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

**Rahman, M. M. [1] and Al-Malack, M. H.[2*]**

[1] University of Western Sydney, School of Engineering, Locked Bag 1797, Penrith South DC, NSW 1797, Australia

[2] King Fahd University of Petroleum & Minerals, Box 1150, Dhahran 31261, Saudi Arabia

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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 ($\mu_m$) 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 $\mu_m$ 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 ($\mu$), 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

*Corresponding author E-mail: mhmalack@kfupm.edu.sa

**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 $\mu_m$ 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 $\mu_{max}$ 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 ($\mu_{maxAOB}$) in CASP varied from $0.45d^{-1}\pm0.04$ to $0.72d^{-1}\pm0.2$ and $\mu_{maxAOB}$ 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 ($Ks$), specific growth rate ($\mu$), 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:

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

Where, $\mu_m$ 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 $\mu$ 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:

[Rate of change of biomass in the reactor] = [Rate of increase due to growth]

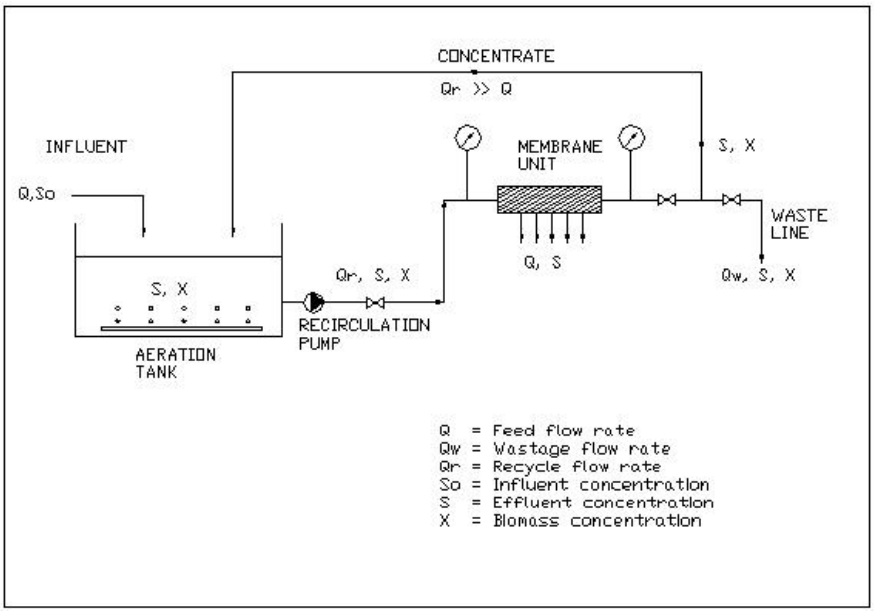


**Fig. 1. Complete mix CF-MBR system**

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

which can be mathematically expressed as:

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

where, $V$ = Reactor volume (l), $X$ = biomass concentration in the reactor (mg/L), $\mu$ = 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:

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

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

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

or,

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

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

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

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

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

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:

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

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

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

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

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

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 $K_s$, $\mu$, $Y$ 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:

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

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

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

If Eq. (10) is plotted as $Q(S_0\text{-}S)/VX$ 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), $SRT/[1+(SRTk_d)]$ versus $1/S$ is plotted. Then from the slope and the Y-intercept kinetic coefficients $K_s$ and $\mu_m$ 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 $160\times10^3$ mg/L and $370\times10^3$ to $2300\times10^3$ 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 $4^0$C. 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, $C_6H_{12}O_6$ | 40,000 | 200 |
| Peptone | 40,000 | 200 |
| Yeast extract | 4,000 | 20 |
| $(NH_4)_2SO_4$ | 32,000 | 160 |
| $KH_2PO_4$ | 6,400 | 32 |
| $MgSO_4.7H_2O$ | 8,000 | 40 |
| $MnSO_4.6H_2O$ | 720 | 3.6 |
| $FeCl_3.6H_2O$ | 40 | 0.2 |
| $CaCl_2.2H_2O$ | 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 G |
| 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 ($2.3 \times 10^6$ 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 |

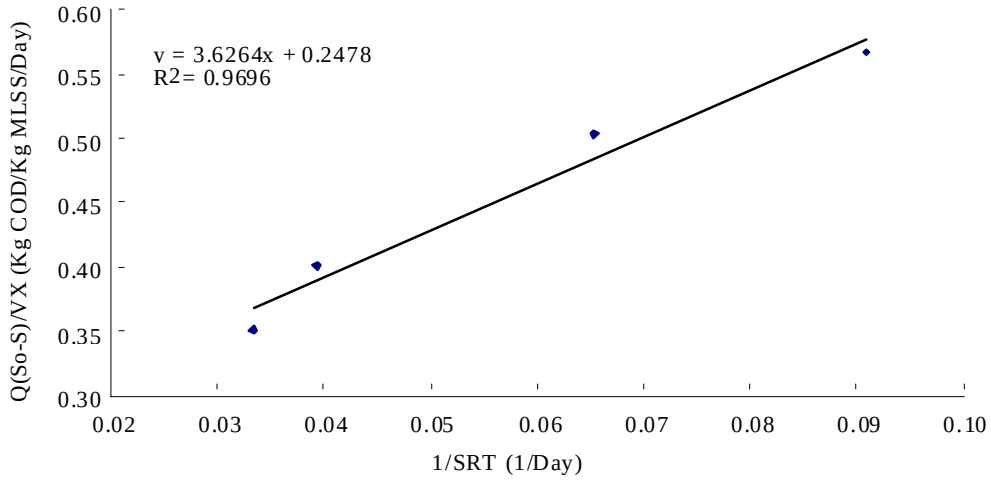


**Fig. 2. Determination of *Y* and $k_d$ at MLSS 5000 mg/L**

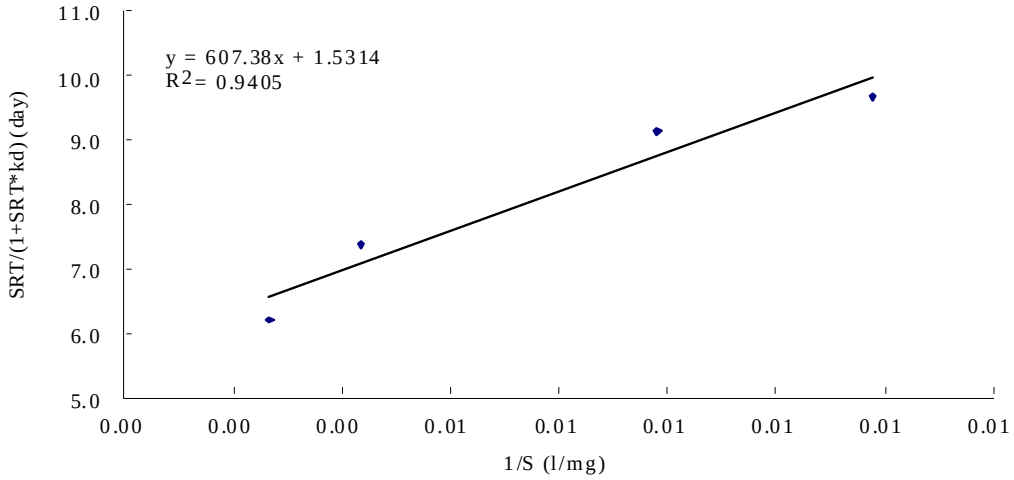


**Fig. 3. Determination of $\mu_m$ and $K_s$ at MLSS 5000 mg/L**

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 ($\mu$) appeared to be predominant at lower SRT while those species having lower value of $\mu$ 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 |

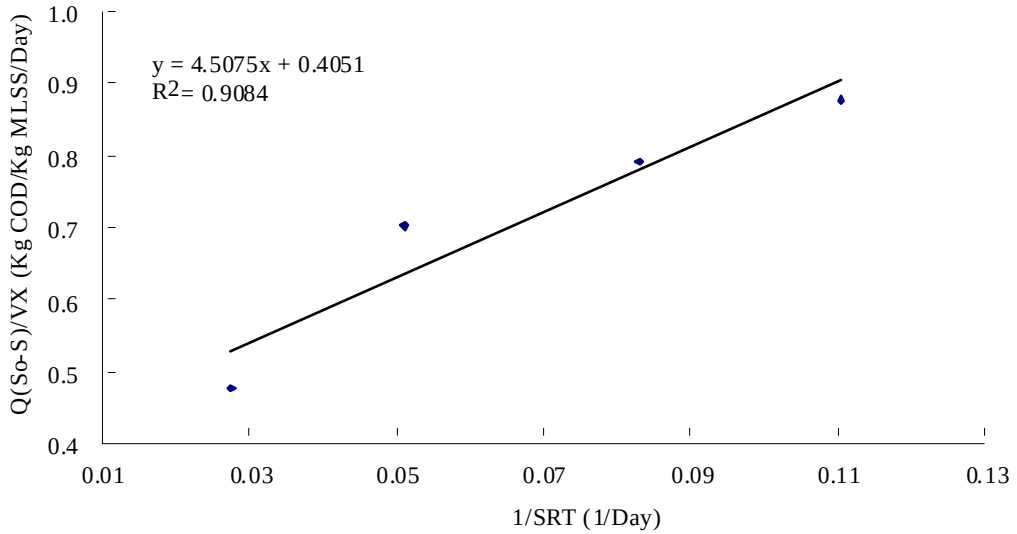


**Fig. 4. Determination of $Y$ and $k_d$ at MLSS 3000 mg/L**

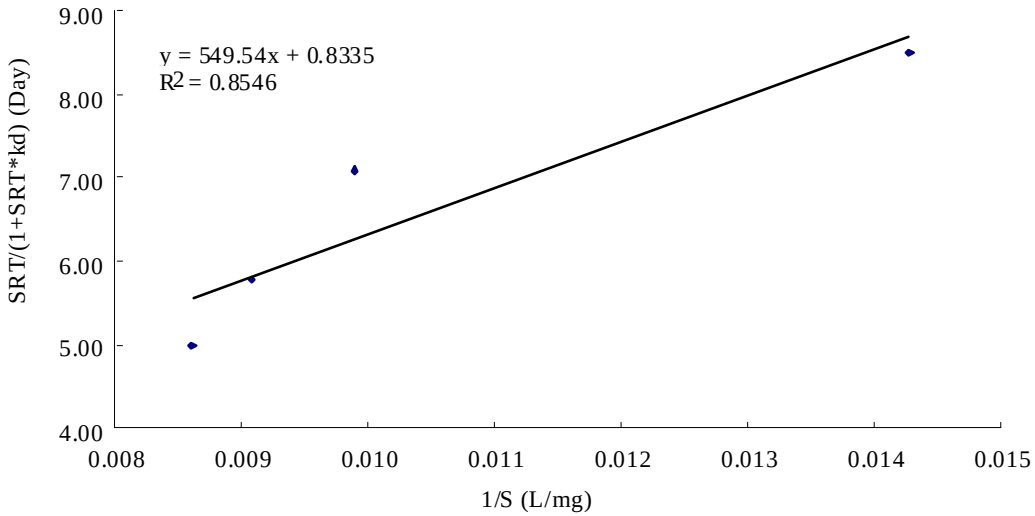


**Fig. 5. Determination of $\mu_m$ and $K_s$ at MLSS 3000 mg/L**

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

| MLSS, mg/L | *Y* (mg/mg) | $K_d$ (/day) | $\mu_m$ (/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, $k_d$, $\mu_m$ 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 $k_d$, $\mu_m$ and $K_S$ were individually varied by ±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 $\mu_m$ is inversely proportional to the effluent substrate concentration. Regardless of the MLSS concentration, the effluent substrate concentration was found to be more sensitive to $\mu_m$ 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 $\mu_m$ is dealt with, since small variations in $\mu_m$ can result in significant changes in the values of the effluent substrate concentration.

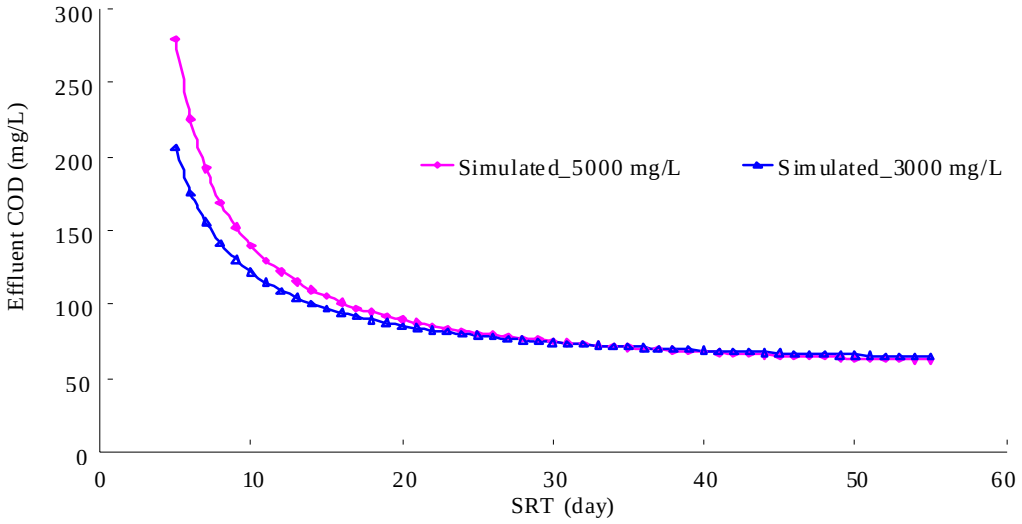


**Fig. 6. Simulated Effluent COD for Different MLSS concentrations**

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

| Substrate | Basis of analysis | $Y$ (mg/mg) | $k_d$ ($day^{-1}$) | $\mu_m$ ($day^{-1}$) | $K_s$ (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 |

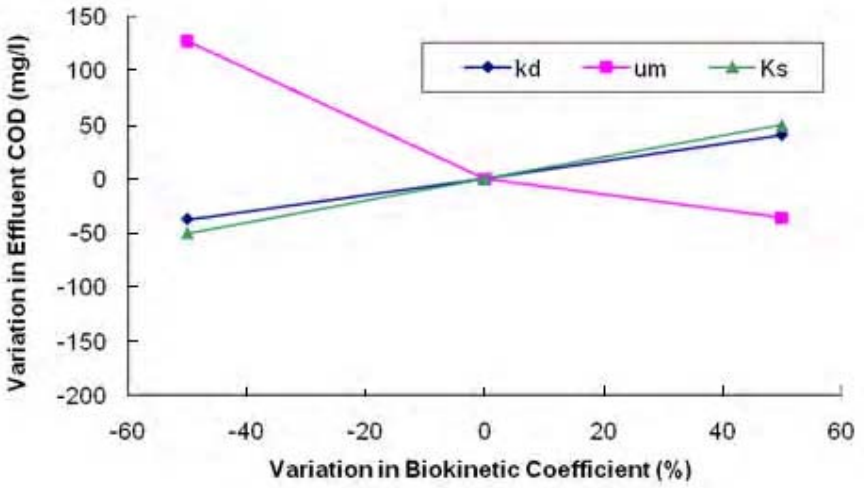


**Fig. 7. Sensitivity analysis of biokinetic coefficients at MLSS of 5000 mg/L**

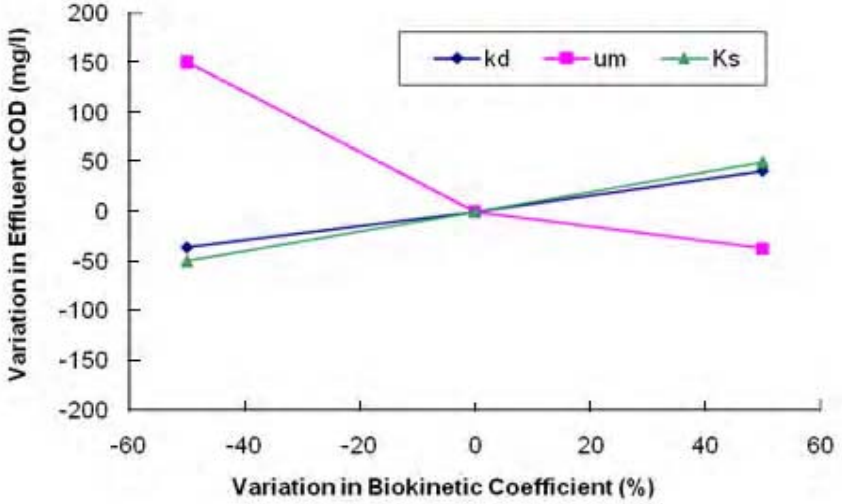


**Fig. 8. Sensitivity analysis of biokinetic coefficients at MLSS of 3000 mg/L**

## CONCLUSION

Biokinetic coefficients $Y$, $k_d$, $\mu_m$ 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 $\mu_m$ 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 $\mu_m$ is dealt with, since small variations in $\mu_m$ can result in significant changes in the values of the effluent substrate concentration.

kaalkei jeno chhobi pai.
bujchho???
Oneeek valo theko..
aj hoyto ar boshbo na...onek kaj
Allah Hafiz.

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