PARAMETRIC SENSITIVITY ANALYSIS OF AN AEROBIC HYBRID GROWTH PROCESS MODEL

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(Received 10 August 2002 Accepted 11 February 2003)

ABSTRACT

Experiments were performed on a laboratory scale hybrid bioreactor consisting of an aeration tank to which support media were added to simulate both suspended and attached growth reactors, a secondary clarifier, and a recycling system. The bioreactor was operated for a period of two months using synthetic wastewater as the substrate medium. Support media were added to the reactor in stages of six nets each stage, so as to evaluate the impact of the addition of the support media on the efficiency of treatment. Relevant parameters were measured regularly and a theoretical model describing the steady state kinetic reactions occurring in this hybrid biological reactor system was then developed. The process state was defined by (1) the effluent substrate concentration (S_e); (2) the suspended microorganisms in the bulk liquid medium (X); (3) the effluent BOD (BOD_{5e}); and (4) the biofilm substrate concentration (S_f). The sensitivity of each of the four state variables to kinetic parameters, and system design variables were investigated under steady-state conditions. The accuracy of the mathematical models used in predicting the performance of the hybrid system was affirmed by comparison with the experimental results. The addition of the nets showed also positive effects on BOD and COD removal efficiencies. The sensitivity analysis showed that the main parameters affecting the process state variables were k and K_s. The analysis identified limitations on kinetic parameters. For instance, k values should be between 2 and 3 d^{-1} and Y values must range between 0.4 to 0.45 mg/mg.

Keywords: activated sludge, attached and suspended growth, hybrid system, mathematical model

INTRODUCTION

Hybrid biological processes have been developed for improving the performance of conventional activated sludge systems (Atkinson *et al.,* 1974; Guarino *et al.,* 1980; Harrison *et al.,* 1984; Warner *et al.,* 1988; and Tyagi and Vembu, 1990). Introducing support media into the aeration basin, with the objective of cultivating biomass on the surface of these media, results in a system that combines both suspended and attached microorganisms, and produces an increased concentration of biomass in the reactor with reduced dependency on

secondary clarification. An increase in biomass in a conventional activated sludge reactor was not favored in the past because of problems presented in the separation of large quantities of biomass in the secondary clarifier. However, with the introduction of the hybrid biological reactor, these problems were eliminated because of the attachment of the bulk of the biomass to the support medium. Studies conducted on operating hybrid biological reactors reported a two to five fold increase in biomass concentration compared to that in a conventional activated sludge process. They also showed that this process leads to a reduced volume of aeration tank, increased treatment system stability, and improved performance in the form of increased BOD removal and solids settling (Warner *et al.,* 1988; Tyagi and Vembu, 1990). It has been also found that in systems where the biofilm was present, nitrification became independent of the solids retention time of the suspended biomass because nitrifying bacteria were predominantly attached on the support material (Warner *et al.* 1988). Moreover, hybrid reactors showed improvement in anaerobic treatment processes. The upflow anaerobic sludge blanket (UASB) reactors increased the stability of the process and helped maintain steady methane production (Lo *et al.* 1994; Cordoba *et al.,* 1994; Kalyuzhnyi *et al.,* 1997; Timur and Ozturk, 1997).

The biomass support media that are commonly used vary in shape, size, and material. They could be stationary or mobile depending on their size. Macrocarriers in the form of modular plastic media and synthetic fiber media are normally fixed in the aeration tank, while porous polyurethane media are suspended. Microcarriers (less than 1,000 μm in size) are invariably used in the suspended form. These provide a large surface area for biomass fixation without reducing the effective volume of the reactor. However, they present a draw back in that special measures are needed for their separation and recycling in order to retain them in the aeration tank. Various types of modular plastic packing materials have been used recently as carriers in full-scale applications (Tyagi and Vembu, 1990). In general, all carriers added to aeration tanks improved the effectiveness of treatment by increasing the activated sludge settling rate, decreasing the sludge volume index and the effluent residual organics, and increasing the clarity of the effluent.

This paper describes an experimental setup of a pilot scale hybrid reactor with coresponding results. A comprehensive mathematical model of a hybrid biological system is presented with its governing equations. The model is then used to evaluate the steady-state process sensitivity to various variables that may influence the system.

EXPERIMENTAL SETUP

The experimental work consisted of designing and consructing a laboratory scale hybrid bioreactor using a support media (Figure 1). A Plexiglas tank (74 cm x 24.5 cm x 20 cm) with a 28 L effective volume, was used as the aeration tank. Plastic nets were placed in the tank. Each net contained 160 cells and each cell has a square face with a side of 1.25 cm and a depth of 0.9 cm with an equivalent surface area of 4.5 cm^2. When immersed in the tank, each net replaced an equivalent of 0.1 L (0.357%) of the effective capacity of the tank. A square hopper-bottomed clarifier with variable outlet levels that provided effective storage volumes of 3, 4.2, 5.3, and 6.25 L was connected to the reactor and was provided with a sludge recycling system composed of a variable flow peristaltic pump. Compressed air was supplied to the reactor through fine-grained porous stone diffuser heads located along one side

at the base of the reactor. The flow was measured and controlled using a rota-flow meter before being released through the diffuser heads.

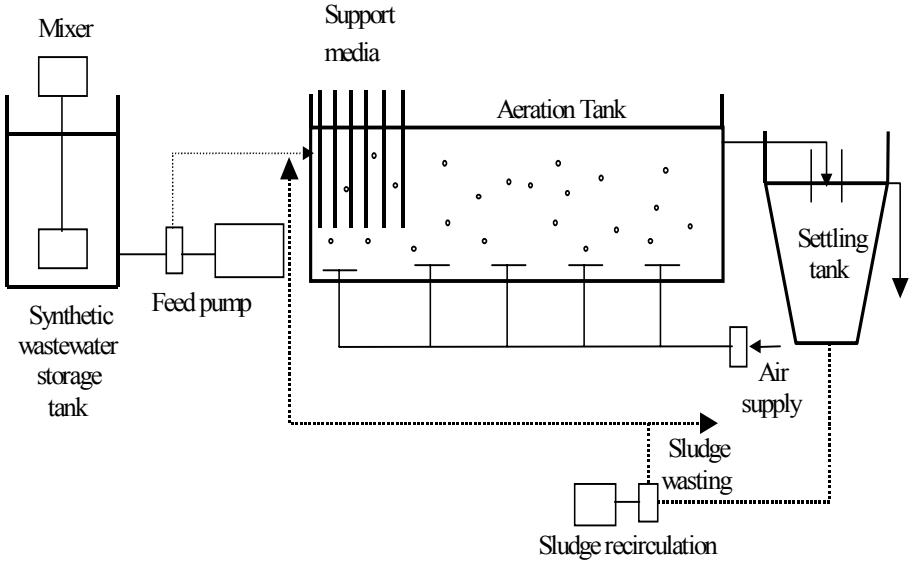

Figure 1. Schematic diagram of the hybrid biological reactor.

Synthetic wastewater, which was prepared by mixing an array of pre-weighed chemicals (Table 1), was used in the experiments.

TABLE 1
Synthetic Wastewater Composition

Constituent	Concentration (mg/l)
$C_{12}H_{22}O_{11}$	300
$(NH_4)_2.SO_4$	75
$MgSO_4.7H_2O$	10
K_2HPO_4	18
$MnSO_4.H_2O$	1
$CaCl_2$	0.26
$FeCl_3.6H_2O$	0.05

Continuous mixing was performed by means of a motorized stirring rod in a 100L cylindrical plastic tank. The wastewater was transferred to the reactor at a rate of 70 ml/min by adjusting the inflow pump speed and ancillary valves. The flow was maintained at this rate, giving a detention period in the reactor of about 6-7 hours, throughout the experimental period. The synthetic wastewater was seeded in the reactor with a 100 ml aliquot of fresh

sewage collected from a sewer outfall located about one km from the laboratory. This was followed by a two-week acclimatization period. The sludge-recycling pump was calibrated to operate at a constant flow rate. Sludge wasting was manually performed on a daily basis, and the wasted volume recorded. Samples were collected from the sludge recycling line to determine the concentration of the return sludge (X_r). Over the first month, the system was operated as a conventional activated sludge system. Four sets of six nets each were then introduced in a time-staggered mode in the aeration reactor. Four operating stages were thus achieved in which the reactor contained 6, 12, 18, and 24 nets, respectively. Each stage was studied for one week and the experimental results were recorded (Gebara, 1998a and b).

MATHEMATICAL MODEL

The aeration reactor in the hybrid growth model can be viewed as two reactors in series. The plastic nets form the first reactor while the bulk water volume forms the second reactor. Generally, the first reactor is modeled using an attached growth biofilm model, while the second reactor is modeled as an activated sludge model. Naturally, a hybrid growth model is a combination of both models.

Conventional Activated Sludge Model

A mass balance for the biomass and substrate concentration in a conventional activated sludge reactor (Figure 2) with sludge recycling can be represented by Equations 1 and 2, respectively.

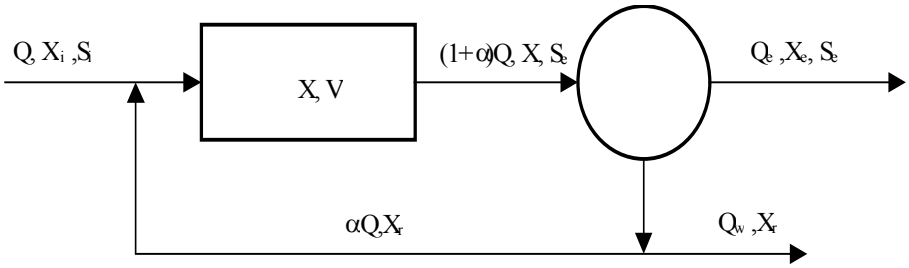

Figure 2. Conventional activated sludge process with sludge recycling.

$$\frac{dX}{dt} = (QX_i + \alpha QX_r) - (1+\alpha)QX + \mu XV - k_d XV \quad (1)$$

$$X = \frac{\theta_c Y(S_i - S_e)}{\theta_h(1+\theta_c k_d)} \quad (1a)$$

$$S_e = \frac{K_s(1+k_d\theta_c)}{\theta_c(kY - k_d) - 1} \quad (1b)$$

$$\mu = \frac{\mu_m S_e}{(K_s + S_e)} \tag{1c}$$

$$V\frac{dS}{dt} = QS_i - (1+\alpha)QS_e - \mu\frac{XV}{Y} \tag{2}$$

where

X	=	biomass concentration, M/L^3
S_e	=	effluent substrate concentration, M/L^3
t	=	time, T
V	=	reactor volume, L^3
Q	=	flow rate, L^3/T
X_i	=	influent biomass concentration, M/L^3
Q_w	=	sludge wasting flow rate, L^3/T
X_r	=	recycled biomass concentration, M/L^3
Q_e	=	effluent flow rate, L^3/T
X_e	=	effluent biomass concentration, M/L^3
k	=	maximum substrate degradation rate, 1/T
Y	=	cell yield units
K_s	=	half-velocity constant, substrate concentration at one-half the maximum growth rate, M/L^3
k_d	=	decay rate, 1/T
θ_c	=	sludge age, T
θ_h	=	hydraulic detention time, T
α	=	recycle ratio
μ	=	specific growth rate, 1/T
μ_m	=	maximum specific growth rate, 1/T
S_i	=	influent substrate concentration, M/L^3

Assuming that the concentration of the biomass in the influent (X_i) may be neglected, and that steady state conditions prevail (dX/dt = 0 and dS/dt = 0), Equations (1) and (2) can be reduced to:

$$X = \frac{Y[S_i - (1+\alpha)S_e] + \alpha X_r}{1 + \alpha\left(\frac{k_d}{D}\right)} \tag{3}$$

$$aS_e^2 + bS_e + c = 0 \tag{4}$$

$D = Q/V$

$a = (1+\alpha)^2 D - (1+\alpha)\mu_m + (1+\alpha)k_d$

$b = \mu_m S_i + \left(\frac{\mu_m \alpha X_r}{Y}\right) + K_s(1+\alpha)^2 D + K_s k_d(1+\alpha) - (1+\alpha)DS_i - k_d S_i$

$c = -K_s(1+\alpha)DS_i - K_s k_d S_i$

Attached Growth Biofilm Model

The attached growth biofilm model assumes that: (a) the substrate utilization inside the biofilm follows the Michaelis-Menten kinetic function for a fully penetrated biofilm, which is expressed by Equation (5); (b) the diffusion of substrate from the bulk liquid of the biofilm follows a simplified form of the Fick's law given by Equation (6); and (c) the rate of substrate utilization inside the biofilm is equal to the rate at which substrate diffuses into the biofilm from the bulk liquid.

$$\frac{dS}{dt} = \left[\frac{kS_f X_f}{(K_s + S_f)}\right] L_f \tag{5}$$

$$J = \frac{D_f (S_i - S_f)}{L_f} \tag{6}$$

$$\left[\frac{kS_f X_f}{K_s + S_f}\right] L_f = \frac{D_f (S_i - S_f)}{L_f} \tag{7}$$

where

S	=	substrate concentration, M/L^3
S_f	=	biofilm substrate concentration, M/L^3
X_f	=	biofilm bacterial concentration, M/L^3
L_f	=	active biofilm thickness, L
J	=	flux of the substrate inside the biofilm, M/L^2T
D_f	=	diffusion coefficient, L^2/T

Based on these three assumptions the final governing equation representing the substrate concentration at steady state ($\frac{dS}{dt} = 0$) can be expressed as Equation (8).

$$aS_f^2 + bS_f + c = 0 \tag{8}$$

$a = 1;$ $\quad b = K_s - S_i + \frac{kX_f L_f^2}{D_f};$ $\quad c = -K_s S_i$

Hybrid Growth Model

The influent substrate concentration (S_i) will leave the first reactor (plastic nets) as substrate concentration (S_1), and the second reactor (aeration tank) will reduce S_1 to the overall aeration tank effluent substrate concentration (S_2) as illustrated in Figure 3. The

effluent substrate concentration in the attached growth reactor can be represented by Equation (9).

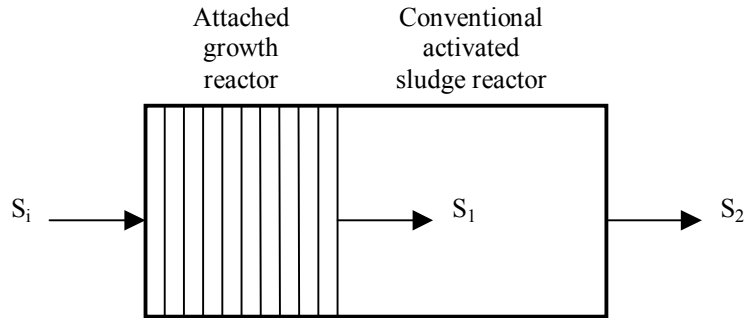

Figure 3. Hybrid model flow process.

$$S_1 = S_i - \frac{JA_cN}{Q} \tag{9}$$

where A_c = surface area of a cell inside the net, L^2
N = number of cells on all nets placed in the aeration tank
Q = flow rate, L^3/T

The effluent substrate concentration (S_2) from the suspended growth reactor is determined from Equation (4) where S_i is replaced by S_1 to give a quadratic equation of the form:

$$aS_2^2 + bS_2 + c = 0 \tag{10}$$

$$a = (1+\alpha)^2 D_2 - (1+\alpha)\mu_{m2} + (1+\alpha)k_{d2}$$

$$b = \mu_m S_1 + \left(\frac{\mu_{m2}\alpha X_r}{Y_2}\right) + K_{s2}(1+\alpha)^2 D_2 + K_{s2}k_{d2}(1+\alpha) - (1+\alpha)D_2 S_1 - k_{d2}S_1$$

$$c = -K_{s2}(1+\alpha)D_2 S_1 - K_{s2}k_{d2}S_1$$

The biomass concentration (X_2) in the suspended growth reactor is determined from Equation (3) where S_i is replaced by S_1 to give:

$$X_2 = \frac{Y_2[S_1 - (1+\alpha)S_2] + \alpha X_r}{1 + \alpha\left(\frac{k_{d2}}{D_2}\right)} \tag{11}$$

If $\theta_c \rightarrow \infty$, the effluent concentration will reach a minimum concentration (S_e^m) which is technically achieved when maximum treatment occurs in the system. S_e^m values can be calculated from Equation (12):

$$S_e^m = \frac{K_s(1 + k_d\theta_c)}{\theta_c(kY - k_d) - 1} \tag{12}$$

Rearranging, neglecting K_s and -1 as being very small compared to θ_c as it approaches ∞, and simplifying Equation (12) yields the following equation;

$$S_e^m = \frac{K_s k_d}{kY - k_d} \tag{13}$$

EXPERIMENTAL RESULTS

Measured parameters

Experimentally measured parameters are presented in Table 2. The data pertain to a steady-state condition averaged for the last two days of each of the five stages of the experiment that extended for a period of at least one week for each stage. The values represent the average of triplicate readings taken for each of the measured parameters except for the SVI which was based on a single reading.

TABLE 2
Experimental Results

Parameter	Definition	Stage – Number of nets				
		0	6	12	18	24
Q (ml/min)	Flow rate	68.5	68.5	685	68.5	68.5
Q_r (ml/min)	Recycled flow rate	70	40	40	40	40
α	Recycling ratio	1.02	0.58	0.58	0.58	0.58
Q_w (ml/d)	Sludge wasting flow rate	667	667	667	667	667
θ_h (d)	Hydraulic detention time	0.28	0.28	0.28	0.28	0.28
MLVSS (mg/l)	Mixed liquor volatile suspended solids	1400	1200	1250	1200	1100
RVSS (mg/l)	Recycled volatile suspended solids	2700	3200	3400	3200	3000
m (mg)	Mass on nets	--	590	590	520	520
COD_i (mg/l)	Chemical oxygen demand (influent)	320	320	320	320	320
COD_e (mg/l)	Chemical oxygen demand (effluent)	90	30	16	14	10
BOD_{5i} (mg/l)	Biochemical oxygen demand (influent)	160	160	160	160	160
BOD_{5e} (mg/l)	Biochemical oxygen demand (effluent)	44	16	8	6	4
SS_e (mg/l)	Suspended solids (effluent)	30	5	2	2	2
SVI (mg/l)	Sludge volume index	350	112	90	78	38

The BOD_5 and COD removal efficiencies as a function of the different experimental stages are depicted in Figure 4. For both parameters, the marked increase in removal efficiency from 72.5 to 90 percent is evident with the addition of the first set of nets. This is followed by a gradual drop in the rising rate of removal upon the addition of more sets of nets. BOD_5 efficiencies of 95, 96.3 and 97.5 percent were recorded with the addition of 12, 18, and 24 nets, respectively. Comparable trends were noted with the COD removal efficiencies where an increase from 71.9 to 90.6 percent was recorded upon the addition of the first set of six nets and to 95, 95.63, and 96.9 percent in the following three stages.

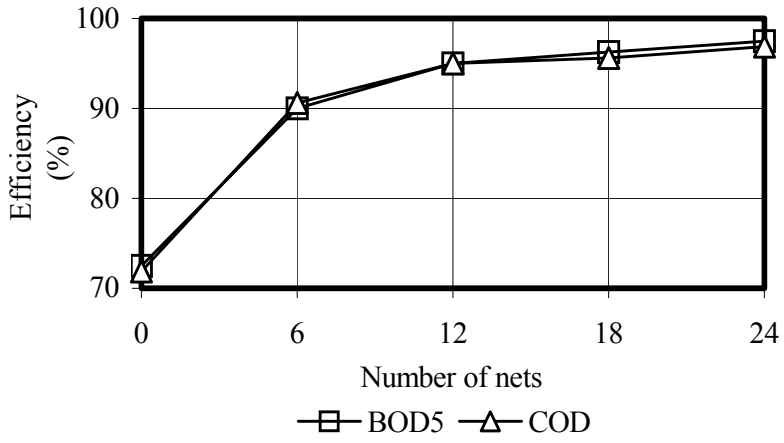

Figure 4. Variation of BOD_5 and COD removal efficiency with number of nets.

The results indicate that an increase in removal efficiency of 17.5 and 18.8 percent was achieved for the BOD_5 and the COD, respectively, on addition of the first six nets and ending by a total increase of 25 percent for the two parameters after the addition of the nets. The reduced values in the BOD_5 removal efficiency, on the addition of 18 and 24 nets, to about 1 percent indicates that the process was reaching stability by moving towards the minimum substrate concentration (S_e^m), which is technically achieved when maximum treatment occurs in the system. Theoretically, this concentration is reached as θ_c approaches $\propto$. In a conventional activated sludge process θ_c cannot be increased indefinitely since the clarification process fails after a certain maximum sludge loading rate. In the present experimental study, this state was accomplished when the biomass concentration in the aeration tank reached 1,400 mg/l. However, when the nets were introduced in the system, the S_e^m became apparent on adding 18 nets. One of the advantages provided by the introduction of supporting media in a conventional activated sludge tank is evident by the fact that the S_e^m may be reached without overloading the clarifier since most of the biomass is retained in the aeration tank.

The sludge settling properties for the process were evaluated from the measurements of the SVI. Measured SVI values as a function of the number of nets in the experiment are shown in Figure 5. The increase in settling efficiency which is proportional to the decrease in the SVI varied by 68, 74, 78 and 89 percent for the four stages where nets were added (6, 12, 18 and 24, respectively). While no significant improvement in the BOD removal was recorded on the addition of 18 and 24 nets, the settling efficiency of the volatile suspended solids increased by 11 percent during the last stage.

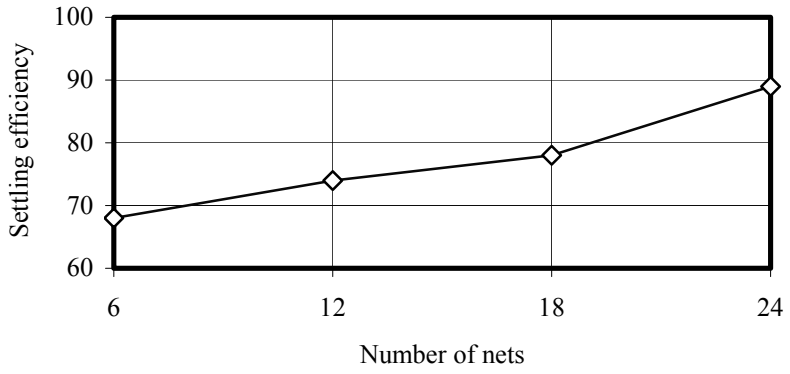

Figure 5. Variation of SVI with number of nets.

Calculated parameters

The calculated parameters included the biofilm bacterial concentration (X_f), the sludge wasting rate (X_w), the sludge age (θ_c), the food to microorganisms ratio (F/M), and the substrate utilization rate (U). X_f is determined by calculating the biofilm cell concentration (X_f^{areal}) from the mass of bacteria collected on one net and then dividing X_f^{areal} by the active biofilm thickness (L_f) as expressed in Equations (14) and (15). The values of X_f and other relevant parameters for the experimental stages are summarized in Table 3.

$$X_f^{areal} = \frac{m}{nA_c} \tag{14}$$

$$X_f = \frac{X_f^{areal}}{L_f} \tag{15}$$

Where n = The number of cells on one net.
A_c = The surface area of a cell inside a net, L^2

TABLE 3
Biofilm Bacterial Density (X_f)

Stage	Mass of Bacteria Per Net (mg)	Areal Bacterial Density X_f^{areal} (mg/cm^2)	Bacterial Density X_f (mg/cm^3)
6 nets	590	0.82	54.63
12 nets	590	0.82	54.63
18 nets	520	0.72	48.15
24 nets	520	0.72	48.15

The values of X_w and θ_c were calculated from Equations (16) and (17), respectively. The total biomass in the aeration tank is calculated using Equation (18). Values of the total biomass in the aeration tank, calculated for the five experimental stages, are presented in Table 4,

$$X_w = (Q_w \text{ x } RVSS) + (Q_e \text{ x } SS_e) \quad (16)$$

$$\theta_c = \frac{VX}{Q_w X + Q_e X_e} \quad (17)$$

$$X = \frac{m}{V} + MLVSS \quad (18)$$

TABLE 4

Total Biomass in the Aeration Tank

Stage	Total Biomass (mg/l)
No nets	1400
6 nets	1326
12 nets	1503
18 nets	1534
24 nets	1546

The F/M ratio and U were calculated from Equations (19) and (20), respectively. For conditions where the nets were fitted in the aeration tank, X in Equations (17), (19), and (20) represents the total biomass. A summary of the calculated results is given in Table 5.

$$\frac{F}{M} = \frac{S_i}{X\theta_h} \quad (19)$$

$$U = \frac{S_i - S_e}{X\theta_h} \tag{20}$$

TABLE 5

Calculated Results

Stage	Calculated Results			
	X_w (mg/d)	θ_c (d)	F/M (1/d)	U (1/d)
No nets	4740	8.27	0.40	0.37
6 nets	2624	12.53	0.43	0.39
12 nets	2464	13.60	0.38	0.36
18 nets	2330	13.49	0.37	0.36
24 nets	2197	12.82	0.37	0.37

MODELED RESULTS

The mathematical model previously described in the paper is used to predict the system output from initial setup parameters. The total biomass in the reactor is calculated using equations (11) and (18). Whereas the clarifier effluent BOD_5 is the sum of the aeration tank effluent substrate concentration and the biochemical oxygen demand for the volatile suspended solids. The theoretical ultimate oxygen demand for the volatile suspended solids is 1.42 mg O_2/mg VSS, and the five days biochemical oxygen demand is 0.68 times the ultimate oxygen demand (Metcalf and Eddy, 1991). The BOD equation will be as follows:

$$BOD_{5e} = S_2^* + 0.68x1.42xSS_e \tag{21}$$

Using the data given in Table 2, the modeled results are then calculated. Figures 6 presents the modeled against the experimental data indicating a good fit.

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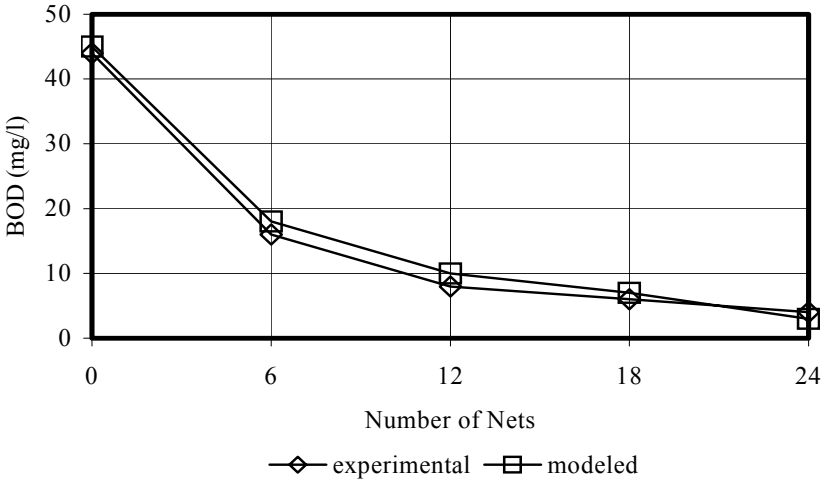
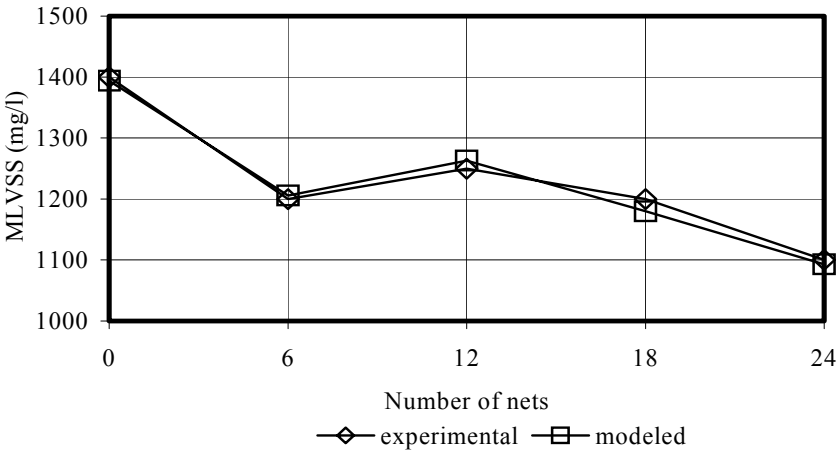
* S_2 is calculated using Equation (10)



(a) BOD



(b) MLVSS

Figure 6. Simulated versus experimental results.

SENSITIVITY ANALYSIS

The sensitivity analysis focused on the effect of variation in model parameters (k, K_s, k_d, Y, D_f and L_f) on state variables, namely (S_e), (X), (S_f) and (BOD_e). Bacterial properties (kinetic coefficients and biofilm characteristics) were emphasized rather than physical and design properties of the system setup. The basic parameters used in conducting the sensitivity analysis are summarized in Table 6. The results presented below are obtained by varying one parameter at a time while holding all other parameters constant. The range of variation for each parameter was selected in accordance to values reported in the literature.

TABLE 6

Reference Parameter Values

Parameter	Average Value	Range	Reference
k (d^{-1})	2.08	2-10	Metcalf & Eddy, 1991
K_s (mg/l)	87	25-100	
K_d (d^{-1})	0.08	(2.5-7.5)x10^{-2}	
Y (mg/mg)	0.72	0.4-0.8	
D_f (cm^2/s)	4.55×10^{-6}	(4.37-4.77)x10^{-6}	Vaughan and Holder, 1984
L_f (μm)	150	50-200	Tyagi and Vembu, 1990
V (l)	28		Experimental Setup
Q (ml/min)	68.5		
X_f (mg/cm^3)	54.63		
SS_e (mg/l)	2		
N (nets)	12		
BOD_i (mg/l)	160		

k versus State Variables

The sensitivity of the state variables with respect to the maximum rate of substrate utilization per unit mass of microorganisms (k) is demonstrated in Figure 7. As k increases, X, BOD, S_f and S_e decrease. Intuitively, the growth of microorganisms (X) should increase with the rate of substrate utilization but the model showed minimal variation of X with respect to k (-0.48 percent). The relative variations of BOD and S_e reached -470 and -340 percent, respectively. A decrease in S_e with increase in k indicates better effluent quality. The important aspect to note in Figure 8 is that S_e becomes smaller than S_e^m at certain values of k, which is theoretically impossible. This observation implies restrictions on acceptable values for k (2-3 d^{-1}) outside of which the model is not valid.

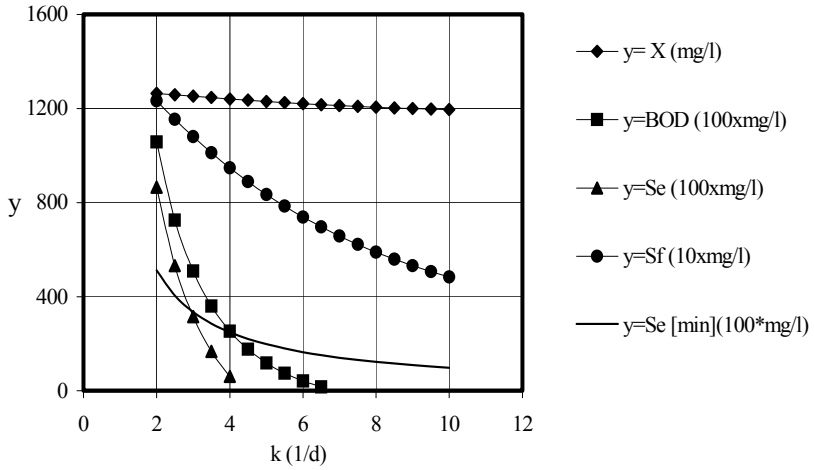


Figure 7. Effect of k on state variables.

K_s versus State Variables

The variation of the state variables with respect to the half-velocity constant (K_s) is shown in Figure 8. As K_s increases from 25 to 100 mg/l, the state variables X, BOD, S_e and S_f increase by 0.12, 13, 31.3 and 1.6 percent, respectively. The increase in BOD and S_e is evidently more significant in contrast to the increments in X and S_f. This can be attributed to the drop in the substrate utilization, which is directly proportional to K_s.

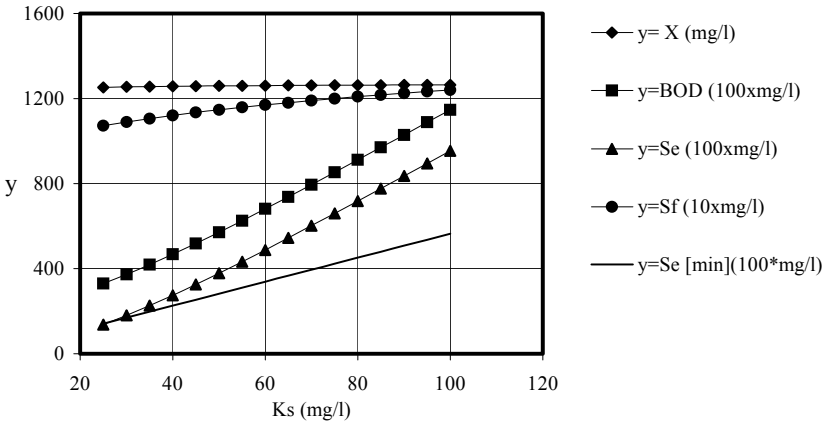


Figure 8. Effect of K_s on state variables.

k_d versus State Variables

The sensitivity of the state variables with respect to the endogenous decay coefficient (k_d) is illustrated in Figure 9. The variation of the state variables with respect to k_d is insignificant (X: -0.08%; BOD: +0.06%; S_e: +0.07%; S_f: 0%). As k_d increases BOD and S_e exhibit minimal change, while X decrease slightly. This can be attributed to the fact that the decay coefficient is not highly dependent on the substrate concentration. As k_d increases more organisms will die leading to a decrease in X. However, the effect is minimal. Note the independence of S_f to changes in K_s is apparent in Equation (8).

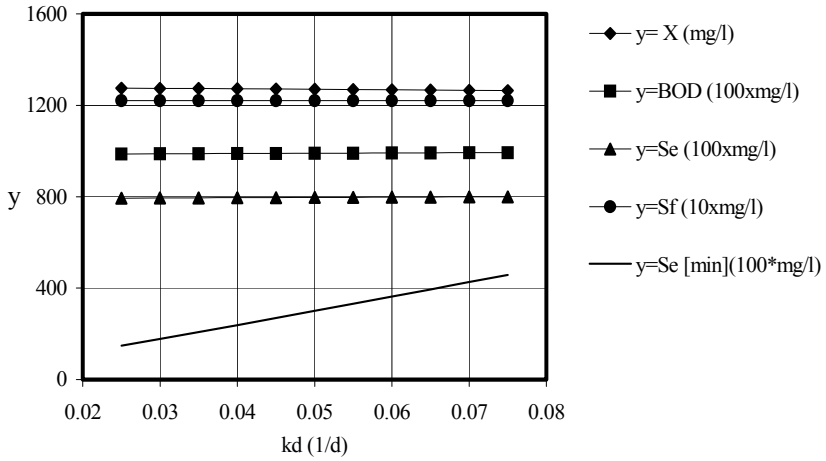


Figure 9. Effect of k_d on state variables.

Y versus State Variables

Figure 10 represents the model sensitivity to the variation in the maximum yield coefficient (Y) measured during a finite period of logarithmic growth (defined as the ratio of the cell mass formed to the mass of substrate consumed). The increase in Y causes an increase in X, a decrease in BOD and S_e, whereas S_f remains constant. The maximum changes of the state variables are relatively minimal: X: +0.07%; BOD: -0.05%; S_e: -0.07%; and S_f: 0%. This can be easily explained through the definition concept of Y. The organisms convert the substrate to produce more cells, thus increasing X, and decreasing BOD and S_e. It is also important to note that as Y increases beyond 0.45mg/mg, S_e gets smaller than S_e^m, which cannot be true. Thus, the range for Y (0.4-0.45mg/mg) must be observed when using the model.

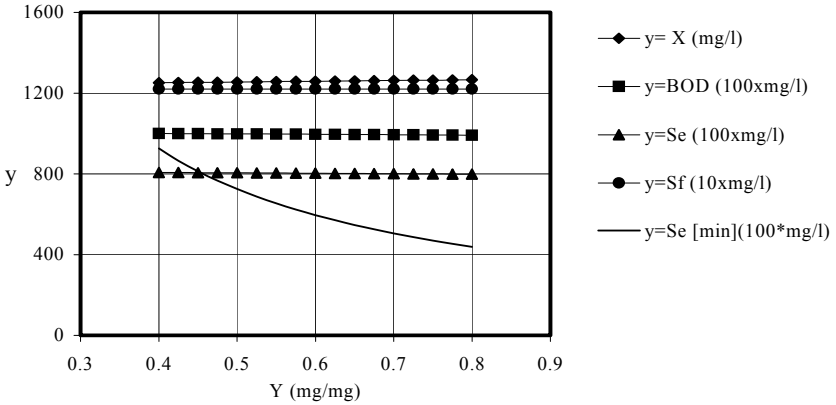


Figure 10. Effect of Y on state variables.

D_f versus State Variables

In spite of the biofilm heterogeneity, the model assumes that substrate are transported by molecular diffusion and, therefore, effective diffusivity is a characteristic constant of the system. The diffusion coefficient varies with temperature and the type of biofilm media. This variation was considered in Figure 11 to assess its effect on state variables. The variation in D_f causes insignificant changes on the state variables. As D_f increases X, BOD and S_e decrease whereas S_f increases; however, this variation is minimal. The maximum relative variations for X, BOD, S_e, and S_f are –0.0027, -0.11, -0.14 and +0.26 percent respectively. The estimation made for calculating D_f from other materials is valid since the substrate in the biofilm (S_f) is not significantly affected by the change in D_f.

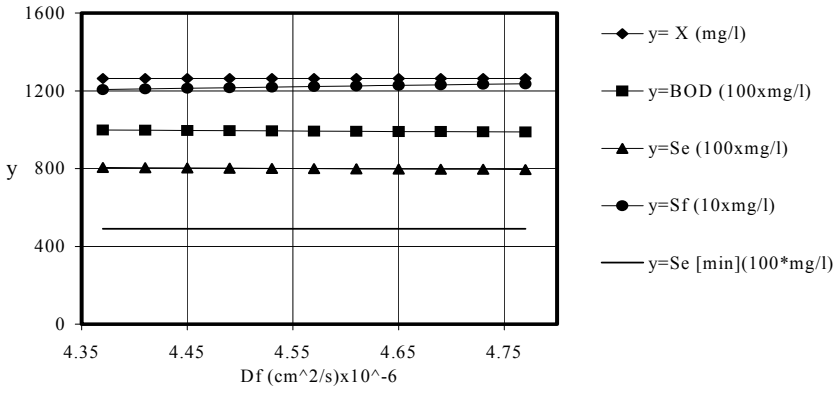


Figure 11. Effect of D_f on state variables.

L_f versus state variables

L_f, defined as the active biofilm thickness, was reported to vary from few microns to more than 1 mm (Tyagi and Vembu, 1990). However, due to mass transfer limitations, only the top layer of a biofilm, ranging in thickness between 50 and 200 μm, is active. Figure 12 illustrates the variation of the state variables with respect to L_f. As L_f increases X, BOD and S_e increase whereas S_f decreases. The diffusion of the substrate into the biofilm becomes subject to increasing resistance, thus, decreasing the substrate concentration in the biofilm. The rejected substrate will increase the concentration in the liquid phase; consequently, the concentration of microorganisms increases. The relative variations are also minimal reaching +0.02, +0.79, +1.00 and -1.82 percent for X, BOD, S_e, and S_f, respectively.

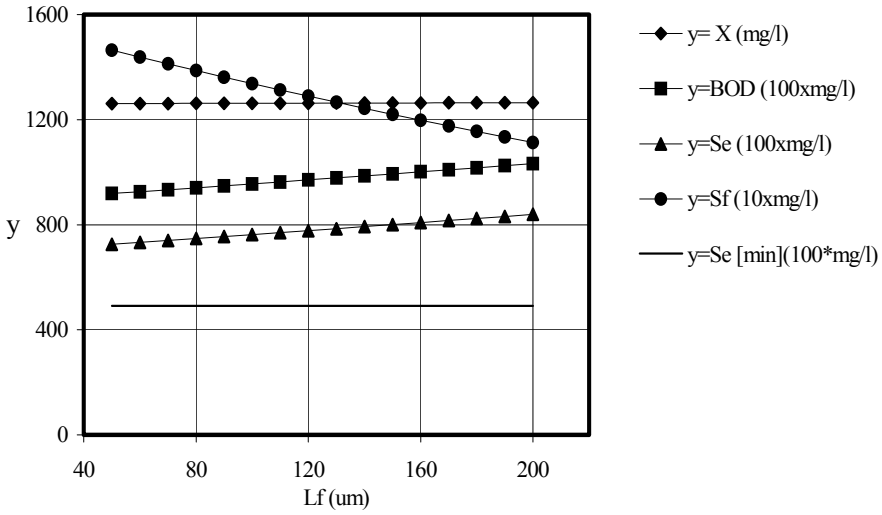


Figure 12. Effect of L_f on state variables.

SUMMARY AND CONCLUSIONS

Plastic nets were placed in the aeration tank of a laboratory scale model to evaluate the performance of a hybrid growth biological system (suspended and attached growth). Biological parameters were measured regularly and a theoretical model describing the steady state kinetic reactions was developed to simulate the experimental results. A sensitivity analysis was conducted to evaluate the effects of variations in kinetic and system design parameters k, K_s, k_d, Y, D_f and L_f) on state variables (S_e, X, BOD_{5e}, and S_f) under steady-state conditions. The study showed that the addition of nets positively affects the BOD_5 and COD removal efficiency (72.5-97.5 percent and 71.9-96.9 percent improvement, respectively) and the settling efficiency (68-89 percent improvement). This fact permits reduction of the aeration tank volume. The mathematical model for the system was experimentally checked

using the labaoratory scale setup. The results affirmed the applicability and accuracy of the model by adequately simulating experimental data. Several conclusions can be derived from the results of the model sensitivity analysis as specified below:

The suspended microorganisms in the bulk liquid are insignificantly varied by the studied parameters which explains the stability of hybrid systems.
The effluent BOD is found to be significantly dependent on k and K_s. A minor variation in BOD concentrations is provoked by the variation in k_d, Y, D_f and L_f.
The effluent substrate concentration seems to be significantly affected by k and K_s. The variation provoked by other parameters is negligible.
The biofilm substrate concentration is significantly dependent on k, while K_s, D_f and L_f provoked a minimal variation. Other parameters were found to have no effect on the substrate concentration.

The mathematical model exhibited several limitations based on sensitivity analysis simulations. It is valid for values of k and Y ranging between 2 and 3 d^{-1} and 0.4 and 0.45 mg/mg, respectively. The limitations on k values are more critical than those for Y, since the system is more sensitive to changes in k than in Y.

ACKNOWLEDGEMENT

The experimental work was conducted at the Environmental Engineering Research Center of the American University of Beirut. The authors wish to express their gratitude to the laboratory staff and students who participated in the experimental set-up and chemical analysis.

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ABBREVIATIONS

A_c	=	surface area of a cell inside a net (L^2)
BOD_{5e}	=	five days biochemical oxygen demand of the effluent (M/L^3)
BOD_{5I}	=	five days biochemical oxygen demand of the influent (M/L^3)
COD_e	=	chemical oxygen demand of the effluent (M/L^3)
COD_i	=	chemical oxygen demand of the influent (M/L^3)
D_f	=	diffusion coefficient (L^2/T)
F/M	=	food to microorganisms ratio (1/T)
J	=	flux of substrate inside the biofilm ($M/L^2.T$)
k	=	maximum substrate degradation rate (1/T)
k_d	=	decay rate (1/T)
K_s (M/L^3)	=	substrate concentration when growth rate is half of maximum
L_f	=	active biofilm thickness (L)
m	=	mass of fixed biomass per net (M)
MLVSS	=	mixed liquor volatile suspended solids (M/L^3)
n	=	number of cells on one net
N	=	number of cells on all nets placed in the aeration tank
Q	=	flow rate (L^3/T)
Q_e	=	effluent flow rate (L^3/T)
Q_r	=	recycled flow rate (L^3/T)
Q_w	=	sludge wasting flow rate (L^3/T)
RVSS	=	returned volatile suspended solids (M/L^3)
S	=	substrate concentration (M/L^3)
S_e	=	effluent substrate concentration (M/L^3)
S^m_e	=	minimum effluent substrate concentration (M/L^3)
S_f	=	biofilm substrate concentration (M/L^3)
S_i	=	influent substrate concentration (M/L^3)
SS_e	=	effluent suspended solids (M/L^3)
SVI	=	sludge volume index (L^3/M)
U	=	substrate utilization rate (1/T)
V	=	aeration tank volume (L^3)
X	=	biomass concentration (M/L^3)
X_e	=	effluent biomass concentration (M/L^3)
X_f	=	biofilm bacterial concentration (M/L^3)
X_r	=	recycled biomass concentration (M/L^3)

X_w	=	sludge wasting rate (M/T)
Xi	=	influent biomass concentration (M/L^3)
Y	=	cell yield
α	=	recycle ratio
μ	=	specific growth rate (1/T)
μ_{max}	=	maximum specific growth rate (1/T)
θ_c	=	sludge age (T)
θ^m_c	=	minimum sludge age (T)
θ_h	=	hydraulic detention time (T)