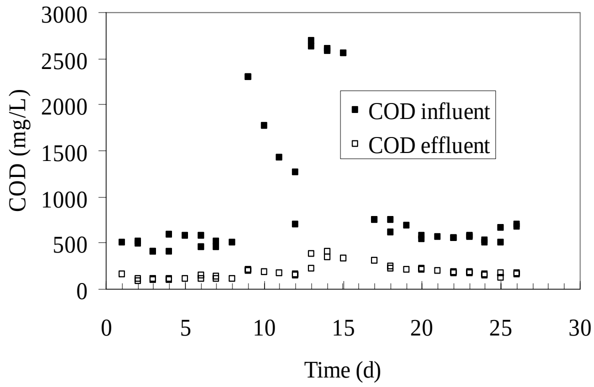

Figure 4. Performance of UF-MBR for treatment of leachate

Performance of MF-MBR was studied at transmembrane pressure of app. 0.2 bar (vacuum), MLSS of app. 3 g/L, and temperature of 31-34^{o}C. Under the conditions, it was observed that high initial permeate flux of app. 95 L/m^{2}h was resulted. The permeate flux started to decrease gradually until app. 20 L/m^{2}h in 12 hours. The flux was stable at values of app. 5-7 L/m^{2}h (Figure 5).

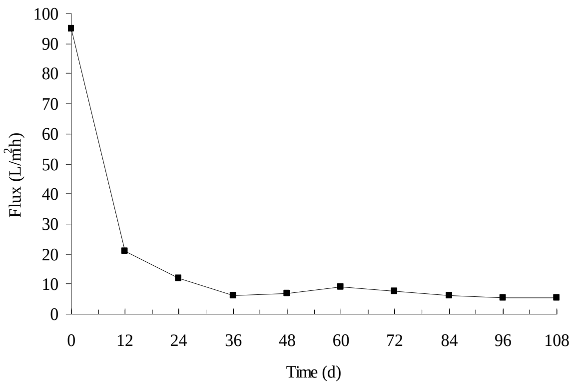

Figure 5. Permeate flux of the microfiltration membrane (leachate)

The flux decrease with increasing the operation time is typical in membrane filtration. The flux decay in the period of process could be explained by building-up of cake layer on the membrane surface which offers the controlling hydraulic resistance to permeation. The cake layer is continuously growing until it reaches a state where further growth is curtailed by the applied axial gas-liquid shear upon the cake layer. At this point, a state flux is reached where the convective transport of solutes or particles to membrane is equal to the diffusive back transport of the particles.

In subsequent experiments, backwash was applied to improve the permeate flux. In general backwashes increased permeate flux of MF membrane, but only effective for short-time, the flux decreased in a couple of hours after backwash and resumed to the initial level before backwash (Figure 6). Backwash leads to flux incensement as result of a partly curtail of cake layer. But it is effective only for short periods of time. New cake layer is built up on the membrane surface as results of convective permeate flow and selective membrane separation. The existing shear upon the cake layer created by applying axial gas-liquid can limit the cake layer growth, but only until to the level where the steady state flux of app. 5-7 L/m^{2}h were reached.

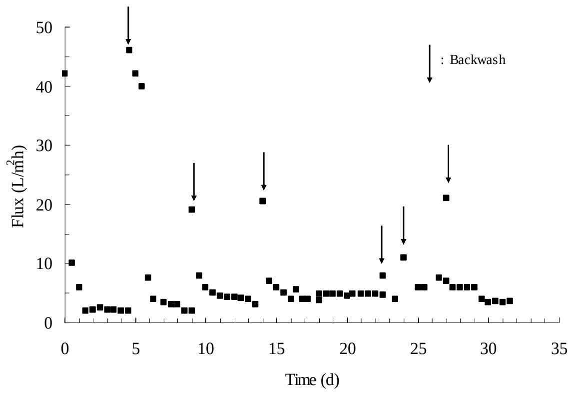

Figure 6. Effect of backwash on MF permeate flux (→: backwash)

Treatment of Pulp and Paper Mill Effluent

Figure 7 shows the COD removal profile as function of time. The ultrafiltration membrane bioreactor system was operated with F/M value of 0.1–0.2 kg COD/kg MLSS.d, equivalent with MLSS of 7–9 g/L and HRT of 0.5-2 d. The membrane bioreactor system showed its capability and reliability to accommodate the shock-load situations. Although COD influent was increased from 500 to 3,000 mg/L, the system could maintain a relatively low effluent COD of app. 135 mg/L. This indicated that the membrane bioreactor system has a stable performance of COD removal eventhough subjected to great variation of influent COD. The system is less sensitive to contaminant peaks compared to conventional activated sludge systems.

The MLSS concentration increased from 7 to 9.5 g/L over the operation period of 23 d (Figure 8). The increased MLSS indicated that bacterial population has been adapted to the system environment. During the period of operation, no excess sludge was wasted from the system except for sludge withdrawn for analytical purposes. From mass balance, it was calculated from this experiment that the specific sludge production of 0.1 kg MLSS/kg COD removed was observed at F/M value of 0.1-0.2 kg COD/kg MLSS.d. This value was extremely small compared with that of the conventional activated sludge process, which is typically in the range of 0.8–1.0 kg MLSS/kg COD eliminated (Bever *et al*, 1993).

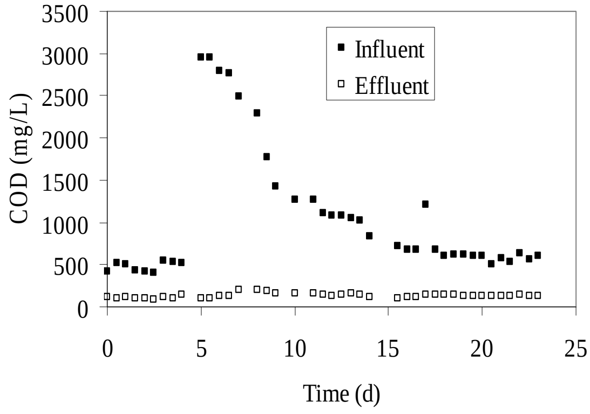

Figure 7. Performance of UF-MBR for treating pulp and paper mill effluent

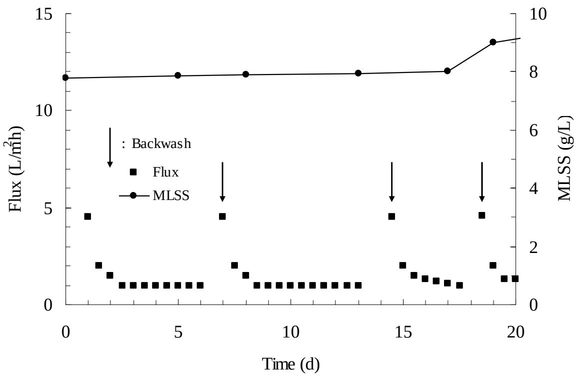

Figure 8. Permeate flux profile of UF membrane (pulp and paper mill effluent)

The experimental results (Figure 8) showed that the use of submerged UF membrane module in separation of activated sludge produced relatively low flux of app. 2 L/m^{2}h in continuous operation. Effects of operating parameters of submerged membrane on permeate fluxes were not investigated comprehensively in this research work. The parameters such as trans membrane pressure (TMP), gas velocity and MLSS are of course the key operating parameters that determine the extent of fouling and consequently the flux. Relationships between these parameters and flux were reported and discussed in detailed by Shimizu *et al.* (1996). By changing TMP and gas velocity during the operation only little effects on flux were observed (data not shown). It possibly due to the formation of a stable and resistance gel layer which will not be diminished at higher gas-liquid velocities and TMPs. A high gas-liquid velocity and low flux since the beginning of operation may be required and this should be maintained to obtain higher fluxes as suggested also by Meindersma *et al* (1995). In addition, module construction should able to guarantee that all or almost all membrane surface is streamed by gas-liquid flow.

When relatively larger solutes or particles are filtered during the operation, the components rejected by membrane tend to form a layer on the membrane surface. Depending on the type of solid, this could be viscous or gelatinous. This addition layer of solutes is known as the gel layer, concentration polarization (CP) layer, cake or polarization layer. This is not to be confused with fouling layer that occurs because of membrane-solute interaction (adhesion) (Cheryan, 1998). In contrast to the fouling layer, cake layer should be strongly affected by hydrodynamic condition created by air-water stream upon the membrane surface. The adhesion and cake layer formation have the same indication in terms of flux decay. Flux decay as a result of adhesion is often irreversible and difficult to remediate by changing of operating conditions such as gas/liquid flow rate; it needs eventually chemical cleaning.

In order to prevent membrane fouling, backwash was applied using particle-free water (permeate). This measure suppressed the deposit layer on the membrane surface and within the membrane pores and thus improved membrane permeability significantly (Figure 8). After 30 minutes of operation, however, the permeate flux started decreasing markedly and reached the initial level before backwash.

Each component of a feed stream will react or interact differently with the membrane. The effectiveness of the backwash is consequently depending on the feed system, the membrane material, the operating conditions and the interaction between these parameters. Backwash will not result in increased flux for long period of time without any improvement in fluid management techniques such as hydrodynamics or turbulence. In this work the backwash increased the flux significantly, but the flux improvement was temporarily. The similar effect was observed in the treatment of both pulp and paper mill effluent and leachate.

As a comparison it should be mentioned here the results of experiments by Yamamoto *et al* (1989), in which domestic wastewater was treated by using submerged hollow fiber membrane with pore diameter of 0.1 µm. Different operating conditions were set-up, and permeate flux and removals of carbon and nitrogen compounds were observed. The experimental unit was operated with hydraulic retention time of 4 h, volumetric loading of 1.5 kg COD/m^3.d and transmembrane pressure of only 0.13 bar. The filtration was operated under intermittent mode, i.e. filtration was switched on every ten minutes, and then switched off after reaching a minimum liquid content of the reactor or filtration duration of 5 minutes. The COD removal was higher than 95% with an average permeate flux of up to 1.5 L/m^{2}h. Guender and Krauth (1998) reported relatively higher fluxes in a trial experiment of submerged membrane reactor for treatment of primary treated municipal wastewater. Permeate fluxes of 16 L/m^{2}h for hollow fiber module and 18 L/m^{2}h plate module were obtained with energy consumption for filtration and aeration of 1-2 kWh/m^3.

One of the main advantages of UF-MBR is that the membrane retained bacteria completely and recovers wastewater pollutants with molecular weight higher than the cut-off of the membrane. This resulted in increased biomass concentration and prolonged pollutants residence time, and thus leading to better degradation and improving effluent quality. Because of the high effluent quality it is possible to reuse the treated wastewater. The high potential of reuse or recycling of wastewater treated using MBR is reported in literatures, e.g. Melin *et al* (2006) and Artisa *et al* (2007).

Improvement of MBR System Performance

The permeate fluxes measured in the experiments were relatively low. These values were typical of hollow fiber membrane system having high solid concentration, and comparable to the flux of the submerged membranes reported by Yamamoto *et al* (1989), Chimchaisri *et al* (1992) and Birima *et al* (2005). The permeate flux determines the economic viability of membrane bioreactors. The low flux was a result of deposit on the membrane surface. The particle or colloid deposition on membrane surface was suppressed by backwash, but reformation of deposit was not prevented effectively by shear-rate created by aeration only. Particle and colloid seemed to accumulate in short time after backwash. Constructions of membrane module and operation mode play a critical role to achieve effective removal of deposit on the membrane surface by aeration.

The flux can be increased by a higher flow rate across the membrane surface (Liao, 2006). High flow rates result, however, in a high energy consumption, because the energy consumption depends on the flow rate by the power of three. The low flux and the high energy consumption are the reasons that MBR is not yet widely used and remain a challenge in the wastewater treatment.

To show a possibility to reduce high pumping energy, previous experimental results with air lift systems (Suprihatin, 1999) will be presented here. A simple change allowed cross flow to be maintained using injecting air at the bottom of the membrane module. In this way, MLSS is transported via an “air-lift” pump through the system. A secondary low-energy pump was also used to increase the net flow through the membranes. This innovative use of engineering controls reduces the energy needed in conventional cross-flow designs. In this experiment, synthetic wastewater was treated by using submerged tubular membrane with an internal diameter of 14.4 mm and a molecular weight cut-off of 50.000 Da (ultrafiltration). The relatively smaller pore size of tubular ultrafiltration membrane, expressed in molecular weight cut-off (MWCO), was chosen instead of microfiltration membrane to minimize blockage of the membrane pores by small size particles. Because the pores are much smaller than the particles to be separated, the particles will not get caught within the pores but will roll off the membrane surface under the shear rate generated by the gas-liquid cross-flow.

The module contained seven membrane tubes of 1.8 m length and an internal diameter of 14.4 mm. The total membrane area was 0.53 m². The tubular ultrafiltration membrane module was supplied by Fa. Stork, the Netherlands. The ultrafiltration membrane module was submerged into a reactor with an effective volume of about 150 liter (diameter of 290 mm, height of 2100 mm). The reactor was equipped with an aerator, diffuser, vacuum pump, vacuum gauge, power supply, regulator valves, and equalization tank. Because of the hydrostatic pressure difference between the aerated membrane tubes and the surrounding annular volume, a loop flow is generated.

In the submerged membrane system, permeate is extracted by pressure difference generated by a vacuum pump. A decrease in flux will result in rise of trans membrane pressure (vacuum pressure) if the membrane system is not equipped by any pressure regulation. In this work the system was operated in approximately constant TMP, namely 0.3-0.4 bar (vacuum) during the first 16 days, 0.5 bar during the period of 16-22 days, and 0.6 bar during the period of 22-30 days. During the operation the changes of flux and MLSS concentration were monitored. The flux, MLSS and TMP are plotted over time of operation. Presenting the measured flux against TMP results in relationship between flux and TMP at various MLSS, including MLSS = 0 (particle free water).

Figure 9 shows the profile of flux, different pressure and mixed liquor suspended solids (MLSS) over time of ultrafiltration.

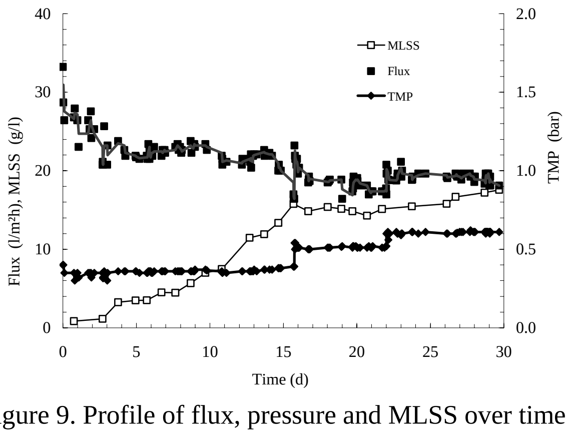

Figure 9. Profile of flux, pressure and MLSS over time of ultrafiltration

The flux is 35 l/m²h at the outset, but drops during the first four days to about 22 l/m²h. Thereafter, the flux remains substantially constant for a long period of time. The MLSS increases from 0.8 to 17 g/l. Eventhough the sludge concentration increases up to 17 g/l the flux does not decrease. It indicates that the increasing of the transport to membrane due to the increase in MLSS can be compensated by the hydrodynamic turbulence and the shear action of the gas-liquid two-phase flow. The flux remains substantially constant at about 20 l/m²h for four weeks. It has to be emphasized that the experiments were conducted continuously and no cleaning or backwash of the membrane was done.

Different levels of pressure were applied, i.e. from 0.40 to 0.50 bars at day 16 and from 0.5 to 0.6 bars at day 22 of the experiment. In Figure 10, the flux is plotted as a function of the transmembrane pressure, whereas the solid line represents the experimental result using tap-water. As shown, the flux is proportional to the pressure, when clean water is permeated through the membrane. On the contrary, the flux is not proportional to the pressure in the presence of MLSS. Even at high trans membrane pressure it was not possible to reach the flux which would correspond to filtration of pure water. This difference may be explained by the existence of deposition of particle at the membrane surface.

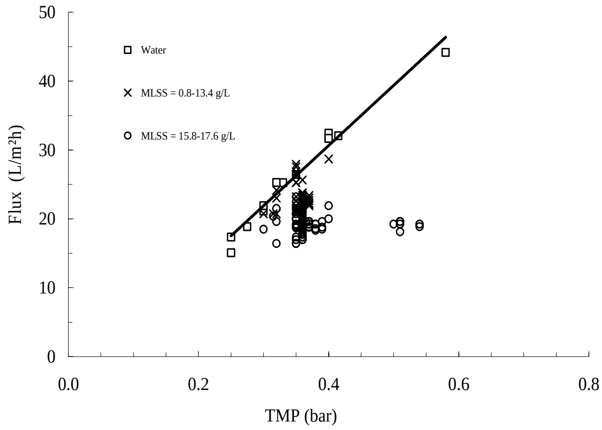

Figure 10. Flux versus transmembrane pressure of the ultratiltration operation

It was possible to determine a critical flux from the experimental results. The critical flux is a flux at which the rates of particles come to membrane surface in relation to the rate of which they are removed shear stresses. Operating below the critical flux or above a critical shear stress/flux ratio may result in little or no flux decline. In this work the critical flux was observed to be at app. 20-25 L/m^{2}h for MLSS of bellow 13 g/L or at flux of less than 20 L/m^{2}h for higher MLSS, corresponding to TMP of 0.3-0.4 bar and less than 0.3 bar, respectively. By knowing the critical flux, one may operate at such a condition that long-term fouling can be minimized. If the flux is increased by increasing the pressure above the critical value at a constant MLSS, the particle deposition will be formed resulting in increased filtration resistance.

CONCLUSIONS

Results of the laboratory analysis on leachate of the municipal solid waste dumping site and the pulp and paper mill effluent showed that these materials could be categorized as hardly biodegradable wastewater. The MF and UF membrane bioreactor systems resulted in COD reduction of 80-90% for both types of wastewater. The membrane-assisted process achieved the desirable effects of maintaining reasonable high biomass concentration and long sludge retention time, while producing a colloid or particle free effluent.

The membrane reactor systems produced low excess sludge. For pulp and paper mill effluent a specific sludge production of 0.1 kg MLSS/kg COD removed was observed. This value was extremely small compared with that of the conventional activated sludge process, in which a typical reported value was in the range of 0.8-1.0 kg MLSS/kg COD eliminated.

A permeate flux of about 5 L/m²h could be achieved with the submerged MF membrane. Experiments using ultrafiltration membrane, however, produced relatively lower permeate fluxes of 2 L/m²h. By applying periodical backwash, the flux could be improved significantly. It was indicated that the particle or colloid deposition on membrane surface was suppressed by backwash, but reformation of deposit was not prevented effectively by shear-rate created by aeration. Particle and colloid seemed to accumulate in short time after backwash. Construction of membrane module and mode of operation, therefore, plays a critical role to achieve effective removal of deposit on membrane surface by aeration.

NOMENCLATURE

COD	=	Chemical Oxygen Demand (mg/L)
BOD$_5$	=	Biochemical oxygen demand five days (mg/L)
F/M	=	Food to Microorganism ratio
MBR	=	Membrane bioreactor
MLSS	=	Mixed Liquor Suspended Solids (kg/m^3)
MLVSS	=	Mixed liquor volatile suspended solids (kg/m^3)
TKN	=	Total Kjeldahl Nitrogen (mg/L)
TMP	=	Transmembrane Pressure (bar)
UF	=	Ultrafiltration

ACKNOWLEDGMENT

A part of this research work was supported financially by the Indonesian State Ministry for Research and Technology through RUT Project FY 2003-2004.

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