COMPARATIVE STUDY ON SUBSTRATE REMOVAL KINETICS

for CONTINUOUS FLOW and SEQUENCING BATCH REACTORS

by
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ABSTRACT

This study has developed a new empirical substrate removal model for continuous flow stirred tank reactor (CFSTR) and sequencing batch reactor (SBR) systems. In this model, an exponential function of volatile suspended solids (VSS) was introduced to express active biomass in substrate utilization kinetics. The proposed empirical substrate removal model is expressed as: $dS/dt = -K'X_v^nS$. The kinetic constants K' and **n** in the model were estimated from batch tests. then, this model was validated for CFSTR and SBR continuous flow systems.

The results obtained from batch tests, conducted with sludge from the CFSTR and SBR systems, showed that the exponential model can more accurately express the substrate removal rate in a batch reactor than the conventional first order equation. A comparison of the new exponential and the first order model indicates that the exponential model can more accurately predict the effluent COD concentrations for both CFSTR and SBR continuous flow systems.

The first order rate constants (K) for both CFSTR and SBR systems were affected by the reactor sludge age, the influent COD and the biomass concentrations. The kinetic constants K,

yield factor (Y), and endogenous decay coefficient (k_d) obtained for SBR system were higher than those for CFSTR.

The statistical analysis results indicated that SBR system performed at a higher substrate removal efficiency compared to the CFSTR. Also the sludge grown in the SBR reactors had a better settleability than that produced in the CFSTR. The optimal organic loadings for controlling sludge bulking in the CFSTR and SBR were found to be less than 0.7 mg COD/mg VSS/d and 1.2 mg COD/mg VSS/d, respectively. In addition, the SBR reactor could be operated at an F/M ratio of 1.4 mg COD/mg VSS/d, which was twice the F/M ratio in the CFSTR without a significant decrease in treatment efficiency.

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GLOSSARY

ATP – adenosine triphosphate

a —— factor related to active biomass

BOD_5– five days biological oxygen demand (mg/L)

COD— chemical oxygen demand (mg/L)

CFSTR continuous flow stirring tank reactor

DNA— deoxyribo-nucleic acid

E_{ave}— overall average standard deviation of error

E_c — treatment efficiency in CFSTR

E_s — treatment efficiency in SBR

f —— active biomass fraction factor

f_c'— relative active mass fraction for CFSTR

f_s'— relative active mass fraction for SBR

f_d—— biodegradable fraction of organic biomass

f_i—— inert fraction of influent suspended solids

f_{ndi}— nonbiodegradable inorganic inert fraction of biomass

K —— first order removal rate constant (L/mg/h)

K'—— modified rate constant in the proposed model (L/mg/h)

K_m—— overall removal rate constant (h^{-1})

K_s—— half velocity constant (mg/L)

k —— max. specific removal rate constant (h^{-1})

k_d—— endogenous decay rate coefficient (d^{-1})

m —— total number of trials

N —— number of observations in each batch test

n —— parameter in the proposed model

n —— number of SBR tanks

n_c—— number of observations in CFSTR operation

n_s—— number of observations in SBR operation

PVA— polyvinyl alcohol

Q —— flow rate (L/h)

Q_r—— recycle flow rate (L/h)

Q_w—— sludge wasted rate (L/d)

R_d—— endogenous decay rate (mg/L/d)

R_g—— total growth rate (mg/L/h)

R_{su}— substrate utilization rate (mg/L/h)

S — substrate concentration (mg/L)

S_{ci}— calculated substrate concentration at time t_i (mg/L)

S_d—— difficult-to-degrade substrate (mg/L)

S_e—— substrate concentration in effluent (mg/L)

S_e'— predicted effluent substrate concentration (mg/L)

S_F—— substrate concentration in feed (mg/L)

S_f—— substrate concentration at the end of fill (mg/L)

S_o—— substrate concentration in influent (mg/L)

S_{obi}— observed substrate concentration at time t_i (mg/L)

S_t—— substrate concentration at time t (mg/L)

SBR— sequencing batch reactor

SRT— sludge retention time (d)

SVI— sludge volume index (mL/g)

s —— combined standard deviation

s_c—— standard deviation of treatment efficiency in CFSTR

s_s—— standard deviation of treatment efficiency in SBR

T_d—— hydraulic detention time (h)

T_{dc}— hydraulic detention time of CFSTR (h)

T_{ds}— equivalent hydraulic detention time of SBR (h)

TOC— total organic carbon (mg/L)

TSS— total suspended solids (mg/L)

T_x—— sludge age (d)

t_f—— fill time of SBR reactor (h)

t_r—— react time of SBR reactor (h)

t_s—— settle time of SBR reactor (h)

t_w—— withdraw time of SBR reactor (h)

t_0—— test statistic

u —— specific growth rate (h^{-1})

u_m—— maximum specific growth rate (h^{-1})

V —— volume of reactor (L)

V_{ab}— available volume of one SBR reactor (L)

V_b—— total volume of one SBR reactor (L)

V_c—— volume of CFSTR aeration basin (L)

V_i—— initial volume of SBR (L)

V_{sc}— volume of settling tank in CFSTR system (L)

VSS— volatile suspended solids (mg/L)

X —— biomass concentration factor in batch test

X_a—— active biomass concentration (mg/L)

X_a'— relative active biomass (mg/L)

X_{ed}— endogenous biomass concentration (mg/L)

X_f—— biomass concentration at end of fill time (mg/L)

X_i—— influent suspended solids concentration (mg/L)

X_o—— biomass concentration in influent (mg/L)

X_r—— recycled biomass concentration (mg/L)

X_{Ti}— inert suspended solids concentration (mg/L)

X_t—— total mass concentration (mg/L)

X_v—— biomass concentration (mg/L)

X_{ve}— biomass concentration in effluent (mg/L)

Y —— yield factor (mg VSS/mg COD)

σ_j—— standard deviation of error for each trial j.

CHAPTER 1

INTRODUCTION

Through several decades, the activated sludge process has been successfully used to remove organic substances present in wastewater. Generally, the continuous flow stirred tank reactor (CFSTR), also known as the completely mixed (CM) reactor, is widely used to carry out this process. Since the late 1970's. the sequencing batch reactor (SBR) has gained the attention of researchers because of its many advantages including promotion of ideal settling conditions, suppression of filamentous growth, as well as no requirement for a separate settling tank and sludge recycle equipment.

In order to optimize the efficiency of biological treatment, many researchers have studied the kinetics of biochemical reactions and proposed several kinetic models to describe microorganism growth and substrate removal. The Monod model (1949) is a well known kinetic equation for describing the growth of microorganism in the log-growth phase. In the case of substrate utilization kinetics, the Monod model (1949) and the first-order model (Eckenfelder, 1966) have been widely

applied to express the substrate removal rate for CFSTR and SBR systems. In both models, substrate removal rate is limited by the reactor substrate concentration, and it is proportional to the biomass concentration which is commonly measured in terms of volatile suspended solids (VSS).

Based on the analysis of the McKinney (1962) and Eckenfelder (1966), Goodman and Englande (1974) proposed the use of active biomass, which is a fraction of VSS, rather than the generic term VSS to express the microbial activity. VSS is a measure of microorganism mass which includes both the active and the decayed portions. Goodman and Englande also reported that the activity of the biomass was related to reactor sludge age, and biomass activity decreases as sludge age increases. However, the concept of the active biomass was not implemented in the Goodman and Englande's model for describing substrate removal kinetics.

Actually, it is only the active biomass portion that is effectively engaged in biodegradation reactions. Thus, compared with VSS, the use of the active biomass concentration to represent the microorganism component in substrate removal equation is theoretically reasonable and more accurate than using the generic term VSS. According to Agardy et al. (1963) and Weddle and Jenkins (1971), the active biomass could be represented by deoxyribo-nucleic acid (DNA) or adenosine

triphosphate (ATP) concentrations, respectively. In practice, however, the procedures for determining DNA and ATP are difficult and complex. Therefore, VSS is commonly used as the measure of biomass concentration since it can be determined with ease and at a very low cost. In order to readily and accurately express the substrate removal rate, there is a need to develop a new approach which can represent the active biomass by measuring VSS only.

In this study, a new empirical model for substrate removal description is proposed. This model will take into consideration the concept of the active biomass being engaged in substrate utilization. The active biomass in the proposed model will be represented by an exponential function of VSS (X_v^n), hence, the complex measurement of the biomass activity becomes unnecessary. This empirical adjustment exhibits the desired behaviour based on analysis of more sophisticated models (Henze, et al., 1986). As VSS increases for a given substrate concentration, the proposed mathematical modification will reduce the magnitude of the biological solids component in the substrate removal expression. This is in agreement with predictions of more sophisticated models (Henze, et al., 1986).

To validate the proposed model, laboratory experiments were conducted on an activated sludge process using CFSTR and SBR.

The parameter **n** and modified rate constant K' in the proposed model were estimated from the substrate removal batch test analyses. The proposed model was tested with test factors of sludge ages, substrate and biomass concentrations over a broad range of conditions to examine its consistency. Then, the new empirical model established from the batch study was tested on the CFSTR and SBR continuous flow systems to examine its suitability.

The specific objectives of this investigation are:

1) Develop an empirical model which incorporates an active biomass term to accurately describe the substrate removal kinetics for CFSTR and SBR systems.
2) Apply this new model to predict CFSTR and SBR treatment results, and to simulate the relative active biomass portions in the mixed liquors from both systems.
3) Compare substrate removal kinetics for CFSTR and SBR systems; and the treatment performance of both systems in terms of the substrate removal efficiency, the sludge settleability and the effect of organic loading on the treatment efficiency.

CHAPTER 2

LITERATURE REVIEW

The major objective of biological treatment processes is the reduction of organic matter through biochemical oxidation. The mechanism and kinetics of the biochemical reaction have been well studied through the years in order to improve the efficiency of organics removal. This chapter presents a brief literature review on the mechanism of biological processes and substrate removal kinetics. It essentially discusses the kinetics of substrate utilization including the Monod model, first order model and the Goodman-Englande model applied to activated sludge treatment in CFSTR and SBR systems.

2.1. Mechanism of Biological Reaction

In biological reactions, bacteria utilize soluble organic substances present in wastewater with the aid of enzymes. This process can be accomplished aerobically, anaerobically or facultatively by using suspended or attached growth microbial populations.

Fig. 2-1 illustrates the conversion of organic substrates in

the presence of oxygen. A fraction of the organic material is oxidized to inorganic end products. The energy obtained from these biological oxidation-reduction reactions is used to synthesize the remaining organic substrate into new cells. The following three reactions represent the overall biological reactions occurring in the aerobic process.

1. Oxidation(heteroxidation)

$$CHONPS + O_2 + Bacteria \longrightarrow CO_2 + NH_3 + H_2O + Energy + Other\ end\ products$$

2. Synthesis

$$CHONPS + O_2 + Bacteria + Energy \longrightarrow New\ cell$$

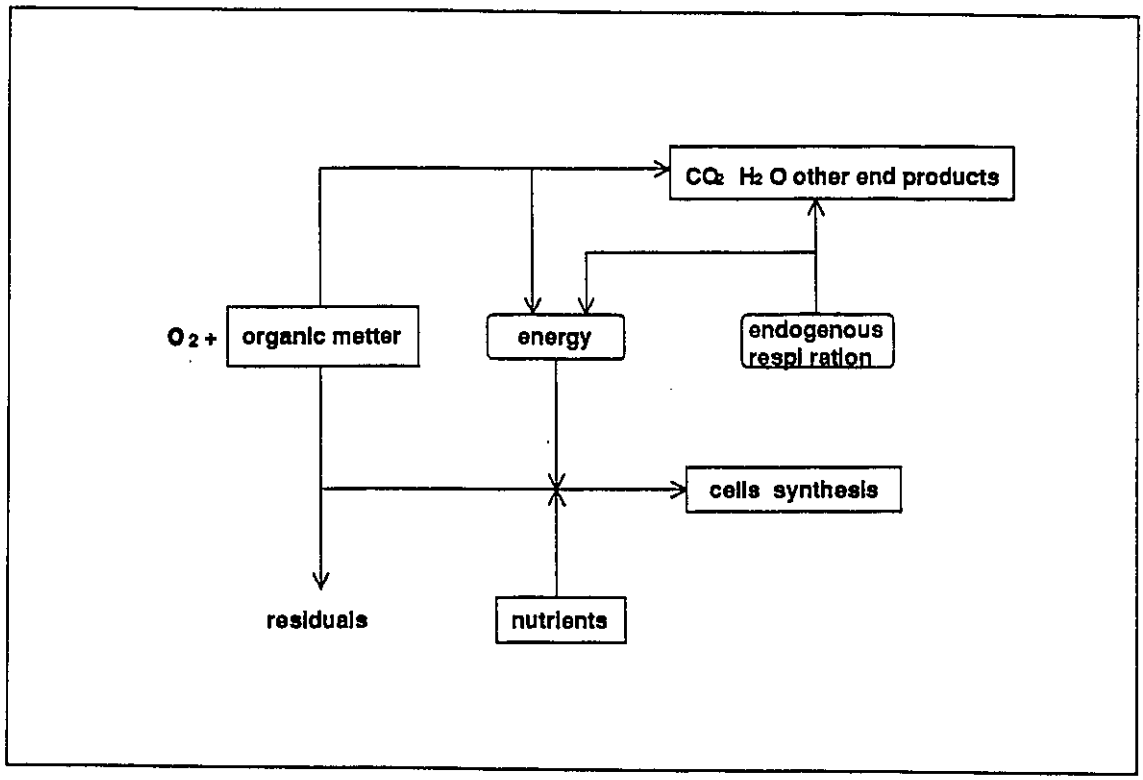


Fig. 2-1 Aerobic Conversion of Organic Substrate (Metcalf and Eddy, 1979)

3. Endogenous Decay(autoxidation)

$$\text{Cells} + O_2 \longrightarrow \text{Energy} + CO_2 + NH_3 + H_2O$$

As the organic substrate in the wastewater becomes limiting, the dead cells will be endogenously respired to end products. The energy released from the endogenous decay reaction can be used by the remaining living microorganisms for maintenance.

The mechanisms of substrate utilization and microorganism growth have been studied in batch and continuous flow reactors. Fig. 2-2 shows the changes in substrate concentration and the mass of a pure bacterial culture in a batch reactor with time.

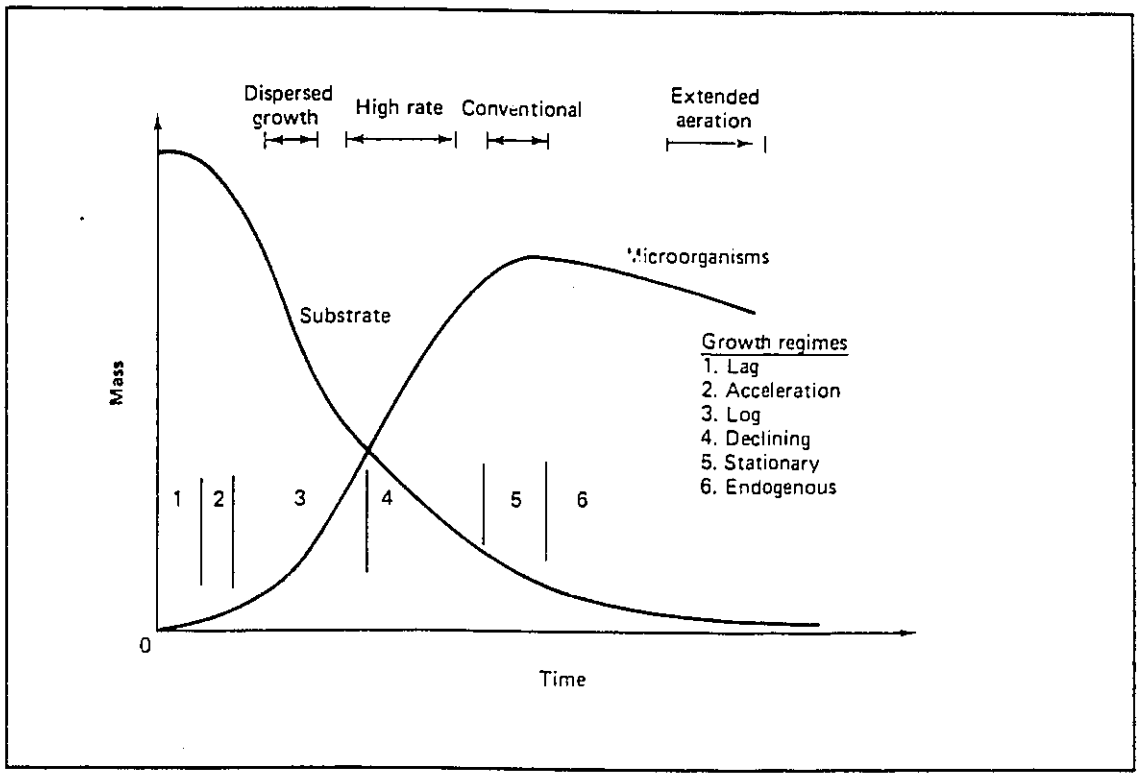


Fig. 2-2 Typical Growth Curves for Batch Reactor (Sundstrom and Klei, 1979)

According to Fig. 2-2, the concentration of microorganisms follows 6 phases as it varies with time.

1. Lag phase —— Bacteria acclimatize to the new substrate.
2. Acceleration phase —— Bacteria begin to grow.
3. Log-growth phase —— Bacteria grow rapidly, it is a first order process resulting in logarithmic growth.
4. Declining growth phase —— Bacteria growth rate decreases because of substrate limitation.
5. Stationary phase —— In this phase the rate of cell death is nearly equal to the rate of cell synthesis.
6. Endogenous decay phase —— Bacteria concentration decreases due to the lack of food. The rate of cell death is greater than the rate of cell synthesis.

2.2. Kinetics of Biological Reaction

Kinetics studies of reaction in biological wastewater treatment system conducted at the turn of this century were based on experimental observations. This section discusses the most common kinetics applied in wastewater treatment practice.

2.2.1 Monod Model

Monod (1949) investigated the growth rate of an homogeneous culture in log-growth phase and proposed a kinetic expression for microorganism growth. The growth was controlled by a

single limiting substrate and the cell concentration was expressed in terms of bacterial density. The assumptions in Monod's experiment were that most of the bacterial synthesis reactions were enzymatic and reversible, and that the growth rate of a bacterial culture represented the overall velocity of a series of reactions by virtue of which new cells were synthesized. The series of reactions were dependent on the concentrations of the reactants, substrate and enzymes.

Based on the experimental data and observations, Monod found the relationship between the specific growth rate and the concentration of growth limiting substrate in the log-growth phase as:

$$u=\frac{u_m S}{(K_s+S)} \qquad (2\text{-}1)$$

Where: u —— specific growth rate (h^{-1})

u_m —— maximum specific growth rate (h^{-1})

S —— substrate concentration (mg/L)

K_s —— half velocity constant (mg/L)

Fig. 2-3 shows a plot of the specific growth rate (u) versus concentration of growth limiting substrate (S).

According to the Monod equation (Eq. 2-1) and Fig. 2-3, the specific growth rate varies as the substrate is converted to

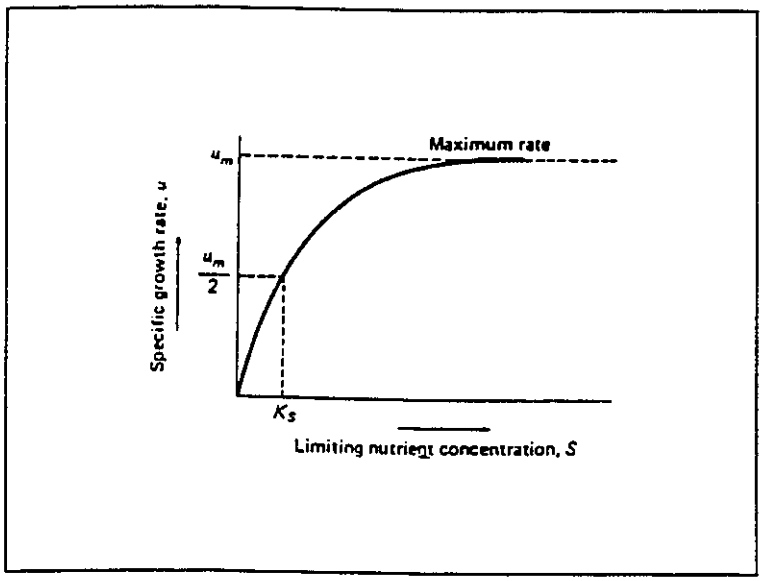


Fig. 2-3 Specific Growth Rate vs. Substrate Concentration (Monod, 1949)

end products in the reactor. It asymptotically approaches a limiting maximum value (u_m) when the substrate concentration (S) increases indefinitely. K_s is the half velocity constant, which is defined as the substrate concentration at which u is equal to half of the maximum rate. The value of K_s determines how rapidly the growth rate curve reaches u_m. With a small K_s, the specific growth rate reaches the maximum rate value rapidly, thus the growth rate curve rises sharply. On the other hand, a large K_s makes the growth rate curve rise more smoothly.

Garrett and Sawyer (1952) have pointed out two conditions as being special cases of the Monod equation. These researchers observed that the specific growth rate was directly proportional to the substrate concentration at low values of S and independent of the substrate concentration at high values of S. When $S << K_s$, Eq. 2-1 reduces to:

$$u=\frac{u_m}{K_s}S \qquad (2-2)$$

Thus, the specific growth rate is a first-order reaction with respect to the substrate concentration. When $S >> K_s$, Eq. 2-1 becomes:

$$u=u_m \qquad (2-3)$$

The specific growth rate becomes a zero-order reaction with respect to the substrate concentration and achieves the maximum value (u_m).

For intermediate substrate concentrations, the relationship between specific growth rate and substrate concentration falls in the reaction order between zero and first order kinetics (Ramalho, 1977).

The Monod equation was developed from experimental results for a pure culture growing on a single substrate. In order to apply the Monod equation for raw wastewater, Garrett and Sawyer (1952), Gaudy and Gaudy (1971) and Andrews (1971) have

studied the specific growth rate of mixed microbial populations. They concluded that the growth rate of microorganisms in a mixed culture was also in agreement with the Monod equation. Consequently, the Monod equation became a generalized model to describe the kinetics of biomass growing in wastewater treatment systems.

Goel and Gaudy (1969), Uden (1969) and Schaezler et al. (1969) proved that in an aerobic process, the concept of growth limiting substrate is suitable not only for organic carbon source, but also for three other basic nutrients required for microbial growth, these are: nitrogen, phosphorous and oxygen. To obtain the optimum for biomass growth, a rule of thumb for the ratio of carbon source as COD to nitrogen and phosphorous was suggested as: COD:N:P = 100:5:1. For an aerobic process, the minimum dissolved oxygen concentration in waste mixed liquor should be above 2.0 mg/L.

In addition to the effect of nutrients, changes in temperature and pH also affect the growth rate. It was found that the rate of biological reactions increased as temperature increased (Muck and Gaudy, 1969). The optimal pH for growth of bacteria is between 6.5 and 7.5 (Ramalho, 1977). Most organisms can not tolerate pH levels above 9.5 or below 4.0.

2.2.2 Endogenous Metabolism

In a conventional biological wastewater treatment process, a portion of the sludge is usually recycled into the aeration basin. The distribution of sludge retention times in the aeration basin is not uniform, thus not all of the microbial mass are in the log-growth phase; some of biomass is in the endogenous respiration phase. Therefore, the expression for biomass growth rate in a kinetic model must be corrected to account for the energy required for cell maintenance. Cell death is another factor to be considered in the kinetic model. It is assumed that the decrease of biomass caused by endogenous decay and cell death is proportional to the biomass concentration, thus, the rate of endogenous decay is expressed as: $R_d = - k_d X_v$

Where: R_d —— endogenous decay rate (mg/L/d)

k_d —— endogenous decay coefficient (d^{-1})

X_v —— biomass concentration (mg/L)

2.2.3 Cell Growth and Substrate Utilization

In order to estimate the amount of cell synthesis, Monod (1949) defined the growth yield (Y) of the limiting substrate as:

$$Y = \frac{\text{amount of bacteria formed}}{\text{amount of substrate utilized}}$$

Thus, the total rate of microorganism growth is proportional to the rate of substrate utilization:

$$R_g = -YR_{su} \qquad (2\text{-}4)$$

Where: R_g —— bacterial growth rate (mg/L/h)

R_{su} — substrate utilization rate (mg/L/h)

Y —— yield factor (mg VSS/mg COD)

The total growth rate of microorganisms is considered to be proportional to the concentration of biomass, and it can be described as (Grady and Lim, 1980):

$$R_g = uX_v \qquad (2\text{-}5)$$

Substituting the Monod equation (Eq. 2-1) into Eq. 2-5 produces the equation for the total microorganism growth rate:

$$R_g = \frac{u_m X_v S}{K_S + S} \qquad (2\text{-}6)$$

As described in Eq. 2-6, the total growth rate is limited by substrate concentration, and it is proportional to the concentration of microbial mass.

Rearranging Eq. 2-4 gives the kinetics for the rate of substrate utilization:

$$R_{su} = -\frac{R_g}{Y} \qquad (2\text{-}7)$$

substituting Eq. 2-5 into Eq. 2-7,

$$R_{su}=-\frac{u}{Y}X_v \qquad (2\text{-}8)$$

Employing the Monod equation in Eq. 2-8 yields the equation for the single substrate utilization rate:

$$R_{su}=-\frac{u_m X_v S}{Y(K_s+S)}=-\frac{kX_v S}{K_s+S} \qquad (2\text{-}9)$$

where: k —— max. specific removal rate constant (h^{-1})

$k = u_m/Y$

Eq. 2-9 indicates that the rate of substrate utilization is limited by substrate concentration and it is first order with respect to the biomass concentration.

2.2.4 Determination of Kinetic Constants

The constants in kinetic model can be evaluated by fitting the kinetic expression to the experimental data obtained from batch reactor (un-steady state system) or continuous flow reactor (steady state system).

When batch reactor is used for kinetic constant determination, the differential kinetic equations are integrated and suitable boundary conditions are applied for initial substrate and biomass concentrations which are varied independently. Since the Monod equation is a rectangular hyperbolic curve, its

integrated equation is not a convenient form for evaluating the kinetic constants K_s, u_m, Y, k_d and k. Therefore, the kinetic coefficients in the Monod model are commonly determined by conducting substrate removal tests in continuous flow reactors under different hydraulic detention times (HDT) and sludge retention times (SRT). At steady state, measuring substrate concentrations as COD in the influent (S_o), in the effluent (S_e), and VSS as the biomass concentration (X_v), the kinetic parameters can be estimated by the following two linear equations (Metcalf and Eddy, 1979):

$$\frac{X_v T_d}{S_o - S_e} = \frac{K_s}{k} * \frac{1}{S_e} + \frac{1}{k} \qquad (2\text{-}10)$$

$$\frac{1}{T_x} = Y \frac{S_o - S_e}{X_v T_d} - k_d \qquad (2\text{-}11)$$

where: T_d —— hydraulic detention time (h)

S_o —— influent substrate concentration (mg/L)

S_e —— effluent substrate concentration (mg/L)

T_x —— sludge retention time (SRT) also named as sludge age (d)

A plot of $X_v T_d/(S_o - S_e)$ versus $1/S_e$ is a straight line, the constant k can be determined from the reciprocal of the intercept, and K_s can be calculated from the slope of the plot and the knowing k value. A plot of $1/T_x$ against $(S_o - S_e)/X_v T_d$ gives a straight line with the slope Y and the intercept k_d. The maximum specific growth rate u_m is computed by: $u_m = kY$.

2.3 Studies on Substrate Removal Kinetics

2.3.1 Lawrence and McCarty Model

Lawrence and McCarty (1970) proposed a CFSTR system model for activated sludge process with sludge recycle, which is illustrated in Fig. 2-4.

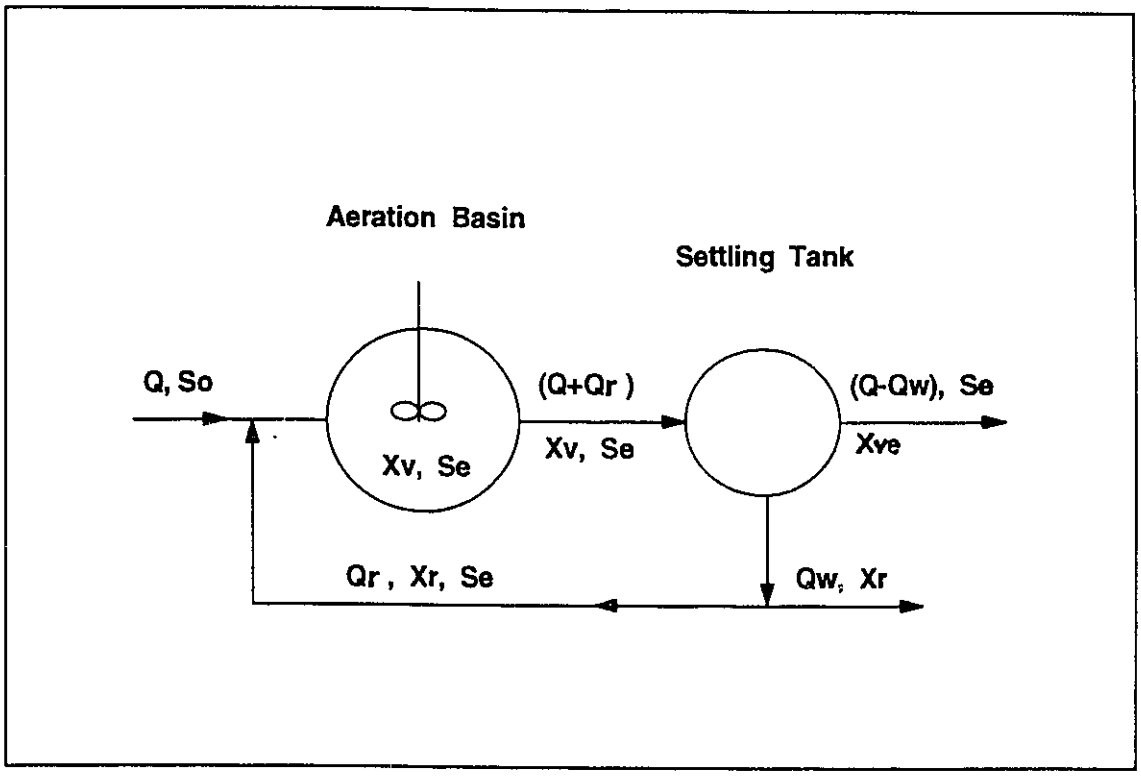


Fig. 2-4 CFSTR System with Sludge Recycle
(Lawrence and McCarty, 1970)

In this system model, Lawrence and McCarty employed the Monod kinetic expression to describe the substrate removal rate and the biomass growth rate. Based on mass balances around the reactor system, the substrate and the biomass accumulation at steady state can be expressed as:

$$\frac{dS}{dt}=QS_o+Q_rS-(Q+Q_r)S-R_{su}V=0 \qquad (2\text{-}12)$$

$$\frac{dX_v}{dt}=QX_o+Q_rX_r-(Q+Q_r)X_v+(R_g-k_dX_v)V=0 \qquad (2\text{-}13)$$

where: Q —— flow rate into CFSTR system (L/h)

Q_r—— recycle flow rate (L/h)

V —— volume of aeration basin (L)

X_o—— biomass concentration in influent (mg/L)

X_r—— recycled biomass concentration (mg/L)

The reactor sludge age (T_x), is defined as the ratio of biomass in the reactor to the net rate of biomass generated.

$$T_x=\frac{X_vV}{\frac{u_mSX_vV}{K_s+S}-k_dX_vV} \qquad (2\text{-}14)$$

At steady state, the net rate of biomass generation is equal to the rate of biomass being washed out of the system. In operation, the sludge age can be maintained by controlling the sludge withdrawal rate from the system.

$$T_x=\frac{X_vV}{Q_wX_r+X_{ve}(Q-Q_w)} \qquad (2\text{-}15)$$

where: Q_w —— sludge wasted rate (L/d)

X_{ve} —— biomass concentration in effluent (mg/L)

Substituting Eqs. 2-9 and 2-6 for R_{su} and R_g, respectively, and assuming X_o to be negligible, Eqs. 2-12 and 2-13 were solved to obtain the system design parameters:

$$S=\frac{K_s(1+k_dT_x)}{T_x(Yk-k_d)-1} \qquad (2\text{-}16)$$

$$X_v=\frac{Y(S_o-S)}{(1+k_dT_x)}*\frac{T_x}{T_d} \qquad (2\text{-}17)$$

Lawrence and McCarty reported kinetic constants for several types of substrate biodegradation using mixed culture. The results are summarized in Table 2-1.

Table 2-1 Kinetic Constants for Mixed Culture

(Lawrence and McCarty, 1970)

Wastewater	Y	k_d d^{-1}	u_m d^{-1}	K_s mg/L	Temp. °C	Basis
Domestic waste	0.5	0.055			20	BOD_5
Skim milk	0.48	0.045	5.1	100		BOD_5
Synthetic waste	0.65	0.18				BOD_5
Glucose	0.42	0.087	3.0	355		BOD_5
Glucose-peptone	0.49		10.3		10	BOD_5
Peptone	0.43		14.5	65	30	BOD_5
Domestic waste	0.67	0.07	5.6	22		COD

2.3.2 First-order Model

Eckenfelder (1966) investigated substrate removal kinetics for wastewater containing mixed substances. It was pointed out that all individual substrates were removed in concurrent zero order reactions at different rates. At first, the overall removal rate remains constant, until the rapidly degradable substances are completely utilized, then the overall rate decreases. Fig. 2-5 illustrates the quantitative scheme of mixed substrate removal proposed by Eckenfelder.

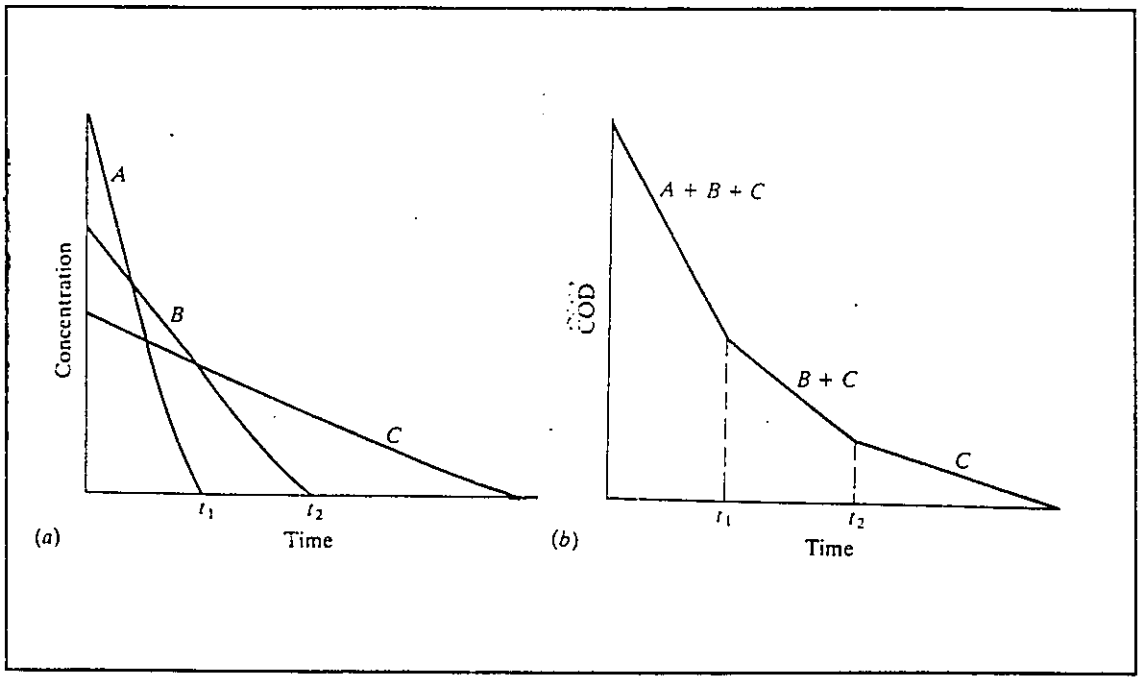


Fig. 2-5 Scheme of Multi-component Substrate Removal (Eckenfelder, 1966)

Fig. 2-5 shows that the overall rate remains constant until the time t_1, when component A is substantially reduced. Then the overall rate decreases to reflect components B and C that are less easy to degrade. Hence, at the time t_2 when component B is completely removed, the overall rate reduces again to reflect only component C.

Fig. 2-6 shows the experimental plots for batch treatment of individual and mixed substrates (Eckenfelder-Tischler, 1969). The figures illustrate that the removal of each individual substrate follows a zero order reaction rate, but the removal of total mixed substrate results in first order kinetics.

To design an activated sludge process for treating industrial wastewater containing many different organic components, Eckenfelder (1966) suggested the use of the first-order kinetics to express the overall substrate removal rate:

$$\frac{dS}{dt} = -KX_v S \qquad (2\text{-}18)$$

where: K —— removal rate constant (L/mg/h)

When X_v is considered as constant, the integrated form of Eq. 2-18 is:

$$S = S_o e^{(-KX_v t)} \qquad (2\text{-}19)$$

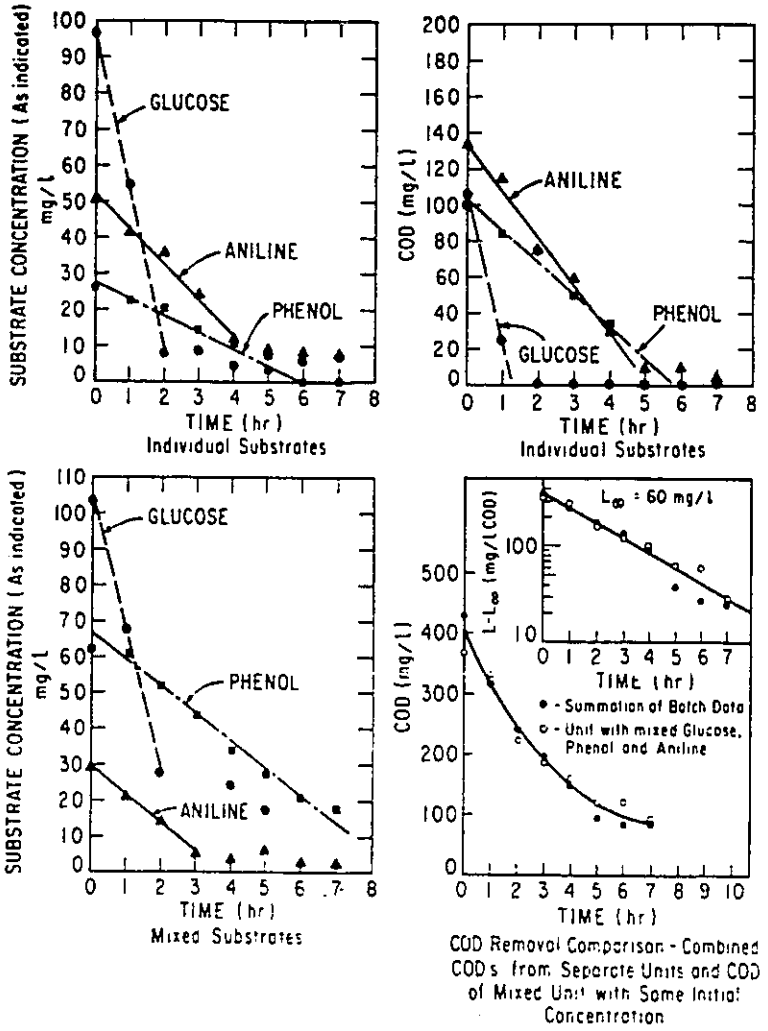


Fig. 2-6 Removal of Individual and Mixed Substrate (Eckenfelder and Tischler, 1969)

Table 2-2 lists several first-order removal rate constants K for various industrial wastewaters.

Table 2-2. Reaction Rate Constants for Organic Wastewaters (Eckenfelder, 1980)

Wastewater	K, L/mgCOD/h	Temp. °C
Potato processing	36.0	20
Peptone	4.03	22
Sulphite paper mill	5.0	18
Vinyl acetate monomer	5.3	20
Polyester fibber	14.0	21
Formaldehyde,propanol,methanol	19.0	20
Cellulose acetate		
AZO dyes, epoxy,	2.6	20
Optical brighteners	2.2	18
Petroleum refinery	9.1	20
Vegetable tannery	1.2	20
Organic Phosphates	5.0	21
High nitrogen organic	22.2	22
Organic intermediates	20.6	26
	5.8	8
Viscose rayon and nylon	8.2	19
	6.7	11
Soluble fraction of domestic sewage	8.0	20

2.3.3 Goodman and Englande Model

From the analysis of the McKinney model (1962) and the Eckenfelder model (1966), Goodman and Englande (1974) suggested a unified model for the activated sludge process.

Considering zero order kinetics for substrate removal, they presented the following unified model for CFSTR system with sludge recycle:

1. **Substrate removal**

$$S_e = \frac{S_o}{K_m T_d + 1} \qquad (2\text{-}20)$$

where: K_m — overall substrate removal rate constant (h^{-1})

$K_m = KX_v$

2. **Active mass accumulation**

$$X_a = \frac{YK_m S_e}{\frac{1}{T_x} + k_d} \qquad (2\text{-}21)$$

where: X_a — active solids concentration (mg/L)

3. **Endogenous mass accumulation**

$$X_{ed} = (1 - f_d)\, k_d X_a T_x \qquad (2\text{-}22)$$

where: X_{ed}— endogenous mass concentration (mg/L)

f_d — biodegradable fraction of microbial organic biomass (mass/mass)

4. **Inert mass accumulation**

$$X_{Ti} = f_i X_i \frac{T_x}{T_d} + f_{ndi}(X_a + X_{ed}) \qquad (2\text{-}23)$$

where: X_{Ti}— inert suspended solids concentration (mg/L)

X_i — influent suspended solids concentration (mg/L)

f_i — inert fraction of influent SS (SS/SS)

f_{ndi} — inorganic inert fraction of biomass (mass/mass)

5. **Total mass accumulation**

$$X_t = X_a + X_{ed} + X_{Ti} \qquad (2\text{-}24)$$

where: X_t —— total mass concentration (mg/L)

6. **Volatile suspended solids**

$$X_v = X_a + X_{ed} \qquad (2\text{-}25)$$

The major features in the Goodman and Englande model are:

1. Total microbial mass is divided into three parts: active mass (X_a), endogenous mass (X_{ed}) and inert mass (X_{Ti}). VSS includes both active mass and endogenous mass.
2. Active mass fraction of VSS is a non-linear function with respect to sludge age. Although the sludge concentration (X_v) can be increased by increasing sludge age, the active mass fraction will decrease as the sludge age increases. Fig. 2-7 shows the relationship between the percent of active mass and the sludge age.
3. Active mass concentration (X_a) is used as the measure of the biomass concentration for the biomass activity.

2.3.4 Zero Order Kinetic Model

Metcalf and Eddy (1979) reported another expression for substrate utilization:

$$R_{su} = -K_m S \qquad (2\text{-}26)$$

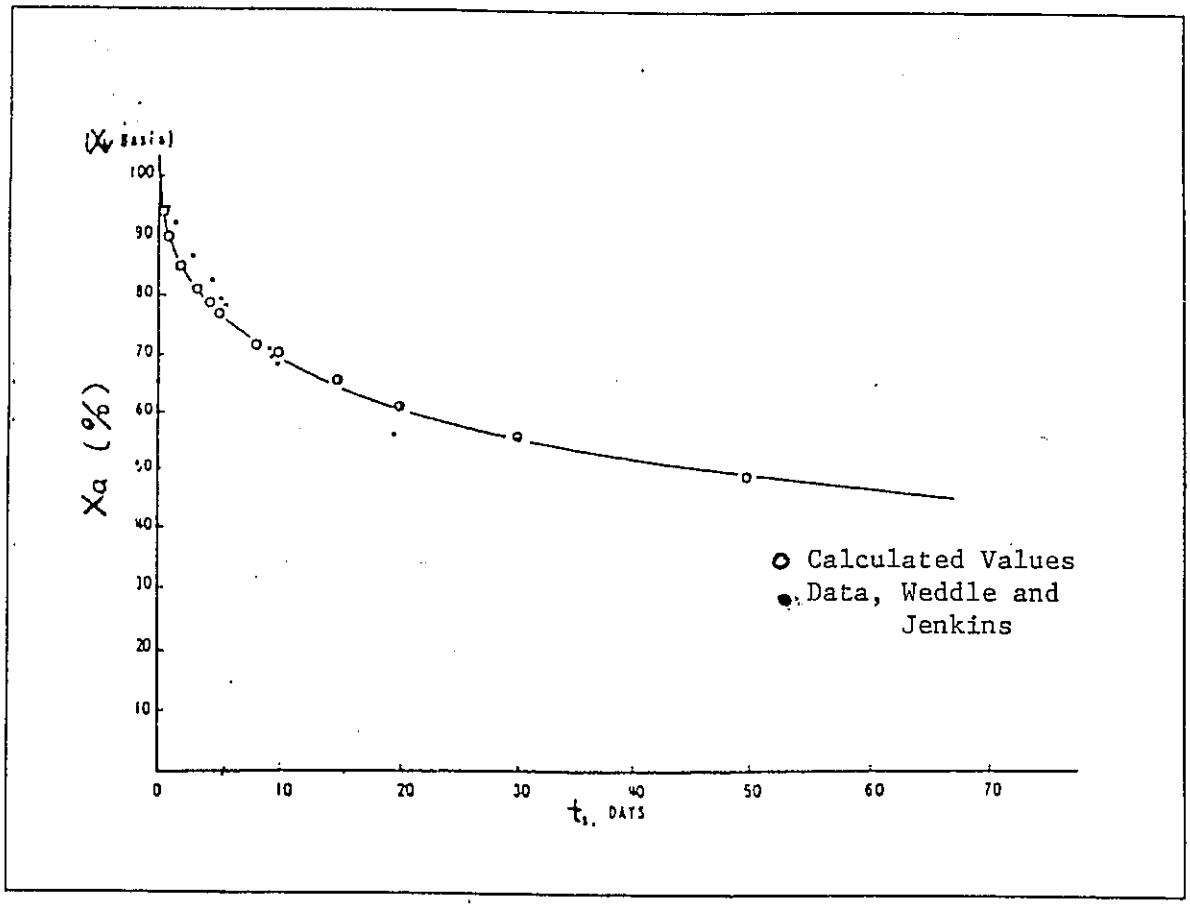


Fig. 2-7 Relationship between Active Mass and Sludge Age (Goodman and Englande, 1974)

In this model, the substrate removal rate is limited by substrate concentration only, it is independent of the biomass concentration. It can be considered that the removal rate is zero order reaction with respect to the microorganism concentration (X_v).

$$R_{su}=-K_m X_v^0 S \qquad (2\text{-}27)$$

2.4 Studies on Sequencing Batch Reactor

Ardern and Lockett (1914) conducted the first study for batch reactors in 1914. However, the SBR reactor lost the attention of researchers because of operational difficulties. With the development of automatic control equipment, SBR has regained the interest of environmental engineers since late 1970's.

Irvine and Busch (1979) and Chiesa and Irvine (1985) reported a number of advantages for the SBR reactor treating wastewater. Since substrate degradation and sludge sedimentation take place in the same reactor, the SBR system is cost effective because it does not require a secondary clarifier and sludge recycle pumping equipment. SBR can tolerate shock loading caused by very high influent concentrations. The substrate concentration gradient in SBR associated with the batch operation style can suppress the growth of filamentous microorganisms which is a major cause of sludge bulking. SBR also offers ideal conditions for sludge settling because there are no inflow and outflow disturbances or short circuiting occurring during the settle sequence.

An SBR system may consist of one or more reactors. In general, each SBR reactor is operated in five phases: fill, react, settle, draw and idle. Fig. 2-8 displays the SBR operating

phases during one cycle. At the beginning of the fill stage, the initial volume of the mixed liquor in the reactor is V_i, then, it increases due to the addition of the influent wastewater and achieves maximum operating volume at the end of the fill period. Both fill and react periods are under aerobic conditions. After aeration is stopped, the biomass is allowed to settle during the settling stage. The treated wastewater is withdrawn from SBR in the draw phase.

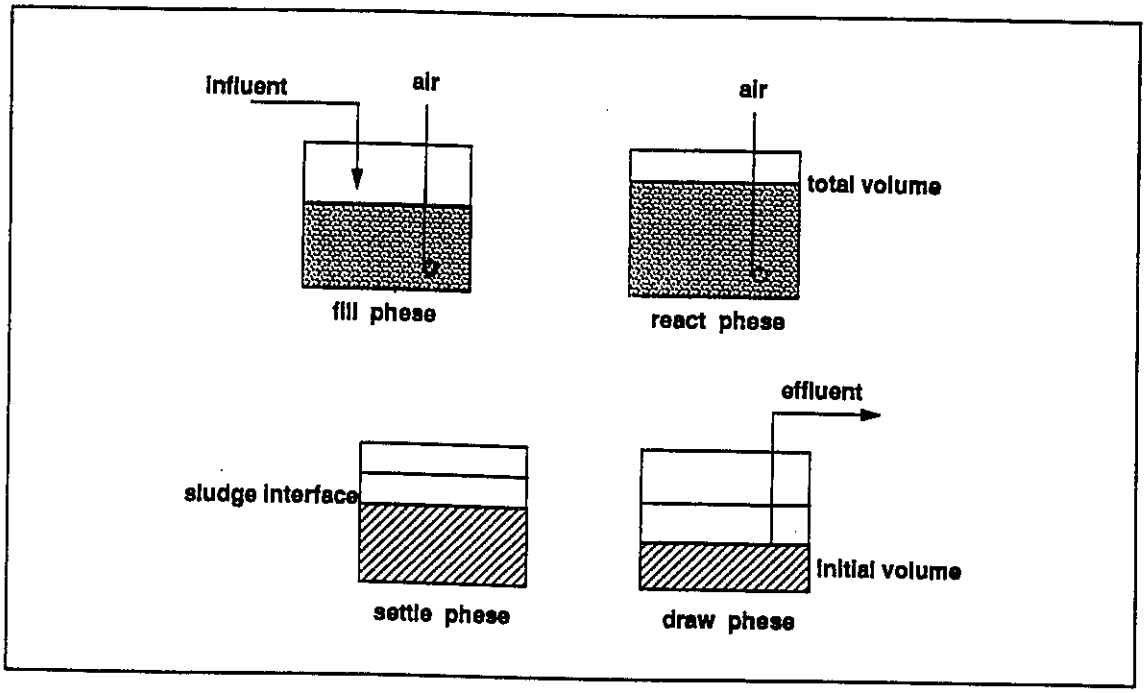


Fig. 2-8 Operating Phases of SBR in One Cycle

Substrate biodegradation mainly occurs during fill and react periods. Fig. 2-9 displays typical variations of COD concentration in one operating cycle of SBR reactor. The substrate concentration rises and reaches a peak value at the end of the fill time. The variation of the substrate concentration is due to the combined effects of the addition of feed, the volumetric dilution of mixed liquor and the biodegradation of the organics. During the react period, substrate concentration decreases mainly due to the effect of biodegradation.

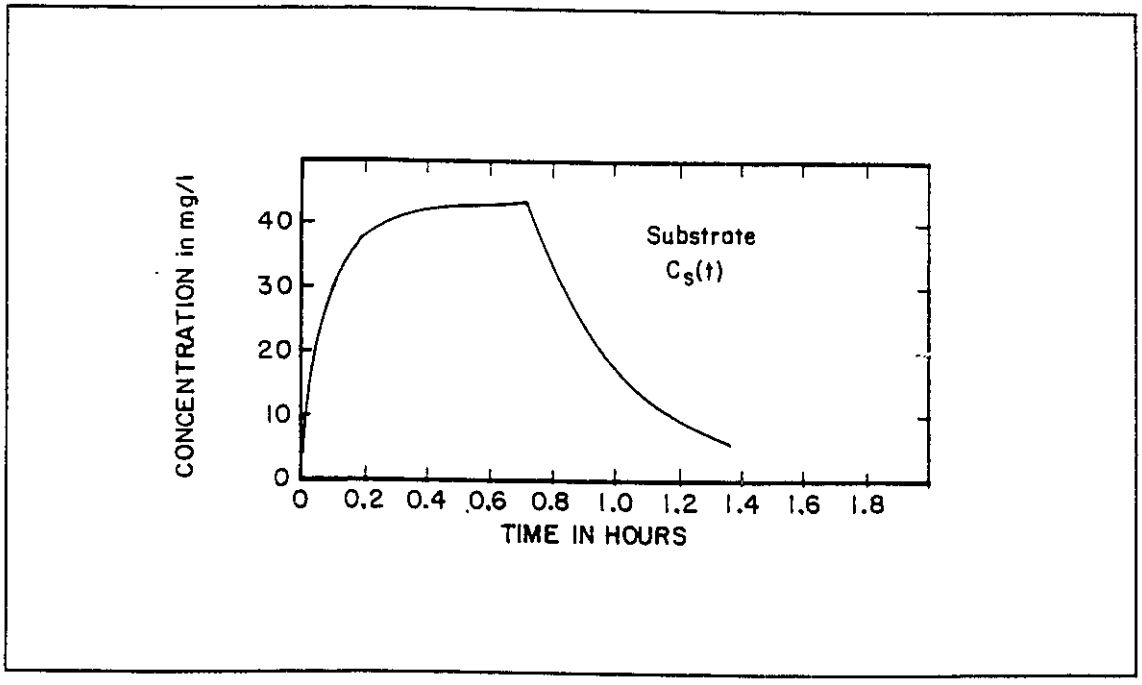


Fig. 2-9 Variation of COD in One Operating Cycle (SBR) (Ketchum, et al, 1979)

2.4.1 Kinetic Studies on SBR

The kinetic models for SBR system were based on the mathematical description of the changes in substrate and biomass concentrations during the operating cycle.

Irvine and Richter (1977, 1978) presented a kinetic study for SBR reactor. Based on the mass balance principle, the system models for substrate biodegradation and microorganisms growth in the fill period were expressed as:

$$\frac{dVS}{dt} = QS_o + VR_{su} \qquad (2\text{-}28)$$

$$\frac{dVX_v}{dt} = QX_o + VR_g \qquad (2\text{-}29)$$

where: V —— liquid volume in the reactor at any time (L)

The first order equation was used for substrate removal and biomass growth: $R_{su} = - KX_vS$, and $R_g = YKX_vS - k_dX_v$
During the react mode, there is no influent flow and the liquid volume is constant. Thus, the kinetic equations reduce to:

$$\frac{dS}{dt} = R_{su} \qquad (2\text{-}30)$$

$$\frac{dX_v}{dt} = R_g \qquad (2\text{-}31)$$

Orhon et al. (1986) studied a kinetic model by employing the Monod equation to describe substrate removal in SBR system. The mass balance equations for substrate removal and microbial mass growth taking place during fill time were expressed as:

$$\frac{dS}{dt} = \frac{Q(S_o - S)}{V_i + Qt} - \frac{u_m S X_v}{Y(K_s + S)} \qquad (2\text{-}32)$$

$$\frac{dX_v}{dt} = -\frac{QX_v}{V_i + Qt} + \frac{u_m X_v S}{(K_s + S)} - k_d X_v \qquad (2\text{-}33)$$

where: V_i—— initial volume of mixed liquor in SBR before the fill stage (L)

Eqs. 2-32 and 2-33 were also applicable to the react mode by merely setting Q = 0.

Droste (1990) presented a theoretical analysis to evaluate the physical and kinetic constraints of an SBR system compared to a CFSTR system on substrate removal efficiency. From kinetic analysis, it was found that an SBR system is an alternative to a CFSTR system when high removals are required. Increasing the number of reactors in an SBR system increases SBR's removal efficiency. As settling time or initial volume in an SBR reactor increase, the kinetic advantage of an SBR system diminished or is eliminated. In Droste's study, the Monod equation and first order kinetics were used for substrate removal expression. The system model for SBR was created based on the mass balance approach:

$$\frac{d(VS)}{dt} = V\frac{dS}{dt} + S\frac{dV}{dt} = QS_o + VR_{su} \qquad (2\text{-}34)$$

$$\frac{dS}{dt} = \frac{Q}{V}(S_o - S) + R_{su} \qquad (2\text{-}35)$$

where: $R_{su} = -kX_vS/(K_s+S)$, or $R_{su} = -KX_vS$

Recent studies for SBR system focused on the system treatment results as well as the reaction kinetics. Table 2-3 summarizes the treatment results from bench scale studies of SBR reactors (Irvine, et al., 1979, Dennis and Irvine, 1979, Hoepker and Schroeder, 1979). The data in Table 2-3 show that SBRs can achieve good treatment efficiency.

Table 2-3 Summary of SBR Treatment Results

influent mg/L	effluent mg/L	SRT d	T_{fill} h	T_{react} h	reference
238 BOD_5	7 BOD_5	3.5	10	5	Irvine et al.
132	5	3.5	4	2	(1979)
132	8	1.6	2	1	
200 TOC	14 TOC	6	2	4	Dennis, R.W.
200	5	6	4	2	Irvine, R.L.
200	11	6	5	1	(1979)
160 TOC	3 TOC	10	8	11	Hoepker, E.D.
320	7	10	8	11	Schroeder, E.D.
640	33	10	8	11	(1979)

2.5 Summary

In the field of biological reaction kinetics, previous researchers have studied the mechanism of substrate utilization and microorganism growth, and have proposed kinetic equations to describe single and multi-component substrate removal. In these substrate removal equations, VSS was the measure for biomass concentration.

Agardy et al. (1963) stated that DNA was superior to VSS as a measure of biomass in anaerobic system treating a soluble synthetic waste. DNA contains all the genetic information for the reproduction of all the cell components and may be considered as blueprint of the cell. Weddle and Jenkins (1971) suggested the use of ATP, instead of VSS, as the measure for biomass activity. ATP energy is stored in phosphate bonds. As ATP is depleted, the cells die. Therefore, measure of ATP can reflect the portion of viable cells. Both DNA and ATP were reported to be good parameters for expressing the activity of microbial mass in the substrate removal equation.

The procedure for determining DNA and ATP are complex and are limited by the test conditions. However, VSS can be determined quite easily. Therefore, there is a need to develop a simple method to present the active biomass fraction in terms of VSS.

In wastewater treatment practice, environmental engineers have applied several kinetic models discussed previously for describing substrate removal and biomass growth in CFSTR and SBR systems. Treatment performance of SBR has been observed in laboratory, but, no comparison of the treatment efficiency between the CFSTR and SBR systems was found. Thus, more research needs to be done in this area.

CHAPTER 3

DEVELOPMENT OF NEW EMPIRICAL MODEL

The development of the new empirical model for substrate removal kinetics was based on the concept that only the active biomass utilizes the substrate in a biological reaction. In the new substrate removal equation, an exponential function of VSS (X_v^n) was proposed to replace X_v as the expression for the relative active biomass.

As discussed previously, the active biomass fraction does not increase linearly with increasing sludge age. Therefore, a non-linear function of X_v needs to be derived in order to express the active biomass. The exponential function (X_v^n) can satisfy this desired characteristic. As the biomass concentration X_v increases due to the increase of sludge age, X_v^n (with **n** less than 1.0) will reduce the magnitude of the biomass concentration, and likewise the active mass fraction (f) represented by the ratio of X_v^n/X_v will decrease with increasing sludge age. Thus, the exponential function of X_v (X_v^n) has potential to represent active biomass concentration.

The proposed exponential model was derived on the basis of the

first order substrate removal equation: Replacing X_v with X_a in the first order kinetics yields:

$$\frac{dS}{dt} = -K' X_a S \qquad (3\text{-}1)$$

Substituting X_v^n for X_a gives the exponential model for the substrate utilization:

$$\frac{dS}{dt} = -K' X_v^n S \qquad (3\text{-}2)$$

Where: K'—— modified rate constant (L/mg/h)

n —— system parameter

Since the active mass is only a fraction of biomass, the value of the exponent **n** in the exponential model (Eq. 3-2) should be great than 0, less than 1.0.

Since **n**<1.0, the value of the parameter K' in Eq. 3-2 will increase due to the reduction in the magnitude of X_v^n. Hence, it can be considered that K' includes the rate constant K with units of L/mg/h and a factor **a** related to the active mass quantity (K'= K**a**). The product of $\mathbf{a}X_v^n$ and the ratio of $\mathbf{a}X_v^n/X_v$ represent the active mass X_a and active biomass fraction f, respectively. Thus, if the active fraction is known by measuring the biomass activity, **a** can be calculated from $\mathbf{a}=fX_v/X_v^n$.

Table 3-1 shows an example of using $\mathbf{a}X_v^n$ and $\mathbf{a}X_v^n/X_v$ to simulate X_a and f values from Goodman-Englande's study, respectively.

Columns (2) and (3) in Table 3-1 illustrate the values of X_v and X_a calculated on the basis of the Goodman-Englande model. The values in Column (4) are the active mass fraction taken from Fig. 2-7. The simulated active mass and active fraction are listed in Columns (5) and (6), respectively. As **n** varied in the range of 0 to 1.0, the aX_v^n/X_v value, which was the nearest to the active fraction in Goodman-Englande's model, resulted in the exponent **n** equal to 0.6 and **a** of 19.5. Appendix A explains the determination of the exponent **n** value and summarizes the parameters from Goodman-Englande's report that were used in the calculation.

Table 3-1 Simulated Active Mass Fraction

T_x d (1)	X_v mg/L (2)	X_a mg/L (3)	$f=X_a/X_v$ % (4)	$X_a=aX_v^n$ mg/L (5)	$f=aX_v^n/X_v$ % (6)
5	3245	2498	77	2493	76.8
10	4340	3040	70	2968	68.4
15	5200	3275	63	3302	63.5
20	5590	3410	61	3455	61.8
30	6180	3585	58	3670	59.3

As shown in Table 3-1, as the reactor sludge age varies from 5 to 30 days, the simulated active mass increases from 2493 to 3670 mg/L, while the simulated active fraction decreases from 76.8% to 59.3%. The simulated active mass and active fraction

are very close to the values of X_a and X_a/X_v in the Goodman-Englande model.

Fig. 3-1 displays the simulated active mass fractions versus sludge age based on the Goodman-Englande data and the exponential model. The dots and the curve were obtained with the data in Columns (4) and (6) in Table 3-1, respectively. As shown in Fig. 3-1, the ratio of aX_v^n/X_v is very close to the fraction of X_a/X_v for sludge ages ranging from 5 to 30 days.

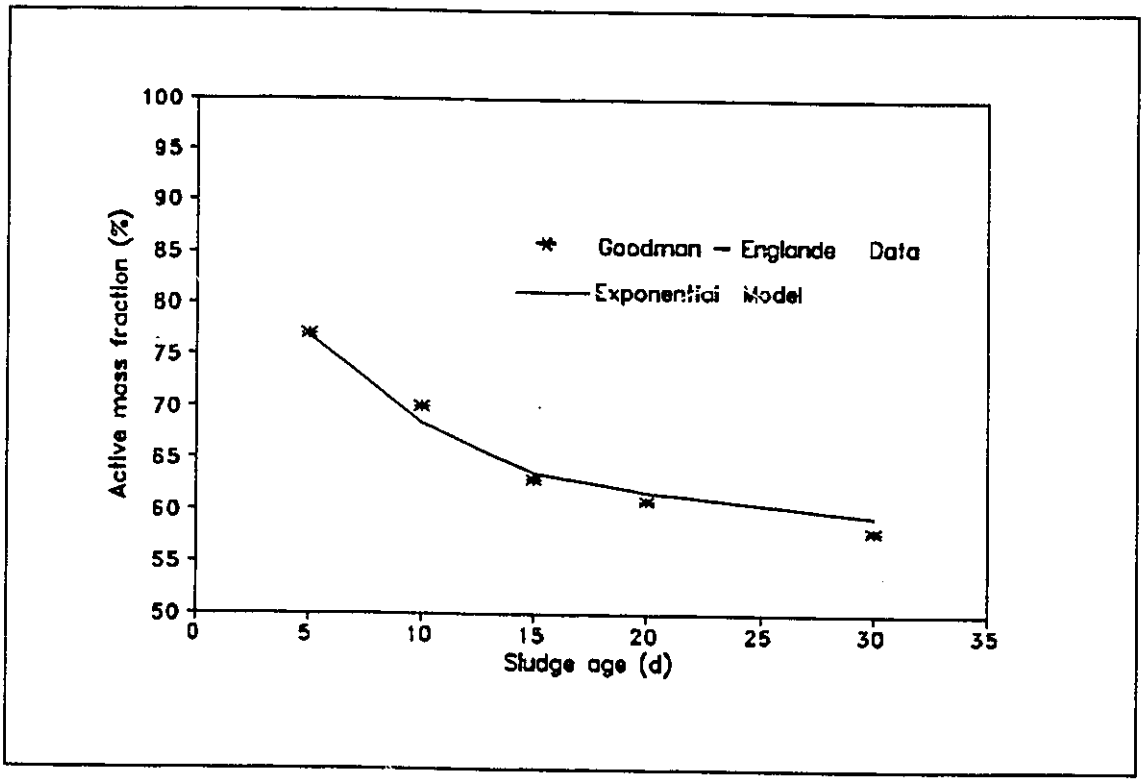


Fig. 3-1 Simulated Active Biomass Fraction

Fig. 3-1 and Table 3-1 indicate that the active mass and active fraction simulated with the exponential model can be a promising technique to accurately express the active fraction X_a/X_v for the reactors operating within a sludge age range of 5 to 30 days.

CHAPTER 4

MATERIALS AND METHODS

To carry out the objectives of this study, laboratory scale experiments were designed to treat a synthetic substrate in CFSTR and SBR reactors using activated sludge process. To evaluate the kinetic constants, a series of batch tests were performed with the mixed liquor drawn from the CFSTR and SBR reactors. This chapter describes the materials and the test methods used in this experimental work.

4.1 Experimental Conditions for CFSTR and SBR

Three CFSTR and three SBR systems with three different sludge ages were operated and tested during this experimental work. In order to compare CFSTR with SBR, both systems were tested under the same conditions. Table 4-1 summarizes the operating conditions for these two systems.

The sludge ages of both CFSTR and SBR systems were maintained at 5, 10 and 15 days by daily withdrawal of a predetermined volume of mixed liquor from each of the reactors. The volume to be withdrawn was determined according to Eq. 2-15. The effluent

Table 4-1 Operating Conditions for CFSTR and SBR

Conditions	CFSTR	SBR
Sludge Age T_x (d)	5 10 15	5 10 15
Feed Conc. S_F (mg COD/L)	250 500 1000	250 500 1000
Hydraulic Detention Time (h)	8	8
Substrate	Protein and Polyvinyl Alcohol	
DO (mg/L)	> 2.0	> 2.0
pH	6.5-7.5	6.5-7.5
Temp. (°C)	20	20

biomass concentration (X_{ve}) in Eq. 2-17 can be considered negligible, because the biomass discharged in the treated effluent from each of the reactors was collected, decanted, and returned to the respective CFSTR or SBR reactor. The decanted effluent liquor was returned to each SBR reactor during the settling period to allow the flocs of activated sludge to settle. The extra effluent liquor was then withdrawn during the draw phase.

In order to obtain a wide range of initial substrate concentrations, the COD concentrations in the influent fed to

the CFSTR and SBR reactors were set at 250, 500 and 1000 mg COD/L. First, all reactors were fed with synthetic substrate containing 250 mg COD/L. When the microorganisms in all reactors were acclimatized to this substrate, the qualities of the influent and treated effluent were tested, and the mixed liquor performance was evaluated. Then, a set of batch tests was conducted to determine the kinetic constants. After all tests under this experimental condition were performed, the feed concentration was switched to the next highest level, and the test procedure was repeated.

The synthetic substrate used in this experiment was made up of protein and polyvinyl alcohol (PVA) which is a large molecular weight compound. PVA was chosen as a portion of the raw substrate because it is difficult to degrade. Since protein and PVA are not easy to volatilize under room temperature and atmospheric pressure conditions, the influence of air stripping on substrate removal was not considered when batch tests were conducted. As the carbon source for microorganisms growth, protein and PVA contributed 90% and 10% of soluble COD in the influent, respectively. The composition of the synthetic feed was:

Protein	1.5 g COD/g protein
Polyvinyl alcohol	2.3 g COD/g PVA

The aerobic and completely mixed conditions were maintained by

distributing air into each CFSTR and SBR reactor through diffusers. To provide suitable environmental conditions for microorganism growth and activity, the dissolved oxygen (DO) concentration in every reactor was maintained above 2.0 mg/L. pH in each reactor was adjusted between 6.5 and 7.5 by adding a buffer solution of saturated sodium carbonate in the feed. The volumetric ratio of saturated sodium carbonate to feed was 1/1000. The operating temperature for the six reactors was maintained at room temperature which was 20 ± 1 °C.

The substrate and the biomass concentrations were expressed as soluble COD and VSS, respectively. For all reactors being tested, the following analyses were conducted on a daily basis throughout the experimental period: COD of the influent, soluble COD of the treated effluent, total suspended solids (TSS) and VSS in the mixed liquor and in the treated effluent. pH and DO were measured daily and weekly, respectively. Sludge settling tests were also performed for each of the reactors to determine sludge volume index (SVI), which is an indicator of activated sludge settleability.

4.2 Sludge Seeding Material

The activated sludge seed used in this experiment was taken from a secondary conventional wastewater treatment plant in Ottawa. This seeding material was acclimatized to the

synthetic (protein and PVA) wastewater by gradually increasing the influent wastewater flow rate over a period of three weeks.

At the beginning of the experiment, seed sludge was added to each of the CFSTR and SBR reactors to fill 50% of the reactor's operating volume. All the reactors were operated on once-a-day feeding schedule for the first two days, then, they were fed on a continuous basis. The flow rate of the influent wastewater was gradually increased from half to the design value in the next two days. Meanwhile, a predetermined volume of sludge was withdrawn daily from each reactor to control sludge age. When the activated sludge was acclimatizing to the synthetic substrate, the soluble COD in the treated effluent and VSS in the mixed liquor gradually decreased to a stable value. When the daily fluctuations of COD and VSS values were less than 15%, it was considered that steady state conditions were achieved.

4.3 Specific Operating Conditions for CFSTR

The CFSTR system used in this experiment contained an aeration basin and a settling tank with a baffle between them. The volumes of the aeration basin and the settling tank were 9 and 2 litres, respectively. Fig. 4-1 shows a schematic of this CFSTR system.

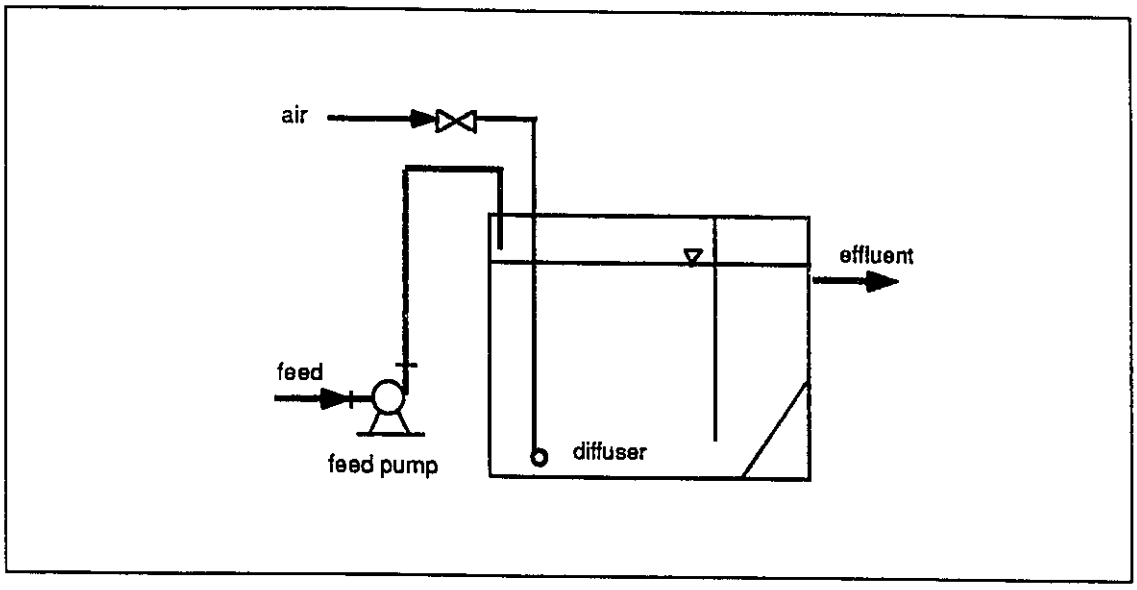


Fig. 4-1 Schematic of CFSTR Reactor with Settling Tank

The hydraulic detention time (HDT) for the three CFSTRs was set for 8 hours, hence, the influent flow rate for the three CFSTRs was 1.125 L/h. The well mixed influent was continuously pumped into the aeration basin, and the treated wastewater was discharged through an overflow pipe at the top of the settling tank. To maintain the sludge ages of the three reactors at 5, 10 and 15 days, the wasted sludge volumes from each aeration basin on a daily basis were determined as being 1800, 900 and 600 mL, respectively.

4.4 Specific Operating Conditions for SBR

In this study, it was assumed that each of the three SBR systems would consist of three tanks. Since each of the three

SBR reactors in an system exhibits the same behaviour, therefore, only three, instead of nine, SBR reactors were operated and tested in this experimental study. Fig. 4-2 depicts the experimental setup of one SBR reactor including the time controlling equipment used in this study.

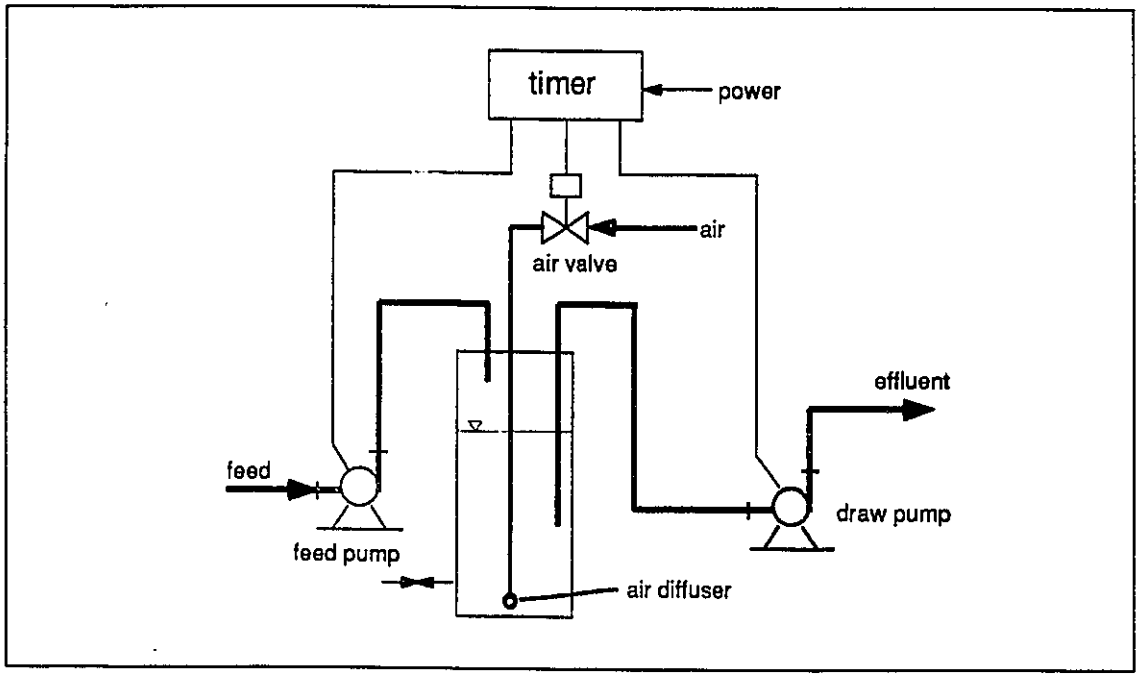


Fig. 4-2 Setup of SBR Reactor and Controlling Equipment

The three SBR reactors were operated on a schedule of 4 cycles per day with 6 hours per cycle. Each cycle consisted of fill, react, settle and withdraw periods. The time distribution of each phase during one cycle was: 2 hours for fill, 3 hours for react, 45 minutes to settle and 15 minutes to draw. Both fill

and react periods were under aerobic conditions with air being supplied through the diffusers.

Each SBR reactor had a total operating volume of 8 L. The initial volume of a SBR at the beginning of the fill period was 2.67 L, thus, the ratio of initial to total volume was 1:3. During the fill period of 2 h, the flow rate for each SBR reactor was 2.67 L/h.

The operating volumes of CFSTR and SBR reactors used in this experimental study were different. Furthermore, the cycle time, division of each phase and number of reactors in an SBR system dictate the allowable continuous flow rate that the SBR system can accommodate. The comparison was made on the basis that the SBR and CFSTR systems were each receiving the same flow rate. The equivalent HDT in the SBR system was computed based on the number of reactors in the SBR system, the initial volume in an SBR reactor and the division of phases in the cycle. Then, for the size of the actual reactors used in this experiments, the appropriate flow rate was chosen to maintain HDT equivalence between SBR and CFSTR systems. Simply stated for two CFSTR systems, HDT equivalence means that if reactor 1 is twice as large as reactor 2, then the flow rate to reactor 1 is twice as high as reactor 2. The same principle applies to SBR and CFSTR systems of different volume.

The procedure to determine the HDT equivalence between SBR and CFSTR systems is described below. The total volume of a CFSTR system is comprised of the aeration basin and settling tank volumes. The HDT of CFSTR is calculated from:

$$T_{dc}=\frac{V_c}{Q} \tag{4-1}$$

where: T_{dc}—— hydraulic detention time of CFSTR (h)

V_c —— aeration basin volume of CFSTR (L)

When an SBR system consists of n reactors, the total volume of the SBR system is:

$$nV_b=V_c+V_{sc} \tag{4-2}$$

where: n —— number of SBR reactors in one SBR system

V_{sc}—— settling tank volume of CFSTR (L)

V_b —— total volume of the SBR system (L)

and the volume of CFSTR reactor can be calculated as:

$$V_c=nV_b-V_{sc} \tag{4-3}$$

The effective volume of one SBR reactor is equal to the total volume of one SBR reactor less its initial volume. Then, the flow rate during the fill period of SBR is computed as:

$$Q=\frac{V_b-V_i}{t_f} \tag{4-4}$$

where: V_i—— initial volume of SBR (L)

t_f—— fill time (h)

Substituting Eqs. 4-3 and 4-4 into Eq. 4-1, yields the HDT of

the CFSTR reactor equivalent to the HDT in the SBR system in one cycle:

$$T_{ds}=\frac{nV_b-V_{sc}}{\frac{V_b-V_i}{t_f}} \qquad (4\text{-}5)$$

where: T_{ds}— hydraulic detention time of SBR system in one cycle (h)

From Eq. 4-5, the HDT of an SBR system consisting of three reactors in one cycle was computed as being equivalent to 8.1 hours hydraulic detention time in a CFSTR system for the values of V_{sc} n, V_b V_i and t_f given above.

To maintain the reactor sludge ages at 5, 10 and 15 days, the daily volumes of mixed liquor being wasted from each SBR were 1500, 800 and 500 mL, respectively.

A timer was set to control the pumps supplying the feed into the reactors and drawing the treated effluents. This timer also controlled an air valve, opening it at the beginning of the fill period and closing it at the end of the react period for each SBR operating cycle.

4.5 Batch Test Conditions

The substrate removal tests were conducted in batch reactors over a period of 8 hours using the synthetic substrate and the

mixed liquor from CFSTR or SBR reactors. The soluble COD concentration and VSS in the batch reactors were measured at several sampling times to determine the kinetic constants and the substrate removal rate.

Table 4-2 summarizes the conditions of batch tests carried out in this experiments. The initial COD concentrations (S_o) of the synthetic substrate fed to the batch reactors were set at 250, 500 and 1000 mg/L. The initial biomass concentration factors in these tests were selected to be 1/2 X_i, X_i and 2 X_i, where X represents the VSS concentration in the mixed liquor drawn from each of the CFSTR and SBR reactors, and i (i=1, 2, 3) corresponded to the sludge ages of 5, 10 and 15 days. The mixed liquor was concentrated to 2 X_i by settling it and withdrawing supernatant. The COD concentration in the influent (S_F) fed to each reactor and sludge age (T_x) are described in Section 4.1. A total of 81 batch tests were conducted with the sludge taken from CFSTRs, and a limited number of 36 batch tests was planned using the sludge from SBRs.

The procedure for batch test is described below.

1. Withdraw 0.5 L, 1 L and 2 L of mixed liquors from each reactor for tests at 1/2X, X and 2X of initial biomass concentration, respectively.

Table 4-2 Conditions of Batch Test

Conditions of Batch Test		Number
Initial COD Conc. S_o (mg/L) fed to batch reactor	250 500 1000	3
Initial Sludge Conc. X	1/2 Xi 1 Xi 2 Xi	3
Influent COD Conc. S_F (mg/L) supplied to reactor	250 500 1000	3
Sludge Age T_x (d)	5 10 15	3
Total Number of Conditions		81

2. Let the mixed liquor settle then decant the appropriate amount of clarified supernatant.
3. Transfer the settled sludge into a beaker of 2 L, and fill the beaker up to 1 L level with the synthetic substrate, thus, the biomass concentrations in the beakers were diluted to 1/2X, maintained at 1X and concentrated to 2X, respectively. The substrate (protein and PVA) concentrations were set at 250, 500 and 1000 mg COD/L.
4. Supply air to each beaker through a diffuser to

maintain the dissolved oxygen above the limiting value of 2 mg/L. Mix the sludge liquor with a magnetic stirrer and a stirring bar.

5. Take samples to determine soluble COD and VSS in the batch reactors. The COD sampling times were set at 0, 30, 60, 90, 120, 180, 240, 360 and 480 minutes, and the VSS samples were taken at intervals of 0, 60, 120 and 480 minutes.

4.6 Assay Methods

In this experiment, all tests and measurements (COD, TSS, VSS, pH, DO, SVI) were carried out according to Standard Methods (1989).

For batch tests, a 40 mL of sample was taken from each beaker at every sampling time. The samples were centrifuged for 20 minutes at a rotating speed of 9000 RPM. The supernatant of the centrifuged sample was used for the determination of soluble COD, and the remaining centrifuged sludge was used to determine TSS and VSS.

A 20 mL sample of mixed liquor was taken from each reactor for measuring the pH value.

A 200 mL sample of mixed liquor was drawn from each reactor to

determine DO concentration.

To conduct the settling test, 1 L of mixed liquor sample was drawn from each reactor, and settled in a one litre graduated cylinder for 30 minutes. Then, the reading of settled sludge volume was taken to determine SVI.

After the test procedures described above were finished, all samples for testing pH, DO and SVI were returned to the reactors from which they were taken.

CHAPTER 5

RESULTS AND DISCUSSION

This chapter presents the results obtained from the substrate removal batch tests using mixed liquor from the CFSTR and SBR reactors. It discusses the effects of the operating conditions on the first order rate constant, and presents the exponential substrate removal model established from the batch test data. Then, this exponential model will be applied to predict effluent COD and the relative active biomass fraction in mixed liquor for both CFSTR and SBR systems. Finally, the current chapter will also present a comparison between CFSTR and SBR systems in terms of the system treatment performance and the application of the exponential model.

5.1 Operating Results for CFSTR and SBR Systems

Table 5-1 lists the average operation parameters for the three CFSTR reactors. The average COD concentrations in the influent were 223, 472 and 969 mg/L. For the above feed conditions, CODs in the treated effluents were in the range of 40-54, 65-74 and 179-203 mg/L, respectively; and the VSS values in

the three reactors were in the range of 635-1435, 1293-2600 and 2990-4577 mg/L, respectively. The sludge age of the CFSTR was calculated by taking into account the amount of sludge removed for sampling and the amount of sludge wasted. The average sludge ages of the three CFSTR reactors were 4.6, 9.2 and 13.5 days. The average food to microorganism ratio (F/M) for CFSTR reactors ranged between 0.5 and 1.1 mg COD/mg VSS/d.

Table 5-1 Operating Parameters for CFSTR Reactors

Reactor No.	S_F mgCOD/L	S_e mgCOD/L	X_v mgVSS/L	X_{ve} mgVSS/L	T_x d	T_d d	F/M d^{-1}
CFSTR1	223	40	1435	39	13.2	0.33	0.50
CFSTR2	223	42	942	46	8.6	0.33	0.72
CFSTR3	223	54	635	36	4.6	0.33	1.06
CFSTR1	472	65	2600	44	13.8	0.33	0.55
CFSTR2	472	69	2067	29	9.6	0.33	0.69
CFSTR3	472	74	1293	73	4.6	0.33	1.11
CFSTR1	969	197	4577	90	13.6	0.33	0.64
CFSTR2	969	179	4244	61	9.5	0.33	0.69
CFSTR3	969	203	2990	37	4.7	0.33	0.98

Table 5-1 shows that three CFSTR reactors receiving constant influent feed exhibited very similar COD removals, although they were operated at different sludge ages. However, when the COD concentration in the feed increased from 223 to 472 mg/L,

the COD concentrations in the treated effluents from the three CFSTRs increased by about 25 mg/L on average. And, as the feed strength increased to 969 COD mg/L, the effluent COD values increased significantly reaching a concentration of about 200 mg/L. These results indicate that a high influent COD concentration affects the treatment result of the CFSTR reactor.

Fig. 5-1 shows a typical plot of the COD values in the influent and the treated effluents from the CFSTR reactors with sludge ages of 4.6, 9.2 and 13.5 days. When the average COD concentration in the feed supplied to the CFSTR reactors was 223 mg/L, the COD concentrations in the treated effluents from all three reactors, operated at 4.6, 9.2 and 13.5 days SRT, averaged 54, 42 and 40 mg/L, respectively. Fig. 5-2 displays the VSS concentrations in the mixed liquors and the treated effluents from the three CFSTR reactors. For the reactors with sludge ages of 4.6, 9.2 and 13.5 days, VSS concentrations averaged 635, 942 and 1435 mg/L, and the VSS values in the treated effluents were on average of 36, 46 and 39 mg/L, respectively.

Table 5-2 summarizes the basic operating parameters for the three SBR reactors. The COD concentrations in the influent averaged 234, 414 and 924 mg/L. Corresponding to above three influent COD concentrations, the effluent CODs from the three

SBR reactors were in the range of 35-47, 43-58 and 107-127 mg/L, and the VSS values in the same reactors were in the range of 549-1113, 873-1584 and 2139-3167 mg/L, respectively. The average F/M ratios in these SBR reactors were in the range of 0.65 to 1.4 mg COD/mg VSS/d. The average sludge ages of the three SBR reactors were calculated as 4, 9 and 13 days, according to Eq. 2-15.

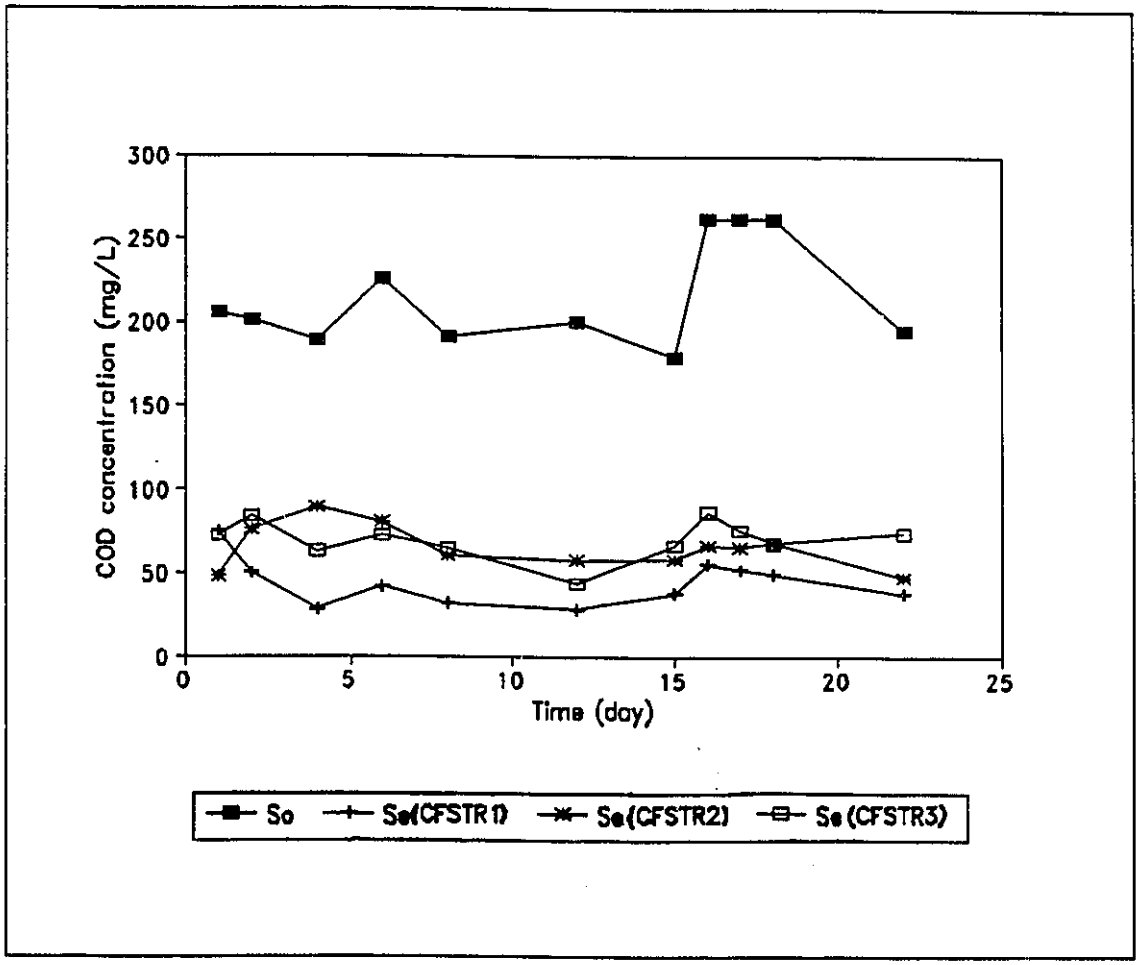
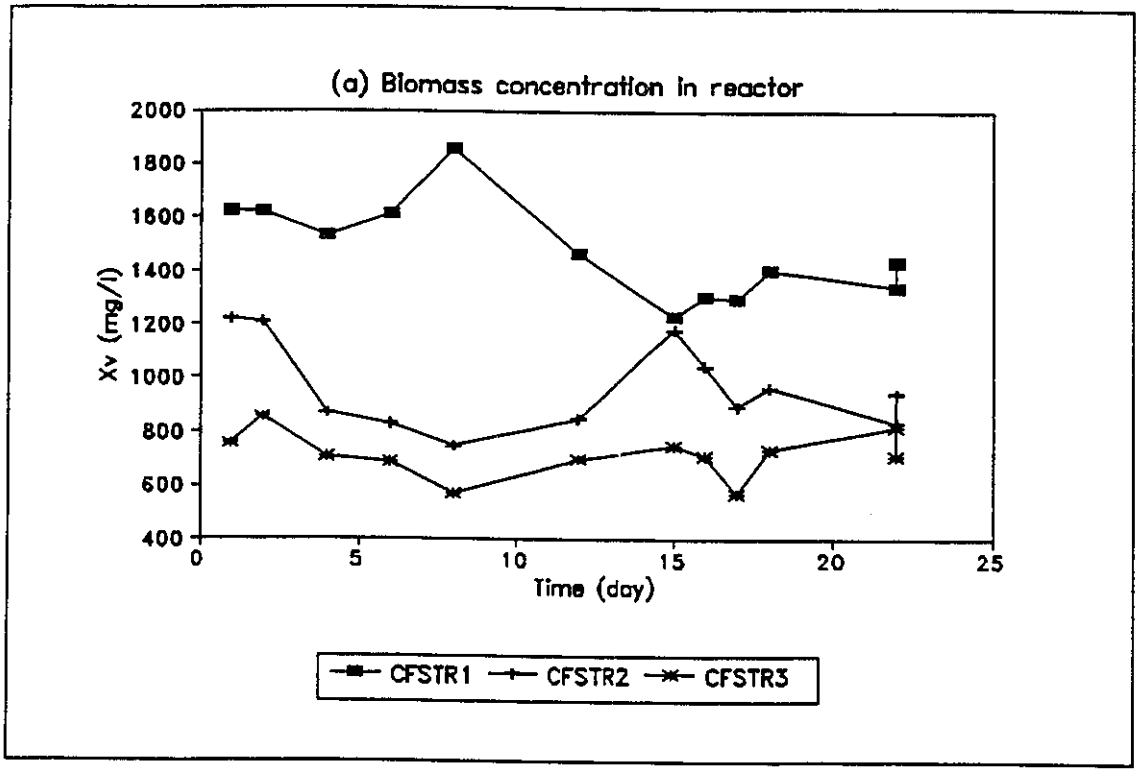


Fig. 5-1 Typical Graph of COD Removal in CFSTR



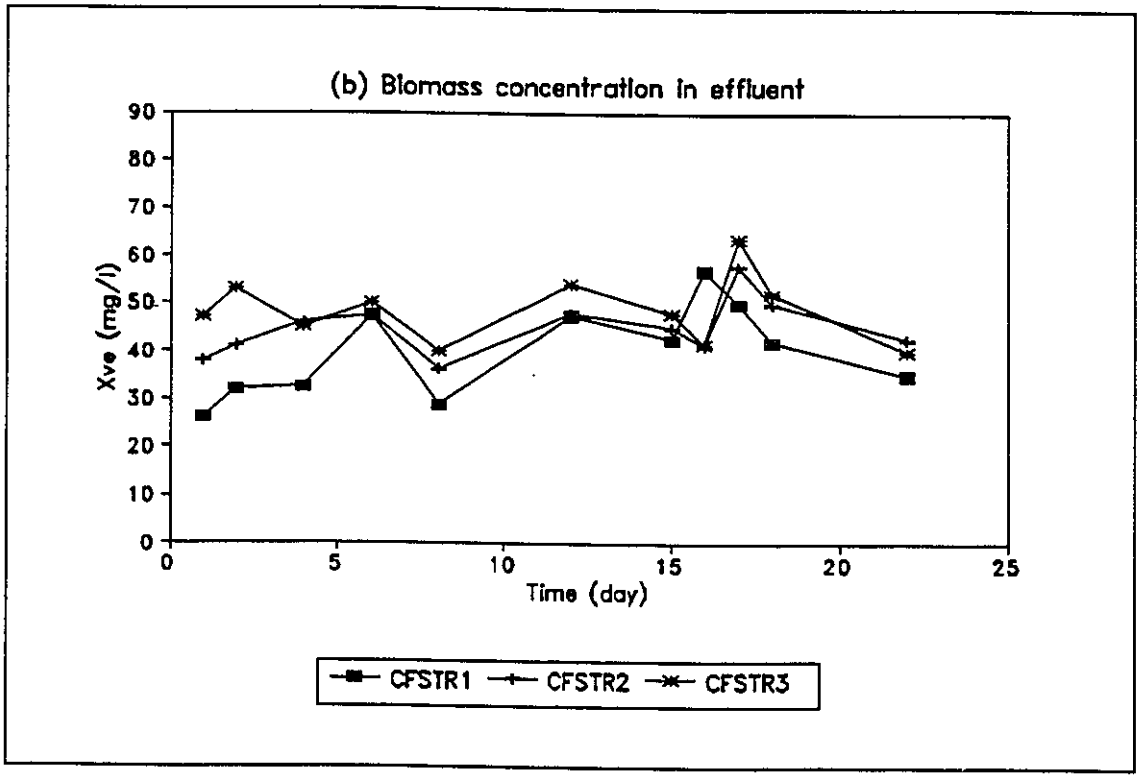


Fig. 5-2 Typical Graph of VSS for CFSTR

Table 5-2 Operating Parameters of SBR Reactors

Reactor	S_P mg/L	S_e mg/L	X_v mg/L	T_x d	T_d d	F/M d^{-1}
SBR1	234	35	1113	13	0.33	0.65
SBR2	234	37	762	9	0.33	0.95
SBR3	234	47	549	4	0.33	1.33
SBR1	414	43	1584	13	0.33	0.68
SBR2	414	45	1283	9	0.33	0.98
SBR3	414	58	873	4	0.33	1.44
SBR1	924	107	3167	13	0.33	0.88
SBR2	924	124	2884	9	0.33	0.97
SBR3	924	127	2139	4	0.33	1.31

Table 5-3 lists the operating environmental parameters of temperature, DO and pH values. For both CFSTR and SBR systems, the temperatures of the mixed liquors were about 20 to 21°C, and the DO concentrations in these reactors were above 5.0 mg/L. The pH values were maintained in the range of 6.5-7.0 for the CFSTRs and 6.7-7.0 for the SBRs.

Table 5-3 Operating Environmental Parameters

Reactor	Temp. °C	DO mg/L	pH
CFSTR	20-21	>5.0	6.5-7.0
SBR	20-21	>5.0	6.7-7.0

5.2 Exponential Model Fitting for CFSTR Batch Study

The exponential model was fitted to the test results obtained from the batch study. A total of 81 batch tests were performed on the mixed liquors taken from CFSTRs. The experimental data for the changes of COD and VSS with time (t_i, S_i, X_v) were collected from each of the batch tests to estimate the first order rate constant K, and the parameters K' and **n** in Eq. 3-2.

Appendix B lists the experimental data collected from 76* batch tests. In 76 batch tests, the initial COD concentrations ranged from 200 to 1300 mg/L, and the biomass concentrations (VSS) varied from 400 to 7000 mg/L. After 8 hours of aeration, the remaining CODs in the batch reactors were on average 60, 90 and 250 mg/L, corresponding to influent COD (S_p) near 250, 500 and 1000 mg/L, respectively. This COD residual at the end of the batch test was considered to be difficult-to-degrade substrate (S_d), and it was taken into account in the exponential model. The S_d values observed in this experiments did not increase proportionally, as the influent COD concentration increases. The test error could be responsible for the low S_d of 90 mg COD/L. However, there was not enough information from the test data to explain these results.

* Five trials failed due to the appearance of sludge worms which caused a decrease in Xv and an increase of soluble COD in the reactors. These conditions were highly abnormal.

5.2.1 Determination and Discussion of First Order Rate Constant K

The first order rate constant K for each of the batch tests was determined by linear regression. Since S_d was considered in this study, Eq. 3-2 was modified as follows:

$$\frac{dS}{dt} = -K' X_v^n (S - S_d) \qquad (5\text{-}1)$$

where: S_d —— difficult-to-degrade substrate concentration (mg/L)

The biomass concentration did not change significantly during the test, thus, X_v in Eq. 5-1 was assumed as a constant. For boundary conditions of: t=0, $S=S_o$, t=t, $S=S_t$, the integration of Eq. 5-1 yields a linear equation in time (t):

$$Ln(S_t - S_d) = Ln(S_o - S_d) - K' X_v^n t \qquad (5\text{-}2)$$

If n=1.0, Eq. 5-2 can be simplified to:

$$Ln(S_t - S_d) = Ln(S_o - S_d) - K X_v t \qquad (5\text{-}3)$$

Dividing Eq. 5-3 by X_v gives a linear function of t with slope K. The average K value (K_{ave}), based on 76 results, was taken as the estimate of the first order rate constant.

Appendix C summarizes the results of regression analysis for the rate constant. The K values ranged from 0.00004 to 0.00092

L/mg/h, the average rate constant was 0.00021 L/mg/h, and its standard deviation was $\pm$0.000106 L/mg/h, or $\pm$33.7%.

As typical examples, Tables 5-4(a) and 5-4(b) list the values of the first order rate constants from 27 batch tests to better indicate the effects of several operating conditions on the K value. Column (1) in Tables 5-4 gives the COD concentration in the influent supplied to the CFSTR reactors. Columns (4) and (5) respectively present the initial COD concentration (S_o) and the biomass concentration (X_v) in the batch tests. The first order rate constant K and the overall rate constant K_m (K_m=KX_v) are listed in Columns (6) and (7), respectively.

Table 5-4(a) shows the variation of the first order rate constant K with respect to the sludge age (T_x). The average rate constants K were 0.000421, 0.000342 and 0.000285 L/mg/h for the mixed liquor withdrawn from CFSTR reactors with sludge ages of 4.6, 9.2 and 13.5 days, respectively. The average overall rate constants K_m were 0.309, 0.353 and 0.393 1/h for these three reactors with SRTs of 4.6, 9.2 and 13.5 days, respectively. These results indicate that: 1) The overall rate constant K_m changed slightly as the reactor sludge age increased. 2) The rate constant K increased with decreasing sludge age. The K value increased by a factor of 1.5 as the sludge age decreased by a factor of 3.

Table 5-4(a) Variation of K with T_x (CFSTR Batch Tests)

S_F mg/L (1)	T_x d (2)	X (3)	S_o mg/L (4)	X_v mg/L (5)	K L/mg/h (6)	K_m h^{-1} (7)
223	13.5	0.5	254	759	0.000469	0.356
223	13.5	0.5	444	690	0.000588	0.406
223	13.5	0.5	1200	862	0.000188	0.162
223	13.5	1	214	1525	0.000289	0.440
223	13.5	1	490	1503	0.000325	0.488
223	13.5	1	1086	1543	0.000219	0.268
223	13.5	2	248	2719	0.000143	0.390
223	13.5	2	491	2915	0.000175	0.513
223	13.5	2	973	2934	0.000173	0.514
				ave.	0.000285	0.393
					±0.000143	
223	9.2	0.5	212	673	0.000585	0.394
223	9.2	0.5	510	471	0.000679	0.320
223	9.2	0.5	1031	759	0.000220	0.156
223	9.2	1	272	921	0.000430	0.396
223	9.2	1	537	1000	0.000340	0.340
223	9.2	1	1122	1119	0.000221	0.247
223	9.2	2	213	2134	0.000167	0.359
223	9.2	2	514	2250	0.000193	0.436
223	9.2	2	986	2226	0.000240	0.535
				ave.	0.000342	0.353
					±0.000190	
223	4.6	0.5	287	407	0.000921	0.375
223	4.6	0.5	438	422	0.000713	0.301
223	4.6	0.5	1048	512	0.000254	0.130
223	4.6	1	273	738	0.000512	0.381
223	4.6	1	580	757	0.000390	0.295
223	4.6	1	978	920	0.000227	0.209
223	4.6	2	197	1310	0.000231	0.303
223	4.6	2	703	1297	0.000280	0.391
223	4.6	2	966	1501	0.000265	0.398
				ave.	0.000421	0.309
					±0.000233	

S_F - COD concentration in influent being fed to CFSTR

S_o - initial COD concentration for batch test

X - factor of X_v in batch test

Table 5-4(b) Variation of K with X_v (CFSTR Batch Tests)

S_F mg/L (1)	T_x d (2)	X (3)	S_o mg/L (4)	X_v mg/L (5)	K L/mg/h (6)	K_m h^{-1} (7)
223	13.5	0.5	254	759	0.000469	0.356
223	13.5	0.5	444	690	0.000588	0.406
223	13.5	0.5	1200	862	0.000188	0.162
223	9.2	0.5	212	673	0.000585	0.394
223	9.2	0.5	510	471	0.000679	0.320
223	9.2	0.5	1031	759	0.000220	0.156
223	4.6	0.5	287	407	0.000921	0.375
223	4.6	0.5	438	422	0.000713	0.301
223	4.6	0.5	1048	512	0.000254	0.130
				ave.	0.000512	0.29
223	13.5	1	214	1525	0.000289	0.440
223	13.5	1	490	1503	0.000325	0.488
223	13.5	1	1086	1543	0.000219	0.268
223	9.2	1	272	921	0.000430	0.396
223	9.2	1	537	1000	0.000340	0.340
223	9.2	1	1122	1119	0.000221	0.247
223	4.6	1	273	738	0.000512	0.381
223	4.6	1	580	757	0.000390	0.295
223	4.6	1	978	920	0.000227	0.209
				ave.	0.000328	0.34
223	13.5	2	248	2719	0.000143	0.390
223	13.5	2	491	2915	0.000175	0.513
223	13.5	2	973	2934	0.000173	0.514
223	9.2	2	213	2134	0.000167	0.359
223	9.2	2	514	2250	0.000193	0.436
223	9.2	2	986	2226	0.000240	0.535
223	4.6	2	197	1310	0.000231	0.303
223	4.6	2	703	1297	0.000280	0.391
223	4.6	2	966	1501	0.000265	0.398
				ave.	0.000207	0.42

S_F - COD concentration in influent being fed to CFSTR

S_o - initial COD concentration for batch test

X - factor of X_v in batch test

Table 5-4(b) and Fig. 5-3 indicate the variation of the rate constant K with the change in the biomass concentration (X_v). For the biomass concentration factors of 0.5X, 1X and 2X in the batch tests, the corresponding average rate constants K were 0.000512, 0.000328 and 0.000207 L/mg/h. Theoretically, the rate constant K should be approximately constant for a specific type of reactor and treatment process. Based on the definition of overall rate constant ($K_m=KX_v$), as X_v increased artificially from 1X to 2X, $K_{m(2X)}$ should equal $2K_{m(1X)}$, however, the results in Table 5-4(b) show that the average value of $K_{m(2X)}$ was about $1.24K_{m(1X)}$. And as X_v decreased from 1X to 0.5X, $K_{m(0.5X)}$ was $0.85K_{m(1X)}$, instead of $0.5K_{m(1X)}$. These results point out deficiencies in the commonly used first order model regardless of whether active mass or total VSS is considered. In the batch tests the ratio of total VSS and active mass was exactly the same, regardless of the dilution or concentration (0.5, 1 and 2) of the mixed liquor VSS.

Table 5-4(b) also displays the effect of the initial COD concentration (S_o) for the batch tests on the rate constant K. As shown in Table 5-4(b), when S_o increased from 250 to 500 to 1000 mg COD/L, the K value fluctuated up or down. These results indicate that the initial COD concentration appears to have an irregular effect on the rate constant K in the batch study.

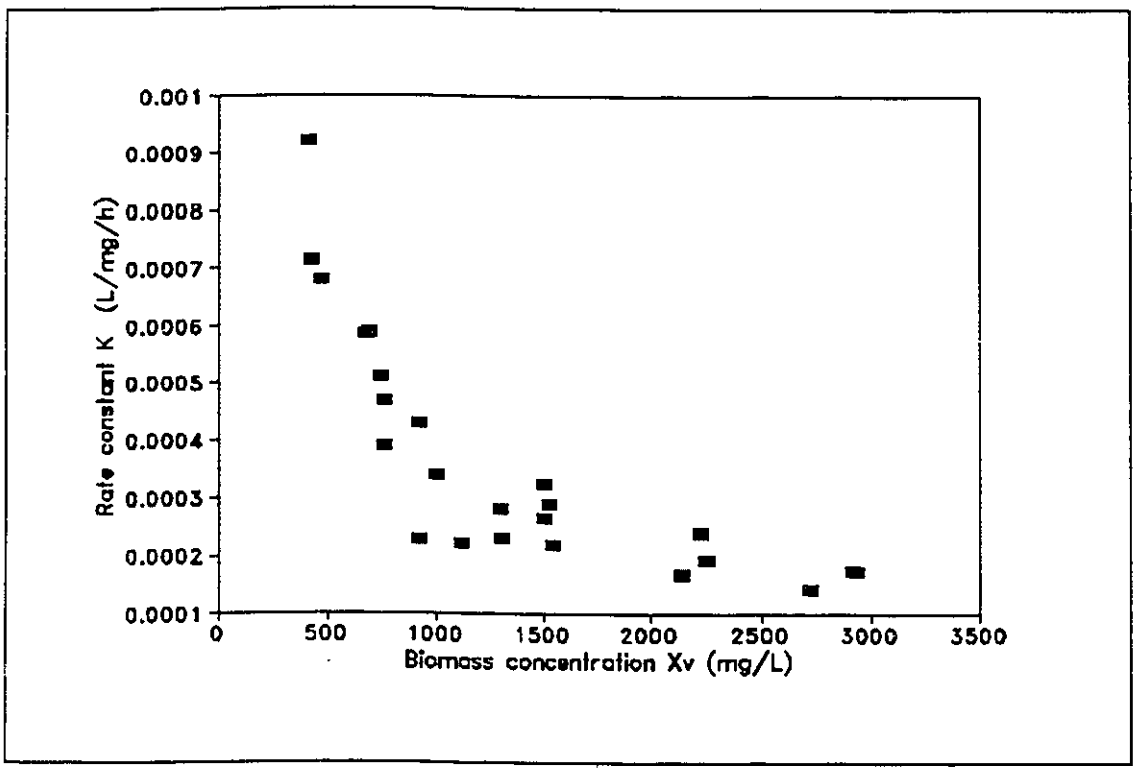


Fig. 5-3 Variation of K with X_v

Fig. 5-3 and Table 5-4(a) also show that the calculated K values for the first order model decrease as X_v increases (sludge age increases). This is expected because active mass is not increasing linearly with X_v. This result is also in agreement with theory presented earlier and supports the X_v^n model.

In summary, the variations of the sludge age, the biomass and the substrate concentrations affect the value of the rate

constant K. It was found that K increased with decreasing sludge age and biomass concentration. In addition, the influent substrate concentration affects the K value in a irregular pattern. These results indicate that there may be some other factors which influence the substrate removal rate, and a more complex model is required to be fully consistent with all conditions.

5.2.2 Determination of Parameters K′ and n

The parameters K′ and **n** were estimated by minimizing the standard fitting error between the observed substrate concentrations (S_{obi}) and the fitted values (S_{ci}) over all 76 batch tests. The average standard fitting error for all trials was calculated from:

$$E_{ave}=\frac{1}{m}\Sigma\sigma_j \tag{5-4}$$

where: E_{ave} — average standard fitting error

m —— number of total trials

σ_j —— standard fitting error for trial j.

The standard fitting error in one trial was computed:

$$\sigma_j=\sqrt{\frac{\Sigma(S_{obi}-S_{ci})^2}{N-1}} \tag{5-5}$$

where: S_{obi}— observed substrate concentration at time t_i (mg/L)

S_{ci}—— calculated substrate concentration at time t_i (mg/L)

N —— number of observations in each batch test

S_{ci} was found from the solution of Eq. 5-2 at a given time t_i:

$$S_{ci}=S_d+(S_o-S_d)\,e^{(-K'X_v^n t_i)} \qquad (5\text{-}6)$$

In Eq. 5-6, S_{ci} is characterized by the two parameters K′ and **n** which were estimated by applying Eqs. 5-4 and 5-6 to find the overall minimum fitting error for the 76 batch tests. The software package of Lotus-123 was used for the fitting error calculation. The procedure for estimating K′ and **n** values is described below.

The **n** value was first chosen as 0 and 1.0, the best K'_0 and $K'_{1.0}$ were calculated from the minimum average fitting errors (E_{ave}). Next, for each **n** in the range from 0.1 to 0.9, a set of K'_n values, which varied between K'_0 and $K'_{1.0}$, were substituted into Eq. 5-6 to compute E_{ave}, and the E_{ave} values were examined to find the lowest E_{ave} which provided the best estimate of K'_n for a given **n**. Then, all values of E_{ave} which corresponded to each pair of **n** and K'_n were presented in a fitting error matrix with **n** and K'_n as the horizontal and vertical axes, respectively. The least E_{ave} value in this matrix gave the best estimate of the K′ and **n** combination.

Since the proposed model was tested under various batch test

conditions including different biomass concentration factors (0.5X, 1X and 2X), therefore, K'_n was categorized in three groups of 0.5X, 1X and 2X, and E_{ave} was presented in three error matrices for these three sets of different initial biomass concentrations. Table 5-5 summarizes the fitting errors for the 27 batch tests with 1X biomass concentration. Appendix D presents all fitting error matrices for the three biomass concentration groups.

Table 5-5 Matrix of Fitting Error for CFSTR Batch Tests (1X)

K'\ n	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0.0
0.000060	132.9	196.9	239.6	262.7	274.2	279.7	282.4	283.6	284.2	284.4	284.5
0.000210	91.6	96.1	152.0	212.3	248.2	267.1	276.3	280.7	282.8	283.8	284.2
0.000450	134.3	87.6	95.5	156.1	215.1	249.8	267.8	276.7	280.9	282.9	283.8
0.000930	199.5	132.3	83.8	95.1	159.1	217.2	250.9	268.3	276.9	281.0	282.9
0.001900	240.9	197.9	129.2	79.9	96.0	163.1	219.8	252.3	269.0	277.2	281.1
0.003900	259.8	240.7	196.6	126.4	76.3	96.9	166.6	222.0	253.4	269.5	277.4
0.007000	265.2	260.3	241.4	197.0	126.1	72.2	96.5	167.7	222.7	253.7	269.7
0.015000	265.8	265.3	260.6	241.3	196.1	124.3	69.2	97.3	169.9	224.0	254.4
0.030000	265.8	265.8	265.4	261.1	242.1	196.8	124.6	66.9	96.7	170.2	224.1
0.065000	265.8	265.8	265.8	265.5	261.3	242.0	196.0	123.3	65.1	97.9	171.7
0.150000	265.8	265.8	265.8	265.8	265.5	261.4	241.8	195.0	121.7	64.3	99.6
0.300000	265.8	265.8	265.8	265.8	265.8	265.6	261.6	241.8	194.7	121.2	64.9
0.350000	265.8	265.8	265.8	265.8	265.8	265.7	262.4	244.5	200.0	127.9	68.0

As shown in Table 5-5, the smallest fitting error for each **n** value appeared along the diagonal elements of the matrix. The minimum fitting error of 64.3 resulted in the estimates of **n** equal to 0.1, and K' equal to 0.15 L/mg/h. Comparing the minimum standard error 64.3 from the exponential model with 91.6 from the first order model, it can be seen that the exponential model can improve the accuracy for the substrate removal expression in the batch test by about 30%.

In addition, it is observed that with fitting errors in the range of 69 to 65 (difference of about 5%), the **n** value ranged from 0.4 to 0. This result indicates that the exponential model, with **n** in the range from 0.1 to 0.4, can be used as a more accurate substrate removal expression for batch reactor, than the first order model.

Fig. 5-4 plots fitting error versus exponent value **n**. For the 0.5X, 1X and 2X factors of X_v, these curves show that the first order substrate removal model (n=1.0) has the highest error for the three groups of the batch test data. When the exponent **n** value reduces from 1.0 to 0, the fitting error decreases as well. For **n** ranges from 0.1 to 0.5, all curves display low fitting errors. These results indicate that the proposed exponential model can more accurately express the substrate removal kinetics for all the batch tests, especially when **n** is between 0.1-0.5. As shown in the same figure, the

zero order X_v model works better than the first order model since it is associated with a much small error.

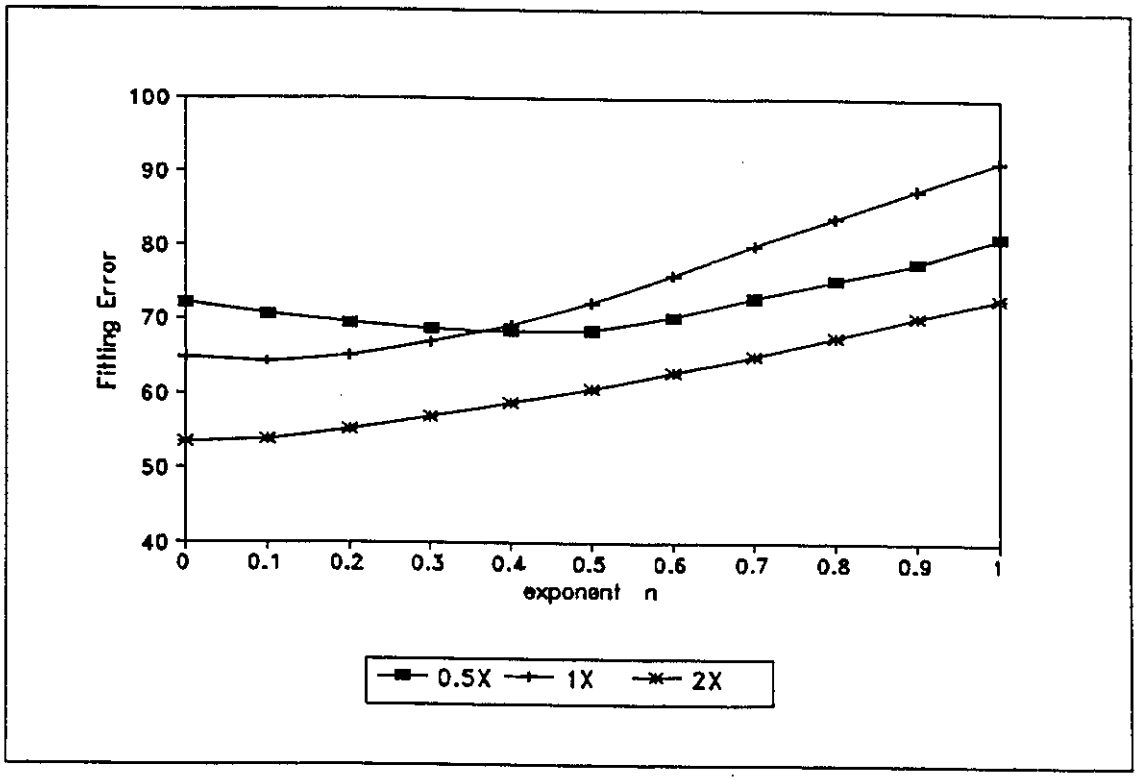


Fig. 5-4 Fitting Error vs. Exponent **n** (CFSTR Batch Tests)

Fig. 5-4 also illustrates that the lowest fitting error occurred at **n** equal to 0.4 for the test data group of 0.5X biomass concentration, 0.1 and 0.0 for the test groups of 1X and 2X biomass concentrations, respectively. These phenomena indicate that the artificial change (dilution or concentration) in biomass concentration affects the value of

the exponent **n** in the proposed exponential model.

Table 5-6 summarizes the K′ values that resulted in the smallest E_{ave} in the three error matrices. As **n** ranged from 0.0 to 0.5, the values of K′ in the three test groups were very close. These results show that the artificial variation in the biomass concentration has less effect on the K′ value. Also the above results exhibit the desired characteristic for the kinetic constant that it should be consistent under different test conditions.

Table 5-6 Determination of K′ from CFSTR Batch Tests

n	1.0	0.5	0.4	0.3	0.2	0.1	0.0
K′ (0.5X)	0.00032	0.0075	0.015	0.030	0.060	0.120	0.25
K′ (1X)	0.00021	0.0070	0.015	0.030	0.065	0.150	0.30
K′ (2X)	0.00014	0.0065	0.015	0.030	0.065	0.145	0.30

The X_v concentrations were changed to 0.5X and 2X in addition

to considering 1X in order to evaluate the consistency of the kinetic model under these "artificial" conditions. The primary analysis was based on the 1X concentration. From the analysis of fitting error for 1X biomass concentration, the best values of the parameters **n** and K' were estimated to be 0.1 and 0.15 L/mg/h, respectively. The new substrate removal model established from the batch tests using sludge from CFSTRs was:

$$\frac{dS}{dt} = -0.15 X_v^{0.1} (S - S_d) \qquad (5\text{-}7)$$

Fig. 5-5 shows 27 plots of the simulated curves for the batch tests with sludge taken from CFSTR reactors that received the same influent COD concentration. The dots in the figures represent the observed soluble COD values remaining in the mixed liquor of the batch tests, and the curve depicts the substrate concentration calculated from applying Eq. 5-7.

As shown in Fig. 5-5, the fitted curves are in good agreement with the measured data. It can also be observed that the best fitted curves, for the sludge concentration factor of 0.5X in the batch tests, appear below the test data, especially in the case of high initial COD concentration (S_o=1000 mg/L). However, most of the predicted curves for the sludge concentration factors of 1X and 2X match the experimental data quite well. These results are caused by the effect of the different biomass concentration factors on the parameter **n** in the proposed model.

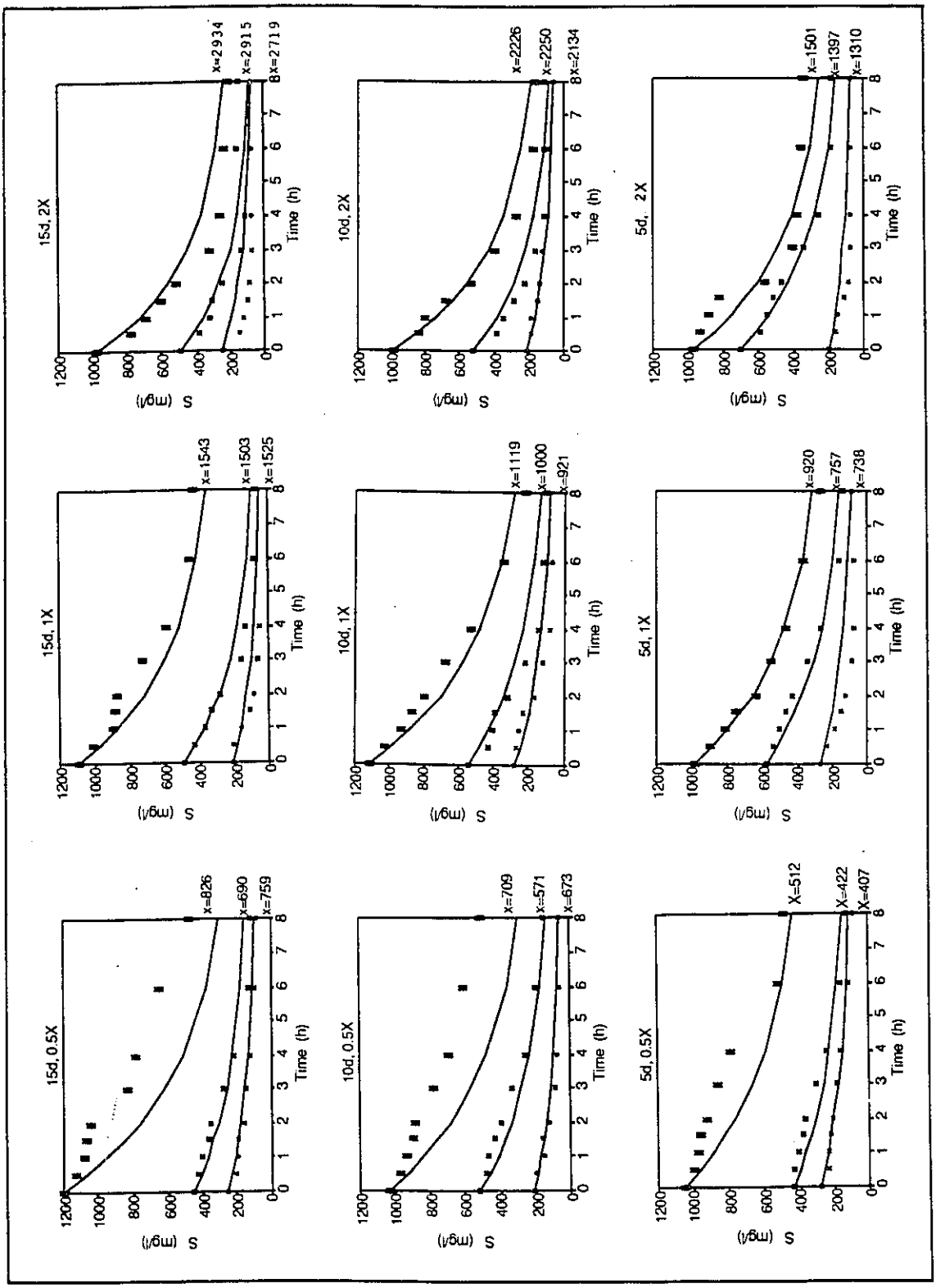


Fig. 5-5 Typical Simulated Curves for CFSTR Batch Tests

Table 5-7 summarizes the standard errors of the fitted curves for these 27 batch tests. Column (7) indicates the standard errors between the observed data and the fitted values by applying the established model. As shown in Table 5-7, the highest errors were observed for the reactor operated sludge ages of 13.5 days in six out of nine cases. Two out of nine and one out of nine highest errors were obtained for other reactors with sludge ages of 9 and 4.6 days, respectively. Otherwise, most of standard errors of fitted curves were relatively smaller for the latter two reactors. These results appear to be influenced by the sludge age, especially the high sludge age of 13.5 days.

The above results indicate the effects of sludge age and artificial change in biomass concentration on the curve simulation. As discussed previously, the change in biomass concentration (dilute or concentrated) affects the **n** value, but has less effect on the K' value in the proposed model. Since the parameters **n** and K' in the proposed model can not concurrently reflect all variations in sludge age and biomass concentration, some error in curve simulation will occur.

Table 5-7 Std. Error of Fitted Curves for CFSTR Batch Tests

S_F mg/L (1)	S_o mg/l (2)	X_v mg/l (3)	T_x d (4)	X (5)	S_d mg/L (6)	Standard Error n=0.1 K'=0.15 (7)
223	253	759	13.5	0.5	70	21.7
223	212	673	9.2	0.5	40	21.5
223	287	407	4.6	0.5	70	16.8
223	444	690	13.5	0.5	115	34.3
223	510	471	9.2	0.5	70	26.3
223	438	422	4.6	0.5	90	30.8
223	1200	826	13.5	0.5	200	162.3
223	1031	709	9.2	0.5	210	138.7
223	1048	512	4.6	0.5	200	93.6
223	214	1525	13.5	1	50	32.2
223	272	921	9.2	1	50	31.9
223	273	738	4.6	1	50	52.4
223	490	1503	13.5	1	70	46.2
223	537	1000	9.2	1	70	58.5
223	580	757	4.6	1	70	31.1
223	1086	1543	13.5	1	210	57.1
223	1122	1119	9.2	1	210	46.7
223	1087	920	4.6	1	210	36.9
223	248	2719	13.5	2	70	57.5
223	197	1734	9.2	2	50	7.5
223	231	1310	4.6	2	70	31.2
223	491	2915	13.5	2	60	50.9
223	514	2250	9.2	2	60	60.1
223	702	1297	4.6	2	110	28.1
223	972	2934	13.5	2	200	99.0
223	986	2226	9.2	2	140	69.2
223	966	1501	4.6	2	200	81.2

S_F - COD concentration in influent supplied to CFSTR

S_o - initial COD concentration for batch test

X - factor of X_v in batch test

5.2.3 Application of Exponential Model for CFSTR System

The proposed exponential model was applied to predict the effluent COD concentration for the continuous flow system, as well as to predict the relative active mass fraction in mixed liquor. This section will present and discuss the predicted results for the three CFSTRs.

5.2.3.1 Prediction of Effluent COD from CFSTR System

To examine the application of the exponential model established from the batch test data to the continuous flow system, the exponential model was applied in a substrate mass balance equation to predict the effluent COD concentrations for three different CFSTR systems. The effluent CODs were also predicted from the first order and zero order models. To calculate the prediction error, the predicted effluent COD (S_e') values were compared with the measured effluent COD (S_e) data collected during experiments with CFSTRs. By using a substrate mass balance equation around the CFSTR system at steady state, the effluent substrate concentration can be computed:

$$S_e' = \frac{S_o}{1 + K' X_v^n T_d} \qquad (5\text{-}8)$$

S_e' was calculated by applying Eq. 5-8 with the first order

model (**n**=1.0); the zero order of X_v model (**n**=0) and the exponential model with **n** ranging between 0.1 and 0.5. The performances of these three referred kinetic models were compared based on their prediction errors.

The best fit K' value for the CFSTR continuous flow system was found by varying the K' value estimated in the batch test analysis. Then, this best K' value for the continuous flow system was compared with K' estimated from the batch test data to check if there was a difference between them.

Due to the differences in the substrate removal in batch kinetic test and continuous flow or semi-continuous flow systems, it was not necessary to normalize substrate with respect to S_d in the continuous flow or semi-continuous flow systems.

Table 5-8 summarizes the predicted results of effluent COD concentrations for the three CFSTR systems. Columns (1) through (4) list the average values of four CFSTR operating parameters: sludge age, COD in the influent and the effluent and VSS in the reactors, respectively. Columns (5) through (8) respectively present the predicted effluent COD concentrations with **n** equal to 1.0, 0.1 and 0. The K' value in column (6) was estimated from the batch test data. The K' values in Columns (7) and (8) resulted in the best fit S_e' for the continuous

flow system. Appendix E presents all other results from the prediction study.

Table 5-8 Predicted Effluent COD for CFSTR Continuous Systems

T_x d	S_F mg/L	S_e mg/L	X_v mg/L	n K'	S_e' 1.0 0.0002	S_e' 0.1 0.15	S_e' 0.1 0.24	S_e' 0.0 0.36
(1)	(2)	(3)	(4)		(5)	(6)	(7)	(8)
13.5	223	40.2	1435		68	61	44	57
9.2	223	46.3	942		89	63	46	57
4.6	223	61.3	635		109	65	48	57
13.5	472	65.5	2600		89	124	90	122
9.2	472	69.4	2067		108	126	92	122
4.6	472	73.7	1293		151	130	97	122
13.5	969	198	4577		110	227	177	249
9.2	969	180	4244		122	245	179	249
4.6	969	203	2990		164	252	184	249
Error					54.0	46.6	16.7	45.4

S_e - observed effluent COD concentration

S_e' - predicted effluent COD concentration

From Table 5-8, the following observations can be made:

1. The exponential model can better predict S_e' for the continuous flow system than the first order model, because the fitting error from the proposed exponential model was smaller than that in the first order model. The

exponential model can improve the accuracy of effluent COD prediction for the continuous flow system by about 14% compared to the first order model.

2. The K' value adjusted for the continuous flow system was 0.24 L/mg/h, because it resulted in the lowest prediction error. This best K' value is higher than K' (0.15 L/mg/h) estimated from the batch analysis. This difference in the K' value is possibly caused by S_d which was considered in the determination of K' from the batch test data, while S_d was not included in K' determination based on the mass balance equation for the continuous flow system.
3. The zero order of X_v model does not predict S_e' accurately for the continuous flow system, although it fits the batch test data well. Otherwise, this model provides the same S_e' values for the three CFSTR reactors with different sludge ages.

5.2.3.2 · Prediction of Relative Active Faction in CFSTR

This section presents a comparison of relative biomass activity when the exponential model is applied to the three CFSTRs.

As described in Chapter 3, the parameter K' in the exponential model includes two portions: the rate constant K and the active mass factor **a**. $K'X_v^n$ represents the product of the rate

constant K and the active mass aX_v^n. Therefore, under the same COD concentration conditions, the fraction of $K'X_{v2}^n/K'X_{v1}^n$ (or X_{v2}^n/X_{v1}^n) can express the relative active ratio between two reactor operating conditions. The general formula for computing the relative active biomass is:

$$X'_{ai}=X_{vi}\frac{X_{vi}^n}{X_{vi}^n} \qquad (5\text{-}9)$$

In Eq. 5-9, i (i=1,2,3) corresponds to the reactor sludge ages of 4.6, 9 and 13.5 days, and X_{a1}' represents the relative active biomass produced in the reactor with the shortest sludge age of 4.6 days. In this study, X_{a1}' was considered as the basis for the relative active biomass.

The relative active fractions in the mixed liquors of the CFSTR systems were calculated based on the 27 batch test data (1X biomass concentration) using the sludge from CFSTRs. Table 5-9 summarizes the predicted results of the relative active fractions in these three CFSTR systems with different sludge ages. As the initial COD concentrations (S_o) for the batch tests ranged from 210 to 1300 mg/L, the average biomass concentration (X_{vavg}) was taken for calculating X_a' and listed in Column (3). Column (5) presents the relative active biomass (X_a') computed by applying Eq. 5-9 with **n** of 0.1 in the exponential model. The relative active fraction in CFSTR systems (f_c'), which is the ratio of X_a' to X_v, is given in

Column (6). Appendix F includes all calculations and pertinent information.

Table 5-9 Relative Active Mass Fraction in CFSTR

T_x d (1)	S_F mg/L (2)	X_{vavg} mg/L (3)	S_o mg/L (4)	X_a' mg/L (5)	f_c' % (6)
4.6	223	774	250-1000	774	100.0
4.6	472	1310	300-1300	1310	100.0
4.6	969	2731	250-1000	2731	100.0
				ave.	100.0
9.2	223	1013	270-1100	795	78.4
9.2	472	2090	260-1300	1373	65.7
9.2	969	3437	230-1000	2795	81.3
				ave.	75.1
13.5	223	1524	210-1000	828	54.3
13.5	472	2560	300-1300	1401	54.7
13.5	969	4066	240-1000	2842	69.9
				ave.	59.6

As indicated in Table 5-9, the exponential model predicted that the relative active biomass increased as the reactor sludge age increased. However, the relative fraction of active mass decreased from 100% to 75% and 60%, as the CFSTR reactor sludge age increased from 4.6 days to 9.2 and 13.5 days,

respectively. These results are in agreement with the Goodman-Englande's study (1974).

The relative active fraction predicted by the exponential model was compared with the active mass fraction reported by Goodman-Englande (1974) shown in Fig. 2-7. From Fig. 2-7, the active mass fraction of 77% in the reactor with sludge age of 5 days was taken as the basis of the relative activity of biomass. Thus, the relative active mass fractions in the Goodman-Englande study for the sludge ages of 10 and 15 days were calculated as 87% and 82%, respectively.

Fig. 5-6 plots the above two relative active fractions versus the reactor sludge age. As the reactor sludge age increased, the relative active fractions from the Goodman-Englande study were higher than the predicted relative active fractions. In addition, Goodman-Englande's relative fraction curve decreases exponentially as sludge age increases, however, the predicted relative fraction decreases linearly with increasing sludge age. This result may be caused by the limitation of the three sludge age conditions in this study.

5.3 Exponential Model Fitting for SBR Batch Study

In an attempt to compare the kinetics of CFSTR and SBR, a parallel experiment for modelling substrate removal rate,

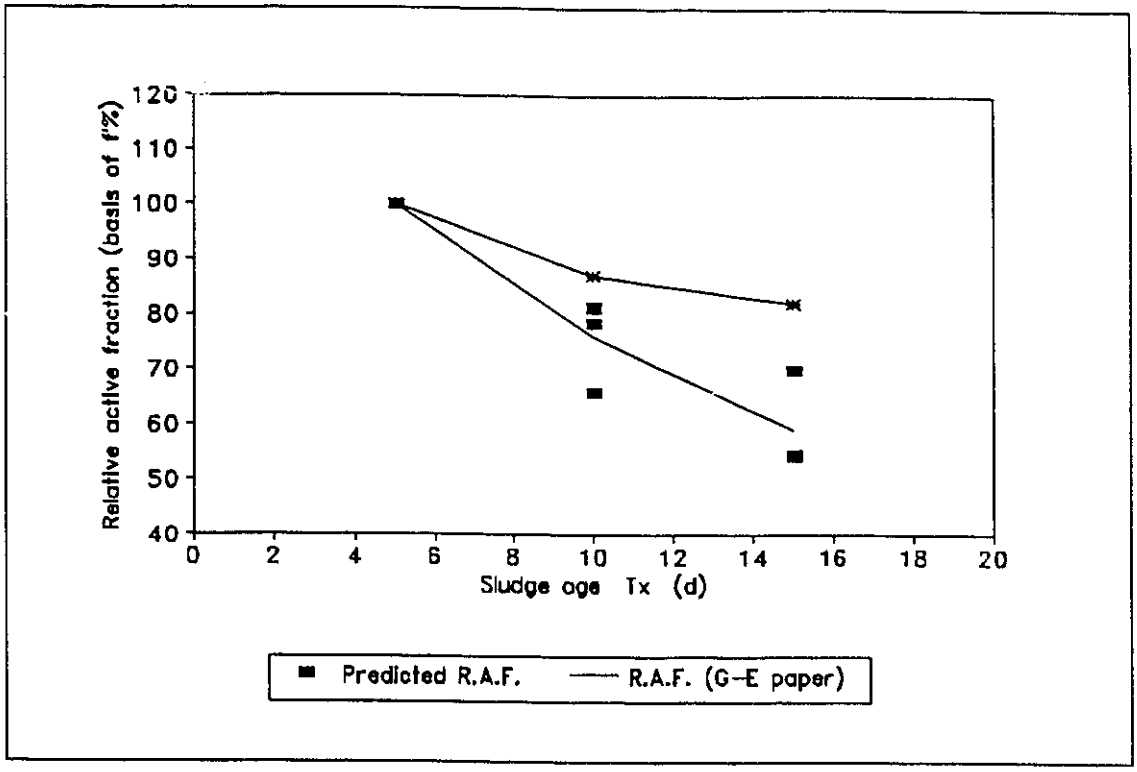


Fig. 5-6 Comparison of Relative Active Mass Fractions

including 36 batch tests was carried out on the sludge taken from three SBR reactors. In 36 batch tests, the initial COD concentrations ranged from 200 to 1100 mg/L, and VSS concentrations in the mixed liquors of SBRs varied from 500 to 6200 mg/L. The remaining COD at the end of the batch test was considered to be difficult-to-degrade substrate. Corresponding to the batch test conditions with initial COD concentrations of 250, 500 and 1000 mg/L, the difficult-to-degrade substrate concentrations averaged 100, 130 and 200 mg COD/L. Appendix G lists the experimental data collected from 36 SBR batch tests.

5.3.1 First Order Rate Constant K

The first order rate constant K was estimated by the linear regression described in Section 5.2.1. The range of K values was between 0.00005 to 0.00095 L/mg/h for all SBR batch tests. The average rate constant K_{ave} for 36 batch tests was 0.00031 L/mg/h, its standard deviation was $\pm$0.000114 L/mg/h, or $\pm$33.5%. Appendix H presents the results of the first order rate constants K for all SBR batch tests.

Table 5-10 summarizes results of the first order rate constant K from 9 SBR batch tests with different sludge ages. The average K values were 0.000488, 0.000417 and 0.000302 L/mg/h for the three SBRs with sludge ages of 4, 9 and 13 days, respectively. It was observed that K increased as the sludge age decreased. The overall rate constants K_m averaged 0.404, 0.488 and 0.477 1/h for SRTs of 4, 9 and 13 days, respectively.

In addition, Table 5-10 indicates that the K value also varied with different initial COD concentrations (S_o) in the batch tests. As S_o increased, the K value varied in an irregular pattern. There was no systematic influence of initial substrate concentration on K.

Table 5-10 Variation of K with T_x (SBR Batch Tests)

S_F mg/L (1)	T_x d (2)	X (3)	S_o mg/L (4)	X_v mg/L (5)	K L/mg/h (6)	K_m h^{-1} (7)
414	13	1	203	1608	0.000229	0.369
414	13	1	406	1551	0.000399	0.620
414	13	1	715	1586	0.000279	0.443
				ave.	0.000302	0.477
414	9	1	215	1103	0.000471	0.478
414	9	1	421	1239	0.000417	0.517
414	9	1	770	1285	0.000364	0.469
				ave.	0.000417	0.488
414	4	1	239	778	0.000528	0.411
414	4	1	368	824	0.000487	0.402
414	4	1	723	890	0.000448	0.399
				ave.	0.000488	0.404

S_F - COD concentration in influent supplied to SBRs

S_o - initial COD concentration for batch test

Table 5-11 displays variations of the rate constant K with different biomass concentration factors (X). The average overall rate constants K_m were respectively 0.208, 0.233 and 0.205 1/h, as the biomass concentration factors were artificially set at 0.5X, 1X and 2X. Corresponding to these three sludge concentration factors, the average rate constants K were 0.000135, 0.000075 and 0.000033 L/mg/h. The results in this table show that the K value increased about 1.8 times as

the biomass concentration was diluted from 1X to 0.5X, and K decreased around 2.3 times, when the sludge concentration was artificially increased to 2X.

Table 5-11 Variations of K with X_v (SBR Batch Tests)

S_F mg/L (1)	T_x d (2)	X (3)	S_o mg/L (4)	X_v mg/L (5)	K L/mg/h (6)	K_m h^{-1} (7)
914	9	0.5	349	1573	0.000115	0.182
914	9	0.5	544	1521	0.000159	0.243
914	9	0.5	1001	1499	0.000132	0.198
				ave.	0.000135	0.208
914	9	1	340	3021	0.000052	0.159
914	9	1	553	3032	0.000092	0.282
914	9	1	1037	3133	0.000081	0.257
				ave.	0.000075	0.233
914	9	2	344	5854	0.000026	0.187
914	9	2	564	6210	0.000038	0.242
914	9	2	1036	5916	0.000036	0.217
				ave.	0.000033	0.205

S_F - COD concentration in the influent supplied to SBR

S_o - initial COD concentration in batch test

As shown in the above two tables, the variations of sludge age, biomass and substrate concentrations have effects on the rate constant K. The K value increases with decreasing sludge

age and biomass concentration. Changes in influent substrate concentration have no systematic influence on K. The above results were possibly caused by the limitation of the number of batch tests and some other factors, such as sludge surface adsorption which affected the K value as sludge age, biomass and substrate concentrations were changed.

5.3.2 Determination of Parameters n and K'

As described in Section 5.2.2, the parameters **n** and K' in the proposed exponential model for the SBR system were estimated by minimizing the fitting error between S_{obi} and S_{ci} calculated with a set of **n** and K'_n values for all 36 batch tests.

Table 5-12 presents the matrix of the fitting error for the batch tests without artificially changing the biomass concentration. Appendix I shows the results of the fitting errors. With the minimum fitting error of 50.4, the estimated value of **n** was 0.1 and K' was 0.22 L/mg/h. Comparing the minimum error of 50.4 with 65.2 obtained for the first order model, the exponential model can improve the accuracy for substrate removal expression by about 23% in SBR batch test.

Fig. 5-7 plots the fitting error versus the exponent **n**. The curve shows that the first order expression for substrate utilization in batch test has the highest error. However, the

Table 5-12 Matrix of Fitting Errors for SBR Batch Tests (1X)

K'\ n	1.00	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10	0.00
0.000250	70.2	101.2	156.3	201.7	229.0	243.5	250.7	254.2	255.8	256.6	257.0
0.000300	65.2	89.0	140.1	190.7	222.8	240.3	249.1	253.4	255.5	256.4	256.9
0.000650	75.8	62.7	88.8	142.2	192.4	223.8	240.8	249.4	253.5	255.5	256.4
0.001300	111.4	73.3	60.7	89.9	145.6	194.8	225.2	241.5	249.7	253.7	255.6
0.002700	137.0	111.4	71.9	58.3	90.0	147.1	195.9	225.8	241.8	249.8	253.7
0.005500	147.0	137.3	111.2	70.4	56.3	90.2	148.7	197.1	226.4	242.1	250.0
0.012000	149.2	147.5	138.3	112.6	70.7	53.9	88.4	147.8	196.5	226.0	241.9
0.025000	149.3	149.2	147.4	137.6	110.5	67.4	53.2	91.4	152.0	199.3	227.6
0.050000	149.3	149.3	149.2	147.7	138.3	111.4	67.5	51.6	90.3	151.6	198.9
0.105000	149.3	149.3	149.3	149.2	147.9	138.4	111.1	66.3	50.8	90.9	152.7
0.220000	149.3	149.3	149.3	149.3	149.2	148.0	138.4	110.6	65.2	50.4	91.7
0.450000	149.3	149.3	149.3	149.3	149.3	149.3	148.1	138.5	110.4	64.5	51.0
0.500000	149.3	149.3	149.3	149.3	149.3	149.3	148.4	140.4	114.6	69.7	57.9

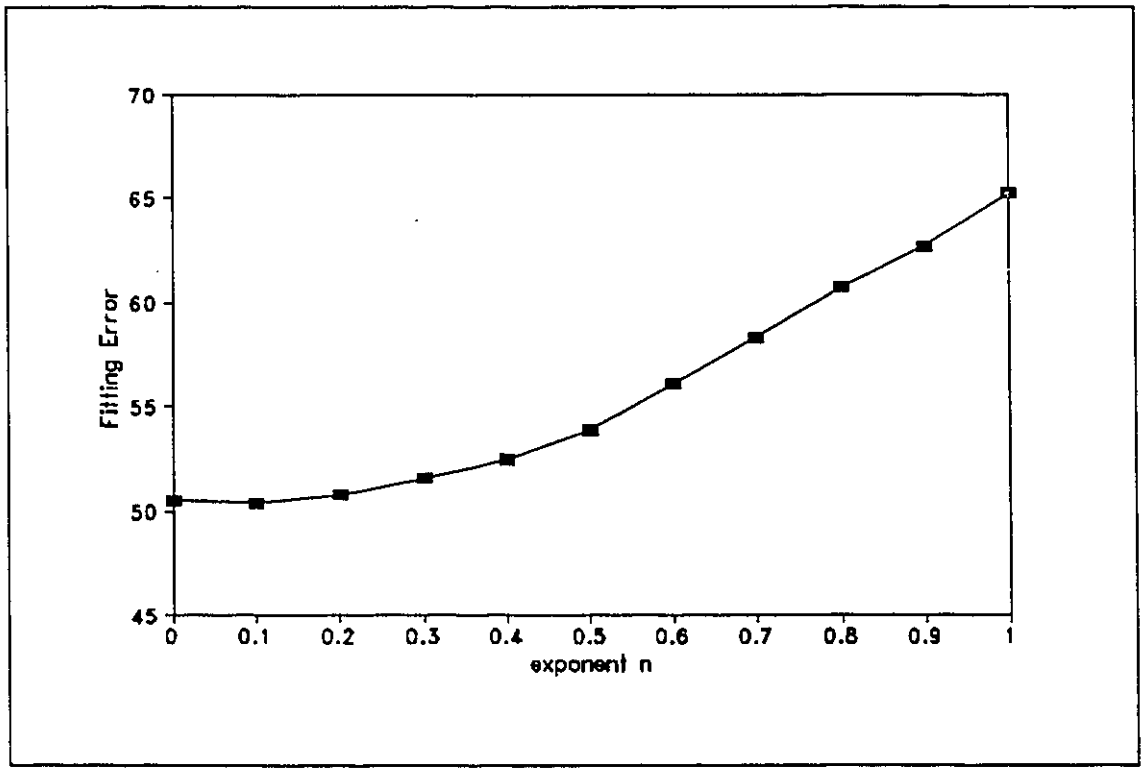


Fig. 5-7 Fitting Error vs. Exponent **n** (SBR Batch Tests)

exponential model, with **n** in the range of 0.1 to 0.3, can more accurately describe substrate removal kinetics.

Based on the analysis of the fitting error, the values of the parameters **n** and K' were estimated at 0.1 and 0.22 (L/mg/h), respectively. The exponential substrate removal model for SBR batch reactor was established as:

$$\frac{dS}{dt} = -0.22 X_v^{0.1} (S - S_d) \qquad (5\text{-}10)$$

Fig. 5-8 shows a set of typical graphs of the curve simulation for the batch tests using sludge from three SBR reactors. The dots in the figures are the COD concentration remaining at time t in the batch reactors. The curves represent the substrate concentrations as predicted by the exponential model. As shown in Fig. 5-8, the exponential kinetic model fits the experimental data quite accurately for the batch test using the sludge from the SBR reactors.

Table 5-13 lists the standard errors of the fitted curves for the typical graphs in Fig. 5-8. As shown in the table, the fitting errors for S_o (initial COD concentration of the batch test conditions) around 1000 mg/L are relatively higher than others. Since the parameters **n** and K' can not concurrently reflect all factors that affect reactor operation, such as sludge age, substrate and biomass concentrations, the change in S_o will cause some fitting error.

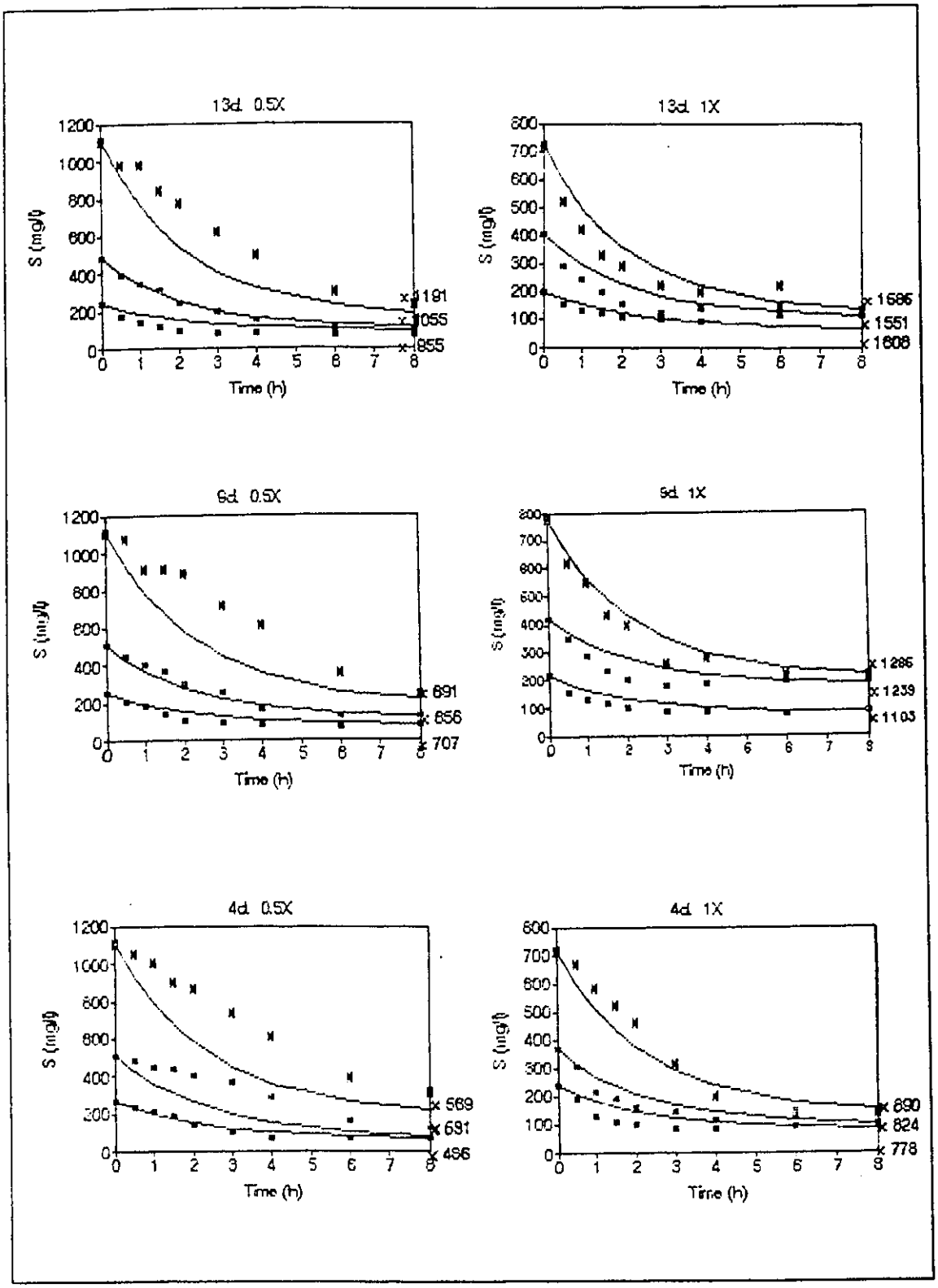


Fig. 5-8 Typical Plots of Simulation for SBR Batch Tests

Table 5-13 Std. Errors of fitted Curves for SBR Batch Tests

S_o mg/l (1)	X_v mg/l (2)	T_x d (3)	X (4)	Standard Error n=0.1, K'=0.22 (5)
242	955	13	0.5	27.7
485	1055	13	0.5	13.5
1105	1191	13	0.5	123.1
203	1608	13	1	24.0
406	1551	13	1	50.5
723	1586	13	1	31.8
251	707	9	0.5	25.2
504	656	9	0.5	26.0
1105	691	9	0.5	175.6
215	1103	9	1	22.7
421	1239	9	1	39.8
770	1285	9	1	39.8
264	486	4	0.5	13.0
513	531	4	0.5	48.6
1103	569	4	0.5	141.9
239	778	4	1	33.1
368	824	4	1	33.4
715	890	4	1	53.8

5.3.3 Application of Exponential Model for SBR System

The exponential model was applied to predict the COD concentration in treated effluents from the three SBR systems, as well as to predict the relative active mass fractions in the mixed liquors of these reactors.

The effluent COD concentration was predicted by applying a substrate mass balance equation around the SBR system given in Eq. 2-35. The first order and the zero order models, as well as the exponential model with **n** in the range from 0.1 to 0.3 were employed for substrate removal expression. The K' value was varied about ±10% to find the best K' value for the SBR continuous system. Since the mixed liquor volume in SBR varies during the fill period, the differential equation (Eq. 2-35) was solved by the Runge-Kutta method (Spiegel, 1971). Appendix J presents the results and the related data for predicting S_e' from SBRs. Table 5-14 summarizes the predicted effluent CODs (S_e') for the SBR systems, as **n** equal to 1.0, 0.1 and 0 for the three referred substrate removal models.

From Table 5-14, it can be observed that:

1. The exponential model is a more accurate model to describe substrate removal in SBR continuous system, since it is associated with the lowest prediction error (9.3). Compared to the first order equation, the exponential model can improve the prediction accuracy of the COD concentrations in the SBR's effluent by about 80%.
2. The K' value estimated from batch test study was in good agreement with the best K' value for the continuous flow system. The best K' value of 0.215 (L/mg/h) for SBR systems resulted in the minimum prediction error, and it

Table 5-14 Predicted Effluent COD for SBR Continuous System

T_x d	S_F mg/L	S_e mg/L	X_v mg/L	n K'	S_e' 1.0 0.0003	S_e' 0.1 0.22	S_e' 0.1 0.215	S_e' 0.0 0.44
(1)	(2)	(3)	(4)		(5)	(6)	(7)	(8)
13	234	35.2	1113		51	33	34	33
9	234	37.0	763		79	35	36	33
4	234	47.4	549		105	37	40	33
13	424	43.2	1584		52	55	60	62
9	424	45.0	1283		75	57	62	62
4	424	58.8	762		144	63	68	62
13	924	107.1	3167		57	105	115	135
9	924	124.0	2884		79	107	117	135
4	924	127.2	2139		195	114	124	135
Error					50.03	10.02	9.28	14.33

S_e - observed COD concentration

S_e' - predicted COD concentration

is very close to the K' value of 0.22 (L/mg/h) estimated from the batch tests.

3. The zero order model for X_v can more accurately predict the effluent COD for SBR continuous flow system than the first order model. However, the zero order model predicts the same effluent COD concentrations for the three SBR system with different sludge ages, which is not in agreement with the observed results.

Based on the batch test data collected in 36 batch tests using the sludge from SBRs, the relative active fractions in the mixed liquors of SBRs were predicted by applying Eq. 5-9 with **n** equal to 0.1 in the exponential model. The biomass produced in the reactor with the shortest sludge age of 4 days was considered as the basis for calculating the relative active fraction. Table 5-15 summarizes the predicted results on the relative active fractions in the mixed liquors of three SBR systems (f_s'). Appendix K presents the rest of the data concerning the active fraction. Fig. 5-9 illustrates the relative active fractions versus sludge age for these SBR systems.

Table 5-15 Relative Active Mass Fraction in SBR System

T_x d (1)	S_F mg/L (2)	X_v mg/L (3)	S_o mg/L (4)	X_a' mg/L (5)	f_s' % (6)
4	424	778	239	778	100
4	424	824	368	824	100
4	424	890	723	890	100
				ave.	100.0
9	424	1013	215	799	78.9
9	424	1239	421	858	69.3
9	424	1285	770	923	71.9
				ave.	73.4
13	424	1608	203	837	52.0
13	424	1551	406	878	56.6
13	424	1586	715	943	59.5
				ave.	56.0

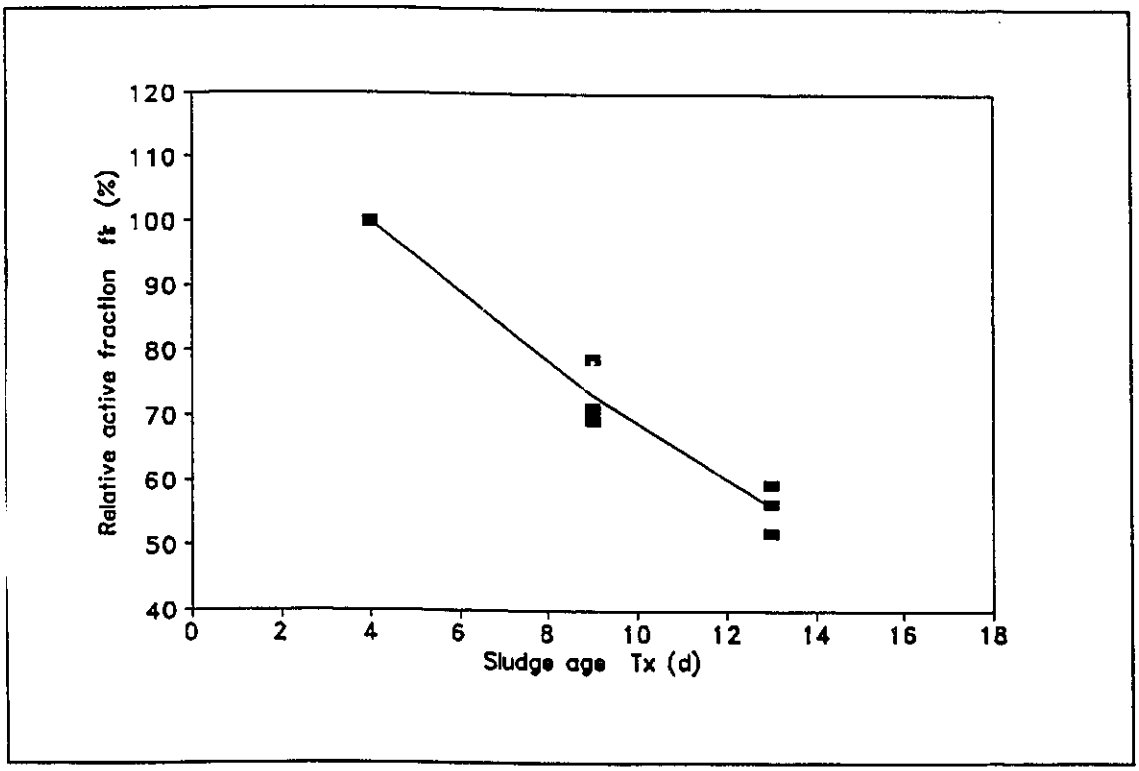


Fig. 5-9 Relative Active Mass Fraction in SBR System

As shown in Table 5-15 and Fig. 5-9, the relative active fraction increased as the reactor sludge age decreased. If the relative active fraction in the biomass from the SBR reactor with 4 days sludge age is assumed to be f_s', the relative active biomass fractions were predicted as 56, 73 and 100% of f_s' for three SBRs operated at sludge ages of 13, 9 and 4 days, respectively.

5.4 Performance of CFSTR and SBR Systems

The evaluation of a biological treatment process is based on its ability to degrade organic compounds in the reactor, and the capacity to separate the activated sludge from the treated effluent leaving the reactor. This section will compare the CFSTR with the SBR system in terms of treatment efficiency, sludge settleability and the effect of organic loading. The comparison of the kinetic model for both systems will be conducted as well.

5.4.1 Substrate Removal Efficiencies in CFSTR and SBR

In this study, the substrate treatment efficiency is expressed in terms of the COD removal efficiency. Table 5-16 and Fig. 5-10 illustrate the COD removal efficiencies for both CFSTR and SBR systems. The COD removal efficiencies in the CFSTR reactors were 79.7%, 82.6% and 82.5%, and those in the SBRs were 84.1%, 86.7% and 87.8%, at sludge ages of 4.5, 9 and 13 days, respectively. The average treatment efficiencies for CFSTRs (E_c) and SBRs (E_s) were 82% and 86%, respectively. The standard deviations of the treatment efficiency for CFSTR (s_c) and for SBR (s_s) were $\pm$3.35 and $\pm$2.83, respectively.

The average removal efficiency in the SBR was about 4% higher than that in the CFSTR. The significance of difference

Table 5-16 COD Removal Efficiencies (CFSTR & SBR)

CFSTR T_x d	S_o mg/L	S_e mg/L	E_c %	SBR T_x d	S_o mg/L	S_e mg/L	E_s %
13.5	223	40.3	81.9	13	234	35.2	85.3
13.5	472	65.5	86.1	13	414	43.2	89.6
13.5	969	197.5	79.6	13	924	107.2	88.4
9.2	223	42.5	80.9	9	234	37.0	84.5
9.2	472	69.4	85.3	9	414	45.0	89.1
9.2	969	179.5	81.5	9	924	124.0	86.6
4.6	223	54.3	75.6	4	234	47.4	80.2
4.6	472	73.7	84.4	4	414	58.8	85.8
4.6	969	202.9	79.1	4	924	127.2	86.2
ave.			82%				86%
standard deviation			3.35				2.83

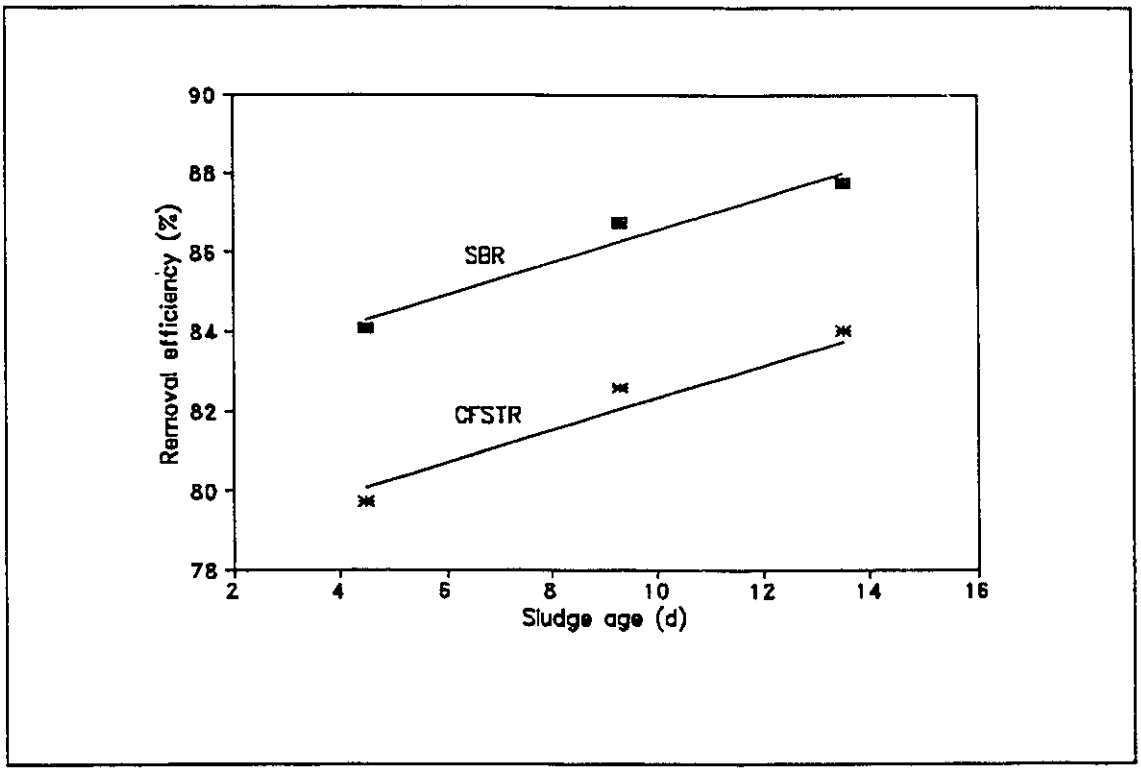


Fig. 5-10 COD Removal Efficiencies (CFSTR & SBR)

between E_c and E_s was checked by the significance test (Chatfield, 1970). The null hypothesis is given by H_o: $E_s=E_c$, the alternative hypothesis is H_1: $E_s>E_c$. Thus, a one-tailed test is appropriate. The statistic test (t_0) is calculated by:

$$t_0=\frac{E_s-E_c}{s\sqrt{\frac{1}{n_s}+\frac{1}{n_c}}} \qquad (5\text{-}11)$$

Where: n_s —— number of observations for SBR system

n_c —— number of observations for CFSTR system

s —— combined standard deviation

The combined standard deviation is given by:

$$s^2=\frac{s_s^2+s_c^2}{2} \qquad (5\text{-}12)$$

Where: s_c —— standard deviation of treatment efficiency for CFSTR

s_s —— standard deviation of treatment efficiency for SBR

By substituting the figures in Table 5-16 into Eqs. 5-11 and 5-12, the statistic test is computed as $t_0=2.737$.

If H_o is true, the statistic test follows a t-distribution with sixteen (n_s+n_c-2) degrees of freedom. From Appendix L (Statistic Table), the statistic critical value at 1% significance level with sixteen degrees of freedom is: $t_{0.01,16}=2.583$, so that: probability ($t_0>2.583$) = 0.01. Thus, the result is significant at the 1% level and we have strong

evidence that H_o is untrue. The statistic analysis result indicates that the SBR reactor is more effective than CFSTR for substrate removal.

Fig. 5-10 shows that the removal efficiencies for both systems vary with the reactor sludge ages. At higher sludge age, higher removal efficiencies can be achieved.

5.4.2 Sludge Settleability in CFSTR and SBR

Sludge settleability is another important factor in evaluating the performance of a biological reactor. It is usually expressed by the sludge volume index (SVI) which is defined as the volume occupied by unit weight of the settled sludge (mL/g). An SVI value below 100 indicates that the sludge has a good settleability.

In most cases, settling problems occur due to sludge bulking which results in a high SVI value. Jingchu (1978) has presented the following factors as influencing sludge bulking: 1) food to microorganism (F/M) ratio, 2) composition of the substrate, 3) dissolved oxygen concentration, 4) pH, 5) temperature, 6) nutrients (N and P), 7) operation conditions such as sludge age, dispersion and flow pattern in the reactor. In this study, the sludge settleabilities of the CFSTR and the SBR were compared based on the F/M ratio and the

different reactor operating regimes. Table 5-17 gives the SVI values and the F/M ratios of CFSTR and SBR reactors. Fig. 5-11 shows the variation of SVI with sludge age.

Table 5-17 SVI of CFSTR and SBR

T_x d.	F/M(CFSTR) mgCOD/mgVSS/d	SVI(CFSTR) mL/g	F/M(SBR) mgCOD/mgVSS/d	SVI(SBR) mL/g
13.5	0.55	75	0.65	59
9	0.70	97	0.95	73
4.5	1.05	118	1.33	110

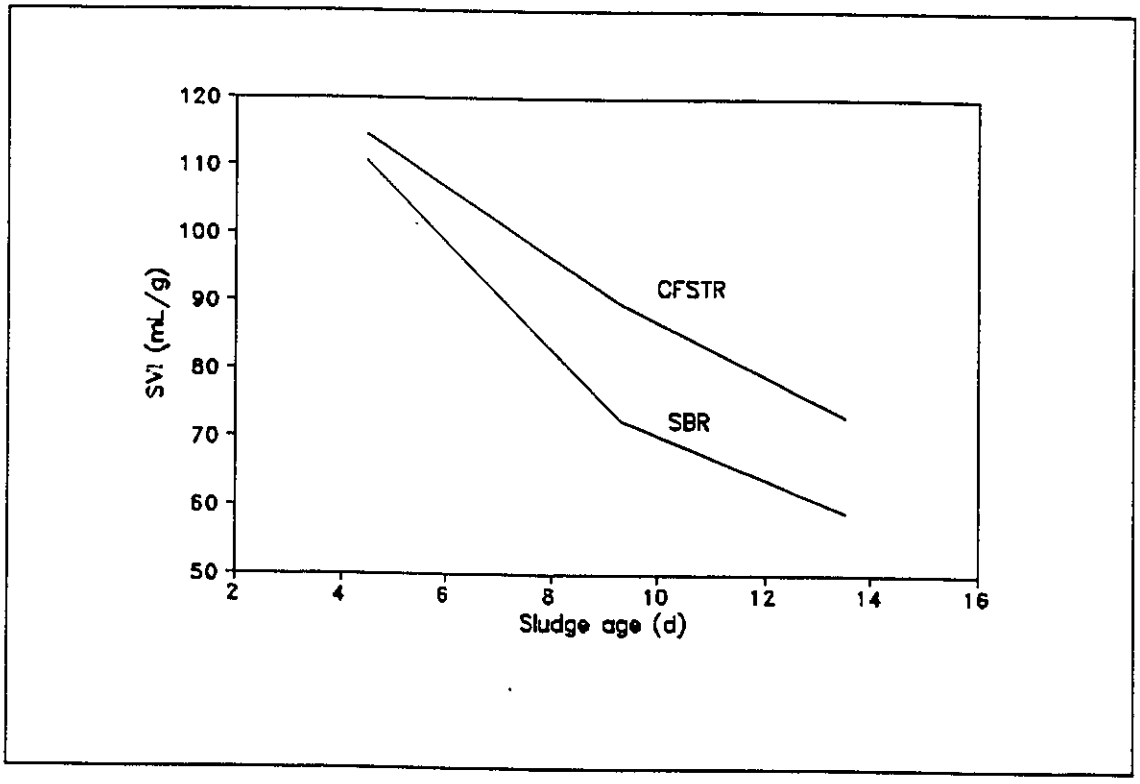


Fig. 5-11 SVI versus Sludge Age (CFSTR & SBR)

The F/M ratio was calculated from $QS_o/X_vV=S_o/X_vT_d$. The hydraulic detention time of CFSTR systems was 8 hours, and the equivalent hydraulic detention time of 8.1 hours was used for SBR systems to compute the F/M value.

As shown in Table 5-17 and Fig. 5-11, the SVI values for SBR are lower than the CFSTR's for a given sludge age. Under the same operating conditions, such as the hydraulic detention time and the sludge age, the biomass produced in the SBR reactor has better settling properties than that in the CFSTR reactor.

This result can be explained as the effect of the COD gradient on the sludge settling property. Chudoba et al. (1972) have reported that the presence of a COD gradient which depends on the hydraulic flow regime can promote the growth of a non-filamentous population and suppress the growth of filamentous microorganisms. Therefore, the COD concentration gradient created in the SBR reactor, as a result of the SBR operating cycle, can favour the production of a sludge that is free from filamentous microorganisms, and a lower SVI value in these reactors can be expected.

Fig. 5-12 shows the variation of SVI value versus F/M for CFSTR and SBR reactors. For the conventional activated sludge process, sludge with an SVI value less than 100 is generally

considered as having good settling properties. From Fig. 5-12, the CFSTR system must be operated at F/M ratio of 0.5-0.7 mg COD /mg VSS/d to keep SVI below 100. This result is in agreement with the F/M ratio criteria of 0.2-0.6 mg BOD_5/mg VSS/d for the conventional activated sludge process treating municipal wastewater (Metcalf and Eddy, 1979). These authors also reported that BOD_5/COD ratio ranged from 0.4 to 0.8 for municipal wastewater. Fig. 5-12 also shows that the SBR reactor can be operated well at an F/M ratio of 0.6-1.2 mg COD/mg VSS/d. This is an important parameter for the process engineer to choose the optimal organic loading condition to avoid sludge bulking in SBR.

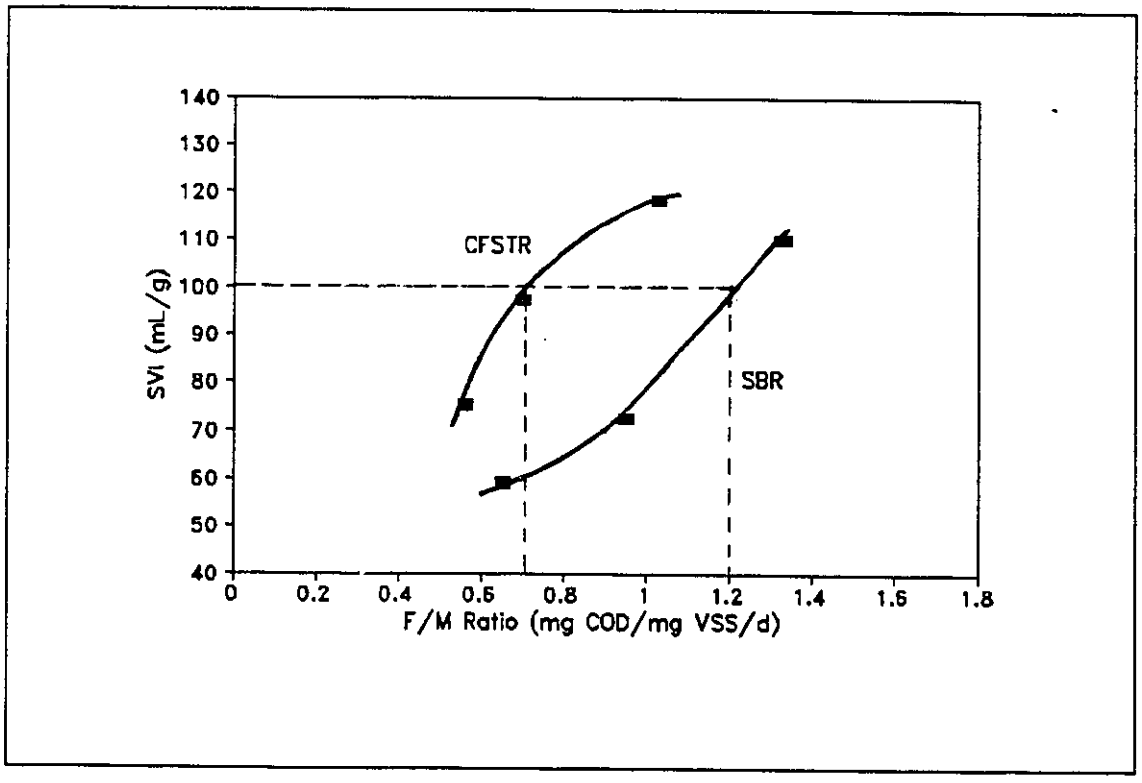


Fig. 5-12 SVI versus F/M Ratio (CFSTR & SBR)

5.4.3 Effect of Organic Loading on CFSTR and SBR

Fig. 5-13 illustrates the treatment efficiency versus F/M ratio for CFSTR and SBR reactors to show the effect of organic loading on both systems. The removal efficiency of SBR is about 5.5% higher than that of CFSTR at any given food to microorganism ratio. In the other words, to obtain the same treatment efficiencies from both systems, the SBR system, can be operated under much higher organic loading conditions. For instance, to obtain an organic removal efficiency of 84%, the CFSTR system must be operated at an F/M ratio less than 0.6 mg COD/mg VSS/d, while the SBR system can tolerate the F/M ratio as high as 1.4 mg COD/mg VSS/d. This is more than double the value of F/M applied to the CFSTR.

5.4.4 Comparison of Kinetic Model for CFSTR and SBR Systems

The comparison of the kinetic models for CFSTR and SBR systems was focused on the kinetic constants and the application of the proposed model.

Table 5-18 lists the kinetic constants and the model parameters for the CFSTR and SBR systems. The yield factor (Y) and the endogenous decay coefficient (k_d) were determined from Eq. 2-11. Appendix M includes the data and calculations used for determining Y and k_d for both systems.

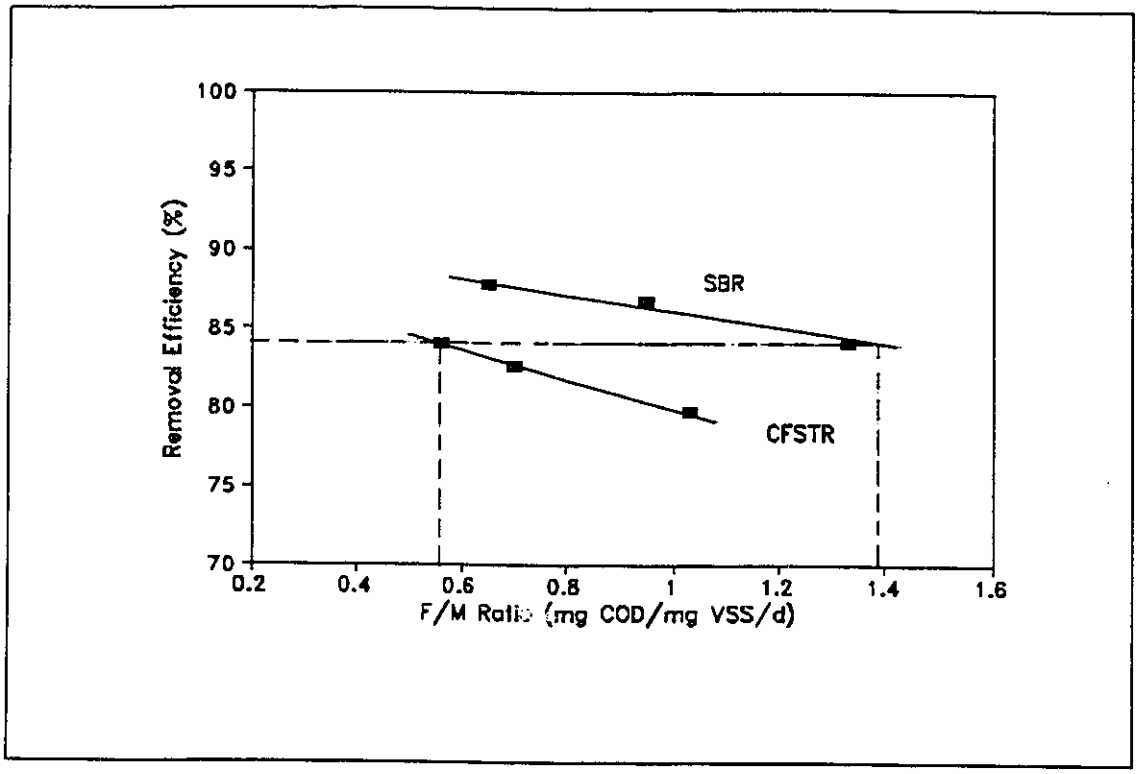


Fig. 5-13 COD Removal Efficiencies versus F/M Ratio

Table 5-18 Summary of Kinetic Constants (CFSTR & SBR)

Reactor	K L/mg/h	Y	k_d d^{-1}
CFSTR	0.00021	0.343	0.08
SBR	0.00031	0.388	0.15

As indicated in Table 5-18, the magnitudes of the first order rate constant K, the yield factor Y and the endogenous decay coefficient k_d for the SBR system were higher than those constants determined for the CFSTR. Since both CFSTR and SBR reactors were operated under the same conditions, the only difference was the operating regime between these two systems, which could have influenced the kinetic constants to different degrees.

Table 5-19 presents the COD concentrations in the treated effluents predicted with the exponential model for the CFSTR and SBR systems. The model parameters K' estimated from the batch kinetic study and adjusted for the continuous system were used in the predictions.

From the results indicated in Table 5-19, the following observations can be made:

1. The exponential model from the batch study can more accurately simulate the SBR continuous system because of its lower predicted error (10.02). However, with a predicted error of 46.6, the exponential model based on the batch analysis can not accurately simulate the CFSTR continuous system.
2. As the exponential model was adjusted for the CFSTR continuous system, it significantly improved the prediction accuracy for the CFSTR continuous system

(comparing error of 46.6 to 16.7). But, the improvement of the prediction accuracy was slight for the SBR continuous system (comparing error of 9.28 to 10.02).

Table 5-19 Predicted Effluent COD Results for CFSTR and SBR

T_x d	S_F mg/L	< S_e mg/L	SBR n K'	S_e' 0.1 0.22	S_e' > 0.1 0.215	< S_e mg/L	CFSTR n K'	S_e' 0.1 0.15	S_e' > 0.1 0.24
13	230	35.2		33	34	40.2		61	44
9	230	37.0		35	36	46.3		63	46
4	230	47.4		37	40	61.3		65	48
13	440	43.2		55	60	65.5		124	90
9	440	45.0		57	62	69.4		126	92
4	440	58.8		63	68	73.7		130	97
13	950	107.1		105	115	197		243	177
9	950	124.0		107	117	179		245	179
4	950	127.2		114	124	203		252	184
Error				10.02	9.28			46.6	16.7

S_e —— observed COD concentration

S_e'—— predicted COD concentration

These results are expected and could be influenced by the different operating regimes which affect the kinetic model. The semi-batch operating regime in SBR system can create a COD

gradient which is similar to that in the batch reactor. However, a COD gradient does not occur in CFSTR reactor due to the complete mixing conditions in the reactor. Thus, the kinetic model based on the batch study can accurately simulate substrate removal for the SBR continuous system because of the similarity in the operating regime. However, the kinetics from the batch study can not accurately describe substrate removal for the CFSTR continuous system due to the difference in the operating regime.

CHAPTER 6

CONCLUSIONS

Based on the previous discussions on the substrate removal rate expression and the operating data of the CFSTR and the SBR, the following conclusions are drawn:

1. The exponential substrate removal kinetics for batch test and continuous flow system (C.F.S.) are:

   CFSTR:

$$\frac{dS}{dt} = -0.15X^{0.1}(S - S_d) \qquad \text{(Batch)}$$

$$\frac{dS}{dt} = -0.24X^{0.1}S \qquad \text{(C.F.S.)}$$

   SBR:

$$\frac{dS}{dt} = -0.22X^{0.1}(S - S_d) \qquad \text{(Batch)}$$

$$\frac{dS}{dt} = -0.215X^{0.1}S \qquad \text{(C.F.S.)}$$

2. A comparison of the first order and the exponential

kinetics indicates that: the exponential model, with **n** in the range of 0.1 to 0.4, can more accurately and consistently express substrate removal in both CFSTR and SBR batch reactors over a broad range of operating conditions.

3. The exponential model predicts that the relative active biomass fractions in both CFSTR and SBR reactors increase with decreasing sludge age. Assuming the active biomass fractions for 4.5 days sludge age of CFSTR and SBR reactors are respectively 100% of f_c' and f_s', then, the average active fractions for reactors operating at 9 and 13 days of SRT are 75% and 60% f_c' for CFSTRs, and, 73%, and 56% f_s' for SBRs, respectively.
4. The above results indicate that the exponential function of VSS (X_v^n) can be a feasible approach to represent the active mass concentration in the substrate removal kinetics.
5. The kinetic model from the batch study can accurately simulate substrate removal for the SBR continuous flow system because of the similarity in the operating regime. However, the batch kinetics can less accurately simulate the CFSTR continuous system because of the difference in the operating regime.
6. The SBR reactor has higher values of kinetic constants K, Y, and k_d, compared with those constants for CFSTR.
7. The statistical analysis indicates that the SBR system

can achieve a significantly higher treatment degree with a COD removal efficiency of 86%, while about 82% COD removal was obtained in the CFSTR.

8. The SBR system displays better sludge settleability, as indicated by its lower SVI values in comparison to SVI results obtained in the CFSTR reactors. The organic loadings for avoiding sludge bulking in SBR and CFSTR reactors for the type of substrate used in this study are observed to be less than 1.2 mg COD/mg VSS/d and 0.7 mg COD/ mg VSS/d, respectively.

9. The SBR system can be operated at a F/M ratio of 1.4 mg COD/mg VSS/d without causing a decline in treatment efficiency. This F/M ratio for SBR is double the value of F/M applied to CFSTR.

CHAPTER 7

FURTHER STUDIES

The following topics can be considered for further studies:

1. Under the same experimental conditions as those presented in this study, the active mass factor **a** can be found by measuring the actual biomass activity, expressed in terms of ATP. Then, the simulated active biomass fraction aX_v^n/X_v^n can be compared with the actual active biomass fraction as determined by the further study and the accuracy of the simulated active fraction can be examined.
2. The relationship between the active biomass represented by X_v^n and the sludge age can be further investigated by running more CFSTR or SBR reactors with different sludge ages.
3. Under anaerobic conditions, the kinetics of the substrate removal rate versus the active biomass represented by X_v^n (or aX_v^n) can also be investigated and compared by running anaerobic CFSTR and SBR systems.
4. In addition, the SBR operation performances, such as

removal efficiency and sludge settling ability can be further examined by varying the hydraulic detention times, reactor sludge ages and, especially, the fill/react time ratios. This examination can lead to an optimization of the best operation conditions for SBR system.

REFERENCES

Agardy, F. J., Cole, R. D. and Pearson, E. A.,(1963), "Kinetic and activity parameters of anaerobic fermentation systems." SERL Report No. 63-2. Berkeley, University of California.

Andrews, J. F., (1971), "Kinetic models of biological waste treatment", *Biotech. Bioeng. Symposium No. 2*, pp 5-33.

Ardern, E. and Lockett, W. T. (1914), "Experiments on the oxidation of sewage without the aid of filters", *Journal of Society of Chemical Industries*, 33, pp 523-539.

Borchardt, J. A. and Azad, H. S., (1968), "Biological extraction of nutrients", *Journal of Water Pollution Control Federation*, 40, pp 1739-1754.

Chatfield, C. (1970), *Statistics for Technology*, Penguin Books Inc., Baltimore, MD.

Chiesa, S. C. and Irvine, R. L., (1985), "Growth and control of filamentous microbes in activated sludge: an integrated hypothesis," *Water Research*, 19, 4, pp 471-479.

Chudoba, J. Ottova, V. and Madera, V. (1972), "Control of activated sludge filamentous bulking - I, effect of the hydraulic regime or degree of mixing in an aeration tank", *Water Research*, 7, pp 1163-1182.

Dennis, R. W. and Irvine, R. L., (1979), "Effect of fill: react ratio on sequencing batch biological reactors", *Journal of Water Pollution Control Federation*, 51, 2, pp 255-263.

Droste, R. L. (1990), "Comparison of continuous flow and sequencing batch reactors for biological wastewater treatment", (*for The Biotechnology of Wastewater Management Workshop*).

Eckenfelder, W. W., Jr. (1966), *Industrial Water Pollution Control*, McGraw-Hill Book Co., New York, NY.

Eckenfelder, W. W., Jr. and Tischler, L. F. (1969), "Linear substrate removal in the activated sludge process", *Advances in Water Pollution Research*, pp 361-374.

Eckenfelder, W. W., Jr. (1980), *Water Quality Engineering for Practising Engineers*, 2nd. Ed., Barnes and Noble Press, New York, NY.

Garrett, M. T. and Sawyer, C. N., (1952), "Kinetics of removal of soluble BOD by activated sludge", *Proceedings of the 7th Industrial Waste Conference*, Purdue University Engineering Extension Series No.79, pp 51-77.

Gaudy, A. F. and Gaudy, E. T., (1971), "Biological concept for design and operation of the activated sludge", *Environmental Protection Agency Water Pollution Research Series*, Report #17090 FQJ 09/71.

Goel, K. C. and Gaudy, A. F. Jr. (1969), "Studies on the relationship between specific growth rate and concentration of nitrogen source for heterogeneous microbial population of sewage origin", *Biotech. Bioeng.* 11, pp 67-78.

Goodman, B. L. and Englande, A. J. Jr., (1974), "A unified model of the activated sludge process", *Journal of Water Pollution Control Federation*, 46, 2, Feb. pp 313-331.

Grady, C. P. L. Jr. and Lim, H. C. (1980), *Biological Wastewater Treatment-Theory and Applications*, Marcel Dekker Inc., New York and Basel.

Henze, M., Grady, C. P. L. Jr., Gujer, W., Marais, G. V. R. and Matsuo, T., (1986), "Activated sludge model No. 1", *IAWPRC Scientific and Technical Report No. 1.*

Hoepker, E. C. and Schroeder, E. D. (1979), "The effect of loading rate on batch-activated sludge effluent quality", *Journal of Water Pollution Control Federation*, 51, pp 264-273.

Irvine, R. L. and Ritcher, R. O. (1977), "Computer simulation and design of sequencing batch biological reactors", *Proceedings of the 31st Industrial Waste Conference*, Purdue University Engineering Extension Series No. 31, pp 182-192.

Irvine, R. L. and Ritcher, R. O. (1978), "Comparative evaluation of sequencing batch reactors", *Journal of the Environmental, Engineering Division*, 6, pp 503-514.

Irvine, R. L. and Busch, A. W., (1979), "Sequencing batch reactors - an overview", *Journal of Water Pollution Control Federation*, 51, 2, pp 235-243.

Irvine, R. L., Miller, G. and Bhamrah, A. S., (1979), "Sequencing batch treatment of wastewater in rural areas", *Journal of Water Pollution Control Federation*, 51, pp 244-254.

Jingchu, (1978), *Water Treatment Engineering Theory and Application*. Architecture Press, Beijing.

Ketchum, L. H. Jr., Irvine, R. L. and Liao, P. (1979), "First cost analysis of sequencing batch biological reactors", *Journal of Water Pollution Control Federation*, 51, pp 288-297.

Lawrence, A. W. and McCarty, P. L., (1970), "Unified basis for biological treatment design and operation", *Journal of the Sanitary Engineering Division, ASCE*, 96, pp 757-778.

McKinney, R. E. (1962), "Mathematics of complete-mixing activated sludge", *Journal of the Sanitary Engineering Division, ASCE*, 88, May, pp 87-111.

Metcalf and Eddy, Inc. (1991), *Wastewater Engineering, Treatment/Disposal/Reuse*, Metcalf and Eddy, Inc. Edited by Tchobanoglous, G., Third edition, McGraw-Hill, New York, NY.

Monod, J. (1949), "The growth of bacterial cultures," *Annual Review of Microbiology*, 3, pp 371-394.

Muck, R. E. and Gaudy, C. P. Jr. (1969), "Temperature effects on microbial growth in CSTRs", *Journal of the Environmental Engineering Division, ASCE*, 100, pp 1147-1163.

Orhon, D., Cimsit, Y. and Tunay, O. (1986), "Substrate removal mechanism for sequencing batch reactors," *Water Science and Technology*, 18, pp 21-33.

Ramalho, R. S. (1977), *Introduction to Wastewater Treatment Processes*, Academic Press, New York, NY.

Roberts, D. V., (1977), *Enzyme Kinetics*, Cambridge University Press, New York, NY.

Schaezler, D. J. et al, (1969), "Kinetic and stoichiometric limitations of phosphate in pure and mixed bacterial cultures", *Proceedings of the 24th Industrial Waste Conference*, Purdue University Engineering Extension Series No. 135, pp 507-533.

Spiegel, M. R., (1971), *Theoty and Problems of Advanced Mathematics for Engineers and Scientists*, McGraw-Hill, New York, NY.

Sundstrom, D. W. and Klei, H. E., (1979), *Wastewater Treatment*. Prentice-Hall Inc., Englewood Cliffs, NJ.

Uden, N. V., (1969), "Kinetics of nutrient limited growth", *Annual Review of Microbiology*, 23, pp 473-486.

Standard Methods for the Examination of Water and Waste Water, 17th Ed. American Public Health Association, Inc, Washington, D.C., (1987).

Weddle, C. L. and Jenkins, D. (1971) "The viability and activity of activated sludge". *Water Research*, 5, pp 621-640.

Wuhrmann, K. and Mikx, M., (1956), *Biological Treatment of Sewage and Industrial Wastes*. Reinhold Publishing Corporation, New York, NY.

APPENDICES

Appendix A Calculation for Simulated Active Mass Fraction

T_x (d)		5	10	15	20	30
f (%)		77	70	63	61	58
X_a (mg/L)		2498	3040	3275	3410	3585
X_v (mg/L)		3245	4340	5200	5590	6180
n	**a**	aX_v^n/X_v(%) (simulated active mass fraction)				
1.0	1.00	100	100	100	100	100
0.9	1.73	77	74.8	73.5	72.9	72.2
0.8	3.88	77	72.7	70.1	69.1	67.7
0.7	8.71	77	70.6	66.8	65.4	63.5
0.6	19.54	77	68.6	63.8	61.9	59.5
0.5	43.86	77	66.6	60.8	58.7	55.8
0.4	98.45	77	64.7	58.0	55.6	52.3
0.3	220.97	77	62.8	55.4	52.6	49.1
0.2	495.98	77	61.0	52.8	49.8	46.0
0.1	1113.23	77	59.3	50.4	47.2	43.1
0.0	2498.05	77	57.6	48.1	44.7	40.4

This table shows an approach of using exponential function X_v^n to simulate the active fraction shown in Fig. 2-7. The first raw lists sludge age ranged from 5 to 30 days. f in second raw is denoted as the active mass fraction taken from Fig. 2-7, corresponding to each T_x. X_a is calculated from Goodman-Englande model (Eq. 2-21), and X_v is computed from active fraction. As **n** (in first column) ranges from 1.0 to 0, the **a** value (in second column) is computed from $a=fX_v/X_v^n$. The

simulated active fraction is given by aX_v/X_v^n. The parameters in Goodman-Englande (1974) paper are: S_o=393 mg/L, S_e=5.37 mg/L, f_{nd}=0.24, T=23°C, Y=0.57, $K_{m(23)}$=457 d^{-1}, $k_{d(23)}$=0.36 d^{-1}.

A calculation example is indicated below. With sludge age of 5 days, and corresponding f of 77%, X_a, X_v and **a** are calculated by following equations:

$$X_a=\frac{YK_mS_e}{\frac{1}{T_x}+k_d}=\frac{0.57*457*5.37}{\frac{1}{5}+0.36}=2498\,(mg/L)$$

$$X_v=\frac{X_a}{f}=\frac{2498}{0.77}=3245\,(mg/L)$$

$$a=\frac{fX_v}{X_v^n}=\frac{0.77*3245}{3245}=19.54$$

An example of the simulated active fraction is computed for sludge age of 10 days and X_v of 4340 mg/L:

$$\frac{aX_v^n}{X_v}=\frac{19.54*4340^{0.6}}{4340}*100\%=68.6\%$$

As **n** equals to 0.6 and **a** is 19.54, the simulated active fractions for above sludge age conditions are the most close to the active mass fractions shown in Fig. 2-7, therefore, **n** and **a** are determined as 0.6 and 19.54, respectively.

Appendix B CFSTR Batch Test Data

Feed mg/L	Tx d	X	Xv mg/L	Sd mg/L	t(h) 0 S	0.5 (mg/L)	1.0	1.5	2.0	3.0	4.0	6.0	8.0
250	15	0.5	759.0	70.0	254	199	189	188	156	138	114	89	80
250	15	0.5	690.0	115.0	444	420	405	368	358	277	211	127	117
250	15	0.5	862.0	200.0	1200	1129	1080	1060	1036	828	789	624	452
250	10	0.5	673.0	40.0	211	193	146	158	119	85	73	64	44
250	10	0.5	471.0	70.0	510	480	463	430	390	337	258	132	90
250	10	0.5	760.0	210.0	1031	971	932	893	885	777	691	510	364
250	5	0.5	407.0	70.0	287	241	236	219	204	185	161	107	91
250	5	0.5	422.0	90.0	438	424	406	379	356	314	246	172	121
250	5	0.5	412.0	200.0	1048	992	967	952	917	859	788	650	489
250	15	1.0	1525.0	50.0	213	205	159	111	85	71	59	49	39
250	15	1.0	1503.0	70.0	489	427	374	329	284	163	133	87	78
250	15	1.0	1543.0	210.0	1086	1010	902	890	775	730	591	460	327
250	10	1.0	921.0	50.0	271	267	248	233	170	115	78	71	66
250	10	1.0	1000.0	70.0	537	430	405	387	317	210	145	114	98
250	10	1.0	1119.0	210.0	1122	1036	930	867	794	669	519	354	219
250	5	1.0	738.0	50.0	273	267	262	233	211	137	93	84	80
250	5	1.0	757.0	70.0	580	537	502	468	429	343	266	159	131
250	5	1.0	920.0	210.0	978	896	804	753	643	559	467	377	267
250	15	2.0	2719.0	70.0	248	145	121	100	87	80	80	78	74
250	15	2.0	2915.0	60.0	491	381	325	310	242	136	118	68	65
250	15	2.0	2934.0	200.0	973	771	692	600	518	421	357	280	214
250	10	2.0	2134.0	50.0	213	190	182	152	136	122	107	92	59
250	10	2.0	2250.0	60.0	514	438	340	287	219	128	115	109	108
250	10	2.0	2226.0	140.0	986	836	806	681	527	401	268	177	155
250	5	2.0	1310.0	70.0	197	148	136	114	91	81	77	75	74
250	5	2.0	1297.0	110.0	702	583	559	512	474	350	255	190	182
250	5	2.0	1501.0	200.0	966	936	887	823	566	407	387	365	342
500	15	0.5	1197.0	50.0	241	207	136	132	102	74	67	63	60
500	15	0.5	1153.0	100.0	445	379	358	312	278	214	154	116	103
500	15	0.5	1494.0	350.0	1296	1275	1262	1246	1209	1103	985	693	401
500	10	0.5	966.0	55.0	257	218	180	139	100	72	64	63	60
500	10	0.5	1177.0	110.0	453	403	388	340	310	245	165	120	119
500	10	0.5	1100.0	350.0	1337	1309	1303	1254	1182	1086	951	750	462
500	5	0.5	662.0	65.0	258	240	213	181	136	92	72	69	68
500	5	0.5	780.0	120.0	450	411	396	376	337	266	162	131	124
500	5	0.5	714.0	300.0	1331	1322	1248	1154	1028	851	595	460	387
500	15	1.0	2467.0	80.0	310	234	171	138	108	101	95	93	90
500	15	1.0	2440.0	110.0	548	467	398	316	240	150	130	124	122
500	15	1.0	2777.0	240.0	1316	1260	1258	1198	1123	1051	923	757	700
500	10	1.0	2066.0	95.0	328	297	196	138	118	101	102	100	99
500	10	1.0	2050.0	135.0	597	497	420	318	230	145	138	141	143
500	10	1.0	2150.0	350.0	1337	1290	1271	1200	1150	1064	876	586	405
500	5	1.0	1343.0	90.0	324	303	213	180	136	105	102	100	98
500	5	1.0	1285.0	150.0	613	559	492	433	334	259	195	167	163
500	5	1.0	1306.0	350.0	1348	1328	1305	1231	1214	1094	1077	978	853

Appendix B cont.

Feed	Tx	X	Xv	Sd	t(h) 0	0.5	1.0	1.5	2.0	3.0	4.0	6.0	8.0
500	15	2.0	4855.0	90.0	248	166	112	109	101	98	97	95	94
500	15	2.0	4255.0		446 - > 700								
500	15	2.0	4524.0		1071 - >1000								
500	10	2.0	3855.0	110.0	261	204	138	126	112	114	122	133	138
500	10	2.0	3845.0	250.0	647	605	562	544	480	417	351	327	304
500	10	2.0	3610.0	240.0	1051	975	903	816	747	631	566	470	381
500	5	2.0	2411.0	100.0	284	270	253	242	232	192	132	112	109
500	5	2.0	2905.0	150.0	647	631	590	577	512	429	348	206	190
500	5	2.0	2750.0	350.0	1147	1036	995	904	842	705	581	402	335
1000	15	0.5	1662.0	80.0	251	218	188	155	127	112	96	91	90
1000	15	0.5	1619.0	80.0	417	280	178	170	158	113	83	82	83
1000	15	0.5	1771.2	300.0	1093	1019	964	907	870	729	598	445	399
1000	10	0.5	2021.2	80.0	213	208	180	148	128	110	93	91	89
1000	10	0.5	1950.0	55.0	433	297	169	140	107	77	69	58	63
1000	10	0.5	2012.4	250.0	1087	989	927	825	712	567	399	312	279
1000	5	0.5	1500.0	100.0	274	223	216	180	150	128	108	106	111
1000	5	0.5	1603.0	110.0	458	321	197	187	170	127	119	116	113
1000	5	0.5	1506.1	250.0	1010	925	816	796	710	579	456	316	281
1000	15	1.0	4170.0	155.0	223	196	199	185	190	194	182	183	163
1000	15	1.0	4137.0	250.0	563	498	455	412	391	364	345	305	276
1000	15	1.0	4097.5	240.0	1053	982	931	892	765	650	601	523	488
1000	10	1.0	3920.0	170.0	212	176	151	144	144	141	135	130	131
1000	10	1.0	3585.0	200.0	506	427	362	331	296	273	247	227	219
1000	10	1.0	4043.8	250.0	1076	984	890	712	700	544	403	341	315
1000	5	1.0	2935.0	170.0	220	164	169	163	167	170	164	175	177
1000	5	1.0	2698.0	210.0	500	405	351	320	292	262	257	237	219
1000	5	1.0	2786.4	300.0	978	896	804	753	642	559	467	377	367
1000	15	2.0	8090.0		386 - >400								
1000	15	2.0	8100.0		510 - >900								
1000	15	2.0	8135.0		909 - >1200								
1000	10	2.0	6960.0	190.0	303	226	218	214	211	213	205	198	202
1000	10	2.0	6980.0	200.0	519	403	328	311	310	286	265	253	245
1000	10	2.0	7025.0	350.0	1045	949	839	793	805	738	709	717	698
1000	5	2.0	4540.0	220.0	313	254	239	231	228	226	225	227	220
1000	5	2.0	4940.0	255.0	545	430	297	254	256	246	251	240	245
1000	5	2.0	4364.0	240.0	969	869	799	749	743	629	573	515	411

Appendix C First Order Rate Constant K (CFSTR Batch Tests)

S_P mg/L	T_x d	X	S_o mg/L	X_v mg/L	S_d mg/L	K L/mg/h	R squared	K_m h^{-1}
223	13.5	0.5	254	759	70	0.000319	0.970	0.549
223	13.5	1	214	1525	30	0.000289	0.850	0.440
223	13.5	2	248	2719	40	0.000143	0.756	0.390
223	13.5	0.5	444	690	70	0.000588	0.972	0.406
223	13.5	1	490	1503	70	0.000325	0.977	0.488
223	13.5	2	491	2915	60	0.000175	0.977	0.513
223	13.5	0.5	1200	862	200	0.000188	0.917	0.162
223	13.5	1	1086	1543	210	0.000219	0.985	0.268
223	13.5	2	973	2934	210	0.000179	0.915	0.514
223	9.2	0.5	212	673	40	0.000585	0.920	0.394
223	9.2	1	272	921	70	0.000430	0.942	0.396
223	9.2	2	179	2134	50	0.000167	0.945	0.359
223	9.2	0.5	510	471	70	0.000471	0.952	0.320
223	9.2	1	537	1000	70	0.000340	0.981	0.340
223	9.2	2	514	2250	60	0.000193	0.988	0.436
223	9.2	0.5	1031	709	210	0.000220	0.980	0.156
223	9.2	1	1122	1119	240	0.000221	0.971	0.247
223	9.2	2	986	2226	210	0.000240	0.974	0.535
223	4.6	0.5	287	407	70	0.000921	0.979	0.375
223	4.6	1	273	738	50	0.000512	0.937	0.381
223	4.6	2	231	1310	60	0.000231	0.769	0.303
223	4.6	0.5	438	422	90	0.000713	0.920	0.301
223	4.6	1	580	757	70	0.000227	0.986	0.209
223	4.6	2	703	1297	110	0.000280	0.983	0.391
223	4.6	0.5	1048	512	200	0.000254	0.932	0.130
223	4.6	1	1087	920	210	0.000227	0.973	0.209
223	4.6	2	966	1501	200	0.000265	0.911	0.398
472	13.5	0.5	241	1197	55	0.000319	0.811	0.549
472	13.5	1	311	2467	70	0.000132	0.700	0.325
472	13.5	2	249	4485	90	0.000088	0.626	0.398
472	13.5	0.5	446	1153	100	0.000336	0.987	0.528
472	13.5	1	548	2440	120	0.000209	0.878	0.511
472	13.5	0.5	1297	1494	250	0.000096	0.910	0.144
472	13.5	1	1316	2777	400	0.000076	0.986	0.210
472	9.2	0.5	257	1077	60	0.000489	0.859	0.472
472	9.2	1	329	2066	100	0.000200	0.681	0.413
472	9.2	2	261	3855	100	0.000146	0.600	0.543

Appendix C cont.

S_F mg/L	T_x d	X	S_o mg/L	X_v mg/L	S_d mg/L	K L/mg/h	R squared	K_m h^{-1}
472	9.2	0.5	454	966	110	0.000472	0.984	0.417
472	9.2	1	597	2005	140	0.000258	0.814	0.529
472	9.2	2	647	3485	240	0.000088	0.939	0.308
472	9.2	0.5	1337	1100	280	0.000144	0.954	0.154
472	9.2	1	1337	2150	350	0.000111	0.934	0.239
472	9.2	2	1051	3160	280	0.000075	0.979	0.272
472	4.6	0.5	259	626	65	0.000688	0.905	0.431
472	4.6	1	324	1343	90	0.000369	0.791	0.496
472	4.6	2	285	2411	100	0.000179	0.954	0.431
472	4.6	0.5	451	780	120	0.000387	0.953	0.302
472	4.6	1	613	1285	150	0.000276	0.916	0.355
472	4.6	2	448	2731	150	0.000119	0.913	0.346
472	4.6	0.5	1331	714	300	0.000158	0.974	0.113
472	4.6	1	1348	1306	350	0.000065	0.986	0.085
472	4.6	2	1147	2750	300	0.000098	0.997	0.270
969	13.5	0.5	251	1662	80	0.000050	0.781	0.103
969	13.5	1	242	4206	80	0.000059	0.869	0.249
969	13.5	0.5	417	1619	50	0.000121	0.869	0.256
969	13.5	1	563	4137	250	0.000065	0.760	0.258
969	13.5	0.5	1093	1771	300	0.000055	0.992	0.120
969	13.5	1	1053	4098	240	0.000057	0.958	0.231
969	9.2	0.5	213	2021	80	0.000082	0.902	0.166
969	9.2	1	212	3920	170	0.000082	0.911	0.265
969	9.2	2	303	6960	190	0.000530	0.867	0.374
969	9.2	0.5	433	1950	55	0.000165	0.840	0.324
969	9.2	1	506	3586	200	0.000080	0.859	0.286
969	9.2	2	519	6980	200	0.000430	0.935	0.302
969	9.2	0.5	1087	2012	250	0.000110	0.982	0.221
969	9.2	1	1076	4044	250	0.000082	0.966	0.277
969	9.2	2	1045	7025	650	0.000046	0.824	0.326
969	4.6	0.5	274	1502	100	0.000102	0.820	0.155
969	4.6	1	220	2935	220	0.000068	0.689	0.197
969	4.6	2	313	4540	220	0.000039	0.795	0.339
969	4.6	0.5	458	1603	110	0.000126	0.792	0.202
969	4.6	1	500	2698	210	0.000077	0.758	0.207
969	4.6	2	545	4940	255	0.000103	0.893	0.435
969	4.6	0.5	1011	1506	250	0.000127	0.996	0.191
969	4.6	1	978	2786	300	0.000096	0.982	0.264
969	4.6	2	969	4364	240	0.000063	0.921	0.278

Appendix D Fitting Error Matrixes for CFSTR Batch Tests

Matrix of the fitting errors (0.5 X)

K'\ n	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0.0
0.000050	166.7	203.7	225.0	236.3	242.1	245.0	246.4	247.1	247.5	247.6	247.7
0.000320	81.2	81.2	133.5	182.5	213.1	230.0	238.8	243.3	245.6	246.7	247.3
0.000600	120.5	77.7	83.8	139.3	186.6	215.4	231.2	239.4	243.6	245.7	246.8
0.001160	181.9	117.8	75.3	85.4	142.5	188.8	216.7	231.9	239.8	243.8	245.8
0.002270	228.6	181.0	116.4	73.4	86.6	144.7	190.3	217.5	232.3	239.9	243.8
0.004000	254.6	229.1	181.1	116.5	70.2	87.0	145.7	190.9	217.8	232.4	240.0
0.007500	264.6	254.9	228.8	179.9	115.4	68.5	88.7	147.7	192.2	218.5	232.8
0.015000	267.1	265.0	255.4	229.3	180.1	116.0	68.3	89.1	148.3	192.6	218.7
0.030000	267.4	267.2	265.3	256.0	230.0	180.7	117.0	68.7	89.2	148.4	192.6
0.060000	267.4	267.4	267.3	265.6	256.5	230.5	181.2	118.1	69.4	89.4	148.3
0.130000	267.4	267.4	267.4	267.3	265.6	256.1	229.0	178.3	116.0	70.6	92.5
0.246000	267.4	267.4	267.4	267.4	267.3	266.0	256.9	230.5	180.6	119.1	72.2

Matrix of the fitting errors (1 X)

K'\ n	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0.0
0.000060	132.9	196.9	239.6	262.7	274.2	279.7	282.4	283.6	284.2	284.4	284.5
0.000210	91.6	96.1	152.0	212.3	248.2	267.1	276.3	280.7	282.8	283.8	284.2
0.000450	134.3	87.6	95.5	156.1	215.1	249.8	267.8	276.7	280.9	282.9	283.8
0.000930	199.5	132.3	83.8	95.1	159.1	217.2	250.9	268.3	276.9	281.0	282.9
0.001900	240.9	197.9	129.2	79.9	96.0	163.1	219.8	252.3	269.0	277.2	281.1
0.003900	259.8	240.7	196.6	126.4	76.3	96.9	166.6	222.0	253.4	269.5	277.4
0.007000	265.2	260.3	241.4	197.0	126.1	72.2	96.5	167.7	222.7	253.7	269.7
0.015000	265.8	265.3	260.6	241.3	196.1	124.3	69.2	97.3	169.9	224.0	254.4
0.030000	265.8	265.8	265.4	261.1	242.1	196.8	124.6	66.9	96.7	170.2	224.1
0.065000	265.8	265.8	265.8	265.5	261.3	242.0	196.0	123.3	65.1	97.9	171.7
0.150000	265.8	265.8	265.8	265.8	265.5	261.4	241.8	195.0	121.7	64.3	99.6
0.300000	265.8	265.8	265.8	265.8	265.8	265.6	261.6	241.8	194.7	121.2	64.9
0.350000	265.8	265.8	265.8	265.8	265.8	265.7	262.4	244.5	200.0	127.9	68.0

Matrix of the fitting errors (2 X)

K'\ n	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0.0
0.000020	180.6	222.2	244.1	254.6	259.5	261.7	262.7	263.2	263.4	263.5	263.5
0.000140	72.9	90.2	155.2	207.6	236.7	251.2	257.9	261.0	262.4	263.0	263.3
0.000300	113.4	70.2	90.9	158.3	209.6	237.7	251.6	258.1	261.1	262.4	263.0
0.000650	171.4	112.0	67.6	91.3	160.5	210.9	238.4	251.9	258.2	261.1	262.5
0.001400	207.5	170.4	110.2	65.1	92.4	163.0	212.4	239.2	252.3	258.4	261.2
0.003100	221.6	208.2	171.2	110.6	62.8	91.5	163.2	212.6	239.3	252.3	258.4
0.006500	224.1	221.9	208.9	172.3	111.6	60.7	90.3	163.0	212.5	239.2	252.2
0.015000	224.2	224.1	222.1	208.9	171.7	110.5	58.7	91.3	164.6	213.4	239.6
0.030000	224.2	224.2	224.1	222.3	209.2	171.9	110.5	56.8	91.5	165.1	213.7
0.065000	224.2	224.2	224.2	224.2	222.5	209.6	172.3	110.9	55.2	91.2	165.2
0.145000	224.2	224.2	224.2	224.2	224.2	222.6	209.6	172.1	110.5	53.8	92.0
0.300000	224.1	223.6	221.5	215.6	204.3	196.2	161.0	130.5	96.4	64.3	52.8
0.340000	224.2	224.2	224.2	224.2	224.2	224.2	222.5	208.6	169.7	107.4	53.8

Appendix E Results of Predicting Effluent COD for CFSTR

System Mass Balance (CFSTR)

$dS/dt = - K' X^n S$

$QSo - QSe - K'X^nSe = 0$

$Se' = So/(1+K'X^nTd)$

App. E(a) Experimental Data

Reactor	Tx d	So mg/l	Se mg/l	Xv mg/l	Td h
CFSTR1	13.2	223	40.3	1435	8
CFSTR2	8.6	223	42.5	942	8
CFSTR3	4.6	223	54.3	635	8
CFSTR1	13.8	472	65.5	2600	8
CFSTR2	9.6	472	69.4	2067	8
CFSTR3	4.6	472	73.7	1293	8
CFSTR1	13.1	969	197.5	4757	8
CFSTR2	9.5	969	179.5	4244	8
CFSTR3	4.7	969	202.9	2990	8

App. E(b) Effluent COD Predicted by Exponential Model

n	1	1	1	1	1	1	1
K'	0.000199	0.0002	0.000205	0.00021	0.000215	0.00022	0.00023
Se mg/l	Se' mg/l	Se' mg/l	Se' mg/l	Se' mg/l	Se' mg/l	Se' mg/l	Se' mg/l
40.3	67.9	67.7	66.5	65.4	64.3	63.3	61.3
42.5	89.2	88.9	87.6	86.3	85.1	83.9	81.6
54.3	110.9	110.6	109.2	107.9	106.6	105.3	102.8
65.5	91.8	91.5	89.7	87.9	86.3	84.6	81.6
69.4	110.0	109.6	107.5	105.5	103.6	101.8	98.3
73.7	154.3	153.8	151.3	148.8	146.4	144.1	139.7
197.5	113.0	112.5	110.1	107.8	105.5	103.4	99.4
179.5	124.9	124.4	121.7	119.2	116.8	114.4	110.0
202.9	168.2	167.5	164.1	160.9	157.7	154.7	149.0
Error	54.06	54.05	54.03	54.09	54.21	54.39	54.91

Appendix E cont.

n	0.5	0.5	0.5	0.5	0.5	0.5	0.5
K′	0.007	0.0085	0.009	0.00925	0.0095	0.01	0.011
Se mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l
40.3	71.4	62.4	59.8	58.6	57.5	55.3	51.5
42.5	82.0	72.2	69.5	68.2	66.9	64.5	60.3
54.3	92.5	82.2	79.2	77.8	76.5	73.9	69.3
65.5	122.4	105.7	101.0	98.9	96.8	92.9	86.0
69.4	133.1	115.4	110.4	108.1	105.9	101.8	94.4
73.7	156.6	137.0	131.5	128.9	126.4	121.8	113.3
197.5	199.3	170.3	162.4	158.8	155.2	148.7	137.1
179.5	208.5	178.5	170.3	166.5	162.8	156.0	143.9
202.9	238.5	205.4	196.3	192.0	187.9	180.3	166.7
Error	47.47	34.36	32.28	31.63	31.22	31.01	32.50

n	0.4	0.4	0.4	0.4	0.4	0.4	0.4
K′	0.015	0.017	0.018	0.019	0.02	0.022	0.024
Se mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l
40.3	69.7	63.9	61.3	58.9	56.7	52.8	49.4
42.5	78.1	71.8	69.1	66.5	64.2	59.9	56.2
54.3	86.2	79.7	76.8	74.1	71.6	67.0	63.0
65.5	124.6	113.5	108.6	104.2	100.1	92.8	86.5
69.4	133.2	121.6	116.5	111.8	107.5	99.8	93.1
73.7	151.9	139.3	133.7	128.6	123.9	115.4	107.9
197.5	213.0	192.9	184.3	176.3	169.0	156.2	145.1
179.5	220.7	200.1	191.2	183.0	175.5	162.2	150.8
202.9	245.5	223.2	213.6	204.7	196.6	182.0	169.5
Error	47.82	36.89	32.94	29.99	28.03	26.81	28.29

n	0.3	0.3	0.3	0.3	0.3	0.3	0.3
K′	0.03	0.035	0.04	0.045	0.05	0.055	0.06
Se mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l
40.3	71.4	64.1	58.2	53.3	49.1	45.6	42.5
42.5	77.6	70.0	63.8	58.5	54.1	50.3	47.0
54.3	83.7	75.8	69.3	63.8	59.1	55.1	51.5
65.5	133.4	119.1	107.6	98.2	90.2	83.5	77.7
69.4	140.0	125.4	113.4	103.6	95.3	88.3	82.2
73.7	154.3	138.7	126.0	115.4	106.5	98.8	92.2
197.5	239.6	212.9	191.6	174.1	159.6	147.3	136.7
179.5	245.9	218.7	196.9	179.0	164.2	151.6	140.8
202.9	265.6	237.0	213.9	194.9	179.0	165.5	153.9
Error	57.03	40.76	29.64	23.82	23.19	26.04	30.33

Appendix E cont.

n	0.2	0.2	0.2	0.2	0.2	0.2	0.2
K′	0.065	0.07	0.08	0.09	0.1	0.11	0.12
Se mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l
40.3	69.1	64.4	59.6	54.6	50.4	46.8	43.7
42.5	73.2	68.3	63.4	58.2	53.8	50.0	46.7
54.3	77.2	72.1	67.0	61.6	57.1	53.1	49.7
65.5	134.6	125.0	115.6	105.6	97.2	90.1	83.9
69.4	139.1	129.3	119.6	109.4	100.8	93.4	87.1
73.7	148.5	138.3	128.2	117.5	108.4	100.7	94.0
197.5	253.1	234.5	216.3	197.1	181.1	167.5	155.8
179.5	257.4	238.6	220.1	200.7	184.5	170.7	158.8
202.9	270.9	251.4	232.3	212.1	195.2	180.7	168.3
Error	58.98	47.21	36.26	26.18	20.52	19.66	22.31

n	0.1	0.1	0.1	0.1	0.1	0.1	0.1
K′	0.14	0.15	0.18	0.2	0.22	0.24	0.25
Se mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l
40.3	67.2	61.1	56.0	51.7	48.1	44.9	43.4
42.5	69.2	63.0	57.8	53.4	49.7	46.4	44.9
54.3	71.1	64.7	59.5	55.1	51.2	47.8	46.3
65.5	136.5	123.9	113.4	104.6	97.0	90.5	87.6
69.4	138.7	126.0	115.4	106.5	98.8	92.2	89.2
73.7	143.3	130.2	119.6	110.4	102.5	95.7	92.7
197.5	268.3	243.2	222.3	204.8	189.8	176.9	171.1
179.5	270.5	245.3	224.3	206.7	191.6	178.6	172.7
202.9	277.4	251.3	230.4	212.4	197.0	183.7	177.7
Error	62.58	46.60	34.01	24.46	18.42	16.67	17.31

n	0	0	0	0	0	0	0
K′	0.28	0.3	0.31	0.32	0.33	0.35	0.36
Se mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l	Se′ mg/l
40.3	68.8	65.6	64.1	62.6	61.3	58.7	57.5
42.5	68.8	65.6	64.1	62.6	61.3	58.7	57.5
54.3	68.8	65.6	64.1	62.6	61.3	58.7	57.5
65.5	145.7	138.8	135.6	132.6	129.7	124.2	121.6
69.4	145.7	138.8	135.6	132.6	129.7	124.2	121.6
73.7	145.7	138.8	135.6	132.6	129.7	124.2	121.6
197.5	299.1	285.0	278.4	272.2	266.2	255.0	249.7
179.5	299.1	285.0	278.4	272.2	266.2	255.0	249.7
202.9	299.1	285.0	278.4	272.2	266.2	255.0	249.7
Error	76.75	67.71	63.52	59.54	55.75	48.70	45.42

Appendix F Calculation of Relative Active Fraction for CFSTR

Model: $dS/dt = -K'X^n(S-Sd)$

$f_a' = Xa'/X$

$Xa' = r*X1$

$r = Xi^n/X1^n$

$n = 0.1$

$K' = 0.15$

Tx d	S_F mg/L	Xv mg/L	So mg/L	r	Xa' mg/L	f% %
4.6	223	744	250	1.00	744	100.0
4.6	223	757	580	1.00	757	100.0
4.6	223	820	1087	1.00	820	100.0
avg.		774			774	100.0
9.2	223	921	272	1.02	760	82.52
9.2	223	1000	537	1.03	778	77.84
9.2	223	1119	1122	1.03	846	75.59
avg.		1013		1.03	795	78.4
13.5	223	1525	214	1.07	799	52.42
13.5	223	1503	490	1.07	811	53.94
13.5	223	1543	1089	1.07	874	56.61
avg.		1524		1.07	828	54.4

Tx d	S_F mg/L	Xv mg/L	So mg/L	r	Xa' mg/L	f% %
4.6	472	1343	324	1.00	1343	100.0
4.6	472	1285	613	1.00	1285	100.0
4.6	472	1306	1348	1.00	1306	100.0
avg.		1310			1310	100.0
9.2	472	2066	261	1.04	1402	67.70
9.2	472	2050	597	1.05	1346	65.68
9.2	472	2150	1337	1.05	1373	63.85
avg.		2090		1.05	1372	65.7
13.5	472	2467	311	1.06	1427	57.85
13.5	472	2440	548	1.07	1370	55.89
13.5	472	2777	1316	1.08	1408	50.45
avg.		2560		1.07	1401	54.7

Appendix F cont.

Relative Active Fraction for CFSTR

n = 0.1
K′ = 0.15

Tx d	S_r mg/L	Xv mg/L	So mg/L	r	Xa′ mg/L	f_b %
4.6	969	2710	251	1.00	2710	100.00
4.6	969	2698	500	1.00	2698	100.00
4.6	969	2786	978	1.00	2786	100.00
avg.		2731			2731	100.0
9.2	969	3328	232	1.02	2766	83.12
9.2	969	3586	506	1.03	2776	77.75
9.2	969	3398	1076	1.02	2842	83.35
avg.		3437		1.02	2795	81.3
13.5	969	4206	242	1.04	2832	67.33
13.5	969	3950	563	1.04	2803	70.95
13.5	969	4042	1053	1.04	2892	71.59
avg.		4066		1.04	2842	69.9

Appendix G SBR Batch Test Data

Feed mg/L	Tx d	X	Xv mg/L	Time (h) Sd mg/L	0 S mg/L	0.5	1.0	1.5	2.0	3.0	4.0	6.0	8.0
500	15	0.5	955.0	90.0	203	156	128	123	105	102	95	111	116
500	15	0.5	1055.0	100.0	485	390	347	312	241	199	146	107	106
500	15	0.5	1191.0	160.0	1105	971	917	843	767	623	497	303	234
500	15	1.0	1608.0	70.0	242	176	143	114	98	83	75	72	71
500	15	1.0	1551.0	110.0	406	288	246	199	154	120	136	144	140
500	15	1.0	1586.0	125.0	723	519	422	332	291	218	199	148	140
500	10	0.5	707.0	75.0	251	211	179	138	101	90	76	74	83
500	10	0.5	656.0	110.0	504	443	398	365	304	259	163	121	120
500	10	0.5	691.0	185.0	1105	1070	980	908	884	716	612	359	237
500	10	1.0	1113.0	80.0	215	160	131	117	101	86	85	81	86
500	10	1.0	1239.0	180.0	421	353	285	234	202	181	185	192	198
500	10	1.0	1285.0	205.0	770	662	547	431	392	259	237	215	208
500	5	0.5	486.0	60.0	264	226	185	152	127	102	95	74	70
500	5	0.5	531.0	65.0	513	487	452	440	404	365	288	157	123
500	5	0.5	568.0	190.0	1103	1047	1001	902	865	735	610	395	309
500	5	1.0	778.0	80.0	238	193	134	109	99	85	86	88	96
500	5	1.0	824.0	95.0	368	309	217	192	163	147	124	113	124
500	5	1.0	890.0	110.0	715	667	579	521	457	315	199	125	122
1000	10	0.5	1573.0	160.0	349	267	239	192	175	167	162	168	164
1000	10	0.5	1521.0	180.0	544	474	424	361	329	247	210	192	183
1000	10	0.5	1499.0	210.0	1001	967	830	810	772	589	487	308	277
1000	10	1.0	3021.0	140.0	339	228	171	166	162	157	153	145	140
1000	10	1.0	3032.0	170.0	553	487	395	270	251	202	198	192	189
1000	10	1.0	3133.0	250.0	1037	925	826	752	598	338	290	274	263
1000	10	2.0	5854.0	150.0	345	250	183	164	164	163	161	162	160
1000	10	2.0	6210.0	180.0	564	437	320	265	221	216	209	195	212
1000	10	2.0	5916.0	280.0	1035	946	836	723	642	489	379	306	289
1000	5	0.5	1139.9	95.0	262	226	185	152	127	102	95	96	93
1000	5	0.5	1197.0	130.0	469	325	289	278	250	223	178	154	141
1000	5	0.5	1274.0	165.0	1001	927	857	840	779	653	578	409	269
1000	5	1.0	2241.0	90.0	254	186	156	127	109	97	97	98	97
1000	5	1.0	2346.0	135.0	372	308	272	242	226	162	146	141	137
1000	5	1.0	2378.0	175.0	986	931	842	835	741	621	497	319	221
1000	5	2.0	4740.0	120.0	292	215	162	149	140	141	136	148	155
1000	5	2.0	4251.0	150.0	382	339	283	236	216	176	168	167	175
1000	5	2.0	4547.0	210.0	995	882	769	686	573	383	280	264	246

Appendix H First Order Rate Constant K (SBR Batch Tests)

S_F mg/L	T_x d	X	S_o mg/L	X_v mg/L	S_d mg/L	K L/mg/h	R squared	K_m h^{-1}
414	13	0.5	242	955	90	0.000708	0.794	0.677
414	13	1	203	1608	70	0.000105	0.882	0.469
414	13	0.5	485	1055	100	0.000548	0.979	0.579
414	13	1	406	1551	110	0.000399	0.848	0.620
414	13	0.5	1105	1191	160	0.000392	0.991	0.447
414	13	1	723	1586	125	0.000279	0.976	0.443
414	9	0.5	251	707	75	0.000657	0.830	0.465
414	9	1	215	1103	80	0.000471	0.757	0.478
414	9	0.5	504	656	110	0.000689	0.982	0.452
414	9	1	421	1239	180	0.000417	0.850	0.516
414	9	0.5	1105	691	190	0.000363	0.965	0.251
414	9	1	771	1285	205	0.000364	0.890	0.469
414	4	0.5	264	486	60	0.000946	0.925	0.460
414	4	1	239	778	80	0.000528	0.641	0.411
414	4	0.5	513	531	65	0.000783	0.942	0.416
414	4	1	368	824	95	0.000487	0.931	0.402
414	4	0.5	1310	569	190	0.000474	0.985	0.270
414	4	1	715	890	110	0.000448	0.932	0.399
914	9	0.5	349	1573	160	0.000298	0.808	0.470
914	9	1	340	3021	140	0.000229	0.594	0.692
914	9	2	345	5854	150	0.000050	0.601	0.297
914	9	0.5	544	1521	180	0.000285	0.993	0.434
914	9	1	553	3032	170	0.000127	0.838	0.388
914	9	2	564	6210	150	0.000053	0.787	0.330
914	9	0.5	1001	1499	210	0.000134	0.986	0.201
914	9	1	1037	3133	250	0.000114	0.892	0.360
914	9	2	1035	5916	280	0.000089	0.976	0.531
914	4	0.5	262	1139	90	0.000392	0.805	0.447
914	4	1	254	2241	90	0.000297	0.834	0.667
914	4	2	292	4740	120	0.000092	0.834	0.439
914	4	0.5	469	1197	130	0.000434	0.903	0.520
914	4	1	372	2364	135	0.000265	0.980	0.623
914	4	2	382	4251	150	0.000169	0.937	0.720
914	4	0.5	1001	1274	165	0.000196	0.991	0.250
914	4	1	986	2378	175	0.000126	0.980	0.302
914	4	2	995	4547	210	0.000125	0.992	0.570

Appendix I Fitting Error Matrixes for SBR Batch Tests

Matrix of the fitting errors (0.5 X)

K'\ n	1.00	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10	0.00
0.000300	66.6	94.9	160.0	206.5	234.3	249.5	257.4	261.5	263.5	264.6	265.1
0.000480	82.4	65.9	116.2	177.2	217.2	240.2	252.6	259.0	262.3	263.9	264.8
0.000950	140.1	81.2	64.0	117.8	178.5	218.0	240.6	252.8	259.1	262.3	263.9
0.001800	194.4	137.1	78.6	63.2	121.6	181.3	219.7	241.5	253.2	259.3	262.4
0.003600	231.5	195.8	138.2	78.9	61.1	121.0	181.0	219.5	241.4	253.1	259.3
0.007200	248.2	232.5	197.1	139.4	79.4	59.3	120.3	180.6	219.2	241.2	253.0
0.015000	252.7	248.4	232.3	196.3	137.9	78.1	59.1	122.5	182.1	220.1	241.7
0.027000	253.3	252.8	248.3	231.8	194.9	135.6	76.3	59.8	125.4	184.1	221.2
0.055000	253.3	253.3	252.9	248.8	232.5	195.9	136.8	77.2	59.3	124.6	183.5
0.110000	253.3	253.3	253.3	253.0	249.4	233.9	198.2	139.9	79.4	58.6	121.8
0.210000	253.3	253.3	253.3	253.3	253.0	249.2	232.8	195.8	136.6	77.5	61.1
0.400000	253.3	253.3	253.3	253.3	253.3	253.0	249.1	232.4	194.9	135.6	77.3
0.450000	253.3	253.3	253.3	253.3	253.3	253.2	250.2	235.8	201.5	144.4	83.2

Matrix of the fitting errors (1.0 X)

K'\ n	1.00	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10	0.00
0.000250	70.2	101.2	156.3	201.7	229.0	243.5	250.7	254.2	255.8	256.6	257.0
0.000300	65.2	89.0	140.1	190.7	222.8	240.3	249.1	253.4	255.5	256.4	256.9
0.000650	75.8	62.7	88.8	142.2	192.4	223.8	240.8	249.4	253.5	255.5	256.4
0.001300	111.4	73.3	60.7	89.9	145.6	194.8	225.2	241.5	249.7	253.7	255.6
0.002700	137.0	111.4	71.9	58.3	90.0	147.1	195.9	225.8	241.8	249.8	253.7
0.005500	147.0	137.3	111.2	70.4	56.3	90.2	148.7	197.1	226.4	242.1	250.0
0.012000	149.2	147.5	138.3	112.6	70.7	53.9	88.4	147.8	196.5	226.0	241.9
0.025000	149.3	149.2	147.4	137.6	110.5	67.4	53.2	91.4	152.0	199.3	227.6
0.050000	149.3	149.3	149.2	147.7	138.3	111.4	67.5	51.6	90.3	151.6	198.9
0.105000	149.3	149.3	149.3	149.2	147.9	138.4	111.1	66.3	50.8	90.9	152.7
0.220000	149.3	149.3	149.3	149.3	149.2	148.0	138.4	110.6	65.2	50.4	91.7
0.450000	149.3	149.3	149.3	149.3	149.3	149.3	148.1	138.5	110.4	64.5	51.0
0.500000	149.3	149.3	149.3	149.3	149.3	149.3	148.4	140.4	114.6	69.7	57.9

Matrix of the fitting errors (2.0 X)

K'\ n	1.00	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10	0.00
0.000085	47.4	118.7	195.6	244.4	269.6	281.2	286.4	288.6	289.5	289.9	290.1
0.000090	46.5	114.0	192.1	242.5	268.6	280.8	286.2	288.5	289.5	289.9	290.1
0.000225	84.2	46.0	106.2	186.3	239.2	267.1	280.1	285.9	288.4	289.4	289.9
0.000530	135.8	84.0	45.9	106.6	186.7	239.4	267.2	280.1	285.9	288.4	289.4
0.001250	159.9	135.5	83.7	45.7	107.3	187.2	239.7	267.3	280.2	285.9	288.4
0.002900	163.9	159.8	135.3	83.4	45.6	108.0	187.8	240.1	267.5	280.3	285.9
0.006800	163.9	163.9	159.8	135.1	83.2	45.5	108.5	188.2	240.3	267.6	280.3
0.015000	163.9	163.9	163.9	159.8	135.1	83.3	45.5	108.6	188.2	240.3	267.6
0.037000	163.9	163.9	163.9	163.9	159.6	134.3	82.2	45.4	110.4	189.6	241.1
0.087000	163.9	163.9	163.9	163.9	163.9	159.6	134.3	82.2	45.4	110.6	189.8
0.210000	163.9	163.9	163.9	163.9	163.9	163.9	160.0	135.4	84.0	45.8	108.0
0.480000	163.9	163.9	163.9	163.9	163.9	163.9	163.9	159.6	134.1	82.2	45.5
0.500000	163.9	163.9	163.9	163.9	163.9	163.9	163.9	160.1	136.0	84.8	46.1

Appendix J Results of Predicting Effluent COD for SBR

Mass balance equation: $dS/dt = Q(So-S)/(Vi+QT)+Rsu$

Substrate removal model: (1) $Rsu = -K'XS$,

(2) $Rsu = -K'X^nS$

Prarameters: Q = 2.67 L/h Vi = 2.67 L
To = 0 Tf = 2 h Tr = 3 h

Runge-Kutta numarical method to solve differential equation:

$$S(t1) = S(t1) + h/6\ (K1 + 2K2 + 2K3 + K4)$$

$$K1 = f\ (t0,\ S(t0)$$

$$K2 = f\ (t0+h/2,\ S(t0)+h/2*K1)$$

$$K3 = f\ (t0+h/2,\ S(t0)+h/2*K3)$$

$$K4 = f\ (t0+h/2,\ S(t0)+h/2*K3)$$

Results of Predicting Se' for SBR System

			n	1.0	1.0	1.0	1.0	1.0
			K'	0.00035	0.00033	0.00030	0.00027	0.00025
So	Tx	Xv	Se	Se'	Se'	Se'	Se'	Se'
234.0	13.0	1113.0	35.2	40.5	45.4	50.9	57.1	64.2
234.0	9.0	763.0	37.0	67.3	73.0	79.2	85.9	93.3
234.0	4.0	549.0	47.4	92.9	98.6	104.6	111.1	118.0
424.0	13.0	1584.0	43.2	37.8	44.3	51.8	60.8	71.4
424.0	9.0	1283.0	45.0	57.6	65.5	74.7	85.2	97.3
424.0	4.0	762.0	58.8	122.1	132.4	143.6	155.8	169.1
924.0	13.0	3167.0	107.1	37.5	46.1	56.8	70.1	86.7
924.0	9.0	2884.0	124.0	54.8	65.7	79.0	95.2	114.9
924.0	4.0	2139.0	127.2	153.9	173.0	194.5	219.0	246.7
			Error	44.17	46.04	50.03	56.66	66.22

			n	0.3	0.3	0.3	0.3	0.3
			K'	0.05100	0.04750	0.04500	0.04250	0.04000
So	Tx	Xv	Se	Se'	Se'	Se'	Se'	Se'
234.0	13.0	1113.0	35.2	36.0	40.5	44.0	47.9	52.1
234.0	9.0	763.0	37.0	43.2	48.0	51.8	55.9	60.4
234.0	4.0	549.0	47.4	50.0	55.1	59.0	63.3	67.9
424.0	13.0	1584.0	43.2	54.0	61.4	67.3	73.9	81.1
424.0	9.0	1283.0	45.0	60.5	68.4	74.6	81.4	89.0
424.0	4.0	762.0	58.8	78.3	87.1	93.9	101.3	109.4
924.0	13.0	3167.0	107.1	76.8	89.7	100.2	112.1	125.5
924.0	9.0	2884.0	124.0	81.8	95.1	106.0	118.2	132.0
924.0	4.0	2139.0	127.2	98.8	113.5	125.5	138.8	153.6
			Error	21.83	18.90	19.71	23.66	30.34

Appendix J cont.

Results of Predicting Se for SBR System

			n	0.2	0.2	0.2	0.2	0.2
			k'	0.11000	0.10600	0.10000	0.09500	0.09000
So	Tx	Xv	Se	Se'	Se'	Se'	Se'	Se'
234.0	13.0	1113.0	35.2	32.0	34.2	37.7	41.0	44.6
234.0	9.0	763.0	37.0	36.5	38.8	42.6	46.0	49.7
234.0	4.0	549.0	47.4	40.7	43.1	47.0	50.6	54.5
424.0	13.0	1584.0	43.2	50.8	54.5	60.6	66.2	72.3
424.0	9.0	1283.0	45.0	55.0	58.9	65.1	70.9	77.3
424.0	4.0	762.0	58.8	66.2	70.4	77.2	83.4	90.1
924.0	13.0	3167.0	107.1	83.4	90.3	101.8	112.5	124.4
924.0	9.0	2884.0	124.0	86.9	93.9	105.6	116.5	128.7
924.0	4.0	2139.0	127.2	98.4	105.9	118.4	130.0	142.8
			Error	18.36	15.35	13.04	14.99	20.37

			n	0.1	0.1	0.1	0.1	0.1
			k'	0.22000	0.21500	0.21000	0.20500	0.20000
So	Tx	Xv	Se	Se'	Se'	Se'	Se'	Se'
234.0	13.0	1113.0	35.2	32.5	33.8	35.2	36.7	38.3
234.0	9.0	763.0	37.0	34.7	36.1	37.6	39.1	40.7
234.0	4.0	549.0	47.4	36.7	38.2	39.7	41.2	42.8
424.0	13.0	1584.0	43.2	55.2	57.5	60.0	62.6	65.3
424.0	9.0	1283.0	45.0	57.3	59.8	62.3	64.9	67.7
424.0	4.0	762.0	58.8	62.9	65.4	68.1	70.8	73.7
924.0	13.0	3167.0	107.1	105.4	110.2	115.2	120.5	126.1
924.0	9.0	2884.0	124.0	107.3	112.2	117.3	122.6	128.3
924.0	4.0	2139.0	127.2	113.7	118.7	124.0	129.5	135.2
			Error	10.02	9.28	9.71	11.30	13.81

			n	0.0	0.0	0.0	0.0	0.0
			k'	0.47000	0.46000	0.45000	0.44000	0.43000
So	Tx	Xv	Se	Se'	Se'	Se'	Se'	Se'
234.0	13.0	1113.0	35.2	29.2	30.4	31.7	33.0	34.3
234.0	9.0	763.0	37.0	29.2	30.4	31.7	33.0	34.3
234.0	4.0	549.0	47.4	29.2	30.4	31.7	33.0	34.3
424.0	13.0	1584.0	43.2	53.5	55.1	57.3	59.7	62.2
424.0	9.0	1283.0	45.0	53.5	55.1	57.3	59.7	62.2
424.0	4.0	762.0	58.8	53.5	55.1	57.4	59.7	62.2
924.0	13.0	3167.0	107.1	115.6	120.1	125.0	130.1	135.5
924.0	9.0	2884.0	124.0	115.6	120.1	125.0	130.2	135.5
924.0	4.0	2139.0	127.2	115.6	120.1	125.0	130.2	135.5
			Error	10.07	9.70	10.36	11.98	14.33

Appendix K Calculation of Relative Active Fraction for SBR

Model: $dS/dt = -K'X^n(S-Sd)$

$fs' = Xa'/Xv$

$Xa' = r*X1$

$r = Xi^n/X1^n$

$n =$ 0.1

$K' =$ 0.22

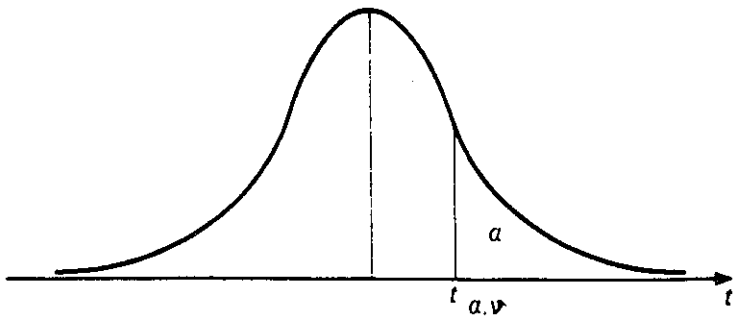
S_F mg/L	Tx d	So mg/L	Xv mg/L	r	Xa' mg/L	f's %
500	5	238.50	778	1.000	778	100.0
500	5	368.08	824	1.000	824	100.0
500	5	723.27	890	1.000	890	100.0
avg.			831		831	100.0
500	10	214.86	1013	1.027	799	78.9
500	10	420.66	1239	1.042	858	69.3
500	10	770.49	1285	1.037	923	71.9
avg.			1179	1.035	860	73.3
500	15	203.40	1608	1.075	837	52.0
500	15	405.63	1551	1.065	878	56.6
500	15	714.69	1586	1.059	943	59.5
avg.			1582	1.067	886	56.0

S_F mg/L	Tx d	So mg/L	Xv mg/L	r	Xa' mg/L	f's %
1000	5	253.90	2241	1.000	2241	100.0
1000	5	371.50	2346	1.000	2346	100.0
1000	5	985.60	2378	1.000	2378	100.0
1000	10	339.90	3021	1.030	2309	76.4
1000	10	552.60	3032	1.026	2407	79.4
1000	10	1037.40	3133	1.028	2444	78.0
						77.9

Appendix L Statistical Table

Table. Percentage points of Student's *t*-distribution

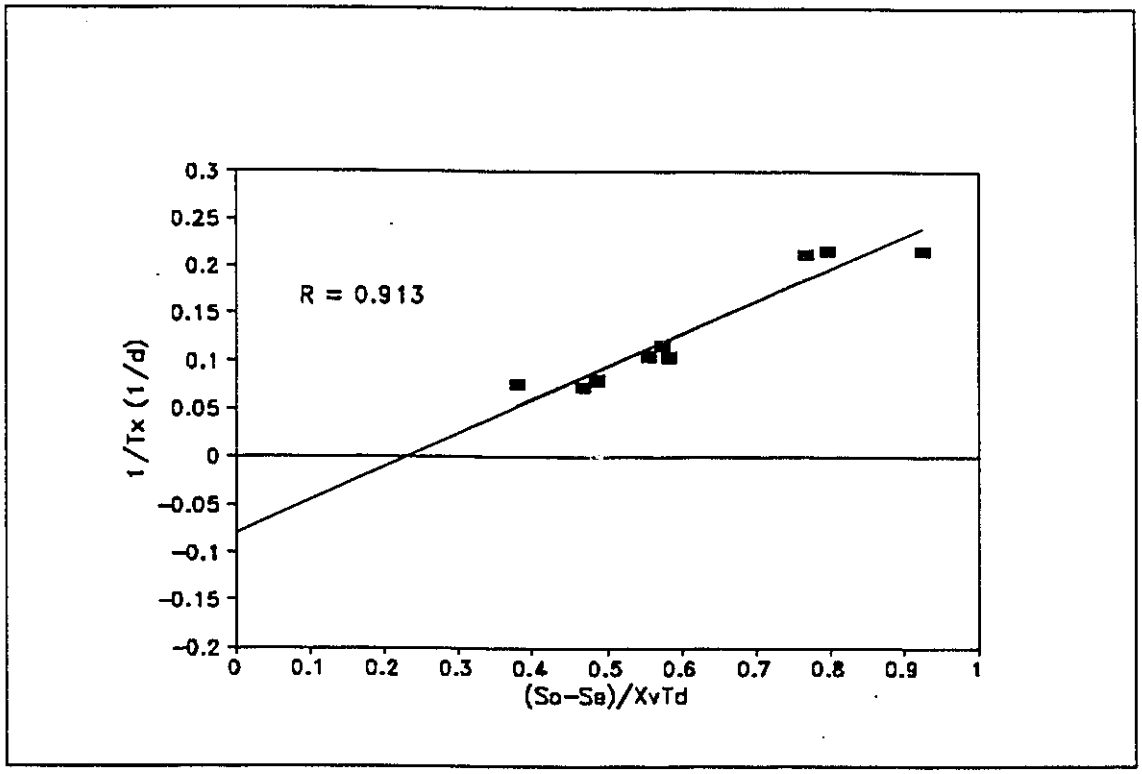
a	·01	·05	·025	·01	·005	·001
ν						
1	3·078	6·314	12·706	31·821	63·657	318·310
2	1·886	2·920	4·303	6·965	9·925	22·327
3	1·638	2·353	3·182	4·541	5·841	10·215
4	1·533	2·132	2·776	3·747	4·604	7·173
5	1·476	2·015	2·571	3·365	4·032	5·893
6	1·440	1·943	2·447	3·143	3·707	5·208
7	1·415	1·895	2·365	2·998	3·499	4·785
8	1·397	1·860	2·306	2·896	3·355	4·501
9	1·383	1·833	2·262	2·821	3·250	4·297
10	1·372	1·812	2·228	2·764	3·169	4·144
11	1·363	1·796	2·201	2·718	3·106	4·025
12	1·356	1·782	2·179	2·681	3·055	3·930
13	1·350	1·771	2·160	2·650	3·012	3·852
14	1·345	1·761	2·145	2·624	2·977	3·787
15	1·341	1·753	2·131	2·602	2·947	3·733
16	1·337	1·746	2·120	2·583	2·921	3·686
17	1·333	1·740	2·110	2·567	2·898	3·646
18	1·330	1·734	2·101	2·552	2·878	3·610
19	1·328	1·729	2·093	2·539	2·861	3·579
20	1·325	1·725	2·086	2·528	2·845	3·552
21	1·323	1·721	2·080	2·518	2·831	3·527
22	1·321	1·717	2·074	2·508	2·819	3·505
23	1·319	1·714	2·069	2·500	2·807	3·485
24	1·318	1·711	2·064	2·492	2·797	3·467
25	1·316	1·708	2·060	2·485	2·787	3·450
26	1·315	1·706	2·056	2·479	2·779	3·435
27	1·314	1·703	2·052	2·473	2·771	3·421
28	1·313	1·701	2·048	2·467	2·763	3·408
29	1·311	1·699	2·045	2·462	2·756	3·396
30	1·310	1·697	2·042	2·457	2·750	3·385
40	1·303	1·684	2·021	2·423	2·704	3·307
60	1·296	1·671	2·000	2·390	2·660	3·232
120	1·289	1·658	1·980	2·358	2·617	3·160
∞	1·282	1·645	1·960	2·326	2·576	3·090



Appendix M Determination of kinetic constants Y and k_d

Determination of Kinetic Constants Y and k_d (CFSTR)

S_o mg/L	S_e mg/L	X_v mg/L	T_x d	T_d d	$\frac{S_o-S_e}{X_v\ T_d}$	$\frac{1}{T_x}$
223	40	1435	13.2	0.33	0.382	0.076
472	65	2600	13.8	0.33	0.469	0.072
969	197	4577	13.6	0.33	0.487	0.080
223	42	942	8.6	0.33	0.575	0.116
472	69	2067	9.6	0.33	0.584	0.104
969	179	4244	9.5	0.33	0.558	0.105
223	54	635	4.6	0.33	0.797	0.217
472	74	1293	4.6	0.33	0.924	0.217
969	203	2990	4.7	0.33	0.769	0.213



Appendix M cont.

Determination of kinetic constants Y and k_d (SBR)

V_b = 8 L, V_{ab} = 5.33 L

S_o mg/L	S_e mg/L	X_v VSSmg/L	T_x d	T_c d	$\frac{V_{ab}(S_o-S_e)}{V_t X_v T_c}$	$\frac{1}{T_x}$
234	35.2	2139	12.5	0.25	0.489	0.079
234	37.0	873	9.0	0.25	0.708	0.111
234	47.4	549	4.5	0.25	0.938	0.250
414	43.2	1584	13.0	0.25	0.623	0.077
414	45.0	1283	9.0	0.25	0.766	0.112
414	58.8	762	4.0	0.25	1.083	0.223
924	107.1	3167	12.5	0.25	0.687	0.087
924	124.0	2884	9.0	0.25	0.739	0.111
924	127.2	2139	4.0	0.25	0.992	0.222