Membrane-Coupled Aerobic Bioreactors for Use in Wastewater Treatment

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ABSTRACT

A membrane-coupled aerobic bioreactor (MBR) can be described as a system coupling the aerobic bioreactor, or activated sludge tank, of a wastewater treatment system with a micro- or ultrafiltration membrane. The membrane serves to separate the suspended material in the sludge so that the permeate stream is free of chemicals, microorganisms, and other contaminants. The membrane may be either internally mounted so that the retentate remains in the bioreactor or externally mounted so that the retentate is either recycled to the bioreactor or wasted. The membranes are available in a variety of structures and materials which can be suited to individual application needs. The MBR has several advantages over conventional activated sludge processes, including reduced area, consistently high effluent quality, and operational separation of solids retention time (SRT) and hydraulic retention time (HRT). A mathematical model has been developed for an MBR and tested against experimental data with reasonable agreement. Additionally, studies have been conducted to investigate the effects of changing operational parameters on the MBR as well as the microbial diversity of an MBR as compared to a conventional activated sludge system.

KEYWORDS

bioreactor, membrane coupling, municipal wastewater, industrial wastewater, microfiltration, ultrafiltration, activated sludge treatment

INTRODUCTION

The demand for sanitary, usable water is ubiquitous. Water is needed for domestic use, agricultural application, industrial operations, food and beverage production, and a practically endless list of other functions. Wastewater treatment is thus an essential process as the human population continues to grow and the need for clean water increases. Treatment of wastewaters from municipal and industrial sources must yield fresh water which is free of pollutants including chemicals, insolubles, bacteria, and viruses. Conventional wastewater treatment systems take advantage of the action of microorganisms to break down the chemical components of wastewater into harmless products which can be discharged to the atmosphere or released in the effluent stream. Growing populations, limited areas for wastewater treatment facilities, and more stringent regulations all necessitate alternatives to the traditional treatment process. Membrane-coupled aerobic bioreactors are one alternative to the conventional wastewater treatment process.

NEED FOR TREATMENT OF WASTEWATER

The main purpose of treating wastewater is to remove pollutants which can harm the aquatic environment once the treated water has been discharged. The biological treatment of wastewater is based on utilizing a population of bacteria and other microorganisms which assimilate the contaminants and use them as nutrients for cell growth (Schultz, 2005, and Winkler, 1981). These contaminants are particularly undesirable because their oxidation reduces dissolved oxygen (DO) concentrations in water, so that releasing wastewaters with large concentrations of pollutants can adversely affect aquatic communities. In wastewater treatment systems, these oxygen-demanding materials are contacted with the microorganisms for a time period sufficient for the organisms to take up and metabolize the pollutants removing them to a desired extent (Winkler, 1981).

The majority of oxygen-demanding compounds found in wastewater are organic compounds; however, nitrogen in the form of ammonia is an inorganic oxygen-demanding compound. In many instances, it is also of interest to remove phosphorus from wastewater streams to prevent the eutrophication, or accelerated aging, of lakes and other bodies of water because of excess algae or plant growth (Grady et al., 1998). Since the oxygen required for breakdown of the chemical pollutants is the factor of interest in wastewater treatment, several measures of oxygen demand have been defined. The biochemical (or biological) oxygen demand (BOD) is the amount of DO required during the microbial oxidation of organic and inorganic matter in wastewater. The chemical oxygen demand (COD) is a measure of the total organic content of a wastewater stream. The COD is evaluated by reaction with potassium dichromate, and it includes both biodegradable and non-biodegradable contributions. The ratio of BOD/COD is thus the proportion of the organic materials in the waste which are biodegradable (Winkler, 1981).

General Reactor Configurations for Wastewater Treatment. Many configurations for aerobic treatment of wastewater can be found in operation. In aerobic treatment, wastewater is contacted with microorganisms and oxygen in a bioreactor such that the microbes utilize the supplied oxygen in the metabolism of wastewater components (Schultz, 2005). Aerobic systems are particularly efficient and rapid for removing organic material, and they yield products which are chemically simple, including carbon dioxide and water. Anaerobic systems can also be used to treat wastewater, but they are biochemically inefficient and slow and yield by-products which are complex and foul-smelling; however, methane gas is produced during anaerobic processing which can then be reclaimed and used as a fuel (Winkler, 1981).

The most commonly-used biological process configuration for the treatment of both municipal wastewater and industrial wastewater is the activated sludge system (Günder, 2001; Grady et al., 1998; U.S. EPA, 1977; and Winkler, 1981). The activated sludge process involves a suspended-growth aerobic bioreactor which includes a flocculent culture of microorganisms in the bioreactor and a form of biomass, or sludge, recycle (Grady et al., 1998). The goal of the activated sludge process is the reduction of BOD to as great an extent as possible.

In the activated sludge process, the influent wastewater is typically first sent to a primary clarifier, or settling tank, where large debris and smaller insolubles can be removed from the stream as primary sludge. Next, the wastewater is fed to an aerobic bioreactor, or activated sludge tank, where it comes into contact with microorganisms in the reactor and oxygen, which is usually supplied through air sparging. The stream in the bioreactor is referred to as mixed liquor, and the mixed liquor is generally aerated in the bioreactor for several hours. From the bioreactor, the mixed liquor enters a secondary clarifier where the floc of microorganisms, or activated sludge, settles from the remaining clear liquid. Part of the settled activated sludge is recycled to the bioreactor as return activated sludge (RAS), and part is removed from the process as waste activated sludge (WAS). The supernatant from the secondary clarifier is the process effluent. Depending on operational regulations, it may be released directly from the clarifier or undergo further treatment. The WAS must be stabilized before it can be released (Günder, 2001, and U.S. EPA, 1977).

A schematic diagram of the traditional activated sludge process can be found in Figure 14-1.

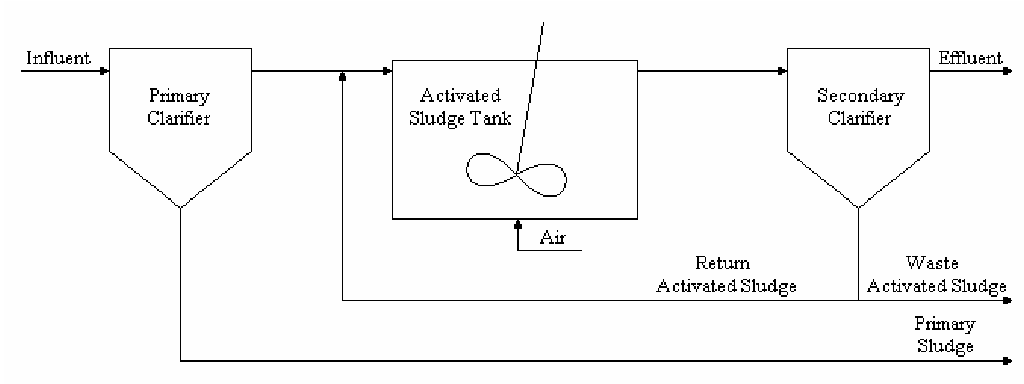

Figure 14-1. Traditional activated sludge process. (Modified from Günder, 2001, and U.S. EPA, 1977.)

The activated sludge process can also be altered to achieve greater removal of nitrogen and phosphorus from wastewater streams. Nitrogen and phosphorus are essential elements for growth, so in microbial metabolism, some nitrogen and phosphorus are incorporated into new biomass. In order to remove significant quantities, however, modifications must be made to the activated sludge treatment process.

Figure 14-2 shows an activated sludge process which has been modified to incorporate nitrification and denitrification for removal of nitrogen. An anaerobic bioreactor has been added in series before the aerobic bioreactor, and the RAS is returned to the anaerobic tank. Additionally, a recycle stream returns mixed liquor from the aerobic to the anaerobic bioreactor. Nitrification, or the oxidation of ammonia to nitrite and nitrate, occurs in the aerobic bioreactor. Denitrification, or the reduction of nitrite and nitrate to nitrogen gas, occurs in the anaerobic bioreactor since for denitrification, the microbes use the nitrite and nitrate as an alternative source of oxygen (Winkler, 1981). The nitrification-denitrification system shown is called a Modified Ludzack-Ettinger (MLE) process.

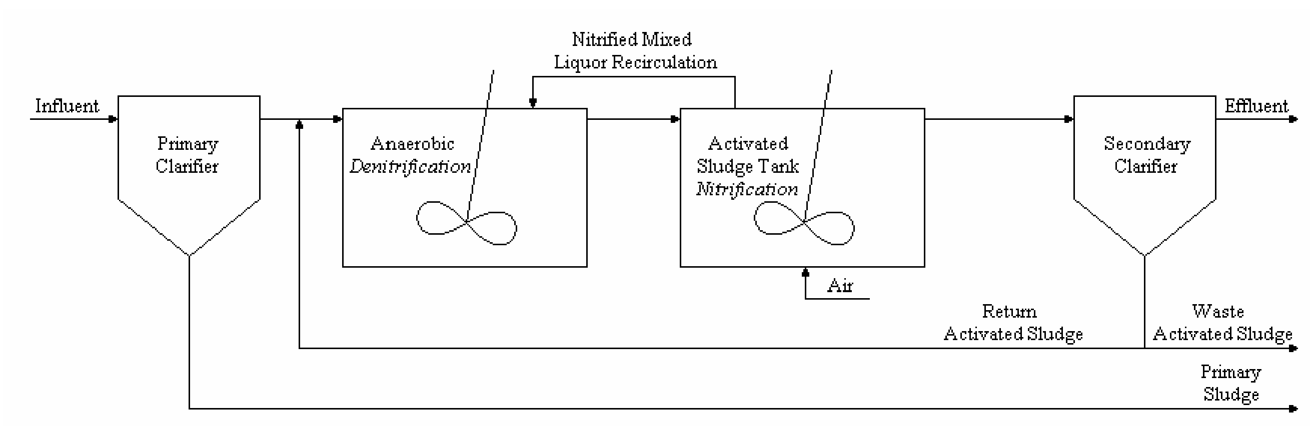

Figure 14-2. Activated sludge process with nitrification-denitrification. (Modified from Winkler, 1981.)

Figure 14-3 illustrates the Bardenpho process, which is a modified activated sludge incorporating both nitrification-denitrification and biological phosphorus removal. In the Bardenpho process, the anoxic and aerobic zones of a nitrification-denitrification scheme are repeated with recycle in only the first pair of reactors. In the development of this scheme, it was determined that phosphorus removal was possible only in an environment free of both oxygen and nitrate, so the completed design includes an additional anaerobic bioreactor before the anoxic-aerobic reactor pairs. Again, the RAS is returned to the first bioreactor in the series (Winkler, 1981).

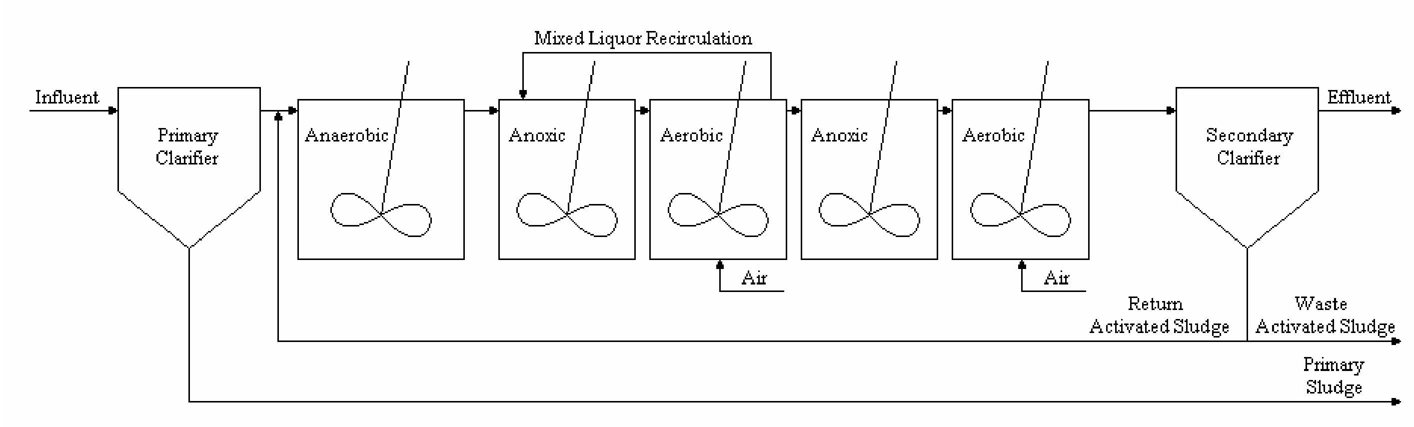

Figure 14-3. Activated sludge process with nitrification-denitrification and biological phosphorus removal. (Modified from Winkler, 1981.)

APPLICATIONS FOR MEMBRANE-COUPLED BIOREACTORS

A recently-developed modification which can be employed to update the activated sludge process is membrane coupling. A membrane-coupled aerobic bioreactor (MBR) combines the aerobic bioreactor of the activated sludge system with an integrated membrane, eliminating the need for a final clarifier (Schultz, 2005). Membrane coupling in the MBR allows for several advantages over the traditional activated sludge system for municipal and also industrial wastewater treatment (Van der Roest et al., 2002, and Cicek, 2002). Microfiltration, ultrafiltration, and reverse osmosis membranes have all been coupled with aerobic bioreactors in the pilot testing of MBRs (Cicek, 2002), but microfiltration and ultrafiltration membranes are the most commonly used in the membrane-coupled activated sludge process (Günder, 2001).

Microfiltration membranes retain larger particle sizes up to bacterial cells and some macrosolutes. Ultrafiltration membranes retain smaller particle sizes as small as cell debris, virus particles, and other solutes. The membranes are called selectively permeable since they retain some solutes while allowing those smaller than their pore sizes to pass through. Representative materials used in micro- and ultrafiltration membranes include cellulose polymers, other organic polymers, and inorganic materials such as glass, metal, and ceramic. The surface structure of the membrane is what determines its permeability. Membranes can be symmetric, with the same pore size throughout the whole membrane, asymmetric, with a smaller pore size at the surface of the membrane, or composite, with a different material applied over the surface of the membrane. Additionally, membranes can be operated in either dead-end or crossflow filtration mode. In dead-end filtration, the direction of flow of the fluid is perpendicular to the surface of the membrane. This results in the formation of a cake on the surface of the membrane and the reduction of permeate flux across the membrane. In dead-end filtration, the membrane needs to be backwashed occasionally to remove the cake and restore permeate flux. In crossflow filtration, the direction of fluid flow is parallel to the surface of the membrane. A cake layer forms on the membrane surface, but because of the shear forces of the suspended material in the fluid, the cake layer is simultaneously formed and stripped away so that the cake thickness and trans-membrane flux remain constant (Günder, 2001).

Micro- and ultrafiltration membranes can be incorporated into the MBR in two different configurations. In the first configuration, the membrane is mounted externally so that the mixed liquor is sent from the bioreactor to the membrane module. From the membrane module, the permeate leaves as the clarified effluent stream, and the retentate is either returned as RAS to the bioreactor or wasted as WAS (Günder, 2001). A schematic diagram of an MBR with an external membrane is shown in Figure 14-4.

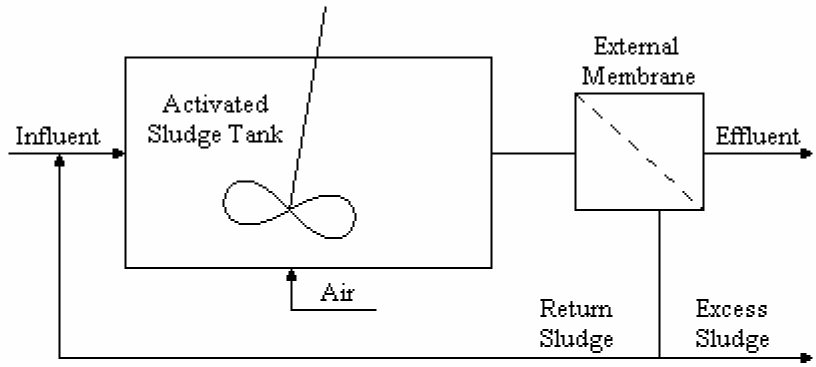

Figure 14-4. Membrane-coupled aerobic bioreactor with an external membrane. (Modified from Günder, 2001.)

In the second MBR configuration, the membrane module is submerged in the bioreactor so that the mixed liquor remains in the bioreactor (Adham and Trussell, 2001). Permeate drawn through the membrane still leaves as clarified effluent, but all of the retentate which is blocked by the membrane remains in the bioreactor as RAS. Waste activated sludge must be removed separately to avoid buildup of sludge in the bioreactor (Günder, 2001). A schematic diagram of an MBR with an internal membrane is shown in Figure 14-5.

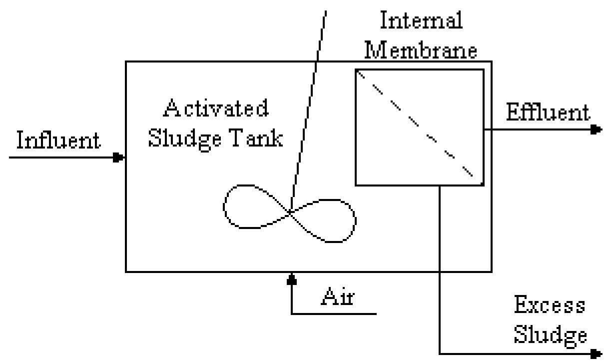

Figure 14-5. Membrane-coupled aerobic bioreactor with an internal membrane. (Modified from Günder, 2001.)

The MBR with the externally-mounted membrane unit can be oriented to operate in either dead-end or crossflow filtration mode. Crossflow operation allows for continuous usage without backwashing and is the optimal design configuration for an external membrane. For the MBR with the internally-mounted membrane unit, the filtration scheme inherent with the design is dead-end; however, crossflow can be produced artificially through ascending air bubbles. To achieve crossflow filtration in the internal MBR, a sparger with an adapted aeration device should be mounted beneath the submerged membrane and operated with a sufficient air flow to effect crossflow (Günder, 2001).

The excess sludge removed from an MBR unit can be treated in the same manner as the waste activated sludge from the traditional activated sludge process (Cicek, 2002, and Van der Roest et al., 2002). It must first be stabilized through either aerobic or anaerobic digestion and then dewatered before it can be released or reclaimed for use in agricultural applications. The supernatant which is removed in the sludge dewatering can be returned to the activated sludge tank (Günder, 2001, and U.S. EPA, 1977).

According to Van der Roest et al. (2002), over 1000 MBRs are in operation throughout the world, and more are planned or under construction. Japan has the highest number with 66 % of the world's MBR applications, and the remaining MBRs are located primarily in North America and Europe. Over half of the MBR systems in place utilize the submerged membrane configuration while the remaining systems have the membrane external to the bioreactor (Van der Roest et al., 2002). Currently, MBRs are used in water recycling for single buildings, municipal wastewater treatment for smaller communities, industrial wastewater treatment, and treatment of landfill leachate. Areas where research on MBR application is being pursued are in treatment of wastewater generated from agricultural and livestock sources and food processing industries; water containing herbicides, pesticides, or endocrine-disrupting substances; and water requiring biological nitrate removal (Cicek, 2002).

Advantages of Membrane-Coupled Bioreactors. Membrane-coupled aerobic bioreactors have several advantages over the conventional activated sludge wastewater treatment process. The effluent quality from an MBR is consistently high because of the membrane's rejection of all suspended particles larger than the pore size (Adham and Trussell, 2001; Cicek, 2002; Günder, 2001; and Van der Roest et al., 2002). The elimination of final clarifiers in an MBR system results in smaller wastewater treatment plant sizes so that plants can operate under limited space allowances (Adham and Trussell, 2001; Cicek, 2002; and Van der Roest et al., 2002). Because the bioreactors themselves remain unchanged between a traditional activated sludge process and an MBR application, the expansion of existing wastewater treatment operations by switching to an MBR is a possibility (Van der Roest et al., 2002). Both organic and inorganic contaminants as well as microorganisms are rejected by the membranes of an MBR, resulting in a sterile effluent which does not require further disinfection (Adham and Trussell, 2001, and Cicek, 2002). This allows for direct water reclamation and reuse. The membrane also retains extracellular enzymes and soluble oxidants which contribute to the degradation capabilities of the mixed liquor. Also, higher molecular weight compounds, which are not readily biodegradable, are retained in the MBR, thus improving the possibility of their oxidation. The elimination of suspended solids leaving in the clarification step results in the complete separation and control of both the solids retention time (SRT) and the hydraulic retention time (HRT). The absence of a clarifier, which selects for flocculating and settling organisms, also enables slower-growing microbes (such as nitrifying bacteria or those capable of degrading complex organic compounds) to remain in the bioreactor. Additionally, high sludge ages can be maintained in the bioreactor since the process is not dependent on the settling in the clarifier; this allows for the treatment of higher strength wastewaters. Finally, the system is robust enough to handle significant fluctuations in nutrient concentrations because of increased microbial acclimation and presence of decaying biomass (Cicek, 2002).

While the MBR has many distinct advantages over the conventional activated sludge process, it has several drawbacks as well. Membrane units can have high capital costs because of the materials of construction and small-scale structuring of the membrane surface (Cicek, 2002). Operational costs of an MBR can also be higher because of the need for crossflow aeration and a pressure gradient across the membrane (Cicek, 2002, and Günder, 2001). Disposal of the WAS may also be problematic in an MBR: because an MBR retains all suspended solids and most soluble matter, WAS may not filter or settle well. Additionally, non-filterable inorganic compounds may also accumulate in an MBR (Cicek, 2002).

MODELING OF A MEMBRANE-COUPLED AEROBIC BIOREACTOR

Gehlert and Hapke (2002) have developed a mathematical black box model which can be used to describe an MBR for the treatment of different types of wastewater. The model considers processes occurring within the MBR system, but it models the MBR as a single functional unit. A simplified diagram of the black box model appears in Figure 14-6. Following is a brief overview of the model.

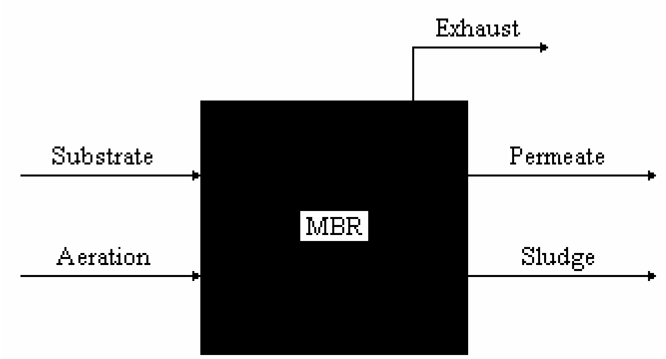

Figure 14-6. Black box model of MBR. (Modified from Gehlert and Hapke, 2002.)

Kinetics. Monod kinetics are assumed for describing the growth of the microorganisms in the bioreactor (Gehlert and Hapke, 2002).

$$\mu = \frac{\mu_{\max} \cdot c_{TOC}}{K_{TOC} + c_{TOC}} \tag{14.1}$$

where μ is the microbial growth rate

$\mu_{\max}$ is the maximum specific growth rate

K_{TOC} is the growth parameter for the Monod model

c_{TOC} is the concentration of total organic carbon in the bioreactor

Material Balances. A material balance is required for each phase and component in the system (Gehlert and Hapke, 2002).

Liquid phase: $$\dot{m}_{l,in} = \dot{m}_P + \dot{m}_{Sl} \tag{14.2}$$

Gas phase: $$\dot{m}_{g,in} = \dot{m}_{g,Ex} \tag{14.3}$$

Oxygen: $$y_{O_2,in} \cdot \dot{m}_{g,in} = y_{O_2,Ex} \cdot \dot{m}_{g,Ex} + \Delta\dot{m}_{O_2,R} \tag{14.4}$$

Carbon: $$x_{TOC,in} \cdot \dot{m}_{l,in} + y_{C.CO_2,in} \cdot \dot{m}_{g,in} = x_{TOC,P} \cdot \dot{m}_P + x_{TOC,Sl} \cdot \dot{m}_{Sl} + y_{C.CO_2,Ex} \cdot \dot{m}_{g,Ex} \tag{14.5}$$

where $\dot{m}$ is a mass flow rate
x is a liquid-phase mass fraction
y is a gas-phase mass fraction

l and g are subscripts referring to the liquid and gas phases

in, P, Sl, and Ex are subscripts referring to influent, permeate, sludge, and exhaust conditions

O_2, $C.CO_2$, and TOC are subscripts referring to oxygen, carbon in CO_2, and total organic carbon

Distribution Coefficients. Constant distribution coefficients are required to calculate output streams and concentrations from influent conditions. The distribution coefficients for the black box model have been derived from experimental data. Distribution coefficients are needed for the liquid phase and for the components oxygen and carbon. These distribution coefficients represent the fraction of the liquid influent stream leaving the system as permeate, the fraction of oxygen in the aeration stream migrating into the liquid phase, and the fraction of all input carbon streams leaving the system as TOC in the permeate, respectively. The input of CO_2 in the aeration stream is not considered because it is assumed inert (Gehlert and Hapke, 2002).

Liquid phase: $$\varepsilon = \frac{\dot{m}_P}{\dot{m}_{l,in}} \qquad (14.6)$$

Oxygen: $$\delta = \frac{\dot{m}_{g,in} \cdot y_{O_2,in} - \dot{m}_{g,Ex} \cdot y_{O_2,Ex}}{\dot{m}_{g,in} \cdot y_{O_2,in}} \qquad (14.7)$$

Carbon: $$\alpha = \frac{\dot{m}_P \cdot x_{TOC,P}}{\dot{m}_{l,in} \cdot x_{TOC,in}} \qquad (14.8)$$

where ε, δ, and α are the distribution coefficients for the liquid phase, oxygen, and carbon, respectively
ε = 0.91
δ = 0.04
α = 0.18

Gehlert and Hapke (2002) compared the results of their mathematical model to experimental MBR wastewater treatment data in order to verify the model. The comparison is shown graphically in Figure 14-7. It can be seen that the model agrees reasonably well with the experimental data. Therefore, this model could be used to approximate MBR wastewater treatment conditions.

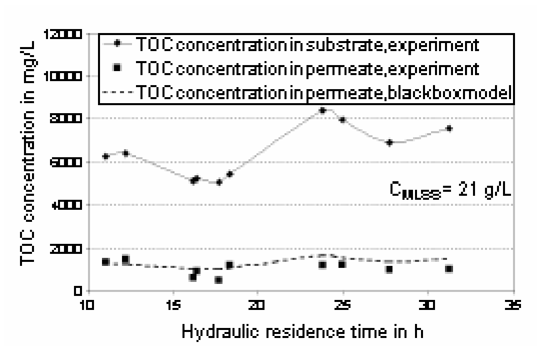

Figure 14-7. Comparison of the black box MBR model with experimental data. (From Gehlert and Hapke, 2002.)

OPERATION OF A MEMBRANE-COUPLED AEROBIC BIOREACTOR

Membrane-coupled aerobic bioreactors can be operated in several different configurations and under various operating conditions. As previously stated, MBRs can have either an external membrane unit or an internal membrane unit. Additionally, many different types of membranes can be used in MBR applications, including tubular, plate and frame, rotary disk, hollow fiber, organic polymer, metallic, and ceramic micro- and ultrafiltration membranes (Cicek, 2002). Commercially available membranes are available in flat-plate, hollow fiber, fiber cartridge, tubular, and porous hollow fiber arrangements (Van der Roest et al., 2002).

Effects of Varying Operating Conditions. Operating parameters which influence the filtration capacity of the membrane, and hence the efficiency of the MBR, are trans-membrane pressure (TMP), crossflow velocity, mixed liquor viscosity (and, consequently, mixed liquor temperature), and microbial community structure. The community structure influences flocculation, charge and structure of cells, and concentration of exo-polymeric substances (EPS). It has been shown that EPS directly affect extent of flocculation (Cicek, 2002).

Cicek (2002) reports that for the treatment of industrial wastewater and sewage using an MBR, COD removal rates greater than 90 % are obtained while high SRTs and concentrations of biomass are maintained in the bioreactor. For MBR treatment of a wastewater stream from an automobile manufacturing facility containing high amounts of oil, grease, and synthetic metalworking fluids, an average of 94 % COD removal and significant reductions of oil and grease are accomplished. In treatment of another wastewater stream from a metal transformation mill using an MBR, biological toxicity of the effluent is decreased tenfold and overall quantity of hazardous wastes is decreased threefold. Another study reveals up to 99.99 % removal rates for MBR treatment of synthetic wastewater streams with fuel, lubricating oils, and surfactants (Cicek, 2002).

In a study performed by Cornelissen et al. (2002) involving treatment of brewery wastewater using an internal MBR, influent COD was varied between 1 500 and 3 500 mg/l. Effluent from the MBR was consistently reported at a concentration of approximately 30 mg/l regardless of fluctuations in influent COD concentration. They also reported, however, that increasing sludge concentrations in the MBR significantly decreased the oxygen transfer coefficient, greatly affecting the aeration characteristics of the system.

Van der Roest et al. (2002) reported that the most significant contributor to correct performance of membrane-coupled systems for municipal wastewater treatment was pre-treatment of the wastewater influent stream. They noted that lack of appropriate pre-treatment resulted in macro fouling of the membrane by abrasive components, fat, and hair. Screening of influent wastewater prevented fouling of the MBR membrane.

Adham and Trussell (2001) conducted tests using two MBR systems and examined effects of varying SRT, HRT, and mixed liquor suspended solids (MLSS). They found that higher SRTs in the MBR yielded higher concentrations of MLSS. They also observed higher MLSS concentrations at lower HRTs in the MBR. In a second study, they noted a direct decrease in MLSS with both SRT and HRT. For average values of HRT (4 h), SRT (15 d), and target MLSS (10 000 mg/l), Adham and Trussell (2001) observed the effluent quality results presented in Table 14-1.

Table 14-1. Municipal wastewater effluent quality results for two MBR processes (median values). (Modified from Adham and Trussell, 2001.)

Analyte	Units	Influent	MBR #1 Effluent	MBR #2 Effluent
Ammonia	mg N/l	24.9	0.13	0.14
BOD_5	mg/l	117	<3	<3
Bromide	mg/l	0.42	0.33	0.35
Chloride	mg/l	218	218	216
Nitrate	mg N/l	<0.02	23.4	22.3
Nitrite	mg N/l	0.02	0.07	0.11
o-Phosphate	mg P/l	3.16	2.74	2.82
Total Phosphorus	mg/l	4.45	2.81	2.76
Sulfate	mg/l	242	251	249
TKN	mg N/l	37.9	1.0	1.0

Van der Roest et al. (2002) performed studies on both full-scale and pilot-plant scale MBR applications in municipal wastewater treatment. Their research in each case was divided into four phases, and these phases differed in the nature of influent pre-treatment to the MBR. Phase one utilized influent after primary sedimentation and pre-precipitation; phase two utilized influent after primary sedimentation and simultaneous precipitation; phase three utilized raw wastewater with simultaneous precipitation; and phase four utilized raw wastewater and an anoxic tank for biological phosphorous removal. The full-scale MBR wastewater treatment operation was tested at the Dutch Beverwijk-Zaanstreek wastewater treatment plant, and the pilot plant studies were conducted using four different commercially available membranes. Process conditions and influent and effluent qualities for the full-scale MBR plant are shown in Table 14-2, and samples of conventional wastewater treatment plant effluent and the MBR plant effluent are shown in Figure 14-8.

Table 14-2. Full-scale municipal wastewater treatment process conditions and influent and effluent concentrations at Beverwijk-Zaanstreek, Netherlands (average values). (Modified from Van der Roest et al., 2002.)

Parameter	Units	Phase 1	Phase 2	Phase 3	Phase 4
Influent Flow	m^3/d	42 300	80 800	52 900	50 700
Process Temperature	°C	21	16	16	21
pH	-	7.3	7.3	7.3	7.3
Biological Loading	kg COD/(kg MLSS·d)	0.12	0.15	0.15	0.12
Sludge Concentration	kg MLSS/m^3	3.7	4.5	4.6	4.1
Organic Part	%	65	63	65	65
Sludge Production	kg MLSS/d	6 150	4 620	5 010	6 780
Sludge Age	d	19	31	29	19
Influent COD	mg/l	386	317	416	402
Effluent COD	mg/l	46	52	48	50
COD Removal Efficiency	%	88	84	88	88
Influent N_{kj}	mg/l	62	41	58	63
Effluent N_{kj}	mg/l	6.5	9.2	7.1	9.1
Effluent NO_3-N	mg/l	8.6	5.6	7.2	5.7
Effluent N_{total}	mg/l	15.2	14.8	14.0	14.8
N Removal Efficiency	%	75	64	76	77
Influent P_{total}	mg/l	9.1	7.6	6.9	7.1
Effluent P_{total}	mg/l	1.3	1.8	1.6	1.4
P Removal Efficiency	%	85	76	77	80

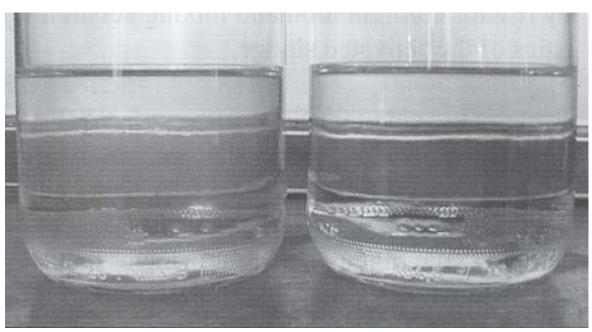

Figure 14-8. Comparison of conventional wastewater treatment plant effluent and MBR wastewater treatment plant effluent at Beverwijk-Zaanstreek, Netherlands. (From Van der Roest et al., 2002.)

Process conditions and influent and effluent qualities for one of the pilot plant studies are shown in Table 14-3 (Van der Roest et al., 2002).

Table 14-3. Representative pilot plant municipal wastewater treatment process conditions and influent and effluent concentrations (average values). (Modified from Van der Roest et al., 2002.)

Parameter	Units	Phase 1	Phase 2	Phase 3	Phase 4
Influent Flow	m^3/d	48	72	51	51
Process Temperature	°C	21	13	12	19
pH	-	7.4	7.4	7.3	7.4
Biological Loading	kg COD/(kg MLSS·d)	0.054	0.060	0.084	0.100
Sludge Concentration	kg MLSS/m^3	10.5	12.0	10.6	10.8
Organic Part	%	59	61	63	63
Sludge Production	kg MLSS/d	4.6	9.0	13.5	10.3
Sludge Age	d	70	41	27	30
Influent COD	mg/l	341	297	568	621
Effluent COD	mg/l	32	21	31	32
COD Removal Efficiency	%	91	93	95	95
Influent N_{kj}	mg/l	61	40	61	58
Effluent N_{kj}	mg/l	2.7	1.5	1.6	3.0
Effluent NO_3-N	mg/l	8.6	7.1	8.0	7.9
Effluent N_{total}	mg/l	11.3	8.6	9.6	10.8
N Removal Efficiency	%	81	79	84	81
Influent P_{total}	mg/l	7.4	8.3	10.1	10.9
Effluent P_{total}	mg/l	2.8	1.3	1.3	0.8
P Removal Efficiency	%	62	84	88	93

Microbial Diversity. The microbial population of activated sludge is an ecological system composed of many different organisms. The microbes present depend on the nutrient composition of the wastewater being treated, and the balance between different microorganisms varies with their individual growth phases. Additionally, the activated sludge microbial population may vary with seasonal fluctuations. The microbial composition adapts itself to available nutrients, and this adaptation in conventional activated sludge systems is a slow process—on the order of the SRT. A wide variety of bacteria contribute to the formation of flocs, and protozoa are also present in significant numbers (Winkler, 1981).

Saikaly et al. (2005) utilized diversity indices to assess the effect that SRT had on bacterial diversity in laboratory-scale activated sludge bioreactors. They found that for a range of SRTs the competition between bacterial species for nutrients allowed for coexistence of multiple species. They suggested that the process of bacterial competition for essential resources was responsible for the dynamic nature of the bacterial community. In comparing several SRTs, Saikaly et al. found that bioreactors operated at shorter SRTs had a higher diversity than those operated at longer SRTs.

The microbial population of a membrane-coupled activated sludge process has been found to differ greatly from that of a conventional activated sludge process. Floc-forming microorganisms, which are selected for in the clarifier of the conventional system, are no longer favored in the MBR process (Cornelissen et al., 2002, and Günder, 2001). Instead, filamentous organisms may have growth advantages as compared to flocculating organisms in an MBR system. Their higher surface area-to-volume ratio is advantageous for substrate uptake since the organisms are dispersed throughout the MBR. These filamentous organisms change the viscosity and flow characteristics of the sludge. Additionally, only small numbers of protozoa have been observed in MBR activated sludge processes (Günder, 2001).

CONCLUSIONS

The traditional activated sludge process is an effective biological method for the treatment of municipal and industrial wastewater. Membrane coupling can be employed with the aerobic bioreactor of the activated sludge process, however, in order to improve upon the conventional system. The resultant membrane-coupled aerobic bioreactor (MBR) eliminates the need for a secondary clarifier in the wastewater treatment process. This allows for smaller wastewater treatment plant areas, and the action of the selectively-permeable membranes can significantly increase the effluent quality by removing small suspended particles. Membrane-coupled aerobic bioreactors are normally arranged in one of two configurations, and several different membrane options exist as well. Application of an MBR instead of a more traditional wastewater treatment system can allow for direct reclamation of effluent water and long SRTs in the bioreactor itself. A suitable mathematical model for and MBR has been developed and tested against experimental data, taking into account the kinetics, material balances, and distribution coefficients in the MBR. Additionally, studies have been conducted which investigate the effects of changing operating parameters on the MBR itself and on the microbial community in the bioreactor. Membrane-coupled aerobic bioreactors are emerging as a promising new alternative to the conventional activated sludge process for wastewater treatment.

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