

Biochemical Kinetics of Cross flow Membrane Bioreactor Processes in the Treatment of Refinery Wastewater

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ABSTRACT: A lab-scale cross flow membrane bioreactor (CF-MBR) was operated to determine the biokinetic coefficients under MLSS concentrations of 5000 and 3000 mg/L. The investigation showed that the yield (Y), the endogenous decay coefficient (k_d), the maximum specific growth rate (μ_m) and the saturation constant (K_s) were 0.276 mg/mg, 0.07 /day, 0.653 /day, and 396.62 mg COD/L respectively for MLSS 5000 mg/L, and 0.222 mg/mg, 0.09 /day, 1.2 /day, and 659.45 mg COD/L for MLSS 3000 mg/L. The values of kinetic coefficients were within the normal range of the activated sludge process found in the literature, except the values of Y . However, value of Y increased with the increase of MLSS. Kinetic parameters determined from CF-MBR process were used to simulate the effluent COD. The simulation study showed good agreement between model prediction and experimental data. Sensitivity analysis was carried out to determine influence of biokinetic parameters on the effluent substrate concentration. From the analysis, it was evident that k_d and K_s were directly proportional to the effluent substrate concentration, while μ_m was inversely proportional.

Key words: Refinery wastewater, Cross flow, Membrane bioreactor, Biokinetic coefficient, Monod Equation

INTRODUCTION

Reclamation of oily wastewater is a major goal in several countries challenged with water shortage problems. A number of treatment alternatives are available for refinery wastewater treatment including membrane filtration (Salahi & Mohammadi, 2010; Zhallg *et al.*, 2005; Peng & Tremblay, 2008; Li *et al.*, 2006; Zhong *et al.*, 2003). Membrane bioreactor (MBR) is becoming increasingly popular for wastewater treatment due to its advantages of high permeate quality, small footprint, and independent control of solids and small hydraulic retention time. Industrial application of the MBR technology has gained attention because of these features and the robustness of the process that allows the operation with shock loading rates and hydraulic fluctuations (Zhidong, 2010; Viero *et al.*, 2008; Soltani *et al.*, 2010; Rahman & Al-Malack, 2006).

In a cross flow membrane bioreactor, the membranes are kept outside of the aeration tank. It is generated by a pump which creates the transmembrane pressure difference for the filtration process. The supply of oxygen to the activated sludge and the required mixing of the activated sludge tank are guaranteed by a

separate aeration, called biology aeration (Gunder, 2001).

The efficient design of MBR depends on empirical and rational parameters based on biological kinetic equations (Al-Malack, 2006). Major factors affecting the biokinetic coefficients are reactor growth rate, waste composition, toxicity, temperature and population diversity (Rozich *et al.*, 1992). Biokinetic coefficients used in the design of activated sludge process include specific growth rate (μ), maximum rate of substrate utilization per unit mass of microorganisms (k), half-velocity constant, or substrate concentration at one-half of the maximum specific growth rate (K_s), maximum cell yield (Y), and endogenous decay coefficient (k_d). Typical values of kinetic coefficients for activated sludge are shown in Table 1 (Al-Malack, 2006).

Different investigations have been carried out to evaluate kinetic parameters of submerged MBR for treating domestic and industrial wastewater. The trend is absent for cross flow MBR. This might be because of high energy expenses related to transmembrane

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Table 1. Typical values of Biokinetic coefficients for activated sludge

Coefficient	Basis	Value	
		Range	Typical
K ($k=\mu_{max}/Y$)	/day	2-8	4
k_d	/day	0.03-0.07	0.05
K_s	mg/L, BOD ₅	40-120	80
	mg/L, COD	20-80	40
Y	VSS/BOD ₅	0.3-0.7	0.5
	VSS/COD	0.2-0.5	0.4

pressure and increased aeration at higher sludge concentration (Hay *et al.*, 2006; Muller *et al.*, 1995; Nelson *et al.*, 2008; Mohammadi *et al.*, 2003; Spérandio & Espinosa, 2008). Zhang *et al.* 2002 used a combinational approach with considering HRT as an evaluation index to discuss factors, such as maximum specific removal rate K , saturation constant K_s , maintenance coefficient m , maximum specific growth rate μ_m and observed yield coefficient Y_{obs} . He reported values of K and K_s for petrochemical wastewater treatment, as 0.185 h⁻¹ and 154.2 mg/L, respectively. In another study, Fan *et al.* 1998 reported a coefficient of COD removal k , for petrochemical wastewater between 0.017 to 0.080 L/(mg.d). Tellez *et al.* 1995 evaluated the biokinetic coefficients of New Mexico oilfield produced water by respirometric technique. Biokinetic coefficients K_s and μ_{max} were estimated as 1.37 mg/L and 0.136 h⁻¹ respectively. Changes in cell yield were also evident, however, yields increased from 0.41 to 0.69 mg biomass/mg total *n*-alkane. According to Raj & Anjaneyulu, 2005, typical values of half velocity constant (K_s), yield coefficient (Y) and endogenous decay coefficient (k_d) in industrial wastewater varies within a range of 850 to 5200 mg/L, 0.3 to 0.72 mg/mg, and 0.05 to 0.18 /day, respectively. Munz *et al.* 2010 investigated the effect of separation technology on biokinetic parameter. Ammonium and nitrite oxidizing biomasses (AOB and NOB) were investigated in parallel pilot plants; a membrane bioreactor (MBR) and a conventional activated sludge process (CASP) fed with domestic wastewater. The maximum specific growth rate of the AOB (μ_{maxAOB}) in CASP varied from 0.45d⁻¹±0.04 to 0.72d⁻¹±0.2 and μ_{maxAOB} in MBR was in the range 0.45 to 0.49 d⁻¹. However, the endogenous decay coefficients of the NOB and AOB and the maximum specific growth rates of the NOB were similar in both MBR and CASP.

Information regarding biokinetic coefficient of CF-MBR for treating refinery wastewater needs more work. CF-MBR process started developing as a new process since late seventies, but still there is a lack of understanding of the interaction between the biological and filtration unit. The main goal of this study was to investigate the kinetics of cross flow membrane bioreactor for treating oily wastewater. Saturation constant (K_s), specific growth rate (μ), yield coefficient (Y) and endogenous decay coefficient (k_d) at two different values of mixed liquor suspended solid (MLSS) i.e., 3000 and 5000 mg/L were determined.

Basic equations that describe the growth of microorganisms and utilization of the growth-limiting substrate in the activated sludge process are based on the Monod model (Monod, 1949). The Monod model is still the most commonly and widely used model for the study of biokinetic coefficients. This model was accepted by the IAWPRC task group (Henze *et al.*, 1987) as the fundamental basis for the development of activated sludge models. The effect of a limiting substrate or nutrient can be defined adequately using the following expression proposed by Monod:

$$\mu = \mu_m \frac{S}{K_s + S} \quad (1)$$

Where, μ_m is the maximum specific growth rate, time⁻¹, S the concentration of growth limiting substrate surrounding the biomass, mass/unit volume, K_s the saturation constant which is numerically equal to the substrate concentration at $\mu = 0.5 \mu_m$, mass/unit volume and μ is the specific growth rate, time⁻¹. Fig. 1 shows the schematic diagram of the CF-MBR system used throughout the Study period. The model is developed with the following assumptions:

- (i) The reactor is completely mixed (mixing was provided by means of stone aerator and recycling pump)
- (ii) The volume of the reactor is constant (the inflow is equal to the permeate flow); this was achieved by using a mechanical float.
- (iii) Complete rejection of MLSS (no biomass is allowed to come out with the permeate)
- (iv) Substrate is not rejected
- (v) No microbial solids are contained in the influent substrate.

The rate equations describing the performance of the system are the mass balance equations of both the biomass and substrate. These can be expressed as follows:

$$[\text{Rate of change of biomass in the reactor}] = [\text{Rate of increase due to growth}]$$

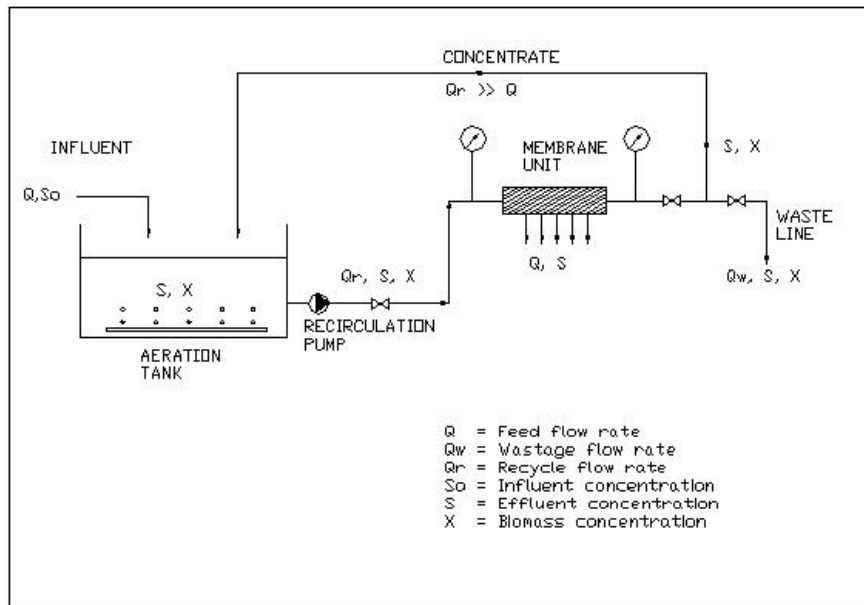


Fig. 1. Complete mix CF-MBR system

- [Rate of loss due to endogenous respiration] –
 [Deliberate wastage]

which can be mathematically expressed as:

$$V \frac{dX}{dt} = \mu XV - k_d XV - Q_w X \quad (2)$$

where, V = Reactor volume (l), X = biomass concentration in the reactor (mg/L), μ = Specific growth rate (/day), Q_w = wastage flow rate (l/day)

At steady state condition, $dX/dt = 0$, hence, Eq. (2) can be expressed as:

$$\mu = k_d + \frac{Q_w}{V} \quad (3)$$

Since the solid retention time (SRT) is defined as:

$$SRT = \frac{\text{Total mass of organism in the reactor}}{\text{Total mass of organisms leaving the system per day}}$$

or,

$$SRT = \frac{VX}{Q_w X} = \frac{V}{Q_w} \quad (4)$$

Substituting Eq. (4) in to Eq. (3), results in:

$$\mu = k_d + \frac{1}{SRT} \quad (5)$$

Substituting Eq. (1) in Eq. (5) yields the steady state for substrate concentration in the reactor:

$$S = \frac{K_s \left(\frac{1}{SRT} + k_d \right)}{\mu_m - \left(\frac{1}{SRT} + k_d \right)} \quad (6)$$

On the other hand, the substrate balance can be expressed as:

[Rate of change of substrate in the reactor] = [Rate of input of feed substrate]

– [Rate of removal due to biomass utilization] – [Rate of removal due to washout] – [Substrate lost during deliberate wastage]

Mathematically, the above statement can be written as:

$$V \frac{dS}{dt} = QS_0 - \mu \frac{XV}{Y} - S(Q - Q_w) - Q_w S \quad (7)$$

At steady state, $dS/dt = 0$, therefore, Eq. (7) can be rewritten as:

$$\frac{Q}{V} (S_0 - S) = \mu \frac{X}{Y} \quad (8)$$

Substituting Eq. (5) into Eq. (8) results in the biomass concentration at steady state condition:

$$X = Y \frac{Q}{V} \frac{(S_0 - S)}{k_d + \frac{1}{SRT}} \quad (9)$$

In continuous-flow complete-mixed reactor, the determination of the kinetic coefficients is usually achieved by collecting data from lab-scale or pilot-plant experiments. The system is operated at various hydraulic retention times (HRT) and/or at various sludge retention times (SRT). At each adapted stage of HRT or SRT, a steady state condition is achieved. Accurate measurements of the biomass and permeate substrate concentration are then recorded. The kinetic coefficients such as K_s , μ , Y and k_d can be determined through linearization of Eq. (6) and Eq. (9). To determine the kinetic coefficients k_d and Y , Eq. (9) can be rearranged to the form of:

$$\frac{Q}{VX} (S_0 - S) = \frac{1}{Y} \frac{1}{SRT} + \frac{k_d}{Y} \quad (10)$$

To determine the kinetic coefficients μ_m and K_s , Eq. (6) can be rearranged to become

$$\frac{SRT}{1 + (SRT k_d)} = \frac{K_s}{\mu_m} \left(\frac{1}{S} \right) + \frac{1}{\mu_m} \quad (11)$$

If Eq. (10) is plotted as $Q(S_0 - S)/VX$ versus $1/SRT$, then from the slope and the Y-intercept, it is possible to determine the kinetic coefficients Y and k_d . After substituting the obtained value of k_d in Eq. (11), $SRT/[1 + (SRT k_d)]$ versus $1/S$ is plotted. Then from the slope and the Y-intercept kinetic coefficients K_s and μ_m are determined.

MATERIALS & METHODS

Fig. 1 shows the schematic diagram of the experimental setup used throughout the investigation. It comprised of two main parts: the cross flow membrane separation unit and the activated sludge bioreactor. The effective volume of the aeration tank was 20 L. The membrane used throughout the experiment was made of ceramic and of hollow tubular configuration. It had 7.0 mm of inside diameter and pore size of 0.2 μm . The general characteristics of membrane are shown in Table 2. Each of the ceramic membranes was clamped to brass bend with the help of a short rubber tube. Five membranes were coupled in series and connected to the circulation pump at one end and to aeration tank at the other end. A rectangular plexi glass tray was used to collect permeate. This tray acted as the stand for the membrane unit as well as temporary storage of permeate which eventually was connected to the main permeate

tank. The oily wastewater used in the investigation was collected from a petroleum refinery. The oil content and COD of oily wastewater were found to be 160×10^3 mg/L and 370×10^3 to 2300×10^3 mg/L, respectively. The COD was determined by a modified approach of the closed reflux titrimetric method.

Table 2. Characteristics of the membrane

Configuration	Hollow Tubular
Material	Alumina (ceramic)
Pore size	0.2 μm
Outer diameter	10 mm
Inner diameter	7 mm
Length	5 x 20 cm
Cross-sectional area	38.5 mm ²
Total surface area	0.022 m ²
Effective surface area	0.019 m ²
Maximum thermal stability	120 ⁰ C
Maximum filtration pressure	15 bar
pH range	1-14

Essential nutrients were added to the bioreactor. Main ingredients of the nutrient were glucose, peptone and east extract. The nutrients provided all the inorganics and micronutrients as well as nitrogen and phosphorus for the development of the biomass. The detailed composition of the nutrient is shown in Table 3. Concentrated nutrient (100,000 mg/L COD) solution was prepared and stored in the refrigerator at 4⁰C. Nutrient concentration of 500 mg/L in terms of COD was then prepared by diluting the concentrated nutrient with tap water in the nutrient feed tank. For the continuous reactor experiments, samples from the reactor and permeate were collected periodically and analyzed for different physical and chemical parameters, in accordance with the Standard Methods for the Examination of water and wastewater (Table 4).

One of the essential parts of the study was to acclimatize the microorganisms (MO) to the oily wastewater. Return activated sludge was brought from Saudi ARAMCO wastewater treatment plant to use as seed for building the acclimatized microorganism culture. The oily wastewater was brought from petroleum refinery.

The nutrient of 500 mg/L COD was continuously supplied to the reactor. The flow of the nutrient supply was matched with the permeate flow rate by keeping the water level constant in the reactor using a mechanical float.

Table 3. Composition of the synthetic nutrient (Al-Malack, 2006)

Component	Contents in Stock Solution	Contents in Typical Feed Solution
Glucose, C ₆ H ₁₂ O ₆	40,000	200
Peptone	40,000	200
Yeast extract	4,000	20
(NH ₄) ₂ SO ₄	32,000	160
KH ₂ PO ₄	6,400	32
MgSO ₄ .7H ₂ O	8,000	40
MnSO ₄ .6H ₂ O	720	3.6
FeCl ₃ .6H ₂ O	40	0.2
CaCl ₂ .2H ₂ O	800	4
COD (mg/L)	100,000	500

Table 4. Analytical methods of different parameters

Parameter	Technique	Methods
Turbidity	Nephelometric	SM-2130B
pH	Potentiometric	SM-4500-H ⁺
MLSS	Filtration 4.5 µm	SM-2540D
DO	Oxygen Probe	SM-4500-O ₂
COD	Closed reflux	SM-5220C
BOD	5-days	SM-5210B
TOC	Combustion infrared	SM-5310B
Phenol	Mass spectrometric	SM-6420C
Oil & grease	Gravimetric	EPA 1664
Ammonia	Ion Selective Electrode	SM-4500-NH ₃ D
Microbial	Heterotrophic Plate Count (HPC)	SM-9215B

The oil was supplied to the reactor intermittently with the help of a peristaltic pump at an interval of two hours for two minutes and mixed completely in the reactor vessel. The COD concentration of nutrient was considerably less than that of oil (2.3×10^6 mg/L) but the volume used was significant. For that reason the COD contribution to the reactor by the nutrient could not be overlooked and associated in the influent substrate COD calculation. It should be mentioned in this regard that as the nutrient supply was continuous and the oil supply was intermittent, influent COD calculation was carried out based on the mass loading

per day rather than the concentration. This was followed throughout the study period. The circulation pump was used to pump the MLSS to membrane separation unit under pressure, where a part of water was permeated through the membrane and the mixed liquor was concentrated in the bioreactor.

The Biokinetic coefficients were determined for MLSS concentrations of 5000 and 3000 mg/L. This was attained by operating the system at various sludge retention times (SRT) and by allowing (at each stage of SRT) a steady state condition to prevail. At the

beginning of the study, an MLSS concentration of 5000 mg/L was attained and maintained under steady state conditions. A steady state condition was achieved when fairly constant biomass growth and filtrate COD were obtained (Standard Deviation 5%) (Diez et al. 2002). Sludge was wasted daily to maintain steady state conditions. Then, by increasing the organic mass loading (gm COD/ day) and controlling the SRT, a second steady state condition for same MLSS concentration was achieved and biomass as well as effluent substrate concentration were recorded. Similarly, the third and fourth steady state points were obtained. Next, the biomass was reduced to 3000 mg/L and similar analyses were carried out after attaining steady state conditions at each of the specified substrate condition.

RESULTS & DISCUSSION

During the study period, SRT was used as a parameter to control the growth rate of the biomass instead of HRT. This was achieved by running the unit at various organic mass loading and also by wasting various volumes of biomass from the system.

As discussed, the concentration of the MLSS of the bioreactor was kept constant by wasting the biomass once and occasionally twice a day. Sometimes it was found from MLSS measurement after wasting that the value of MLSS was more than before wasting. It might happen either because of erroneous sample collection due to the non uniform mixing of the biomass in the reactor or the rapid increase in biomass. So the MLSS was wasted for the second time to keep the MLSS concentration constant.

The kinetic study was initiated with a biomass concentration of 5000 mg/L. Because of the long acclimatization period of microorganisms (150 days) to the oil and glucose based nutrient, the first steady

state condition was achieved after only eighteen days from the start of the unit operation. The steady state was maintained for five days. Then the organic mass loading was increased from 41.110 gm/day to 45.469 gm/day. At this point it was observed interestingly that increasing the mass loading did not increase the effluent COD significantly. When the effluent COD variation was found within the chosen standard deviation (5%) for four days, the duration was considered as the second steady state condition. To get the third and fourth steady state point, the mass loading was increased up to 57.861 gm/day and 64.693 gm/day, respectively, and for both points the steady state conditions were prevailed for four days. Table 5 shows the steady-state data obtained at an MLSS concentration of 5000 mg/L, while Figs. 2 and 3 show the determination of the coefficients using Eqs. (10) and (11). The biokinetic coefficients were found to be as follows: $Y = 0.276$ mg/mg, $k_d = 0.07$ /day, $\mu_m = 0.653$ /day and $K_s = 396.62$ mg COD/L.

During the kinetic coefficients study period at MLSS 3000 mg/L, various mass loading were applied and four steady state points were obtained accordingly. The loading was varied from 35.775 to 62.545 gm/day to attain the steady state points. All the four steady state conditions were maintained for four days except the third point. Table 6 shows the steady-state data obtained at an MLSS concentration of 3000 mg/L, while Figs. 4 and 5 show the determination of the coefficients using Eqs. (10) and (11). The biokinetic coefficients were found to be as follows: $Y = 0.222$ mg/mg, $k_d = 0.09$ /day, $\mu_m = 1.2$ /day and $K_s = 659.45$ mg COD/L. Table 7 shows a summary of the biokinetic coefficients obtained for all MLSS values during the investigation.

It is apparent from Table 7 that the coefficients change with the change of MLSS concentrations. Off

Table 5. Steady state data at MLSS 5000 mg/L

Q (day ⁻¹)	X_{avg} (mg/l)	S (mg/l)	1/S (l/mg)	QS ₀ (gm/day)	QS (gm/day)	SRT (day)	Q(S ₀ -S)/VX (day ⁻¹)	SRT/ (1+SRT*k _d) (day)
38	5458	72.00	0.0139	41.110	2.741	30.00	0.35	9.68
36	5300	84.00	0.0119	45.469	3.003	25.42	0.40	9.15
33	5393	109.00	0.0092	57.861	3.590	15.30	0.50	7.39
19	5511	120.00	0.0083	64.693	2.281	11.00	0.57	6.21

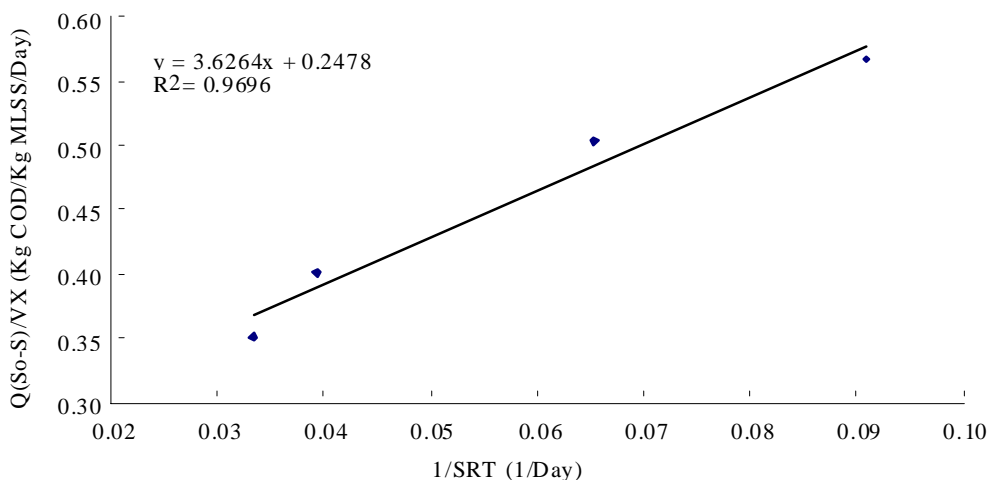


Fig. 2. Determination of Y and k_d at MLSS 5000 mg/L

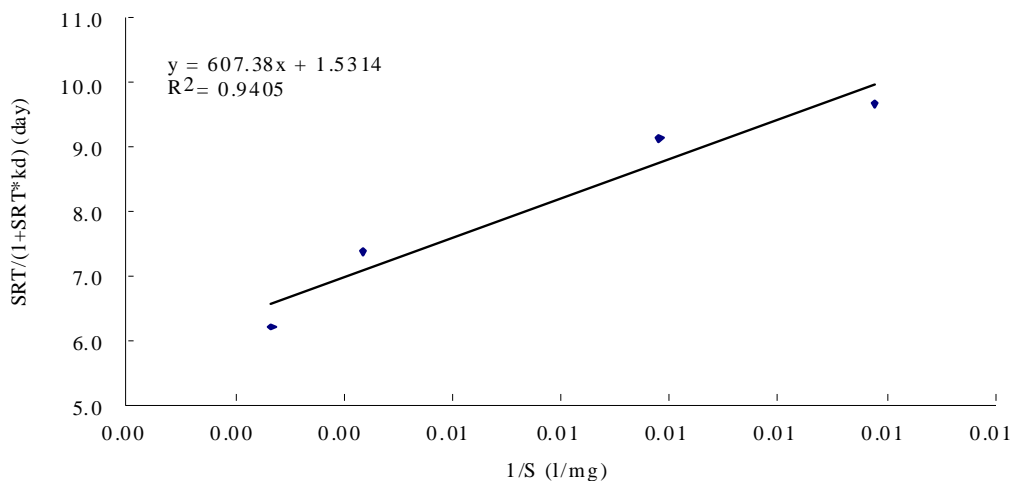


Fig. 3. Determination of μ_m and K_s at MLSS 5000 mg/L

course this variability does not follow any particular pattern to draw a straight-forward conclusion. This variability might be attributed to the character of the system itself, as the system could be a selective process and kinetic coefficient obtained might represent different species (Al-Malack, 2006). This is supported by the performance investigation of the unit during the study period. For an instance, when the unit was running at MLSS 3000 mg/L, after the operation of five days as the organic mass loading increased, the effluent COD decreased, which was supposed to be increased at the increased mass loading. The same occurrence happened at MLSS 5000 mg/L also. The reasons behind this phenomenon might be as follows:

- Since the growth rate was controlled by the SRT which was carried out daily by wasting a certain amount of MLSS, this might have affected the growth kinetics of the microbial population in the system. The

continuous culture process is a competitive process, which results in the enrichment of a bacterial species at a particular SRT, i.e. species with higher values of specific growth rate (μ) appeared to be predominant at lower SRT while those species having lower value of μ were enriched in the system only at high SRT (El-Kebir, 1991).

- Due to harsh conditions imposed on the populations in the system (shear and pressure), the system could have contributed towards selecting species that can be stand, grow and survive the applied conditions.

Generally, the values of kinetic coefficients presented in Table 7 are within the normal range of the activated sludge process found in the literature, except the values of Y . The reason behind the relatively low value of Y might lead to the oxidation state of the carbon source and nutrient elements (Metcalf & Eddy,

Table 6. Steady state data at MLSS 3000 mg/L

Q (day ⁻¹)	X _{avg} (mg/l)	S (mg/l)	1/S (l/mg)	QS ₀ (gm/day)	QS (gm/day)	SRT (day)	Q(S ₀ -S)/VX (day ⁻¹)	SRT/(1+SRT*k _d) (day)
27	3547	70	0.0143	35.775	1.918	36.25	0.48	8.5
22	3184	101	0.0099	46.966	2.241	19.58	0.70	7.09
25	3224	110	0.0091	53.775	2.724	12.04	0.79	5.78
28	3382	116	0.0086	62.545	3.292	9.05	0.88	4.99

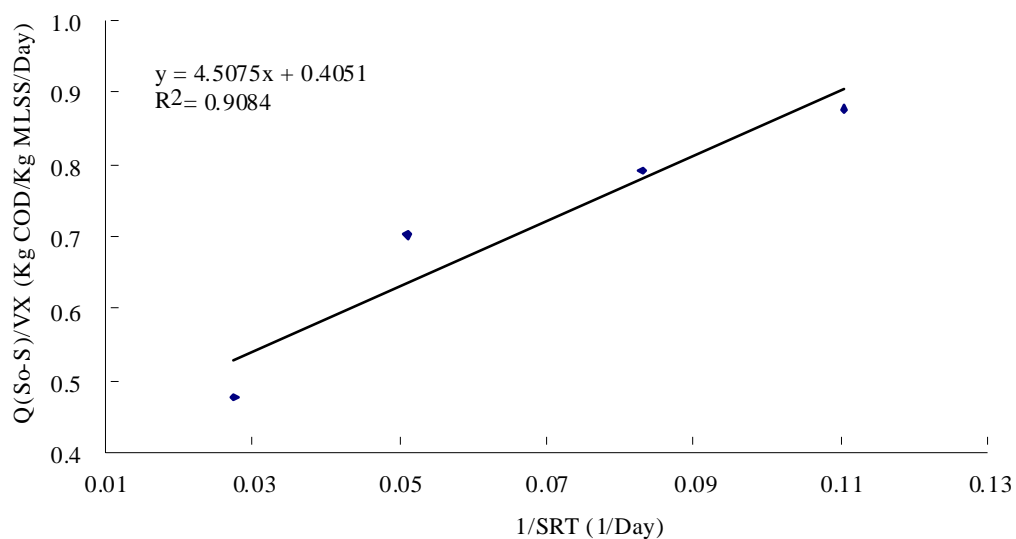
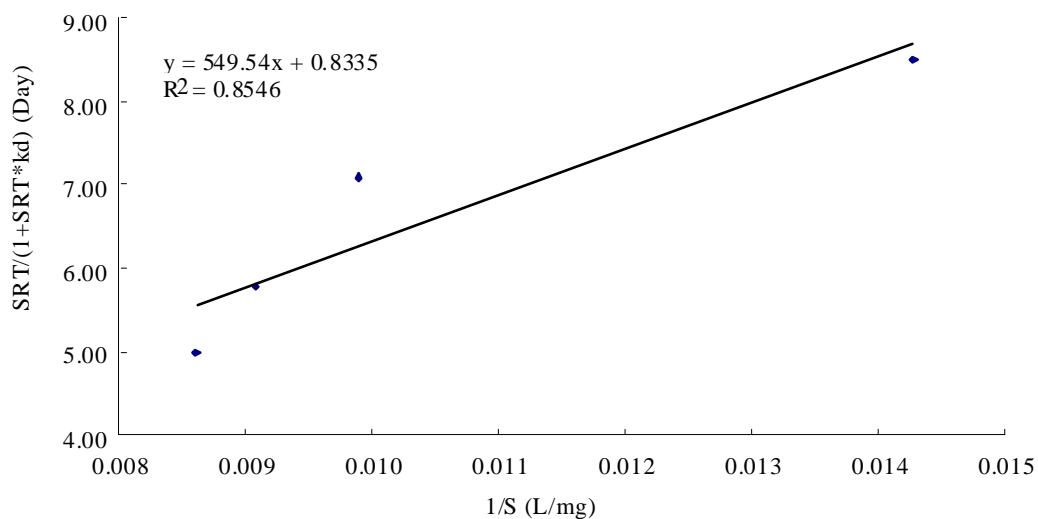
Fig. 4. Determination of Y and k_d at MLSS 3000 mg/LFig. 5. Determination of μ_m and K_s at MLSS 3000 mg/L

Table 7. Kinetic Coefficients for CF-MBR at different MLSS concentrations

MLSS, mg/L	Y (mg/mg)	K_d (/day)	μ_m (/day)	K_s (mg COD/L)
5000	0.276	0.07	0.653	396.62
3000	0.222	0.09	1.2	659.45

1991). The Y values were increasing with the increase of MLSS concentrations as they represent all the amount of biomass produced by the growth during the removal of substrate. The decay rate k_d , as listed in Table 7, shows an increase as the MLSS concentration decreases. This probably is a result of the harsh condition, which biomass was subjected to. These effects appear more pronounced at low concentrations because the likelihood of the biomass cells being subjected to physical stress is higher at lower concentration. Table 8 summarizes some of the kinetic coefficients obtained from different sources. Although, k_d , μ_m and K_s are within the reported values, they also differ quite significantly.

In order to verify the validity of Eq. (6) in predicting the effluent COD at various SRT, a simulation was carried out. The kinetic parameters summarized in Table 7 were used in the simulation of the model. Fig. 6 shows the variation of simulated effluent COD at various SRT for different MLSS concentration. Plotting both the simulated curves for different MLSS concentration on the same graph provides an assessment of how the performance of the unit can be described by the Monod model. It is clear from the simulated curves that up to a certain point, as the SRT increased, effluent COD

decreased; after this the SRT had no effect on the effluent COD concentrations. Also, as the MLSS concentrations in the aeration tank increased, the Effluent COD increased. This phenomenon might result from the accumulation of end-products (El-Kebir, 1991), which contain a wide variety of high and low molecular weight compounds, including humic and fulvic acids, organic acids, amino acids, antibiotics, enzymes, structural components of cells and products of metabolism.

In order to determine influence of biokinetic parameters on the effluent substrate concentration, a sensitivity analysis was performed. The values of each of the k_d , μ_m and K_s were individually varied by $\pm 50\%$, while the other parameters were kept constant. The sludge retention time was kept at 25 days during the sensitivity analysis. The sensitivity was studied by simulating the effluent COD using Eq. (6). The results of the sensitivity analysis are shown in Figs. 7 and 8. It can be clearly seen that k_d and K_s are directly proportional to the effluent substrate concentration, while μ_m is inversely proportional to the effluent substrate concentration. Regardless of the MLSS concentration, the effluent substrate concentration was found to be more sensitive to μ_m when compared to k_d and K_s . Also, the effluent substrate concentration showed almost the same level of sensitivity to both k_d and K_s . From the sensitivity analysis, it is clear that care should be taken when using these biokinetic coefficients in the Monod model for the design of cross flow membrane bioreactors. Extra caution should be exercised when μ_m is dealt with, since small variations in μ_m can result in significant changes in the values of the effluent substrate concentration.

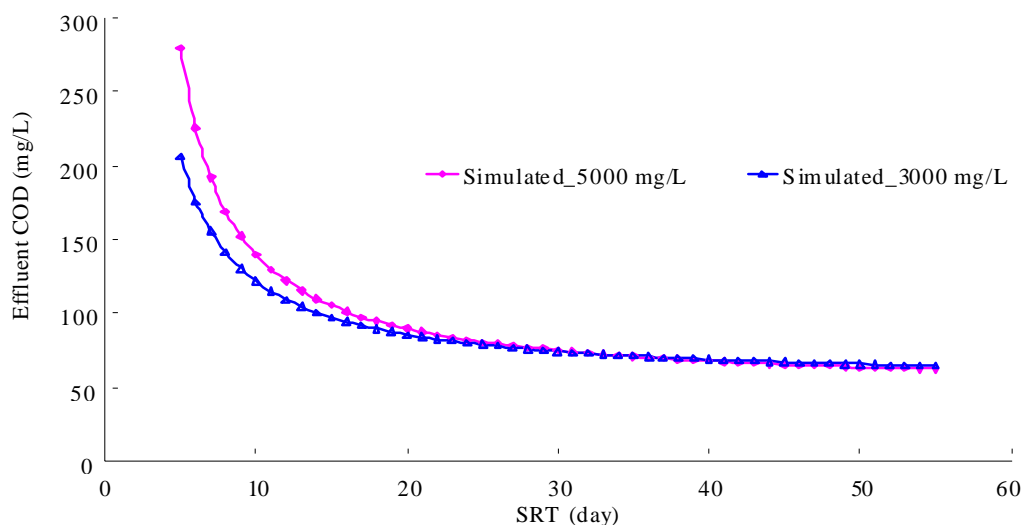
**Fig. 6. Simulated Effluent COD for Different MLSS concentrations**

Table 8. Some of typical values of the kinetic coefficients for aerobic bacteria

Substrate	Basis of analysis	Y (mg/mg)	k_d (day^{-1})	μ_m (day^{-1})	K_s (mg/l)	Treatment system	Reference
Municipal waste	COD	0.5-0.62	0.025-0.48	7.4-18.5	11-181	ASP	Gaudy & Gaudy, 1980
Municipal waste	COD	0.4-0.8	0.025-0.075	2-10	15-70	ASP	Metcalf & Eddy, 1991
Municipal waste	COD	0.48-0.6	0.05-0.16	5.6-8.10	250-3720	CF-ASP	El-Kebir, 1991
Synthetic waste	COD	0.49-0.58	0.037-0.151	1.28-6.46	289-2933	SM-MBR	Al-Malack, 2006
Industrial waste	COD	0.3-0.72	0.045	0.77	2980.5	ASP	Raj & Anjaneyulu, 2005
Acetic Acid	COD	0.29 ± 0.02	0.23 ± 0.01	13.1 ± 0.68	180.6 ± 14.2	SM-MBR	Kurian et al. 2006
Propionic Acid	COD	0.29 ± 0.03	0.23 ± 0.01	7.53 ± 1.99	271 ± 32.6	SM-MBR	Kurian et al. 2006
Rendering wastewater	COD	0.20 ± 0.01	0.14 ± 0.02	4.11 ± 0.57	806 ± 192	SM-MBR	Kurian et al. 2006
Dairy Wastewater	COD	0.2281	0.1383	1.69	174	MSBR	Kaewsuk et al. 2010
Oily wastewater	COD	0.22-0.28	0.07-0.09	0.65-1.2	397-660	CF-MBR	This Study

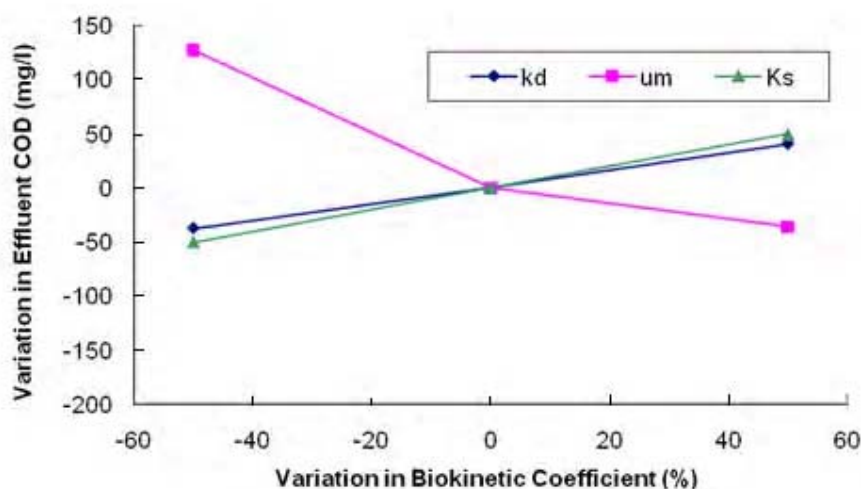


Fig. 7. Sensitivity analysis of biokinetic coefficients at MLSS of 5000 mg/L

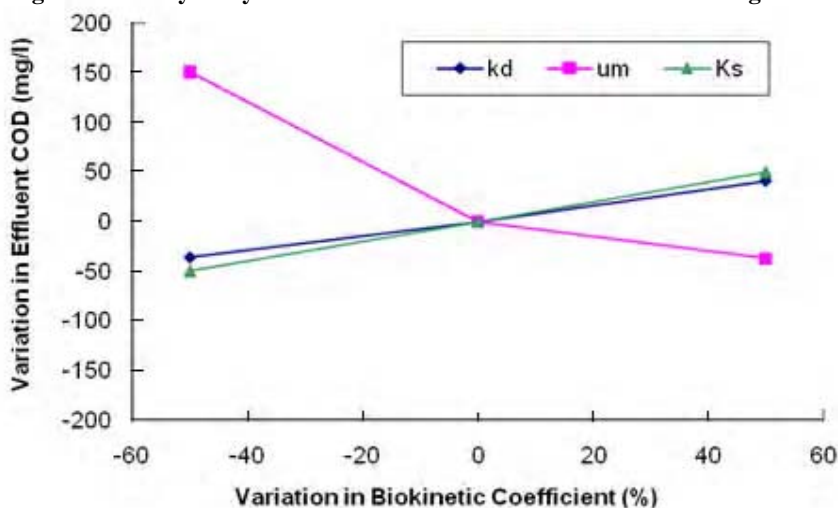


Fig. 8. Sensitivity analysis of biokinetic coefficients at MLSS of 3000 mg/L

CONCLUSION

Biokinetic coefficients Y , k_d , μ_m and K_s were found to be 0.276 mg/mg, 0.07 /day, 0.653 /day, and 396.62 mg COD/L respectively for MLSS 5000 mg/L, and 0.222 mg/mg, 0.09 /day, 1.2 /day, and 659.45 mg COD/L for MLSS 3000 mg/L. Generally, the values of kinetic coefficients were within the normal range of the activated sludge process found in the literature, except the values of Y . However, value of Y increased with the increase of MLSS. The simulation study showed good agreement between model predictions and experimental data. It is clear from the simulated curves that up to a certain point, as the SRT increased, effluent COD decreased; after this the SRT had no effect on the effluent COD concentrations. The sensitivity of the various biokinetic coefficients was studied by simulating the effluent COD. From the analysis, it is evident that k_d and K_s are directly proportional to the effluent substrate concentration, while μ_m is inversely proportional to the effluent substrate concentration.

The model can be used to simulate and investigate different operational strategies. However, extra caution should be exercised when μ_m is dealt with, since small variations in μ_m can result in significant changes in the values of the effluent substrate concentration.

kaalkei jeno chhobi pai.

bujchho???

Onееk valo theko..

aj hoyto ar boshbo na...onek kaj

Allah Hafiz.

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REFERENCES

- Al-Malack, M. H. (2006). Determination of biokinetic coefficients of an immersed membrane bioreactor. *Journal of Membrane Science*, **271**, 47–58.

- Diez, M. C., Castillo, G., Aguilar, L., Vidal, G. and Mora, M. L. (2002). Operational factors and nutrient effects on activated sludge treatment of *Pinus radiata* kraft mill wastewater. *Bioresource Technology*, **83**, 131–138.
- El-kebir, A. A. (1991). Application of Cross flow Filtration for Biomass Retention in Aeration Tank. Dissertation, University of Newcastle upon Tyne, U.K.
- Fan, Y. B., Wang, J. and Jiang, Z. C. (1998). Test of membrane bioreactor for waste water treatment of a petrochemical complex. *Journal of Environmental Sciences (China)*, **10** (3), 269–275.
- Gaudy Jr., A. F. and Gaudy, E. T. (1980). *Microbiology for Environmental scientists and engineers*. (McGraw-Hill Book Company, New York).
- Gunder, B. (2001). *The Membrane-Coupled Activated Sludge Process in Municipal Wastewater Treatment*. Technomic Publishing Company Inc., Lancaster, Pennsylvania, USA.
- Hay, C. T., Sun, D. D., Khor, S. L. and Leckie, J. O. (2006). Effect of 200 days' sludge retention time on performance of a pilot scale submerged membrane bioreactor for high strength industrial wastewater treatment. *Water Science & Technology*, **53** (11), 269–276.
- Henze, M., Grady, C. P. L., Gujer, W., Maraia, G. V. R. and Matsuo, T. (1987). *Activated sludge model no. 1*. Report published by IAWPRC, London.
- Kaewsuk, J., Thorasampan, W., Thanuttamavong, M. and Seo, G. T. (2010). Kinetic development and evaluation of membrane sequencing batch reactor (MSBR) with mixed cultures photosynthetic bacteria for dairy wastewater treatment. *Journal of Environmental Management*, **91**, 1161–1168.
- Kurian, R., Nakhla, G. and Bassi, A. (2006). Biodegradation kinetics of high strength oily pet food wastewater in a membrane-coupled bioreactor (MBR). *Chemosphere*, **65**, 1204–1211.
- Li, Y. S., Yan, L., Xiang, C. B. and Hong, L. J. (2006). Treatment of oily wastewater by organic-inorganic composite tubular ultrafiltration (UF) membranes. *Desalination*, **196**, 76–83.
- Metcalf & Eddy. (1991). *Wastewater Engineering: Treatment, Disposal and Reuse*, Third Edition. (McGraw-Hill Inc.).
- Mohammadi, T., Kazemimoghadam, M. and Saadabadi, M. (2003). Modeling of membrane fouling and flux decline in reverse osmosis during separation of oil in water emulsions. *Desalination*, **157**, 369–375.
- Monod, J. (1949). The Growth of Bacterial Cultures. *Annual Review of Microbiology*, **3**, 371–394.
- Muller, E. B., Stouthamer, A. H., Van verseveld, H. W. and Eikelboom, D. H. (1995). Aerobic domestic waste water treatment in a Pilot plant with complete sludge retention by cross-flow filtration. *Water Research*, **29** (4), 1179–1189.
- Munz, G., Mori, G., Vannini, C. and Lubello, C. (2010). Kinetic parameters and inhibition response of ammonia- and nitrite-oxidizing bacteria in membrane bioreactors and conventional activated sludge processes. *Environmental Technology*, **31** (14), 1557–1564.
- Nelson, M. I., Balakrishnan, E., Sidhu, H. S. and Chen, X. D. (2008). A fundamental analysis of continuous flow bioreactor models and membrane reactor models to process industrial wastewaters. *Chemical Engineering Journal*, **140**, 521–528.
- Peng, H. and Tremblay, A. Y. (2008). Membrane regeneration and filtration modeling in treating oily wastewaters. *Journal of Membrane Science*, **324**, 59–66.
- Rahman, M. M. and Al-Malack, M. H. (2006). Performance of a cross flow membrane bioreactor (CF-MBR), when treating refinery wastewater. *Desalination*, **191**, 16–26.
- Raj, S. and Anjaneyulu, Y. (2005). Evaluation of biokinetic parameters for pharmaceuticals wastewater using aerobic ox integrated with chemical treatment. *Process Biochemistry*, **40**, 165–175.
- Rozich, A. F., Gaudy Jr. and Anthony, F. (1992). Design and operation of activated sludge process using respirometry. (Lewis Publishers Inc. USA).
- Salahi, A. and Mohammadi, T. (2010). Experimental investigation of oily wastewater treatment using combined membrane systems. *Water Science & Technology*, **62** (2), 245–255.
- Soltani, S., Mowla, D., Vossoughi, M. and Hesampour, M. (2010). Experimental investigation of oily water treatment by membrane bioreactor. *Desalination*, **250**, 598–600.
- Spérandio, M. and Espinosa, M. C. (2008). Modelling an aerobic submerged membrane bioreactor with ASM models on a large range of sludge retention time. *Desalination*, **231**, 82–90.
- Tellez, G., Nirmalakhandan, N. and Torresdey, J. L. (1995). Evaluation of biokinetic coefficients in degradation of oilfield produced water under varying salt concentrations. *Water Research*, **29** (7), 1711–1718.
- Viero, A. F., De Melo, T. M., Torres, A. P. R., Ferreira, N. R., Sant'Anna Jr. G. L., Borges, C. P. and Santiago, V. M. J. (2008). The effects of long-term feeding of high organic loading in a submerged membrane bioreactor treating oil refinery wastewater. *Journal of Membrane Science*, **319**, 223–230.
- Zhang, J. C., Wang, Y. H., Song, L. F., Hu, J. Y., Ong, S. L., Ng, W. J. and Lee, L. Y. (2005). Feasibility investigation of refinery wastewater treatment by combination of PACs and coagulant with ultrafiltration. *Desalination*, **174**, 247–256.
- Zhang, S. Y., Houten, R. V., Eikelboom, D. H., Jiang, Z. C., Fan, Y. B. and Wang, J. (2002). Determination and discussion of hydraulic retention time in membrane bioreactor system. *Journal of Environmental Sciences (China)*, **14** (4), 501–507.
- Zhidong, L. (2010). Integrated Submerged Membrane Bioreactor Anaerobic/Aerobic (ISMBR-A/O) for Nitrogen and Phosphorus Removal During Oil Refinery Wastewater Treatment. *Petroleum Science and Technology*, **28**, 286–293.
- Zhong, J., Sun, X. and Wang, C. (2003). Treatment of oily wastewater produced from refinery processes using flocculation and ceramic membrane filtration. *Separation and Purification Technology*, **32**, 93–98.