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Modelling of Organic Removal in a Moving Bed Biofilm Reactor (MBBR)

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In this paper, a new Moving Bed Biofilm Reactor (MBBR) has been developed, in which biomass is attached to small plastic elements that move freely in the bioreactor. The biofilm carrier elements, shaped like small corrugated cylinders, are made of polyethylene with a density of 0.95 gr/cm^3 slightly lower than the density of water, allowing them to circulate with the currents in the reactor. The unit was tested under different organic loads and the substrate loading removal rate was compared with predictions of the Kincannon-Stover and Monod models. In this experiment, the influent COD concentration was between 225 mg/l to 4370 mg/l. The Hydraulic Retention Time (HRT) was 24 hr and the temperature was kept constant at 25°C. Data analysis indicates that the Kincannon-Stover model can produce the best fit with the experimental results. The kinetic studies indicate that the biofilm diffusion is a more important parameter in controlling the mass transfer phenomena compared to hydraulic factors in the system.

INTRODUCTION

In 1988, the state pollution control authority of Norway recommended the design of small wastewater treatment plants [1]. At that time, a Norwegian company (Kaldnes Miljøteknologi A/S), together with the SINTEF research organization that were developing the so-called "Moving Bed Biofilm Reactor (MBBR)" initiated the construction of small treatment plants according to these recommendations. The basic idea behind the MBBR was to have a continuously operating system with low head loss, no need for backwashing, a non-cloggable biofilm reactor with high specific biofilm surface area, no need for sludge recycling, no bulking problem and satisfactory operation under high loads. The result of these studies was the development of a bioreactor with floating packing, which was then called the Moving Bed Biofilm Reactor (MBBR).

In this system, the microorganisms (biofilm or biomass) grow on small carrier elements that move freely with water in the reactor. Due to errosion caused by frequent collision between the plastic elements, very little biofilm grows on the outside surface of carrier elements, however, floating microorganisms appear to have some effect on the efficiency of organic removal.

The flow regime is a completely mixed system with no "dead" or unused space in the reactor. Although the results of many studies on the performance and application of MBBR have been published so far, very little attempt has been made to describe the kinetics and modeling of this reactor.

In this research, the organic removal rate in a new MBBR system (using corrugated cylinders as packing, shown in Figure 1) was studied and different mathematical models, which could describe the behavior of the reactor, were tested. The objective was to find a model which could closely follow the

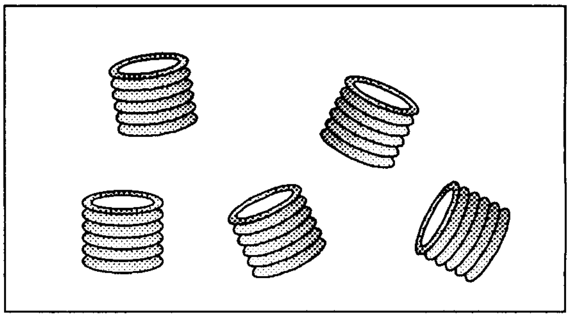

Figure 1. Carrier elements in bioreactor. Height: 1.1 cm; thickness: 0.5 mm and diameter: 1.5 cm.

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experimental results and could describe the kinetics of the system.

Mathematical models for the description of the biofilm processes, especially biological filters and Rotating Biological Contactors (RBC), have been proposed in [2-8].

Kincannon and Stover [8] proposed a design concept for biofilm systems based on total organic loading rate and established a kinetic model for such reactors. Experiments and research carried out on moving bed biofilm reactors indicate that the models proposed by Monod and Stover-Kincannon are the closest models, which can describe the process and predict the results.

The main difference between the two models is that in Kincannon-Stover model, the substrate utilization rate is expressed as a function of the organic loading rate, which is considered to be the most important parameter influencing the behavior of the reactor.

MATERIALS AND METHODS

The experiments were performed in laboratory and pilot scale. A simplified flow-sheet of the pilot scale plant is shown in Figure 2. The pilot plant consisted of a 4 mm-wall thickness plexiglass tube with 15 cm inner diameter and 150 cm height. The effective height of the unit was 126 cm, incorporating a reactor volume of 22 l. Sampling taps were provided along the height of the reactor for extraction of samples for analysis.

The bioreactor was filled with floating biofilm carrier elements which were made of polyethylene with a density of 0.96 gr/cm^3 slightly lower than the density of water and shaped like small corrugated cylinders, providing a specific inside surface area of about 300 m^2/m^3.

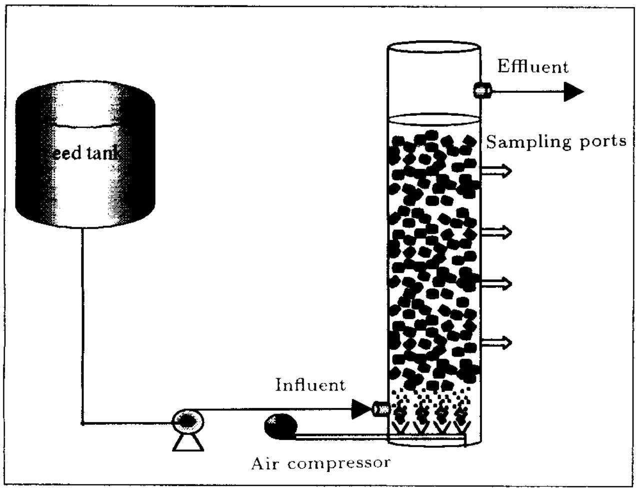

Figure 2. Schematic diagram of pilot scale moving bed biofilm reactor.

Table 1. Composition of the prepared substrate.

Composition	mg/l
Calcium	20.5
Sodium	9.2
Potassium	24
Zinc	0.25
Iron	0.208
Manganese	0.048
Ammonia-Nitrogen	15.25
Magnesium	10
Nickel	0.083
Ammonium Phosphate	17.39
Urea	80.15
COD	750

The floating biofilm medium is shown schematically in Figure 1.

The movement of carrier elements in MBBR systems is caused by aeration in the aerobic version of the reactor or mechanical mixers when the aeration is insufficient to provide circulation. In the present unit, aeration was used as the mechanical force for circulation of carrier elements; moreover, to keep the biofilm media in the reactor, a sieve (with 5 mm opening) was placed at the outlet of the reactor. Percentage occupation of plastic elements in the reactor was about 70% (volumetric filling of plastic elements in an empty reactor) which indicated that the specific and effective inside surface area was approximately 250 m^2/m^3.

Before starting the experiments, tracer studies were carried out to find the hydraulic characteristics of the flow in the reactor. Applying lithium chloride as tracer, it was found that the flow regime inside the reactor was completely mixed.

Dissolved Oxygen concentration (DO) was normally kept above 4 gr.O$_2$/m^3. The pH varied between 6.5 to 7.6 and the temperature was about 25$\pm$1°C. The prepared synthetic wastewater used as the reactor feed consisted of beet sugar molasses diluted with tap water and some added nutrients. Each gram of molasses has a COD concentration equal to 750 mg/l. Table 1 shows the characteristic of the synthetic wastewater used as the feed of the pilot reactor during the test period using 1 gram per liter of water. More concentrated feed was prepared using more molasses.

All analyses for COD, TSS, MLSS and MLVSS were conducted in accordance with the Standard Method for the Examination of Water and Wastewater [9].

START UP

To start the reactor, sludge samples from the aeration tank of a conventional activated sludge plant

Table 2. Experimental values.

Date	HRT (hr)	COD_{in} (mg/l)	COD_{out} (mg/l)	kg/m^3.day	gr/m^2.day	VSS (mg/l)
24/4/2000	24	225	31	0.225	0.682	380
27/4/2000	24	258	41	0.258	0.781	420.3
30/4/2000	24	321	62	0.321	0.972	470
3/5/2000	24	371	71	0.371	1.124	200.5
6/5/2000	24	422	47	0.422	1.278	537.6
8/5/2000	24	470	61	0.470	1.424	586.53
10/5/2000	24	512	51	0.512	1.551	623
18/5/2000	24	561	49	0.561	1.699	663.5
22/5/2000	24	607	59	0.607	1.839	712.05
24/5/2000	24	647	71	0.647	1.960	709
27/5/2000	24	721	99	0.721	2.184	790.3
29/5/2000	24	764	131	0.746	2.260	825.57
31/5/2000	24	830	159	0.830	2.514	870.9
3/6/2000	24	869	181	0.869	2.632	860.11
5/6/2000	24	911	201	0.911	2.759	947
7/6/2000	24	959	209	0.959	2.905	990
10/6/2000	24	1019	248	1.019	3.087	1020.8
18/6/2000	24	1208	288	1.208	3.659	1070
21/6/2000	24	1348	368	1.348	4.083	1075.6
24/6/2000	24	1498	448	1.498	4.537	1120
3/7/2000	24	2011	647	20.11	6.091	1192.3
10/7/2000	24	2319	742	2.319	7.024	1230
12/7/2000	24	2998	1141	2.998	9.081	1237.6
20/7/2000	24	3361	1241	3.361	10.180	1314.3
22/7/2000	24	3721	1488	3.721	11.271	1360.8
25/7/2000	24	4280	1712	4.280	12.964	1392.67
29/7/2000	24	4361	1918	4.361	13.209	1470

near Tehran was used for inoculation. Phosphorous, nitrogen and micronutrients were added and pH was adjusted to 7 using sodium carbonate. After three or four weeks, significant biofilm was grown on carrier elements and the continuous feeding of synthetic wastewater was started. The reactor was first fed at an Organic Loading Rate (OLR) of 50 gr.COD/m^3.day, which gradually increased to 400 gr.COD/m^3.day at the end of the fourth week. After start-up, the COD concentration was increased from 225 mg/l to 4370 mg/l at hydraulic retention time of 24 hr. During this period, while increasing the COD concentration, VSS (volatile suspended solids or the suspended biomass) was increased from 1000 mg/l to 3500 mg/l; therefore, the ratio of suspended solid in the reactor to fixed film biomass varied from 0.28 to 0.5.

RESULTS AND DISCUSSION

Several methods have been used to describe the overall kinetics of biological and biofilm reactors. Here, the Kincannon-Stover and Monod models were selected for considering COD removal in moving bed biofilm reactors. It was assumed that steady-state conditions prevailed throughout the reactor and the experimentation. Table 2 shows the complete experimental results.

Kincannon-Stover Model

Equation 1 is Kincannon-Stover model, which was first used for RBC (Rotating Biological Contactor) systems. In that model, the disc surface area A is used to represent some relationship to the total attached-growth active biomass concentration in an RBC.

$$\frac{ds'}{dt} = \frac{U'_{\mathrm{Max}}(\frac{QS_i}{A})}{K'_B + (\frac{QS_i}{A})}, \qquad (1)$$

where ds'/dt is the substrate removal rate (g/m^2.day). In this equation, it is assumed that the suspended solid in the RBC system is negligible in comparison to the attached biomass [8]. Previous study by A. Broch-Due et al. [10] has shown that suspended biomass in the reactor is a significant factor in producing high and stable removal efficiency in moving bed biofilm reactors. They demonstrated that the suspended biomass in this reactor contributes to approximately one half of the total waste removal. Therefore, in Equation 1, volume of the reactor is used instead of the surface area of the carrier elements. Implying this modification results in:

$$\frac{ds}{dt} = \frac{U_{\text{Max}}(\frac{QS_i}{V})}{K_B + (\frac{QS_i}{V})}. \tag{2}$$

A mass balance of substrate into and out of the volume can be made as follows:

$$\frac{ds}{dt} = \frac{Q}{V}(S_i - S_e). \tag{3}$$

Using Equations 2 and 3, the following relationship is obtained:

$$\frac{ds}{dt} = \frac{Q}{V}(S_i - S_e) = \frac{U_{\text{Max}}(\frac{QS_i}{V})}{K_B + (\frac{QS_i}{V})}. \tag{4}$$

Previous studies by Kincannon-Stover [8], Henze and Harremöes [11] have shown that removal rate and efficiency depend on the total organic load rather than the organic concentration or Hydraulic Loading Rate (HLR).

Figure 3 illustrates the experimental data of specific substrate removal rate $Q(S_i - S_e)/V$ versus total organic loading rate QS_i/V. Linearization of Equation 4, results in the following equation:

$$\left(\frac{ds}{dt}\right)^{-1} = \frac{V}{Q(S_i - S_e)} = \frac{K_B}{U_{\text{Max}}}\left(\frac{V}{QS_i}\right) + \frac{1}{U_{\text{Max}}}. \tag{5}$$

Plotting $V/Q(S_i - S_e)$, the inverse of the loading removal rate, against V/QS_i, the inverse of the total organic loading rate, a straight line should be obtained, which is shown in Figure 4. Measuring the intercept and slope of this line, the U_{Max} and K_B can be determined and so were calculated as $K_B = 9.4553$ and $U_{\text{Max}} = 8.3402$. Therefore, the regression line had a R^2 of 0.9941, where R is the degree of regression.

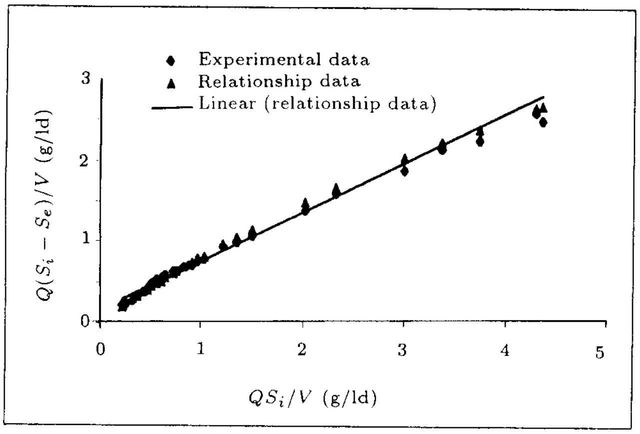

Figure 3. Removal loading rate versus total loading rate by Kincannon-Stover equation.

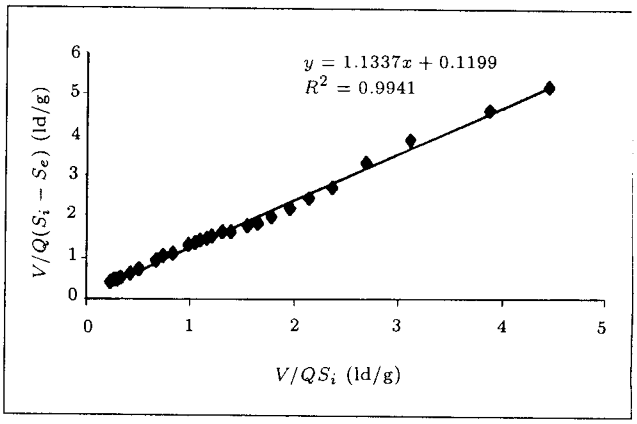

Figure 4. Kincannon-Stover model.

Substituting Equation 5 into Equation 3, results in:

$$QS_i = QS_e + \left(\frac{U_{\max}(\frac{QS_i}{V})}{K_B + (\frac{QS_i}{V})}\right)V. \tag{6}$$

This equation can then be solved for either the volume of reactor or the effluent substrate concentration. Thus:

$$V = \frac{QS_i}{(\frac{U_{\text{Max}}S_i}{S_i - S_e}) - K_B}, \tag{7}$$

$$S_e = S_i - \frac{U_{\text{Max}}S_i}{K_B + \frac{QS_i}{V}}. \tag{8}$$

Substituting $K_B = 9.4553$ and $U_{\text{Max}} = 8.3402$ in Equations 7 and 8 results in the following:

$$S_e = S_i - \frac{8.3402 S_i}{9.4553 + \frac{QS_i}{V}}, \tag{9}$$

$$V = \frac{QS_i}{(\frac{8.3402 S_i}{S_i - S_e}) - 9.4553}. \tag{10}$$

Equations 9 and 10 can be used to calculate the reactor volume and effluent organic concentration for moving bed biofilm reactors, operating under similar circumstances.

Monod model

The Monod model is described as:

$$\frac{ds}{dt} = \frac{Q}{V}(S_i - S_e) = \frac{KXS_e}{K_x + S_e}. \tag{11}$$

Linearization of Equation 11 provides the following relationship:

$$\frac{XV}{Q(S_i - S_e)} = \frac{K_S}{K}\frac{1}{S_e} + \frac{1}{K}. \tag{12}$$

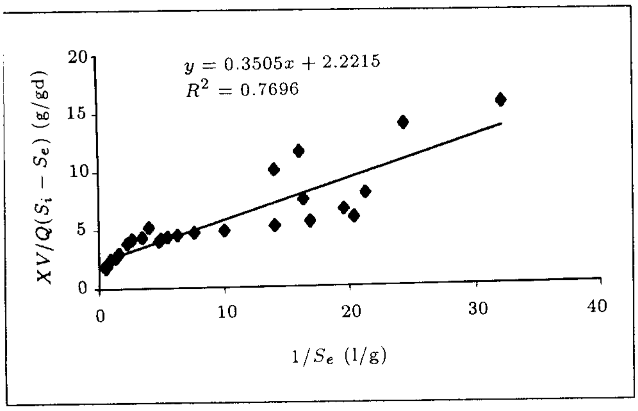

Figure 5. Monod model.

Applying experimental results to Equation 12, Figure 5 is plotted. In this figure, $XV/(S_i - S_e)$ is plotted against $1/S_e$. The K_s and K values obtained from this figure can be estimated as 0.157 g/l and 0.45 l/d, respectively.

In Equation 11, X value is the concentration of Volatile Suspended Solid (VSS) in the reactor. It is the sum of the attached biomass concentration and suspended biomass concentration. The attached biomass concentration was obtained by taking some carrier elements out of the reactor, washing and weighting the detached biomass both in wet and dry conditions. The suspended biomass concentration was obtained by drawing samples from the reactor through taps and, subsequently, measuring the suspended solid concentration. From this figure, the degree of regression (R^2) was found to be 0.7696, which is lower than that found for Kincannon-Stover model. This finding indicates that Kincannon-Stover model is a more applicable model for describing the kinetics of organic removal in moving bed biofilm reactors and, thus, for treating this type of wastewater.

Biofilm Kinetics

Biofilm Kinetics can help to describe substrate removal rate and the parameters which could affect the transport phenomena in microbial films. It is, therefore, very useful to study and understand the mechanisms that control the process. There are two cases which are usually considered in describing the kinetics of biofilms. The first case is the liquid film theory, maintaining that the liquid film thickness is the main obstacle in removal rate, and the second case is the hydraulic film theory, which indicates that flow characteristic is the more important factor in controlling removal rate.

Data analysis of half-order kinetics [12] indicated that soluble COD was the limiting factor in mass transfer diffusion, therefore:

$$r_{V,\mathrm{COD}} = m(S_{\mathrm{COD}})^n \qquad (13)$$

By plotting the COD removal rate versus effluent COD concentration, m and n can be obtained. Thus:

$$Ln(r_{V,\mathrm{COD}}) = Lnm + nLnS_{\mathrm{COD}}. \qquad (14)$$

Actual data points and removal rates predicted by this model are shown in Figure 6. Using this figure, the values for the constants m and n are 6.011 and 0.513, respectively. Substituting these constants in Equation 13, the following equation is obtained:

$$r_{V,\mathrm{COD}} = 6.011 S_{\mathrm{COD}}^{0.513}. \qquad (15)$$

Equation 15 shows that the order of reaction is 0.513, slightly higher than 0.5, which means that both biofilm diffusion and hydraulic film diffusion control the reaction rate. The value of 0.513 is close to 0.5, thus the effect of hydraulic film seems to be negligible. The reason behind this behavior can be explained by the strong turbulence caused due to high air flow rates throughout the reactor, minimizing the effect of hydraulic film diffusion. Based on the experimental results, Hem and his coworkers [13] proposed that at low air flow rates, the hydraulic film diffusion is an important parameter in moving bed biofilm reactors, but at high aeration rate the effect of hydraulic film is negligible.

CONCLUSIONS

1. Kincannon-Stover model is one of the best mathematical models for describing the substrate removal rate in moving bed biofilm reactors.
2. Using Kincannon-Stover model, the reactor volume and effluent substrate concentration can be determined if the model constants are available.
3. In the present study, Kincannon-Stover model constants U_{Max} and K_B were found to be 8.3402 and 9.4553, respectively.

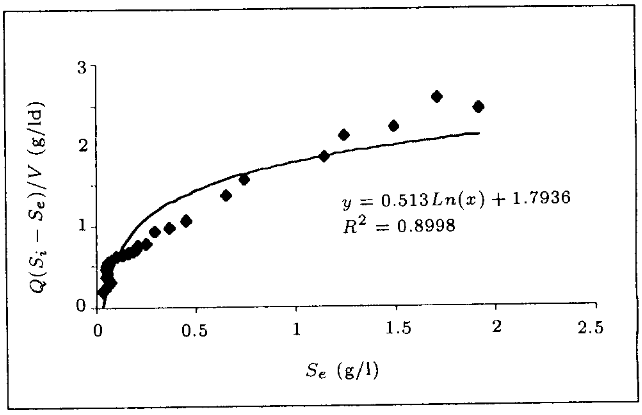

Figure 6. COD removal rate versus effluent concentration.

4. Based on the experiments and data analysis on biofilm kinetics, it was concluded that both biofilm diffusion and hydraulic diffusion are limiting factors in moving bed biofilm reactors at low air flow rates; however, at high air flow rates, strong turbulence caused by air flow reduces the effect of liquid film diffusion.

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NOMENCLATURE

ds/dt	substrate removal rate (g/l.d)
ds'/dt	substrate removal rate (g/m^2.d)
U_{Max}	maximum utilization rate constant (g/l.d)
U'_{Max}	maximum utilization rate constant (g/m^2.d)
Q	flow rate (l/d)
S_i	influent COD concentration (g/l)
S_e	effluent COD concentration (g/l)
K_B	saturation constant (g/l.d)
K'_B	saturation constant (g/m^2.d)
K_S	half velocity constant (g/l)
K	maximum substrate removal rate (d^{-1})
$K_{1/2}$	half order reaction constant $[(\text{g O}_2\text{m}^{-1})^{1/2}d^{-1}]$
r_A	reaction rate per unit area ($\text{gm}^{-2}d^{-1}$)
X	biomass concentration (VSS) (g/l)
V	reactor volume
S_{COD}	soluble COD concentration in the reactor (g/l)
λ	dimensionless parameter
$r_{V,\text{COD}}$	volumetric removal rate of total COD(g/l.d)
m, n	constants
A	surface area of carriers (m^2)

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