Mathematical Modeling of Hollow-fiber Membrane System in Biological Wastewater Treatment

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ABSTRACT

A set of mathematical models were derived based on the bio-kinetics and material balance principles to describe the performance of membrane system in this research. A synthetic wastewater and a meat packing wastewater were processed through a lab-scale membrane bioreactor system to generate experimental data for calibration and verification of the derived models. For the synthetic wastewater treatment, a high and stable Total Organic Carbon (TOC) removal was achieved with volumetric organic loading from 0.2 to 24.2 kg TOC/m^3d). It was found that the derived system models fit the experimental data well. The bio-kinetic coefficients of k, K_s, Y and k_d in the models were found to be 0.16 d^{-1}, 1.0 mg/L, 1.75 mg Mixed Liquor Volatile Suspended Solids (MLVSS)/mg TOC and 0.11 d^{-1}, respectively. For the meat packing wastewater treatment, the bio-kinetic coefficients of k, K_s, Y and k_d were found to be 0.48 d^{-1}, 56.3 mg/L, 0.53 mg MLVSS/mg COD and 0.04 d^{-1}, respectively. F/M ratio of 0.08 was found to be the proper operating condition for the system. Based on the proposed system models, the optimum MLSS concentration and F/M ratio can be computed to yield minimum cost of a membrane bioreactor system without excess biomass production.

Keywords: submerged membrane bioreactor, system modeling, wastewater treatment.

1. INTRODUCTION

Biological treatment has been a conventional method for treating biodegradable wastewater since the nineteenth century. The activated sludge process is one of the most common aerobic biological wastewater treatment methods. However, in recent years the combination of membranes with the activated sludge process has redefined basic sewage treatment, allowing optimization of the biological treatment operation and yielding a treated effluent that is suitable for reuse.

The primary role of a membrane is to act as a selective barrier. It permits passage of certain components and retains some other components found in the liquid [1]. Since solids are totally retained by membrane separation, membrane bioreactor (MBR) for wastewater treatment offers several advantages over the conventional processes, including high quality of final effluent, small size of treatment plant, low sludge production rate and more reliable process performance.

In order to design a submerged MBR system, flux prediction equation, which describes the relationships of the operating parameters, fluid characteristics and membrane properties to the flux, is required [2]. However, the permeate flux of a submerged MBR system is usually unstable and difficult to predict due to the complexity of the system and the membrane fouling that decreases the membrane flux. Eq. (1) represents the simplest resistance-in-series model based on Darcy's law to predict the flux [3], where J is permeate flux; ΔP is trans-membrane pressure; μ is viscosity of the permeate; R_m is intrinsic membrane resistance; R_c is external fouling resistance formed by cake layer, and R_f is internal resistance due to materials absorbed into the pores.

$$J = \frac{\Delta P}{\mu(R_m + R_c + R_f)} \tag{1}$$

The primary goal of this research was to systematically model the performance of a submerged MBR system that does not produce excess sludge waste. A lab-scale membrane bioreactor was designed and built. The MBR system was operated under different organic substrate to biomass ratios (F/M) to observe the effects upon biomass growth and substrate utilization rate. An empirical relationship between biomass concentration and permeate flux was determined by analyzing the observed variations of permeate flux in response to different MLSS concentrations. Based on the biomass coefficients and the relationships determined in the experiment, a method was developed to find the proper operating parameters leading to minimum capital cost of the membrane bioreactor system.

Sludge retention time (SRT) was not considered in this study. Instead, the system was designed to produce no excess sludge during the operation. The advantage of designing a submerged MBR system without excess sludge production is that the settling facility is not required. It saves the capital costs for sludge settling and treatment facilities. This savings would be very useful in hotels and small communities. Furthermore, a system without excess sludge production can prolong the sludge retention time so that slow growing nitrifying bacteria can develop in the bioreactor, which enhances the nitrification process in the system.

2. MODEL DEVELOPMENT

A schematic representation of the system is shown in Figure 1. Several key operating parameters such as organic loading, biomass concentration and permeate flux were varied during the experiment so that their influences on the system performance can be observed. The other operating parameters such as trans-membrane pressure, operating temperature and cycle time were maintained relatively constant to avoid any unnecessary complexity.

In order to determine biomass coefficients, the typical procedure is to operate the units over a range of volumetric organic loading. Thus in this experiment, the membrane system was operated under different F/M levels and the corresponding biomass growth rate and substrate utilization rate in the submerged membrane bioreactor were observed.

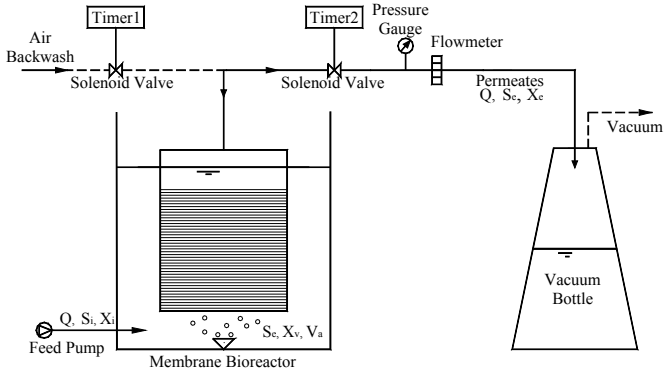

Figure 1. Schematic diagram of submerged MBR system

Material balance of substrate in bioreactor

The working volume of the bioreactor was maintained constant during the experiment. The membrane bioreactor is assumed to be under completely mixed condition. Using data collected at steady-state conditions (Q, S_i, S_e and V_a) and applying material balance principle for the substrate around the bioreactor leads to:

$$r_{su} = \frac{Q(S_i - S_e)}{V_a} \tag{2}$$

Where: V_a = volume of the reactor (L); Q = flow rate (L/d); S_i = influent COD or TOC (mg/L); S_e = effluent COD or TOC (mg/L); r_{su} = rate of substrate utilization (mg/L/d).

The substrate utilization rate in biological systems is assumed to follow Michaelis-Menten equation for the specific growth rate of bacteria in which the limiting substrate is available to the microorganisms in a dissolved form [4]:

$$r_{su} = \frac{kS_e X_{avg}}{K_s + S_e} \tag{3}$$

Where: X_{avg} = average MLVSS concentration (mg/L); k = maximum specific substrate utilization rate (d^{-1}); K_s = half-velocity constant (mg/L).

Combining Eq. (2) and Michaelis-Menten equation given in Eq. (3) leads to:

$$S_e = \left[\frac{X_{avg} S_e}{r_{su}}\right] \cdot k - K_s \tag{4}$$

The values of k and K_s can be determined by plotting the term S_e versus $X_{avg}*S_e/r_{su}$. If Michaelis-Menten equation applies to the substrate utilization rate in the membrane bioreactor systems, then a linear relationship between $X_{avg}*S_e/r_{su}$ and S_e will be observed as shown in Eq. (4).

Material balance of biomass in bioreactor

The biomass concentration in this study is measured as MLSS and MLVSS. However, it should be noted that the VSS measurement includes other particulate organic matter in addition to biomass such as nonbiodegradable volatile suspended solids and inert inorganic total suspended solids. Therefore, the measurement of MLSS and MLVSS concentration may still contain non-viable and inactive biomass in the bioreactor.

Since there is no biomass concentration in the influent and effluent, performing a material balance of biomass around the bioreactor results in the following expression:

$$r_g = \frac{dX_v}{dt} \tag{5}$$

Where: r_g = net biomass production rate (mg/L/d).

Biomass growth rate can be expressed by the following relationship between the rate of growth and the rate of substrate utilization that is applicable in both batch and continuous culture systems [4]:

$$r_g = Yr_{su} - k_d X_{avg} \tag{6}$$

Where: k_d = endogenous decay coefficient (d^{-1}); Y = biomass yield coefficient (mg/mg).

It is assumed that the change of $k_d X_{avg}$ with time is negligible due to its relatively small value which is normally less than 10 mg/L/d. The value of Yr_{su} is usually higher than 300 mg/L/d and is assumed to be constant with time by using data collected at steady-state conditions (Q, S_i, S_e and V_a). Therefore, substituting Eq. (6) into Eq. (5), and integrating on both sides of the equation leads to:

$$\int_{t_1}^{t_2} (Yr_{su} - k_d X_{avg}) dt = \int_{X_1}^{X_2} dX_v \tag{7}$$

Where: t_1 = the time when samples are collected and analyzed for system performance; t_2 = the next time when samples are analyzed again following t_1; X_{avg}= average MLVSS concentration from t_1 to t_2 (mg/L); X_1 = MLVSS concentration at time t_1 (mg/L); X_2 = MLVSS concentration at time t_2 (mg/L).

Substituting Eq. (2) into Eq. (7) yields:

$$YQ(S_i - S_e) - k_d X_{avg} V_a = \frac{V_a (X_2 - X_1)}{t_2 - t_1} \tag{8}$$

Since samples were taken once every day and the time interval between samplings was one day in the experiment, simplifying Eq. (8) leads to:

$$\frac{\Delta X_v}{X_{avg} V_a} = Y(F/M) - k_d \tag{9}$$

Where ΔX_v = daily excess MLVSS (g/d); F/M = food to biomass ratio (mg TOC or COD/mg MLVSS·d). $\Delta X_v/(X_{avg}V_a)$ in Eq. (9) is also expected to be linear with F/M.

There is no sludge wasting in the continuous operation because the system is expected to produce no excess sludge, Eq. (9) then reduces to:

$$(F/M) = \frac{k_d}{Y} \tag{10}$$

Therefore, F/M = k_d/Y is the operating condition of the membrane bioreactor system that does not produce excess sludge.

Calculation of the operating parameters

It is assumed that permeate flux of the membrane is a function of the MLSS concentration as shown in Eq. (11), and the major capital cost of a membrane bioreactor system is proportional to the volume of the reactor and the total area of the membrane surface as shown in Eq. (12):

$$J = f(X) \tag{11}$$

$$C = P_m A + P_v V_a \tag{12}$$

Where: C is the major cost of an MBR system ($); P_m is the cost of membrane per square meter of membrane surface area ($/m^2); P_v is the cost of the reactor per cubic meter of reactor volume ($/m^3); A is the total membrane surface area that is

needed in the system (m^2); X is the operating MLSS concentration in the bioreactor (mg/L).

The membrane surface area needed in the system is expressed as:

$$A = \frac{Q}{J} \tag{13}$$

For zero excess sludge production rate based on Eq. (9), the volume of the reactor can be found as:

$$V_a = \frac{YQ(S_i - S_e)}{k_d bX} \tag{14}$$

Where b is the MLVSS/MLSS ratio.

To calculate the cost of the system, substituting Eq. (13) and Eq. (14) into Eq. (12) yields:

$$C = P_m \frac{Q}{f(X)} + P_v \frac{YQ(S_i - S_e)}{k_d bX} \tag{15}$$

Q, S_i, and S_e are the desired operating condition of the system. Biomass coefficients k_d, Y and b can vary as a function of the wastewater source, microbial population and temperature, and can be determined in the preliminary bench-scale experiment. Then C is a function of MLSS concentration. The minimum capital cost of a MBR system can be found by equating the derivative of Eq. (15) to zero:

$$\frac{dC}{dX} = \frac{P_m Q}{f'(X)} - \frac{P_v YQ(S_i - S_e)}{k_d bX^2} = 0 \tag{16}$$

By solving Eq. (16), an operating MLSS concentration that results in minimum capital cost based on zero excess sludge production can be determined.

3. EXPERIMENTAL METHODS

In this work, a lab-scale membrane bioreactor was designed and built. A hollow-fibre membrane module (Mitsubishi Rayon UMF00224LI) was submerged into the bioreactor. The pore size of the membrane was 0.1μm. The membrane surface area was 0.2 m^2. The upper limit MLSS concentration for this membrane unit was 12000 mg/L [5]. The experiment was conducted at 20°C.

As shown in Figure 1, the membrane was connected to a vacuum bottle for filtration and an air regulator for air backwash. The vacuum bottle was connected to the university's building supply to create vacuum pressure. The vacuum pressure was maintained as a constant by a vacuum pressure gauge on the filtration line. One solenoid valve was placed on the filtration line, and one was on the air backwash line. These two solenoid valves were then connected to two timers to regulate the intermittent filtration and air backwash in such a way that while one solenoid valve was open for filtration and the other one was closed to stop air backwash, or one solenoid valve was open for air backwash and the other one was closed to stop filtration. Therefore, by using these two solenoid valves and time arrangements, intermittent filtration and air backwash could be operated in the experiment.

The time interval for each cycle of filtration and air backwash was 15 minutes, with 13 minutes of filtration and 2 minutes of air backwash as recommended by Mitsubishi Rayon [5]. Using this operation mode, the effluent could be filtered from the membrane through the solenoid valve to the vacuum bottle intermittently (13 minutes of filtration and 2 minutes of idle). A flow meter was also placed on the filtration line to record the effluent flow rate of the system. A feed pump supplied the influent to the bioreactor continuously. The influent flow rate was regulated, by adjusting the feed pump manually, to be 15% lower than the effluent flow rate. Therefore, the working volume of the bioreactor could be maintained at a constant value.

The bioreactor was made of a glass cylinder with 29 cm of inner diameter and 60 cm of height. The air backwash pressure was maintained at 150 kPa by the air regulator to reduce the filtration resistance during each cycle (2 minutes of air backwash and 13 minutes of idle). In order to avoid considerable membrane flux decrease, the trans-membrane pressure was maintained at around 20 kPa by the pressure gauge. One air diffuser was placed on the bottom of the reactor to provide oxygen and turbulence around the membrane surfaces. Due to the difficulties of measuring the air flow rate, the aeration rate of the air diffuser was regulated by monitoring a Dissolve Oxygen (DO) probe (YSI 5905) to maintain a dissolved oxygen around 2 mg/L in the bioreactor.

Treatment of synthetic wastewater

During the first 45 days, synthetic wastewater was treated in the membrane bioreactor system. The working volume of the bioreactor was maintained at 17 litres with 30 cm of water depth. The composition of the concentrate of synthetic wastewater is shown in Table 1. The concentrate was stored in the refrigerator and diluted with tap water for the desired concentration in the experiment. The bioreactor was seeded with biomass taken from the Saskatoon Wastewater Treatment Plant. After 5 days of batch tests, the submerged MBR was switched to continuous mode with the initial MLVSS concentration at 3000 mg/L.

Table 1. Composition of synthetic substrate

Components	Concentration (g/L)
Glucose	60
Peptone	60
Yeast Extract	6
K_2HPO_4	6.3
$(NH4)_2SO_4$	24
$MgSO_4 \cdot 7H_2O$	12
$MnSO_4 \cdot H_2O$	1.4
$FeCl_3 \cdot 6H_2O$	0.06
$CaCl_2 \cdot 2H_2O$	1.2

Three samples of influent, effluent and biomass were taken at 9:30 am every morning. Total Organic Carbon (TOC) was measured for influent and effluent samples as the substrate concentration by a TOC analyzer (Tekmar Dohrmann Phoenix-8000). Samples of biomass taken from the bioreactor were analyzed by the gravimetric tests of MLSS and MLVSS according to Standard Methods 2540D and 2540E [6].

As the system began to treat the synthetic wastewater, parameters such as MLSS, MLVSS, TOC, influent and effluent flow rate were monitored and analyzed on a daily basis. In order to determine the biomass coefficients, the system was operated

under different F/M levels by adjusting the organic strength of the synthetic influent.

Treatment of meat packing wastewater

After completing the synthetic wastewater treatment experiment, the system was used to process a wastewater from a local meat packing factory. One hundred and eighty litres of wastewater were taken from this factory to the laboratory once a week. The wastewater was stored in a refrigerator at 2°C for sedimentation. Every morning at 9:30 am, the supernatant of wastewater was transferred to a reservoir for influent supply. The typical COD and BOD values of the meat packing wastewater were 850 and 630 mg/L, respectively.

Three samples of influent, effluent and biomass were taken at 9:30 am every morning. Samples of influent and effluent were measured by COD according to Standard Methods 5220C [6]. Samples of biomass were analyzed by the gravimetric tests of Standard Methods 2540D and 2540E [6]. All equipment was cleaned before starting the meat packing wastewater treatment. Again the bioreactor was seeded with biomass taken from the Saskatoon Wastewater Treatment Plant with an initial MLVSS concentration of 1800 mg/L.

As the biomass grew in the bioreactor fed with meat packing wastewater, the MLVSS concentration in the bioreactor increased. This experiment involved 3 phases during 110 days of experiment. Phase 1 lasted 69 days. In this phase, biomass growth rate and substrate utilization rate were observed as the MLVSS concentration increased in the bioreactor. Phase 2 lasted 27 days. In phase 2, both MLVSS concentration and F/M ratio reached steady state when the system was operated under endogenous respiration condition.

Phase 3 lasted 14 days. In phase 3, to further test the operating condition of MBR at different ranges of biomass concentrations, the concentration of MLVSS was first reduced to 8000 mg/L by manual dilution. The influent of wastewater was also diluted manually to reach the same level of F/M as obtained in phase 2. Then the system was operated for 7 days to observe the change of MLVSS concentration. After that, MLVSS concentration was then reduced from 8000 mg/L to 5000 mg/L. The influent of wastewater was diluted manually to reach the same level of F/M.

4. RESULTS AND DISCUSSION

Treatment of synthetic wastewater

The performance of the system is shown in Figure 2. The influent TOC was decreased from 800 to 100 mg/L for system stabilization at the beginning and then was increased from 100 to 950 mg/L, while the effluent TOC during the operation was always below 20 mg/L. The TOC removal efficiency was higher than 96%. The concentration of MLSS increased from 3000 to 12000 mg/L in the bioreactor. The trans-membrane pressure was maintained at the range of 18±2 kPa and no significant increase of pressure was observed in the experiment, which indicates the intermittent filtration and air backwash were effective in preventing membranes from fouling.

After the system was stabilized, it was operated under different F/M levels to determine the biomass kinetic coefficients. k and K_s can be determined by fitting Eq. (4) to the experimental data as shown in Figure 3. A linear relationship was found between S_e and $X_{avg}*S_e/r_{su}$, proving that Eq. (3) is satisfactory for describing substrate utilization rate. The values of k and K_s were found to be 0.16 d^{-1} and 1.0 mg/L, respectively.

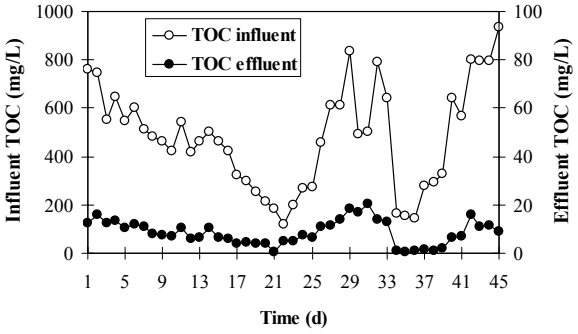

Figure 2. Synthetic wastewater treatment

Y and k_d can be determined using Eq. (9), by plotting specific net growth rate versus F/M ratio as shown in Figure 4. The values of Y and k_d were found to be 1.75 mg MLVSS/mg TOC and 0.11 d^{-1}, respectively.

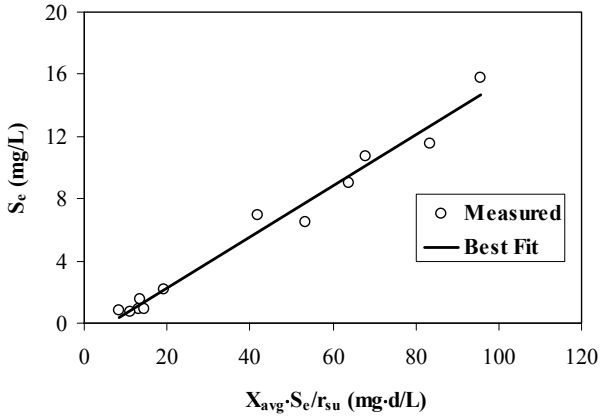

Figure 3. Substrate utilization for synthetic wastewater

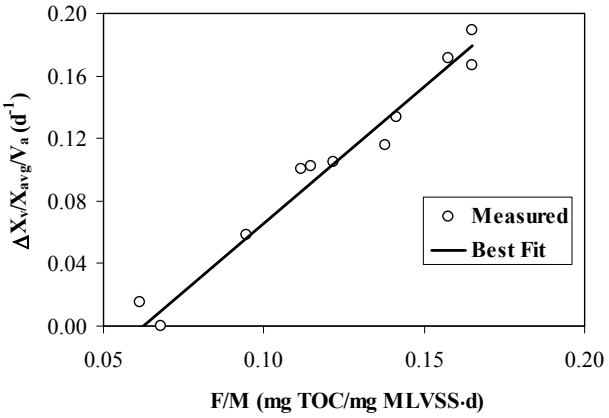

Figure 4. Biomass growth for synthetic wastewater treatment

Treatment of meat packing wastewater

The performance of the system for meat packing wastewater treatment is shown in Figure 5. MLVSS/MLSS ratio was 0.8 during 110 days of experiment. Substrate was measured in COD in this experiment. The influent COD ranged from 800 to 1200

mg/L during experiment. The COD removal efficiency of the system was higher than 97%, which is similar to the results obtained by Suwa [7] from using a MBR system to treat food processing wastewater.

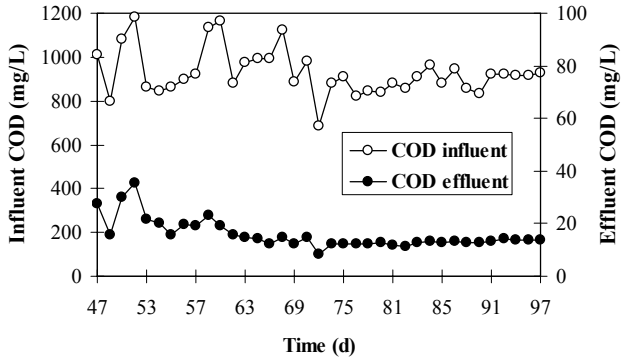

Figure 5. Meat packing wastewater treatment

Biomass coefficients were determined by using the same method as described in the synthetic wastewater treatment. The values of k, K_s, Y and k_d were found to be 0.48 d^{-1}, 56.3 mg/L, 0.53 mg MLVSS/mg COD and 0.04 d^{-1} respectively as shown in Figures 6 and 7.

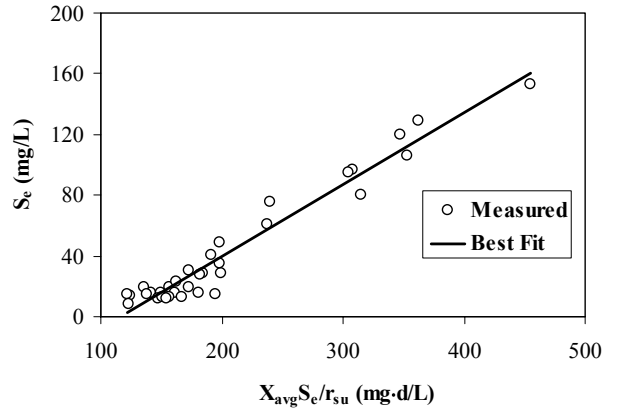

Figure 6. Substrate utilization for meat packing wastewater

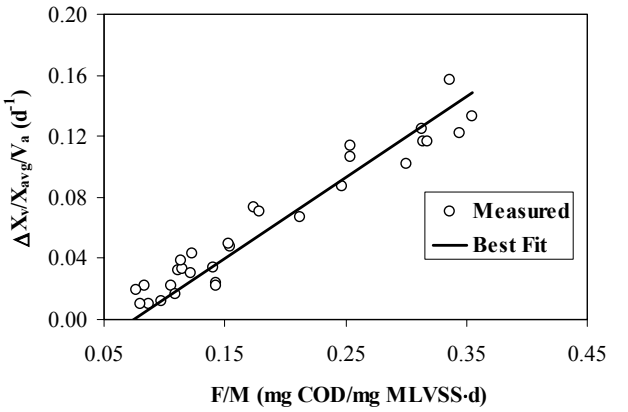

Figure 7. Biomass growth for meat packing wastewater

The results of k, K_s, Y and k_d are close to the typical values published by Tchobanoglous et al. [4] for domestic wastewater as shown in Table 2. This indicates the biomass activities and performance in a MBR system are similar to the conventional activated sludge system. However, the maximum specific substrate utilization rate (k) in this study is much lower than the typical value. This is probably due to the difference of water source, high operating biomass concentration and long sludge retention time of the system since these kinetic coefficients can vary as a function of the wastewater source, microbial population, and temperature.

Table 2. Comparison of biomass coefficients to typical results

Wastewater type	Domestic wastewater	Meat packing wastewater
k (d^{-1})	5	0.48
K_s (mg/L)	40	56.3
Y (mg MLVSS/mg COD)	0.4	0.53
k_d (d^{-1})	0.1	0.04
References	[4]	This experiment

According to the resistance model shown in Eq. (1), R_c is the external resistance resulted from the concentration polarization and the boundary layer along the membrane surface. It is related to the concentration of suspended solids in the bioreactor. Therefore, MLSS concentration in the bioreactor has a direct impact on the permeate flux of the system. Figure 8 shows the exponential relationship between MLSS concentration and permeate flux. The exponent shown in Eq. (17) was found to be –0.49, which was very close to the reported value of –0.50 by Shimizu [2]. However, a discrepancy between the experimental results and the exponential relationship was found in a region of high MLSS in the study by Shimizu [2]. But in this experiment, all results were consistent with the exponential relationship in Eq. (17). This is probably due to the frequent cleaning effect of air backwash during the operation.

$$J = J_i \cdot X^{-0.49} \tag{17}$$

Where J is the flux of permeates and J_i is the initial flux based on the properties of the membrane and the turbulence created by aeration around the membrane surface.

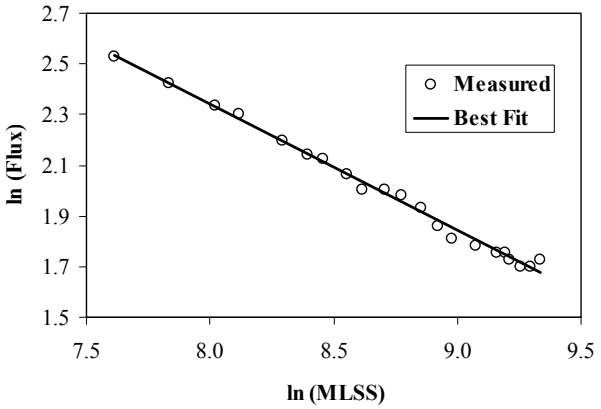

Figure 8. Flux vs. MLSS for meat packing wastewater

It is found that F/M of 0.08 is the operating condition for the system without excess sludge production, by substituting the biomass coefficients into Eq. (10). Figure 9 shows the change of MLVSS and F/M during the operation from Day 55 to 110 after the biomass was adapted to the new environment. As MLVSS

concentration increased to 10000 mg/L in the bioreactor, the operating F/M ratio decreased to 0.08 as shown in Figure 9. Then both the MLVSS concentration and F/M ratio stabilized to constant levels, which indicates that the biomass growth rate equalled the decay rate and the system was under the endogenous respiration condition. The experimental results shown in Figure 9 prove that Eq. (10) can predict operating condition for a submerged membrane bioreactor system without excess sludge production sludge.

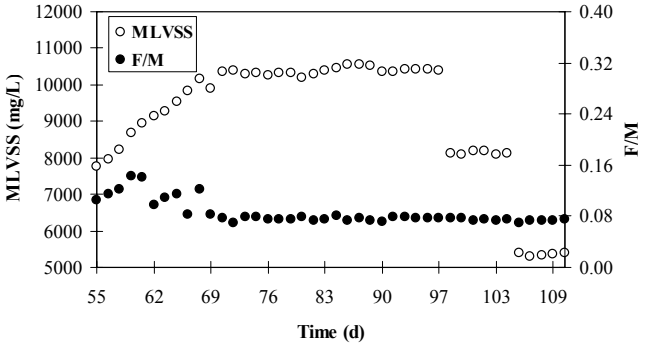

Figure 9. MLVSS concentration and F/M ratio for meat packing wastewater treatment

To further test the effectiveness of Eq. (10) under different biomass concentrations, the concentration of MLVSS was decreased to 8000 mg/L and 5300 mg/L respectively. The influent of wastewater was diluted to reach the same F/M value of 0.08. As shown in Figure 9, MLVSS concentration again approached to a constant level, indicating that Eq. (10) is valid in predicting the system operating condition with MLVSS concentration ranging from 5000 to 10000 mg/L.

Application example

This application example is to show a method of a membrane bioreactor system for this local food processing factory, since all the required parameters have already been obtained in the experiment as listed below:

S_i = 1200 mg/L, S_e = 20 mg/L, J_i = 13.5 $m^3/m^2/d$, k = 0.48 d^{-1}, K_s = 56.3mg/L, Y = 0.53 mg MLVSS/mg COD and k_d = 0.04d^{-1}.

Assuming the ratio of MLVSS/MLSS (b) is fixed and equal to 0.8, substituting Eq. (17) and the determined biomass coefficients into Eq. (16) yields:

$$X = \left[\frac{34 P_v J_i (S_i - S_e)}{P_m} \right]^{0.67} \qquad (18)$$

Eq. (18) may lead to different results because the cost of membrane and bioreactor (P_v and P_m) may vary with time and location. For example, if the cost ratio of P_v/P_m equals 1.0, substituting all the parameters into Eq. (18), the desired operating MLSS for the membrane bioreactor system is found to be 6950 mg/L. However, if P_v/P_m decreases to 0.1 when the price of membrane is much higher than the cost of bioreactor, the calculated MLSS will be only 1500 mg/L. This concentration is almost the same as the usual operating MLSS concentration for conventional activated sludge processes. So in this case, membrane bioreactor treatment process cannot be smaller than the conventional activated sludge processes. Therefore, membrane bioreactor treatment might not be a good alternative if the cost ratio of bioreactor to membrane is rather too low.

5. CONCLUSIONS

As compared to the conventional two-stage activated sludge processes, the membrane bioreactor treatment is an attactive technology that can replace two stages of biodegradation and settlement with a single, integrated step.

A set of system models to describe the performance of membrane biological treatment system were developed based on the bio-kinetics and material balance principles and validated with the experimental data.

A synthetic wastewater and a meat packing wastewater were treated by a membrane system to determine the biomass coefficients, and to correlate the relationship between the biomass concentration and the permeate flux. The experimental results showed that membrane system offered excellent organic removal efficiency in treating wastewater. Michaelis-Menten equation and mass balance principle were found to be applicable to determine the biomass coefficients and predict the substrate utilization and biomass growth rate. An exponential relationship between MLSS concentration and the permeate flux was found from the experiment. A method was proposed to determine the operating parameters for minimum capital cost of a membrane bioreactor system without producing excess sludge waste.

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