MODELLING AND SIMULATION OF A SUBMERGED MEMBRANE BIOREACTOR (SMBR) SYSTEM FOR WASTEWATER TREATMENT

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree of

MASTER OF TECHNOLOGY

in

CHEMICAL ENGINEERING

(With Specialization in Computer Aided Process Plant Design)

By

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CANDIDATE'S DECLARATION

I hereby declare that the work which is being presented in this dissertation entitled **"Modelling and Simulation of a Submerged Membrane Bioreactor (SMBR) System for Wastewater Treatment"** in partial fulfillment of the requirement for the award of the degree of Master of Technology in the Department of Chemical Engineering with specialization in **"Computer Aided Process Plant Design"**, submitted in **Chemical Engineering Department, Indian Institute of Technology, Roorkee, (India)**, is an authentic record of my own work carried out during the period from July 2005 to June 2006 under the guidance of **Dr. C. B. Majumder**, Assistant Professor, Chemical Engineering Department, and **Dr. Partha Roy**, Assistant Professor, Department of Biotechnology, Indian Institute of Technology, Roorkee, (India).

The matter embodied in this dissertation has not been submitted by me for the award of any other degree of this institute or any other institute.

Dated: 29-06-2006

Place: IIT Roorkee

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CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

This work provides wastewater treatment in a submerged membrane bioreactor (SMBR) process, it is essential to comprehend the behavior of microorganism in such wastewater treatment processes. In their natural environment microorganisms encounter changes in substrate availability. They have to adapt to the new conditions in order to survive. In this study, a mathematical model has been developed for the submerged membrane bioreactor to take into account high substrate concentration inhibition present in the system with consideration of Haldane's model. An interesting property of the inhibition model is that the presence of a single resource result in a constant maximum specific consumption rate is a function of substrate concentration for growth on one substrate. The steady-state model for the treatment of synthetic wastewater in a submerged membrane bioreactor (SMBR) system has been made and the simulation results have showed that the biokinetic coefficients, maximum specific growth rate (μ_m), maximum cell yield (Y), endogenous decay coefficient (k_d) and substrate inhibition constant K_{s_i} in the range of 0.1853-0.2975 day^{-1}, 0.5413-0.6189 mg/mg, 0.1061-0.1984 day^{-1}, and 534-646 mgCOD/l, respectively. Values of the coefficients, except that of μ_m, are with in the range of those reported for conventional activated sludge processes. This model has been able to predict the biomass concentration at steady-state operation under various initial concentration of biomass present in the system for a large variation of sludge retention time (SRT). Saturation constant (K_S), how does it effect in inhibition kinetics, has also been predicted in this work.

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NOMENCLATURE

μ_m	Maximum specific growth rate, day^{-1}
μ	Specific growth rate, day^{-1}
Y	Maximum cell yield, mg/mg
k_d	Endogenous decay coefficient, day^{-1}
K_{s_I}	Substrate inhibition constant, mg/l
K_s	Saturation constant, mg/l
K_2	Rate constant, day^{-1}
V	Reactor volume, l
V_w	Volume of the wasted sludge per day, l/day
Q_w	Wastage flow rate, l/day
X	Biomass concentration in the reactor, mg/l
X_{incr}	The MLSS before wasting, mg/l
X_{avg}	The average MLSS, mg/l
S	Growth rate limiting substrate concentration, mg/l
E	Biomass concentration, mg/l
t	Time, day

INTRODUCTION

1.1 INTRODUCTION

Rapid industrialization and urbanization has resulted in an immense environmental degradation. Population growth and poor environmental management practices have led to deterioration of environmental quality in most of the developing countries. The composition of the domestic refuge has radically changed in character over the last fifty years, due to the rise of an affluent society.

The coupling of conventional biological wastewater treatment processes with membrane separation processes has led to the development of a variety of generic membrane bioreactor (MBR) processes. First applications of MBRs in wastewater treatment date back to the early 70s. In the meantime, three generations of MBR treatment plants have been developed and an increasing number of technical plants are coming into operation. Although several practical experiences and data are available for MBR processes there is still considerable optimization potential [1]. A membrane bioreactor, a combination process of biological reactor coupled with membrane separation device, is commonly regarded as innovative technology for wastewater treatment. Membrane filtration replaces the conventional sedimentation unit for separation of the treated water from the sludge and also serves as an advanced treatment unit for coliform bacteria and suspended solids (SS), which cannot be removed completely by conventional processes [2]. Current and impeding legislation on wastewater treatment effluent has led to the need for improved treatment processes capable of removing higher percentages of nutrients, suspended solids, bacteria etc [3]. In addition, MBR technology enables enhanced treatment quality, through complete retention of particulate COD (residual particulate COD after clarifiers can be high in industry), and further degradation of refractory COD through biomass adaptation (development of specific bacteria) which is a big step towards process water reuse.

based on the output of simulation studies. No comprehensive models for membrane bioreactor systems exist so far, which integrate interdependencies between biological processes and filtration performance as well as mathematically describe the main flux-determining phenomena, occurring in submerged membrane units for wastewater treatment. The mentioned phenomena, determining filtration performance in membrane bioreactors, will be mathematically described within this work and an integrated model will be presented [6].

1.2 BACKGROUND OF MEMBRANE BIOREACTOR TECHNOLOGY (MBR) DEVELOPMENT

Membrane bioreactor technology combines the use of biological processes and membrane technology to treat wastewater and provide organic and suspended solids removal. A high standard of wastewater treatment can be achieved, without the conventional arrangement of aeration tank, settling tank and filtration to produce a tertiary standard effluent of 5: 5: 5 BOD: Suspended Solids: Ammonia. Flow passes through the membranes, while solids remain in the biological treatment system. The membrane bioreactor system combines the benefits of a suspended growth reactor with the solids separation capability of an ultrafilter or microfilter membrane unit. The membrane provides a long solids retention time, usually 30 - 60 days, which can greatly enhance the biological degradation of influent organics [7].

1.2.1 Membrane Technologies

These processes differ depending on the type of substance to be removed; there is still plenty of scope for technological improvement, and increasing the field of application. The membrane processes, which cites as being of practical interest for water purification, are micro filtering, ultra filtering, reverse osmosis and electro dialysis. Membrane types can be broadly placed into four categories, with classification being dependent on the pore size of the membrane [7]. These categories, from largest to smallest pore size, are listed below. Nanofiltration has been included to demonstrate the relativity of the categories.

1.2.1.2 Ultra filtration

- Selectively filters only molecules of a specified size and weight.
- Removes e.g. various viruses.
- Used for sterilization, clarification, wastewater treatment.
- Membrane size 1 λ - 0.01 μm.

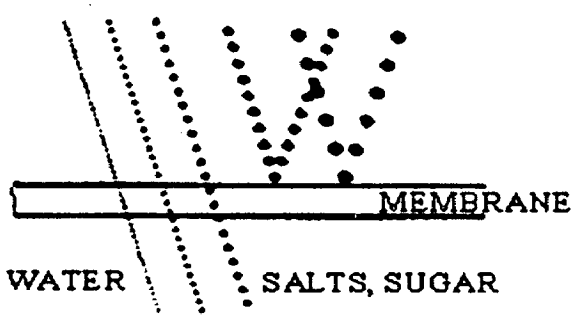

Figure 1.2: Ultrafiltration

1.2.1.3 Nanofiltration

- Used for partial desalination.
- Removes e.g. sucrose, egg albumin.
- Used for blood osmosis, blood filtration, water purification.
- Membrane size 10 λ - 0.001 μm.

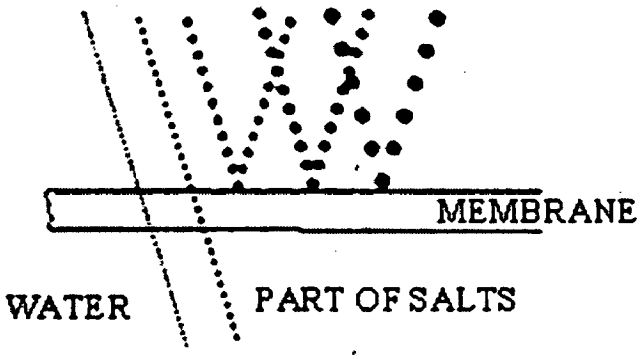

Figure 1.3: Nanofiltration

treatment of industrial outflows it is still a little developed technology: its first applications are in fact in metal finishing for the recovery of metal.

1.2.2 Membrane materials and properties

Membranes can be made from a large number of different materials. A first classification can be made into two groups, biological and synthetic membranes. Synthetic membranes can be divided into organic and inorganic membranes. The organic membrane materials (polymers or macromolecules) are the most important. The choice of a given polymer as a membrane material is based on very specific properties, originating from structural factors. Basically all polymers can be used as a barrier or membrane material but the chemical and physical properties differ so much that only a limited number are used in practice.

A further classification can be made between the open, porous membranes, which are used in microfiltration and ultrafiltration, and the dense nonporous membranes, used in gas separation and pervaporation. For porous membranes, it is not the choice of material that determines the separation characteristics, but the pore size and the pore size distribution relative to particle or molecular size. The material is considered for its adsorption, cleansing abilities and chemical stability under the actual application conditions. Some of the polymers most frequently used as materials for micro filtration are [6]:

- Polycarbonate.
- Polyvinylidene-flouride.
- Polytetrafluoroethylene.
- Polypropylene.
- Polyamide.
- Cellulose-esters.
- Polysulfone.
- Polyetherimide.

Although membrane processes may be very different in their mode of operation, in the structures used as separating barriers, and in the driving forces used for the transport of the different chemical components, they have several features in common, which make them attractive as a separation tool. In many cases membrane processes are faster, more efficient, and more economical than conventional separation techniques. With membranes, the separation is usually performed at ambient temperatures, thus allowing temperature sensitive solvents to be treated without the constituents being damaged or chemically altered. Membranes can also be tailor made so that their properties can be adjusted to a specific separation task [3].

1.2.4 MBR benefits and disadvantages

The Environment Protection Authority (1995) lists the following benefits: -

1 Cost-effective - low life-cycle costs.
2 Difficult contaminants degraded.
3 High-quality effluent produced.
4 Small footprint.
5 Faster system start-ups.
6 Long solids retention times.
7 Minimal operating labor required.
8 Minimal generation of biosludge.

Caetano et al (1995) list the advantages of the membrane process as: -

- Reduction of costs.
- Reduction of pollution.
- Recovery of high-value products.
- Recovery of energy.
- Increase of productivity.
- Improvement of quality.
- Creation of new products.
- Easy to expand the system.

LITERATURE REVIEW

2.1 MEMBRANE CHARACTERISTICS AND COMPARISON WITH A CONVENTIONAL SYSTEM

There are two types of configurations for the membrane array: the membrane can be placed either outside or inside the bioreactor. Taking into account current knowledge, a future market share could be anticipated as follows: for wastewater applications, it is expected that the hollow-fiber submerged configuration would be competitive for medium-to-large size plants. For small-to-medium sizes, plate-and-frame technologies would have an advantage, whereas larger applications could be designed with secondary/tertiary treatment followed by MF/UF membrane filtration.

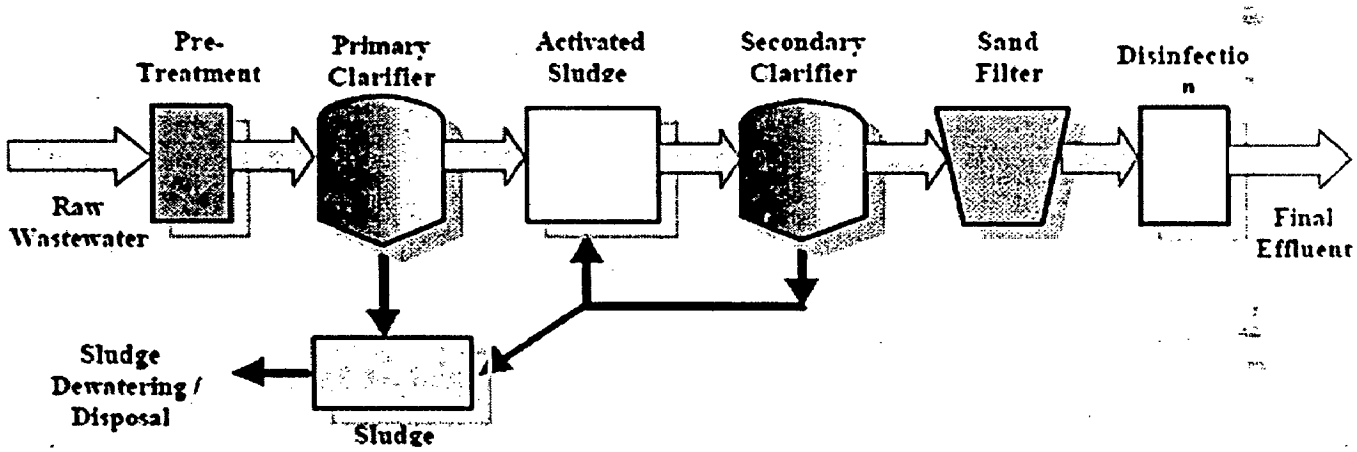

Figure 2.1: Activated Sludge Process

For the external configuration, the mixed liquor is filtered under pressure in a specific membrane module, whereas for the submerged configuration, filtration is carried out in the aeration basin by the suction removal of the effluent. In the external system, the permeate flux varies between 50 and 120 $L.h^{-1}.m^{-2}$ and transmembrane pressure (TMP) is in the range of 1 to 4 bar. In the submerged configuration, the permeate flux varies from 15 to 50 $L.h^{-1}.m^{-2}$ and trasmembrane pressure is about 0.5 bar. The submerged configuration appears to be more economical based on energy consumption for two main

With poor settling flocs avoided, biological degradation is more complete and treatment efficiency is higher. The biomass concentration involves in a reduction in the oxygen mass transfer rate depending on the type of wastewater and reactor used.

Table 2.1: Description of Membrane Bioreactor Design - Submerged Versus Side-stream Systems:

Membrane/ module type	Unit	Plate-and-Frame (Flat sheet)	Hollow fiber (Bundles)	Side stream (Tubular)
Net flux	$L/h.m^2$	15-25	20-30	70-100
Recommended MLSS	gMLSS/L	10-15	10-15	15-30
Fraction of aerobic volume occupied by membrane	%	30-100	10-40	External set-up
Energy consumption (membrane system only)	kWh/m^3	0.3-0.6	0.3-0.6	2-10
Cost	m^{-2}	High	Medium	Very high
pH- range	-	1-12	2-12	1-13
T^0- resistance	^0C	< 60	<40	<100

Other advantages of this system are as follows:

1. The volume of the aeration tank can be also reduced since a higher concentration of biomass can be stored in the bioreactor.
2. The production of sludge, the disposal of which is often difficult, is decreased by a factor of 2 or 3, resulting in a reduction of the overall operating costs.
3. The membrane bioreactor is perfectly integrated in the industrial process because the wastewater can directly be treated in situ, allowing water reuse and contaminant reduction of the manufacturing costs linked to water consumption.

- Feed flows axial on cylindrical module and permeate flow into the central pipe.
- This type of membranes are high pressure durability, compactness, low permeate pressure drop and membrane contamination, and minimum concentration polarization.

The specific sludge activity during organic matter decomposition and nitrification depends on the sludge retention time. The sludge retention time is a significant operational factor for the biological process. The nitrifying activity of sludge is maximum at a sludge retention time of 10 days, but the organic decomposition rate decreases while the sludge retention tine increases. A small reduction in COD consumption was observed in the bioreactor with short sludge retention times. In the membrane process, COD removal (90%) remains constant whatever the sludge retention time.

Defrance et al. [24] were the first to undertake a study of the traditional activated sludge process (AS) and the membrane bioreactor. This study confirms that the performance of membrane bioreactor is better than that of conventional activated sludge processes, especially for COD removal and solid suspension separation. These results were obtained with nonconstant airflow rate, which is not without influence on the system operation. Judd et al. [23] showed that the sludge in a membrane bioreactor system is made up of small flocs of regular size. These flocs were composed of zoogleal bacteria and of a small number of filamentous bacteria. The sludge in a conventional AS system is made up of large flocs and many filamentous bacteria generally located inside the flocs (floc backbone). Because of the presence of the filamentous bacteria, settling problems appear on the clarifier at the outlet of the activated sludge process. An excessive amount of filamentous bacteria indicates a lack of oxygen and/ or substrate and/ or nutrients (N, P).

Wei et al. [20] carried out a comparative study of the performance of a membrane bioreactor system and aerated biological filters for gray water recycling. Once again, the membrane bioreactor system was the more efficient process in removal of biological oxygen demand, turbidity, coliforms.

Organic loading rates of MBRs are typically higher than conventional ASP, owing to the shorter HRTs.

Increasing organic loads to an ASP produces increased heterotrophic activity, as organic matter removal follows first-order kinetics, and this can be assumed to be the case in MBRs. Organic matters removal in MBRs appears not to be significantly affected by low temperatures, such as those between ~5 and 20°C, which may be due to the number of heterotrophic bacteria in the biomass remaining constant, albeit with a decreased activity at lower temperatures [14].

2.2.2 Nitrogen removal

Biological nitrogen removal has been done by using membrane systems to concentrate the nitrifier in a reactor [13]. Small increase in the oxygen supply rate and the improved nitrification rate [17] facilities the growth of microbial flocs. In spite of such improved nitrification capability in membrane processes, an anaerobic denitrification reactor is still needed for achieving complete nitrogen removal. Nitrification has been shown to be greater in an MBR than with a conventional ASP owing to the longer retention times of the nitrifying bacteria (high sludge age, low food/microorganism ratio) and the smaller floc sizes, allowing slightly greater mass transport of nutrients and oxygen into the floc.

MBRs achieve almost complete nitrification owing to the retention of the slow-growing autotrophic bacteria. At nitrogen loads of between 0.1 and 3.3 $kgNH_3\ m^{-3}\ day^{-1}$, ammonia removal is greater than 90%. As with conventional processes, nitrification is sensitive to feed water quality determinants and operational parameters such as dissolved oxygen (DO), temperature, organic loads, inorganic and organic compounds, and pH. Nitrification can be maintained at higher rates with lower DO concentrations (<5 $mg\ l^{-1}$). Denitrification, the reduction of nitrate to various gaseous end-products such as molecular nitrogen and dinitrogen oxide, can proceed alongside nitrification if:

1. aeration is supplied intermittently,
2. hydrodynamics are such that an anoxic area results, or
3. high organic loads are added allowing anoxic micro-sites to develop within the flocs.

Unfortunately, the complexity of fouling is increased by a biological activity, and progression in this field of research is relatively slow. Membrane fouling is influenced by the membrane's chemical nature, but also, as Dhouib et al. [11] emphasizes, by the membrane operational parameters. For example, the use of hollow-fiber microfiltration membrane induces transmembrane pressure gradients, which have an impact on flux rates. The magnitude of the flux depends on the design of the hollow-fiber (length, internal diameter, permeability) and on the properties of the cake. In the membrane bioreactor, the resistance of the cake, generally composed of microorganisms, inorganic and organic substances including extracellular polymers, is the main contributor to resistance. Xu et al. [12] also so that the structure of the membrane pores have a significant effect on the fouling. Zhang et al. [13] describe reverse osmosis and nanofiltration membrane fouling, which depends on the surface morphology, i.e., the rougher the surface the faster the fouling by attachment of colloids on the membrane surface. Atomic force microscopic images reveal that the particles accumulate mostly in the small hollows of rough membranes, leading to their fouling and a severe flux decline.

Ueda et al. [14] show the existence of a linear relation between the surface roughness of the reverse osmosis membrane and flux, but unlike the previous researchers, they found that the permeate flux increase with the membrane roughness. They conclude that a greater membrane roughness increases the local turbulence and wall shear stress and the permeate flux.

Despite the many investigations, the role of membrane surface properties in colloidal fouling of reverse osmosis and nanofiltration membranes is not yet entirely understood. Studies have shown that it would be better to use hydrophilic membranes rather than hydrophobic ones because the flux decreases much more slowly.

2.4 CONCEPT OF CRITICAL FLUX

Field et al. were the first to introduce the concept of the critical flux. As long as one operates below this critical flux, the membrane fouling can be neglected and thus membrane cleaning is not required. It is important therefore to choose an adequate initial permeate flux or transmembrane pressure.

The disposal of undesirable organic and mineral matter occurs with the help of flocculating bacteria which from flocs that are the base of sludge. However, these bacteria are not distributed uniformly in the floc and also located in the central part of the floc are not in the contact with the pollutant to be eliminated. The biological flocs are disintegrated by the circulation inside of the membrane bioreactor. Changes in the particle size distribution modify the fouling properties of the suspension; the presence of smaller particles, resulting from the breakdown of the flocs, increases the membrane fouling. For an external type of membrane bioreactor, the membrane fouling depends on the intensity of shear stress imposed on the bacterial flocs by the recycling pump. The pumps breaks down the flocs, generating more the colloidal particles and releasing the extracellular polymeric substances (EPS, principal compounds of the soluble organic matter) from the interior of the floc to the bioreactor.

The bacterial suspension is divided into three fractions:

1. the soluble fraction (or dissolved; $d<10^{-3}\ \mu m$),
2. the colloidal fraction (polymers, fragments of cells; $10^{-3}<d<1\ \mu m$),
3. the particulate fraction (solids in suspensions, mainly bacterial flocs with the solids concentration depending on the sludge age; $d>1\ \mu m$).

However, the lack of any pH measurements is prejudicial, actual strong influence of pH on the colloidal membrane fouling.

2.6 WASHING AND REGENERATION

Effective washing requires an understanding of the interaction between the fouling products and the membranes as well as the effect of the washing procedures on elimination of the deposit. Membrane washing is performed when the permeability is less than 10% of initial permeability. Details of the different methods in chronological order of their applications are as follows:

2.7 VARIOUS MODEL EQUATIONS IN BIOMASS GROWTH PHENOMENA

Many papers have been published on model development and many correlations are given by research workers, which take into account the basic phenomena occurring during biomass growth in a membrane bioreactor (MBR). These models and correlations include the basic mechanism such as substrate inhibited model, biological activity, single substrate microbial growth, stability analysis of the biodegradation, improved dynamic analysis on cell growth etc. In this section model equations and correlations are given which take into account the above mechanism.

Villadsen et al. [26] have developed a fundamental understanding of the coupling between kinetic, hydrodynamic, and transport process in a bioreactor may also favorably impact process economics. The discoveries related to the genome of the many newly sequenced microorganism and information pathways between the genome, the proteins expressed and the metabolites produced by the proteins have caused considerable excitement the near term potential for biology.

The most promising kinetics approach is based on the concept of a limiting substrate with concentration S_l in the reactor. If any other substrate S_j is in excess the volumetric rate of production q_x from a sterile feed, and the consumption of other substrates and production of metabolites (q_{pi}) can be found from

$$q_x = f(s_1)x, \qquad -q_{s_1} = Y_{xs_1} q_x, \qquad q_{s_j} = Y_{s_1 s_j} q_{s_1} \text{ and}$$

$$-q_{p_i} = Y_{s_1 p_i} q_{s_1}. \tag{2.7.1}$$

The yield coefficients are all positive while the rates q_i are positive if i is produced, and negative if i is consumed. For constant yield coefficients Y_{ij}:

$$Y_{s_j s_1}(s_{if} - s_j) = (s_{1f} - s_1) \qquad \text{and}$$

$$Y_{p_i s_1}(p_i - p_{if}) = (s_{1f} - s_1). \tag{2.7.2}$$

Luedeking-Piret kinetics includes a maintenance term m_{s_1} for non-growth-related substrate consumption and corresponding term for the product formation m_{p_i}.

2. Andrews and Noack model (1968)

$$\mu = \frac{\mu_{max} C_s}{(C_s + K_s)(1 + C_s/K_I)} \tag{2.7.7}$$

3. Han and Levenspiel model (1988)

$$\mu = (1 - C_s/K_I)^n \frac{\mu_{max} C_s}{C_s + K_m(1 - C_s/K_I)^m} \tag{2.7.8}$$

At low substrate concentrations, the term in the denominator of Han and Levenspiel model, i.e. $K_m(1 - C_s/K_I)^m$, has a significant effect as the factor ($1-C_s/K_I$) is appreciable. But as the substrate concentration increases this factor keeps decreasing and at high substrate concentrations $C_s/[C_s + K_s(1 - C_s/K_I)^m]$ tends to one.

Lee et al. [29] have been developed for the submerged membrane bioreactor (SMBR) combining the activated sludge model. Membrane bioreactor (MBR), especially MBR with submerged type membranes, has been gaining lots of attentions for wastewater treatment in the aspect of better effluent quality and lower sludge production comparing to conventional activated sludge processes.

Authors have established four additional 1st-order linear equations to describe the fate of soluble microbial products.

1. Aerobic growth on S_{SMP}:

$$\mu = \mu_{SMP}\left(\frac{S_{O_2}}{K_{O_2} + S_{O_2}}\right)\left(\frac{S_{SMP}}{K_{SMP} + S_{SMP}}\right)\left(\frac{S_{NH_4}}{K_{NH_4} + S_{NH_4}}\right)\left(\frac{S_{ALK}}{K_{ALK} + S_{ALK}}\right).X_H \tag{2.7.9}$$

2. Anoxic growth on S_{SMP}:

$$\mu = \mu_{SMP}\eta_{NO_3}\left(\frac{S_{SMP}}{K_{SMP} + S_{SMP}}\right)\left(\frac{K_{O_2}}{K_{O_2} + S_{O_2}}\right)\left(\frac{K_{NO_3}}{K_{NO_3} + S_{NO_3}}\right)\left(\frac{S_{NH_4}}{K_{NH_4} + S_{NH_4}}\right)\left(\frac{S_{ALK}}{K_{ALK} + S_{ALK}}\right).X_H \tag{2.7.10}$$

3. Heterotrophic organism lysis producing S_{SMP}:

$$\mu = b_{H,SMP} X_H \tag{2.7.11}$$

4. Autotrophic organisms lysis producing S_{SMP}:

$$\mu = b_{A,SMP} X_H \tag{2.7.12}$$

Ideal conditions in the settler allow the following simple relation between the exit biomass X and the recycle biomass X_R concentrations,

$$X_R = X\left(\frac{1+R-W}{R}\right) \tag{2.7.17}$$

Or equivalently

$$D_r\left(X_f - WX\right) + \left(r_1 + r_2\right)X = \frac{dX}{dt}. \tag{2.7.18}$$

The two substrates S_1 and S_2 are involved in an uncompetitive cross-inhibitory interaction with growth rates given by

$$r_1 = \frac{\mu_1 S_1}{K_1 + S_1 + S_1^2/K_I + K_3 S_1 S_2} \tag{2.7.19}$$

and

$$r_2 = \frac{\mu_2 S_2}{K_2 + S_2 + K_4 S_1 S_2}. \tag{2.7.20}$$

The culture grows on substrate S_1 following Andrews kinetics (Andrews, 1968). In the absence of S_1 the culture growth on substrate S_2 following the Monod model. When the medium contains both S_1 and S_2 the culture utilizes both of them simultaneously.

Juang et al. [27] have established a simple two-phase model, originated from the Haldane model, was presented to predict the behavior of batch culture operations, in which the substrates show an inhibition effect on biomass growth. The model was based on the two regions of metabolic activity: the lag phase and the log phase.
Haldane model, it was demonstrated that the proposed two-phase Haldane model much better predicted the dynamics of biomass growth including the transient region from the lag to the log phases.

One phase model: The specific growth rate of cells in a batch system, μ (h^{-1}), is defined as:

$$\mu = \frac{1}{X}\frac{dX}{dt} = \frac{d\ln X}{dt} \tag{2.7.21}$$

And,

$$\frac{dX}{dt} = \mu X = \frac{\mu_{\max}^{\log} SX}{K_S^{\log} + S + \left(S^2/K_I^{\log}\right)} \tag{2.7.28}$$

$$\frac{dS}{dt} = \left(\frac{dS}{dX}\right)\mu X = \left(\frac{-1}{Y_{XS}^{\log}}\right)\left(\frac{\mu_{\max}^{\log} SX}{K_S^{\log} + S + \left(S^2/K_I^{\log}\right)}\right) \tag{2.7.29}$$

Where, log phase $t \geq t_L$.

In this work, they have compared the results predicted according to the one- and two-phase Haldane models. The sets of equation were solved using Excel/C software and a fourth order Runge–Kutta numerical scheme with a small time step (0.1 h) to ensure numerical stability.

Okpokwasili et al. [30] have derived the relation between the specific growth rate (μ) of a population of microorganisms and the substrate concentration (S) is a valuable tool in biotechnology. The classical model models, which have been applied to microbial population growth, Verhuslst and Gompertz function. The Gompertz function was originally formulated for actuarial science for fitting human mortality data but it has been applied deterministically to organ growth. The Gompertz function is based on an exponential relationship between specific growth rate and population density. Equation represents one of its parameterization.

$$N_{(t)} = C\exp\{\exp[-B(t-M)]\} \tag{2.7.30}$$

Where t = time, $N_{(t)}$= population density at time t, C = upper asymptotic value, that is the maximum population density, M = time at which the absolute growth rate is maximal, and B = relative growth rate at M time.

The modified Gompertz function which could be applied to the description of cell density versus time in bacterial growth curves in terms of exponential growth rates and lag phase duration.

$$LogN_{(t)} = A + D\exp\{-\exp[-B(t-M)]\} \tag{2.7.31}$$

Sl. No.	Objective	Parameters	Results & Discussion	Conclusion	Author
1.	Studies of anionic surfactants degradation kinetics.	pH = 6.27, Temperature = 30 ^{0}C, Volume = 4.5 m^3, Pressure = 2-3.6 bars	Experiment shows the concentration of the pollutant increase in the effluent and the efficiency of degradation of the microbial system decreased.	The MBR system showed excellent pollutant removal efficiency. The membrane fouling affected the permeate flux and directly increased the energy consumption.	Dhonib et al. [11]
2.	Evaluating the fouling behavior in MBR and effect of aeration intensity and backflush.	pH = 8.8, Volume = 60 l, Pore size = 0.4 μm.	Membrane filtration resistance increases with time. Suction and non-suction time is found to have strongest influence on fouling.	Suction time strongly affected fouling resistance, followed by aeration intensity. The most cost relevant parameters affected by time and aeration intensity.	Fuchs et al. [5]
3.	Membrane fouling control and Feasibility criteria of the MGSBR are used to treat wastewater.	pH = 7.4 ± 0.4, Temperature = 20 ± 5 ^{0}C, Volume = 20 l.	COD removal efficiency is 80-95 % and the membrane permeability of MGSBR is more 50 % higher than of a MFSBR.	The treatment performance of a MGSBR system is very stable and on a high level. The novel MBR advantages in controlling of membrane fouling.	Chen et al. [10]

4.	To determine the fouling is only caused by soluble and colloidal fraction of biological suspension.	Temperature = 25 ^{0}C, Volume = 12 l	Viscosity varies only due to the slight difference in temperature.It is possible to describe fouling in MBR with the help of an inverse diffusivity.	$\chi = \mathrm{Re}^{1.3}/Jd_h$ a model based on an energy comparison between the shear forces, respected by τ_0 and the kinetic energy linked to permeation described by ρJ^2.	Grasmick et al. [4]
5.	Studies of membrane fouling. Determination of the critical flux for deposition of the colloidal particles.	pH = 8.5, Temperature = 25 ± 1 ^{0}C Volume = 20 l, Pressure = 0.5 bar, Pore size = 0.05 μm.	Under standard physicochemical conditions, only a low and constant fouling resistance is observed if the permeate flux is maintained below the critical flux.	Alkalinity of the suspension can cause the precipitation of $CaCO_3$ if pH value is in between 8 to 9. The role of precipitation can be pointed out as a cause of system instability even if the system works in subcritical conditions.	Ognier et al. [9]
6.	Studies of energy consumption and effect of resistance to membrane fouling.	pH = 6.5-7.2, Temperature = 23 ± 2 ^{0}C Volume = 650 l, Pressure = 1-5 bar, Pore size = 0.2 μm.	The effluents from the MBR and CAS process are not significantly different in the aspect of COD and NH_4^+-N. The low energy MBR produced a more stable effluent quality.	The membrane module consumed the large part consisting of 37.66-52.2 % of the total energy consumption.	Zhang et al. [13]

7.	Effect of turbulence promoter in ceramic membrane bioreactor system.	pH = 7.5, Temperature = 25 ^{0}C, Pore size = 0.2 μm.	The ceramic membrane is suitable for membrane bioreactor with activated sludge for the system high energy required. The average reduction rate of COD is greater than 95 %.	The winding insert is found to be simple and effective to reduce energy consumption in the CMBR.The permeate flux is improved about 2.5 times with the introduction of the winding insert.	Xu et al. [12]
8.	Long term treatment performance of a membrane bioreactor with complete sludge retention for municipal wastewater.	pH = 7-7.5, Temperature = 20-27 ^{0}C Pressure = 0.5 bar, Volume = 3.9 m^3, Pore size = 0.2 μm.	After start up with wastewater, the permeate difference increased to 0.33 bar. The abrupt decline is due to the deposition of slimy substances and lipids.	Complete sludge retention eventually leads to a constant sludge concentrations at very low F/M ratio. Most probably zero net sludge production depends on the compositions.	Kraume et al. [3]
9.	Study of simulation for calculating cross flow velocity, and dimensional parameters of the bioreactor.	Temperature = 17-20 ^{0}C Velocity = 0.3 m/s, Volume = 2.4 m^3, Pore size = 0.1 μm.	Transmembrane pressure increases with operation time, but the increasing rate differs with cross flow velocity and decrease when the cross flow velocity is higher.	The cross flow velocity increase with aeration intensity. Cross flow velocity accurately in a submerged membrane bioreactor process with in the range of the air flow rate applied.	Huang et al. [8]

10.	Compare the modes of filtration of constant TMP and constant flux in a membrane bioreactor.	Temperature = 20 ^{0}C, Velocity = 1-5 m/s, Volume = 1000 l, Pore size = 0.1 μm.	The flux increases linearly with TMP independently of velocity. The permeate flux and TMP varies with circulation velocity and wall shear stress.	In long term cross flow filtration process membrane bioreactors operated at fixed flux filtration just below the critical flux to reduced the operating cost.	Jaffrin et al. [24]
11.	Performance of a submerged membrane bioreactors with gravitational filtration.	Volume = 1.56 m^3, Pore size = 0.4 μm.	Accumulation of cake layers increase Δp and filtration resistance. The removal of organic matter and suspended solids is quite successful except N_2 removal.	The simulated inflow fluctuation showed that the system could cope with a short term fluctuation of inflow without deteriorating filtration performance.	Ueda et al. [14]
12.	Determination the organic loading on membrane fouling in a submerged membrane bioreactor.	pH = 6.5, Temp. = 20 ^{0}C, Pressure = 0.07-0.48 bar, Volume = 1514 l, Pore size = 0.035 μm	Foaming occurred when the intermittent coarse-air valve failed and foam accumulated on the surface of the membrane tank and membrane fouling rate increase in SMBR.	The COD concentration in the SMBR does not change significantly. There is no relationship between the median soluble COD concentration and the membrane fouling rate for the MCRT (F/M) range tested.	Trussell et al. [15]

13.	Compare the advantages of internal MEMBIOR to a conventional treatment system.	Pressure = <0.3 bar, Flow rate = 100-200 l/h.	Biological performance is very effective in internal MEMBIOR. TMP applied below 0.3 bars to avoid stress on the membrane.	Lower O_2 transfer coefficient is found. This needs an additional aeration or a different aeration mode to diminish membrane fouling.	Cornelissen et al. [22]
14.	Strategies for reducing sludge production in biological wastewater treatment process.	pH = 6.2-8.0, Temperature = $25 \pm 5\ ^0C$	The strategies use to reduce sludge, cost analysis and environmental impact assessment. Sludge reduction increase the total O_2 demand and thus result in an increase the aeration costs.	Reducing sludge production exists according to strategies based on mechanism of lysis-cryptic growth uncoupling metabolism, maintenance metabolism and bacteriovorous predation.	Wei et al. [20]
15.	Effect of air-sparging on a SMBR to treat municipal wastewater.	Volume = 0.06 m^3, Pressure = 3.4-7.1 kPa, Pore size = 0.2 μm.	Bubble flow: $\varepsilon < 0.2$, air bubbles are dispersed in the liquid phase. Slug flow: $0.2 < \varepsilon < 0.9$, flow comprises of gas and liquid. Annular flow: $\varepsilon > 0.9$, continuous gaseous phase occupies the centre of the pipe.	The air lift modules, permeate flux is found to increase by 43 % when coarse bubble aeration is employed.	Judd et al. [23]

16.	Determine the effect of the SRT for the plants design and on the microbial growth rate.	Temperature = 10 ^{0}C, Volume = 4 l.	SRT below the critical value, concentration difference is not effective or distribution according to the adsorption equilibrium. SRT higher than the critical value degradation will occur.	Low effluent concentration can be achieved in WWTPs at operating SRT higher than 10 days.	Clara et al. [21]
17.	Performance of the membrane separation activated sludge (MSAS) process to municipal waste-water treatment.	Temperature = 14.7-28.4 ^{0}C, Flow rate = 6.7 m^2/d, Pore size = 0.4 μm.	The reactor is operated under aerobic and nitrification proceeded, pH is constant through the operation. DO drop in the reaction, the O_2 supply is insufficient.	Continuous operation for 140 days with out chemical cleaning of the membrane is possible. Small scale pilot plant is operated without excess sludge withdrawal.	Murakami et al. [19]
18.	Investigation the organic removal performance and the behavior of microbial products during long term operation.	pH = 6.5, Temperature = 25 ^{0}C, Volume = 15 l.	Experiment shows the organic removal performance is achieved satisfactory. The growth of the biomass and a steady-state is observed after 50 days.	Accumulation of the supernatant TOC in the MBR and its subsequent degradation are observed. Satisfactory organic removal performance in a submerged membrane bioreactor.	Liu et al. [18]

19.	Study of membrane fouling mechanism of a membrane coupled anaerobic bioreactor (MCAB) system.	pH = 3.7, Temperature = 53-55 ^{0}C, Volume = 4 l.	Membrane fouling is mainly attributed to external fouling, which is closely related to the movement of the cell population to the membrane surface and inorganic precipitation at the membrane surface.	MCAB system revealed high COD removals in the bioreactor. To remove the biomass from membrane use physical cleaning such as depressurization and flow stopping, resulting in a transient elevation in the permeate flux.	Lee et al. [16]
20.	Study of municipal wastewater.	pH = 8.1 ± 0.2, Pressure = 5-30 psi, Flowrate = 500 l/h, Pore size = <0.1 μm	In first stage treatment, an effluent with a biochemical oxygen, BOD< 20 mg/l and total suspended solid, TSS< 20 mg/l. Further treatment of effluent by microfiltration resulted in a BOD< 5 mg/l and TSS< 2 mg/l and turbidity < 0.2 NTU.	Two stage schemes are capable to produce better quality of an effluent that again meets or surpasses to industry and agriculture.	Messalem et al. [17]

2.8 OBJECTIVE

- To develop substrate inhibition kinetics, Haldane's model.
- To deduct a simple equation for high substrate concentration from Haldane's equation.
- Development of model equations for continuous flow submerged membrane bioreactor system.
- To determine the kinetic parameters by using model equations.
- To show the saturation constant, how does it effect in inhibition kinetics.

DEVELOPMENT OF MODEL EQUATIONS

3.1 SUBSTRATE INHIBITION KINETICS

The relationship of specific growth rate to substrate concentration often assumes the form of saturation kinetics. Here we assume that a single chemical species, S, is growth rate limiting (i.e., an increase in S influences growth rate, while changes in other nutrient concentrations have no effect). High substrate concentrations may cause inhibition in some enzymatic reactions, known as substrate inhibition. The reaction scheme is uncompetitive substrate inhibition [31]:

$$E + S \xleftrightarrow{K_s} ES \xrightarrow{K_2} E + P$$

$$+$$

$$S$$

$$\updownarrow K_{s_I}$$

$$ES_2$$

Where,

$$K_{s_I} = \frac{[S][ES]}{[ES_2]}, \quad K_s = \frac{[S][E]}{[ES]}$$

The assumption of rapid equilibrium yields

$$\mu = \frac{\mu_m [S]}{K_s + [S] + \frac{[S]^2}{K_{s_I}}} \tag{3.1}$$

Equation (1) is also known as Haldane's inhibitory growth kinetics.

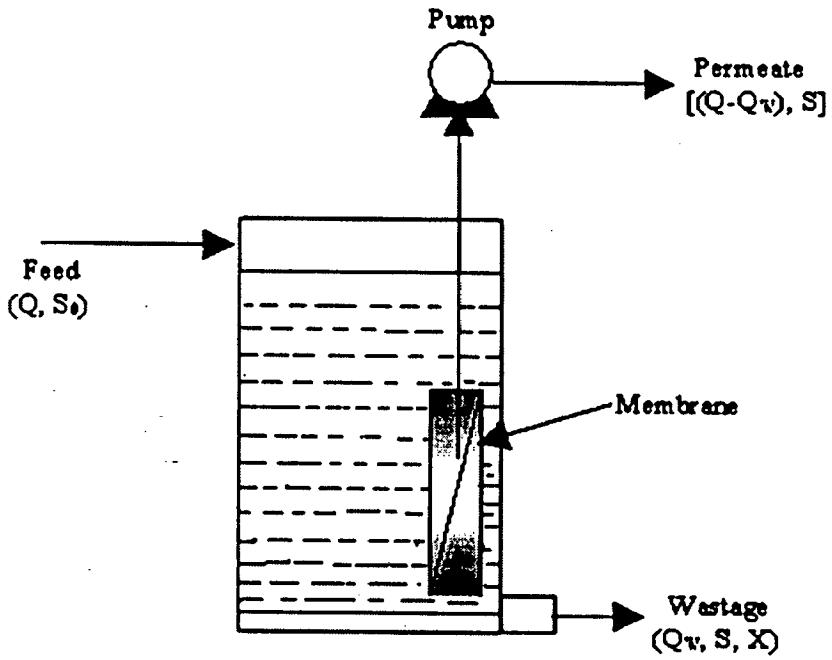

Figure 3.1: Schematic diagram of a single membrane bioreactor system.

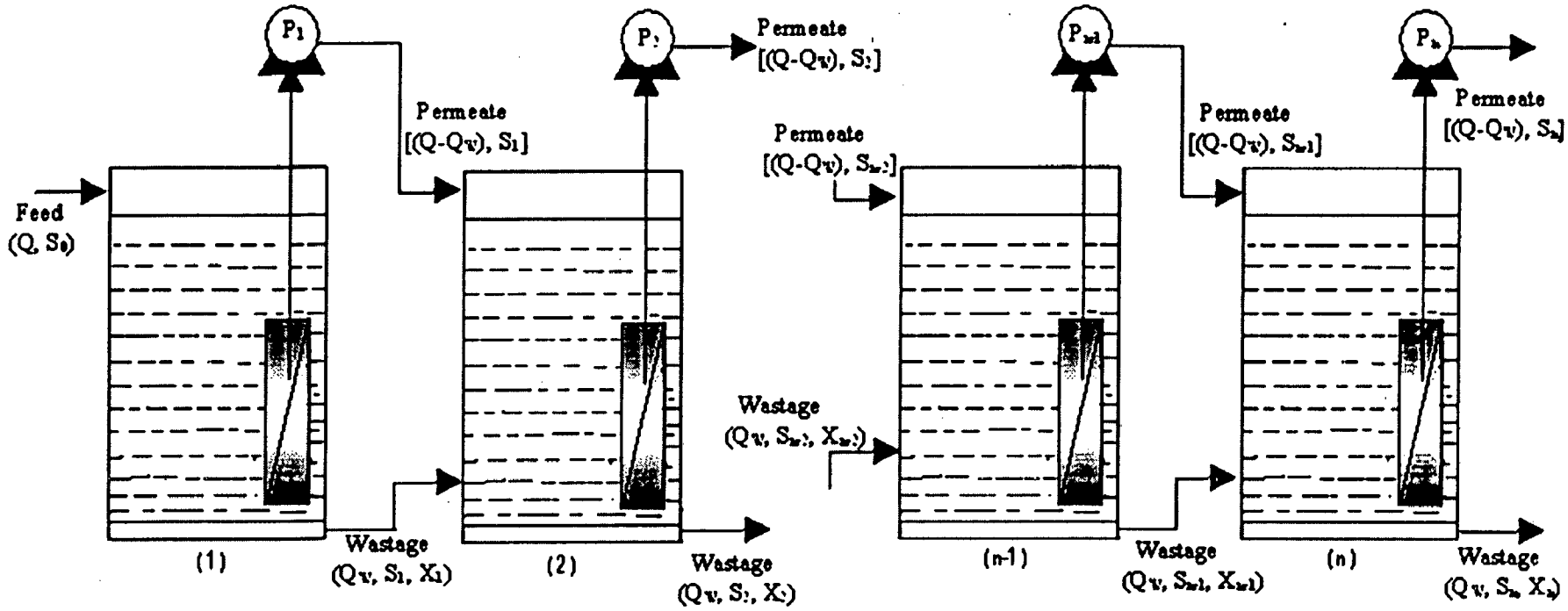

Figure 3.2: Schematic diagram of nth order membrane bioreactor system in series.

3.2 DEVELOPMENT OF MODEL EQUATIONS IN BIOMASS GROWTH KINETICS

The model has been developed based on the following assumptions [32]:

(1) the reactor is completely mixed (mixing has been provided by stone aerators installed at the bottom of the filtration unit as well as at the near end of the tank);

(ii) influent substrate concentration remains constant (this has been achieved by using synthetic wastewater as the influent substrate);

(iii) no microbial solids are contained in the influent substrate (i.e. for sterile nutrient);

(iv) the volume of the reactor is constant (the inflow rate has been kept equal to the permeate flux, which was achieved by the use of a mechanical float);

(v) complete rejection of the mixed liquor suspended solid (MLSS) (the membrane is capable of retaining all solids),

(vi) substrate is not rejected (the membrane has a high molecular weight-cutoff and, therefore, it would not reject glucose, which has a low molecular weight);

(vii) steady-state conditions prevail throughout the system;

(ix) the biokinetic coefficients (μ_m, K_{s_1}, Y, and k_d) are constant.

Mass balance equations of both of the biomass and substrate are required to describe the performance of the system.

Biomass and Substrate mass balance for 1st reactor

Biomass mass balance can be expressed as:

[rate of change of biomass in the reactor] = [rate of increase due to growth] – [rate of loss due to endogenous respiration] – [deliberate wastage].

This can be mathematically expressed as

$$V\frac{dX_1}{dt} = \mu_1 X_1 V - k_d X_1 V - Q_w X_1 \qquad (3.5)$$

Where V is reactor volume (l); X_1 is biomass concentration in the 1st reactor (mg/l); k_d is biomass decay coefficient (day^{-1}); Q_w is wastage flow rate (l/day); and t is time (day).

At steady-state, $dS_1 / dt = 0$, therefore, Equation (3.10) becomes:

$$\frac{Q}{V}(S_0 - S_1) = \mu_1 \frac{X_1 V}{Y} \tag{3.11}$$

Substituting Equation (3.8) into Equation (3.11), it gives the biomass concentration at steady-state condition:

$$X_1 = Y \frac{Q(S_0 - S_1)}{V\left(k_d + \frac{1}{SRT}\right)} \tag{3.12}$$

In continuous-flow and completely-mixed reactor, determination of the biokinetic coefficients is usually achieved by collecting the data from lab-scale or pilot-scale experimental setup operated at various hydraulic retention times (HRTs) and/ or at various sludge retention times (SRTs) and by allowing steady-state condition to prevail for each HRT or SRT under investigation. Accurate measurements of the biomass and permeate substrate concentration are then recorded. Parameters, such as μ_m, Y, k_d, and K_{s_1} can be determined by using Equation (3.9) and through linearization of Equation (3.12).

We can determine the biokinetic coefficients, k_d and Y by rearranging the Equation (3.12) to become in the form of

$$\frac{Q}{X_1 V}(S_0 - S_1) = \frac{1}{SRT}\frac{1}{Y} + \frac{k_d}{Y} \tag{3.13}$$

To determine the biokinetic coefficients, μ_m and K_{s_1}, rearranging the equation (3.9), we get,

$$\frac{SRT}{1 + (SRTk_d)} = \frac{1}{\mu_m K_{s_1}} S_1 + \frac{1}{\mu_m} \tag{3.14}$$

Biomass and Substrate mass balance for 2nd reactor

Biomass balance mass can be expressed as

[rate of change of biomass in the reactor] = [rate of input from 1st reactor due deliberate wastage] + [rate of increase due to growth] – [rate of loss due to endogenous respiration] – [deliberate wastage].

Substituting Equation (3.18) into Equation (3.21), it gives the biomass concentration at steady-state condition:

$$X_2 = Y\frac{Q(S_1 - S_2)}{V\left(k_d + \frac{1}{SRT}\right)} + \frac{X_1}{(1 + SRT.k_d)} \tag{3.22}$$

We can determine the biokinetic coefficients, k_d and Y by rearranging the equation (3.22) to become in the form of

$$\frac{Q}{X_2 V}(S_1 - S_2) = \frac{1}{SRT}\frac{1}{Y}\left(1 - \frac{X_1}{X_2}\right) + \frac{k_d}{Y} \tag{3.23}$$

To determine the biokinetic coefficients, μ_m and K_{s_l} , rearranging the equation (3.19), we get,

$$\frac{SRT}{\left(1 - \frac{X_1}{X_2}\right) + (SRT.k_d)} = \frac{1}{\mu_m K_{s_l}} S_2 + \frac{1}{\mu_m} \tag{3.24}$$

Biomass and Substrate mass balance for nth reactor

Biomass balance can be expressed as like as 2nd reactor and the mathematically expressed as:

$$V\frac{dX_n}{dt} = Q_w X_{(n-1)} + \mu_n X_n V - k_d X_n V - Q_w X_n \tag{3.25}$$

At steady state conditions, $dX_n / dt = 0$, hence, Equation (3.25) becomes

$$\mu_n = k_d + \frac{Q_w}{V}\left(1 - \frac{X_{(n-1)}}{X_n}\right) \tag{3.26}$$

Substituting the value of μ_n for inhibition kinetics by using Equation (3.4) into Equation (3.26), we get

$$S_n = \frac{K_{s_l}\left[\mu_m - \left\{k_d + \frac{1}{SRT}\left(1 - \frac{X_{(n-1)}}{X_n}\right)\right\}\right]}{\left[k_d + \frac{1}{SRT}\left(1 - \frac{X_{(n-1)}}{X_n}\right)\right]} \tag{3.27}$$

RESULTS AND DISCUSSION

The experimental data are undertaken from a lab-scale membrane bioreactor system for a period of more than one year with the pore size of the membrane (20-40 μm) and it showed that the pore size of the membrane was significantly reduced [32]. The hydraulic retention time is not used as a key parameter in the biomass growth rate where sludge retention time is used as a controlling parameter throughout the simulation and it is calculated as the following equation:

$$SRT = \frac{V_r X_{avg}}{V_w X_{incr}}$$

Where V_r is the reactor volume (l), X_{avg} the average MLSS (mg/l), V_w the volume of the wasted sludge per day (l/day), and X_{incr} is the MLSS before wasting (mg/l).

4.1 DETERMINATION OF BIOKINETIC PARAMETERS

The experimental results [32] have been used to simulate the above developed model. A steady-state condition was assumed for fairly constant biomass growth with respect to time and first stage was achieved after 22 days from the start of the experiment. Table A1 shows that the steady-state data obtained at MLSS concentration of 3000 mg/l and the Figures 4.1 and 4.2 has been drawn to determine the coefficients using equations (3.13) and (3.14). The biokinetic coefficients are found to be as follows:

Y=0.5413 mg/mg, k_d=0.1984 day^{-1}, μ_m=0.2975 day^{-1}, and K_{s_l} =646 mg/l.

The second phase steady-state conditions at an MLSS concentration of 5000 mg/l has been shown in Table A2 and Figures 4.3 and 4.4 have been plotted using these data. The simulate values of the biokinetic coefficients are as follows:

Y=0.5597 mg/mg, k_d=0.1743 day^{-1}, μ_m=0.2955 day^{-1}, and K_{s_l} =615 mg/l.

During the third phase of the investigation, the steady-state conditions at an MLSS concentration of 10000 mg/l has been presented in Table A3. Values of the biokinetic coefficients obtained from Figures 4.5 and 4.6 are as follows:

to steady state phase. Tables A7 and A8 have showed the maximum biomass concentration for the particular substrate influent and effluent concentrations. After gaining the steady-state the system would be inhibited due to increase in the substrate concentration in the system.

4.3 INHIBITED GROWTH PROFILE WITH VARIATIONS OF SRT AND SUBSTRATE CONCENTRATION

Figure 4.13 shows that the specific growth rate gradually decreases with the increase in sludge retention times (SRTs) for a particular biomass concentration (MLSS are 3000 mg/l, 5000 mg/l, 10000 mg/l, and 15000 mg/l), i.e. shows that the total biomass would be increased in the system with increasing the sludge retention time (SRTs). The specific growth rate has been found to be higher for low biomass concentration, containing various biomass concentrations in the reactor at a constant SRT.

Figures 4.14-4.17 are plotted with Equation 3.1 and show the inhibition effect of the membrane bioreactor system for a various initial biomass concentration system. These plots are shown that the inhibition profile after reaching at the maximum specific growth rate in the growth kinetics. This system is shown as totally inhibited, i.e. at zero substrate concentration inhibition effect is present. The saturation constant is zero for the consideration of higher substrate concentration inhibited system. The plots are drawn from a constant value of $K_S = 0.001$ and at the value of $Ks = 0$, the value of μ is infinite with the value of S = 0. It is also shown that the maximum specific growth rate is decreasing with increase in K_S value. The inhibition periods are pronounced at the initial stage; afterwards they have reached a steady state value.

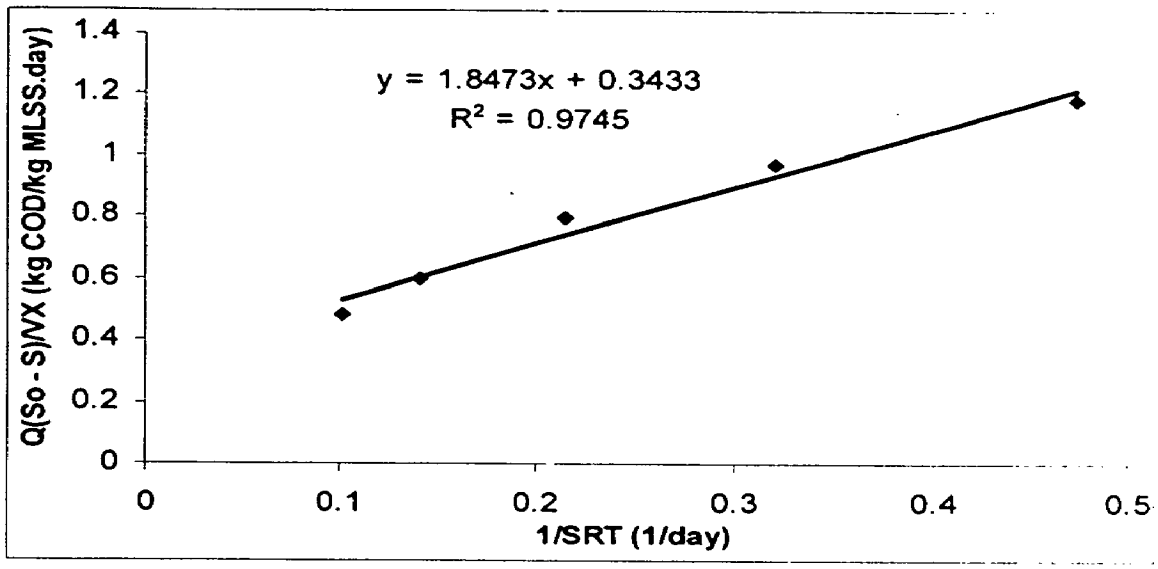

Figure 4.1: Determination of Y and k_d at MLSS of 3000 mg/l

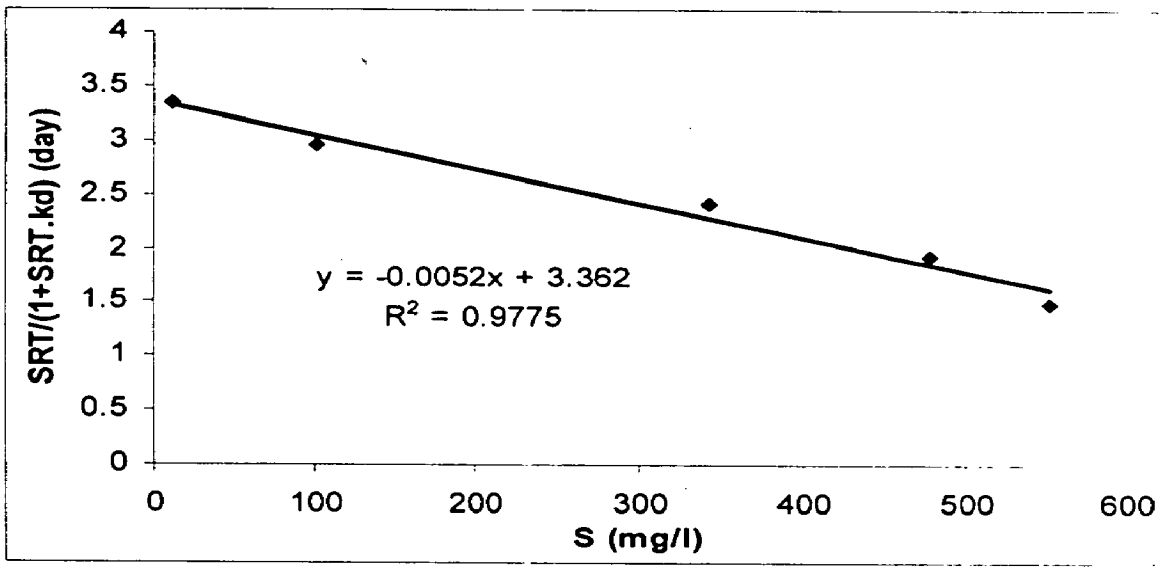

Figure 4.2: Determination of μ_m and K_S at MLSS of 3000 mg/l

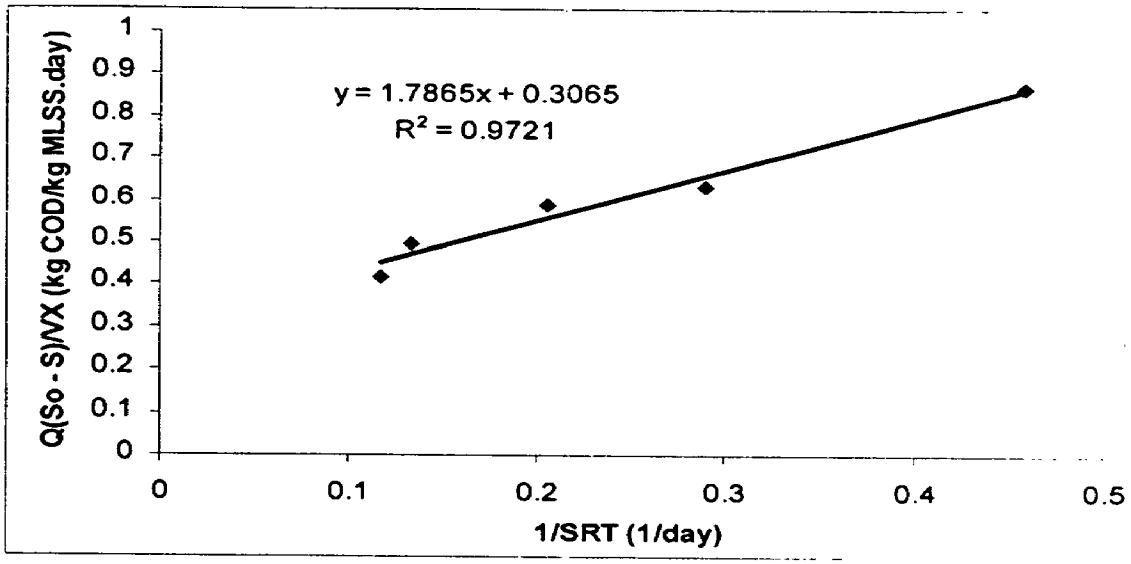

Figure 4.3: Determination of Y and k_d at MLSS of 5000 mg/l

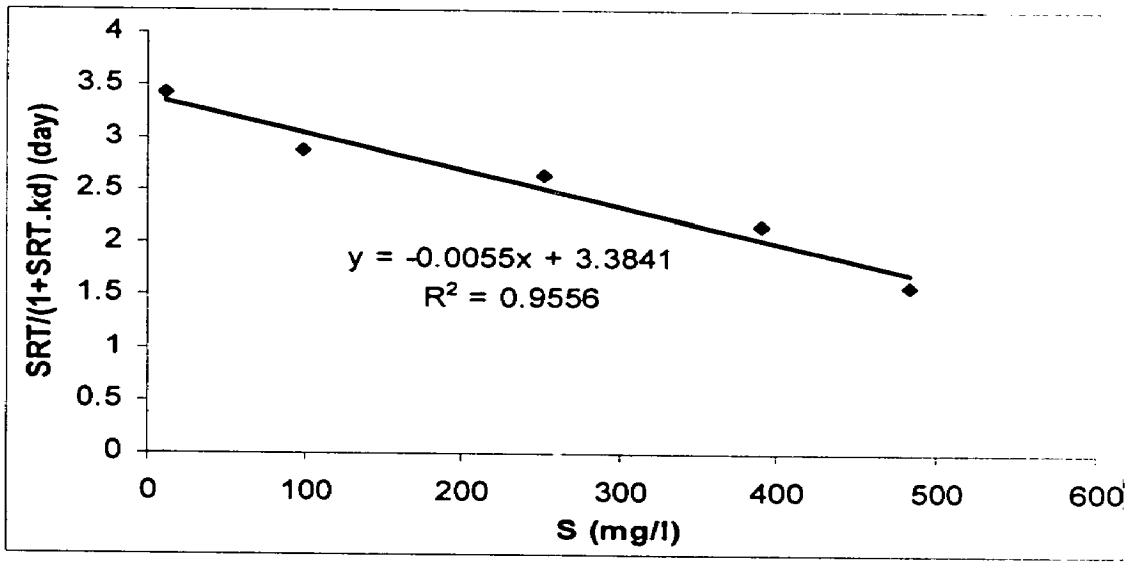

Figure 4.4: Determination of μ_m and K_{S_1} at MLSS of 5000 mg/l

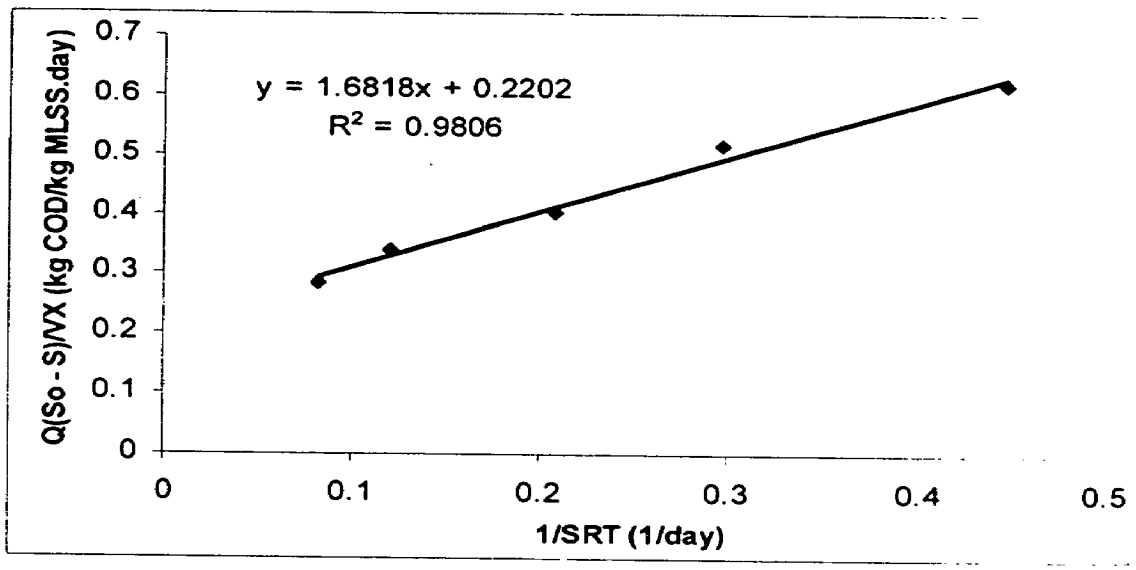

Figure 4.5: Determination of Y and k_d at MLSS of 10000 mg/l

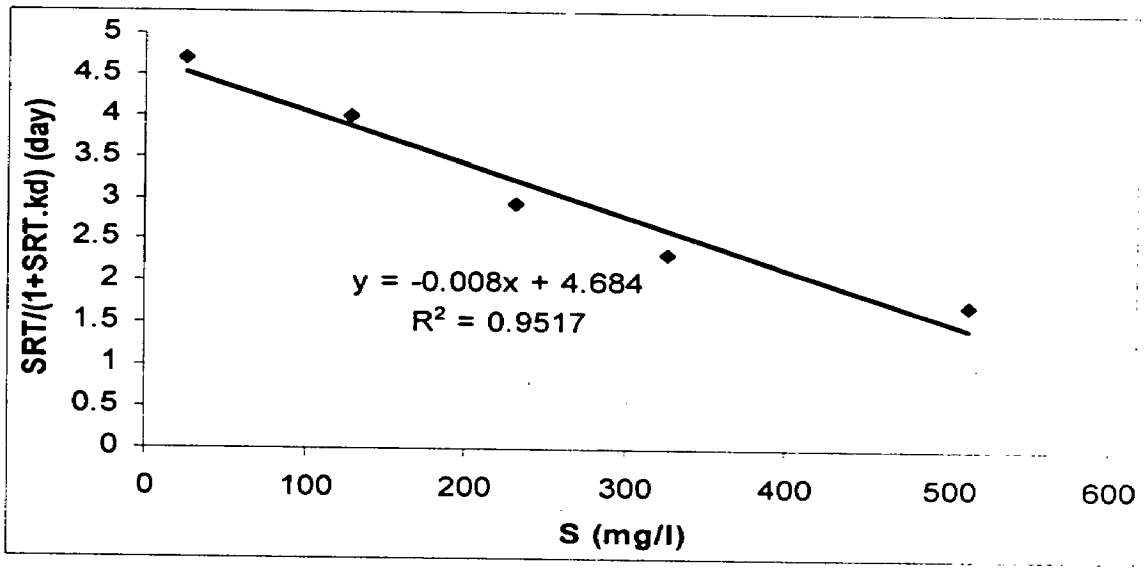

Figure 4.6: Determination of μ_m and K_{S_i} at MLSS of 10000 mg/l

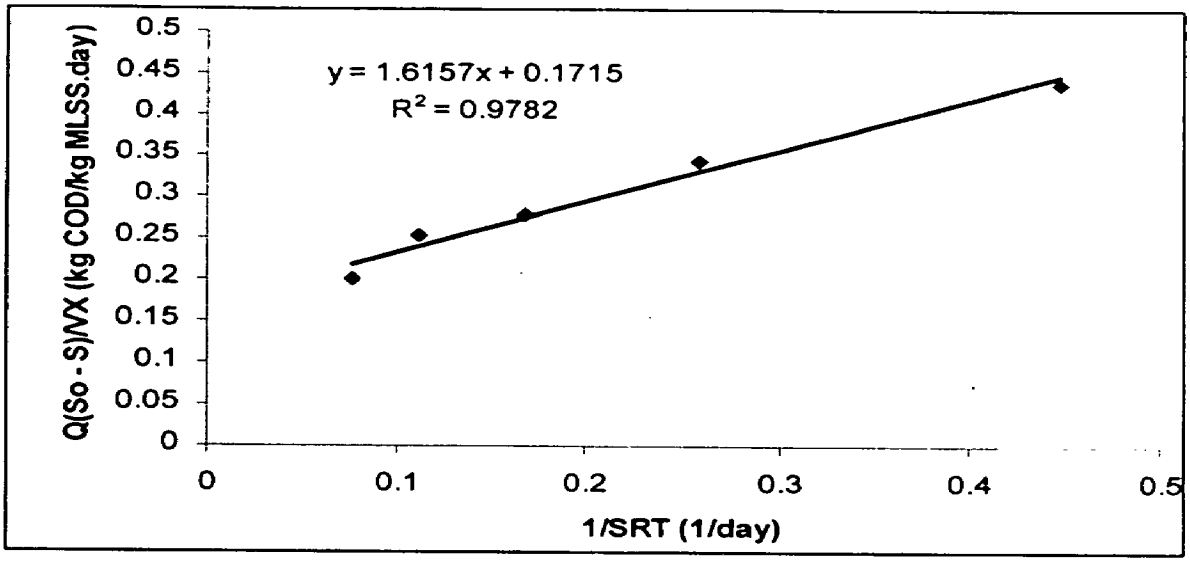

Figure 4.7: Determination of Y and k_d at MLSS of 15000 mg/l

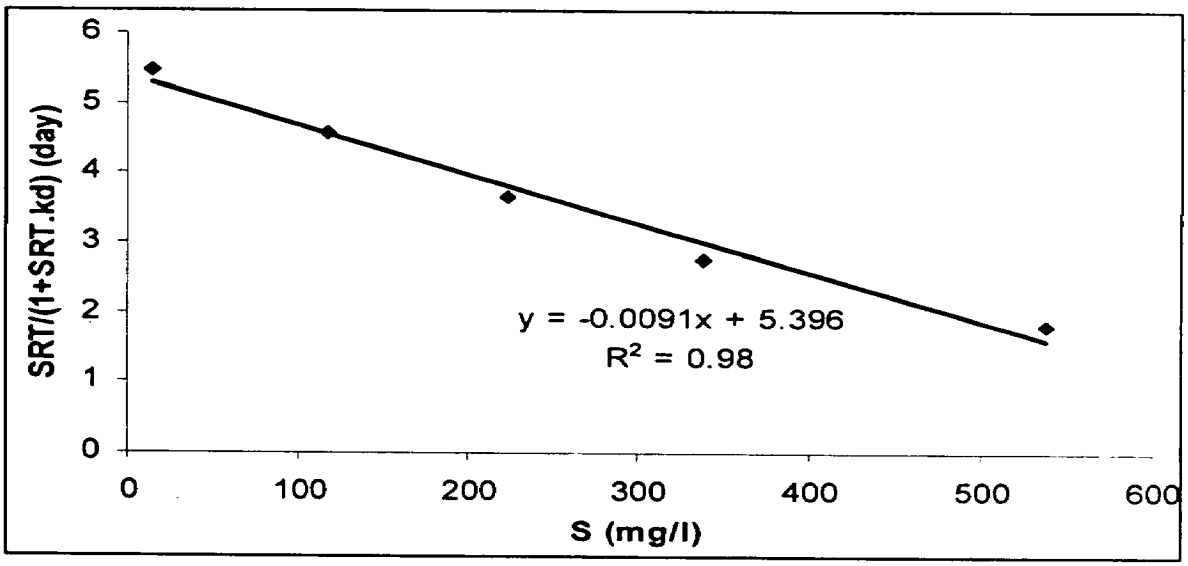

Figure 4.8: Determination of μ_m and K_{S_1} at MLSS of 15000 mg/l

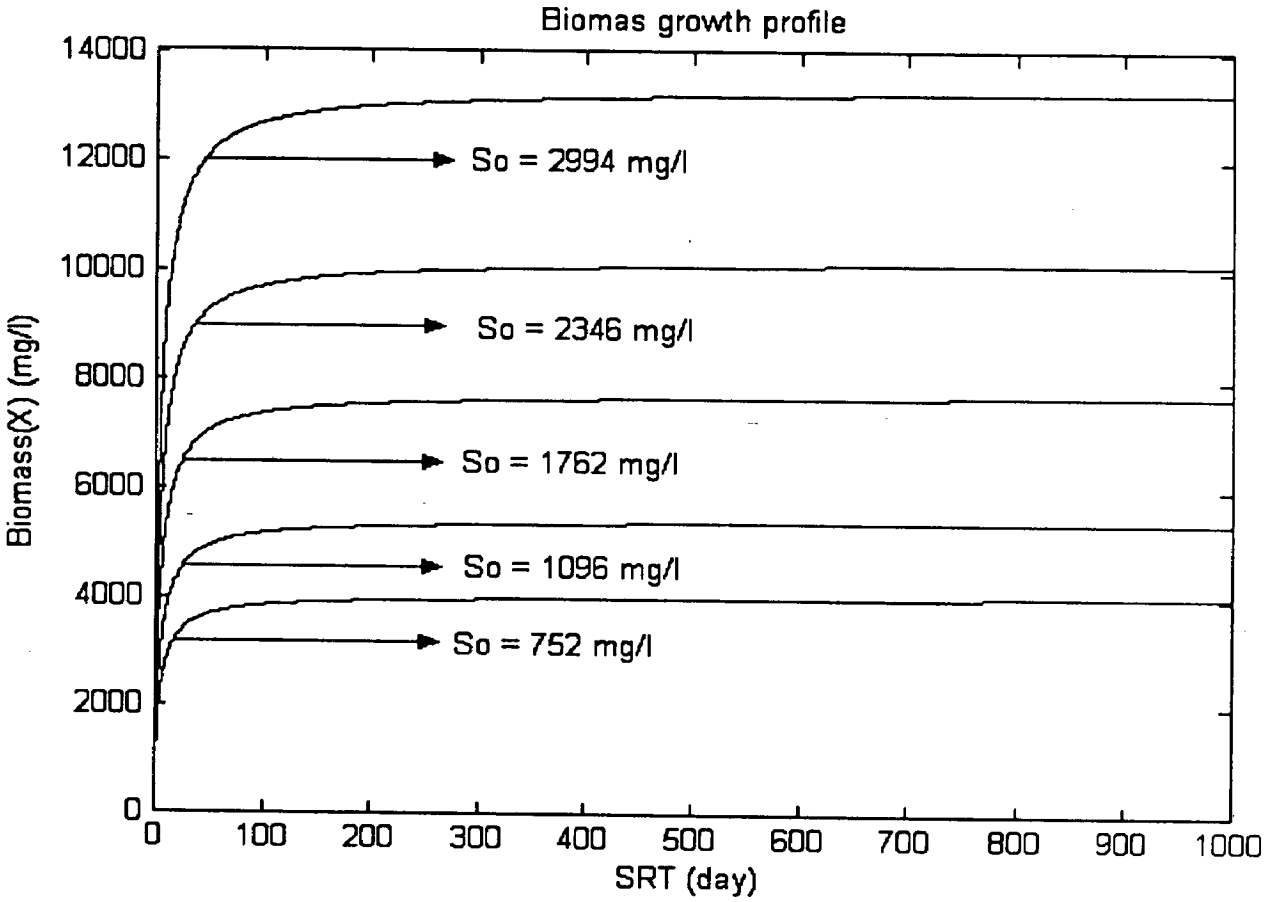

Figure 4.9: Biomass growth for various initial substrate concentrations at MLSS = 3000 mg/l

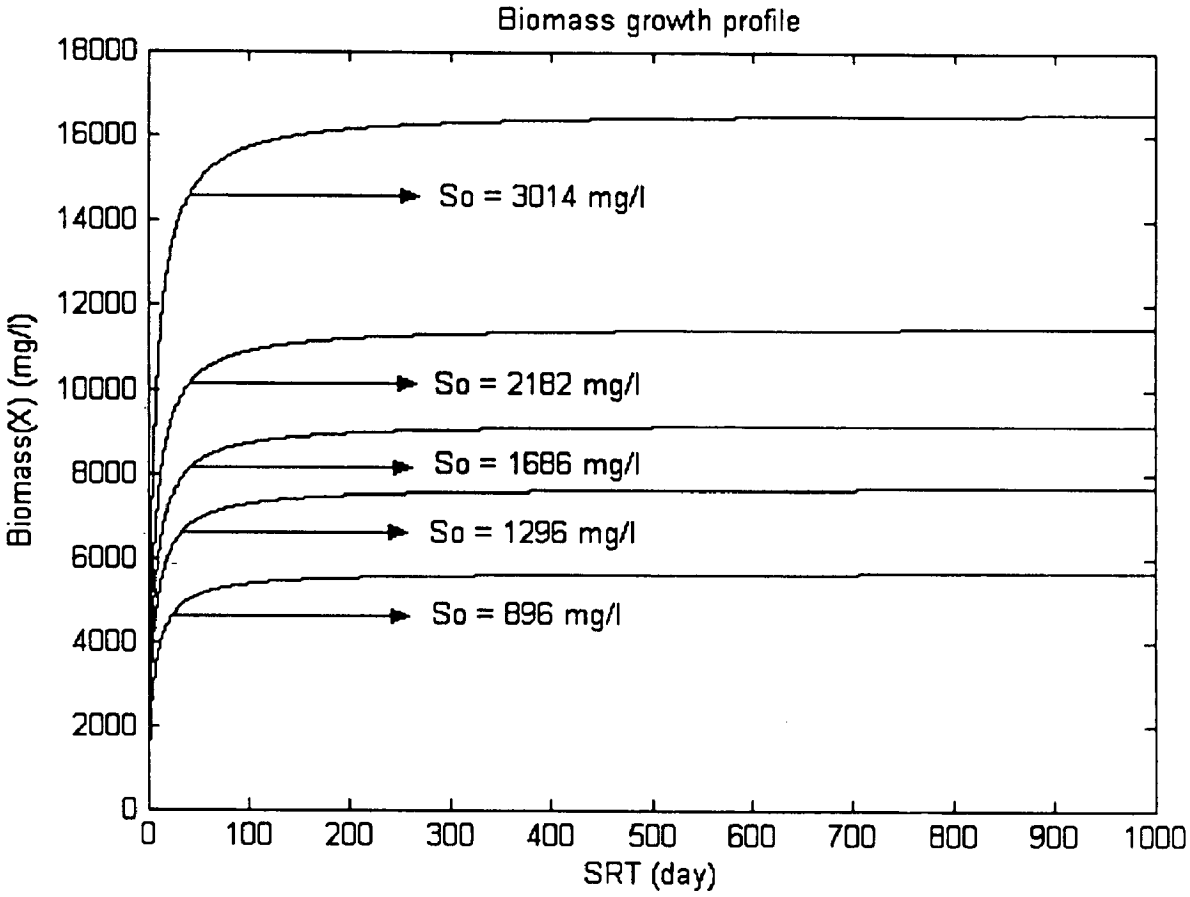

Figure 4.10: Biomass growth for various initial substrate concentrations at MLSS = 5000 mg/l

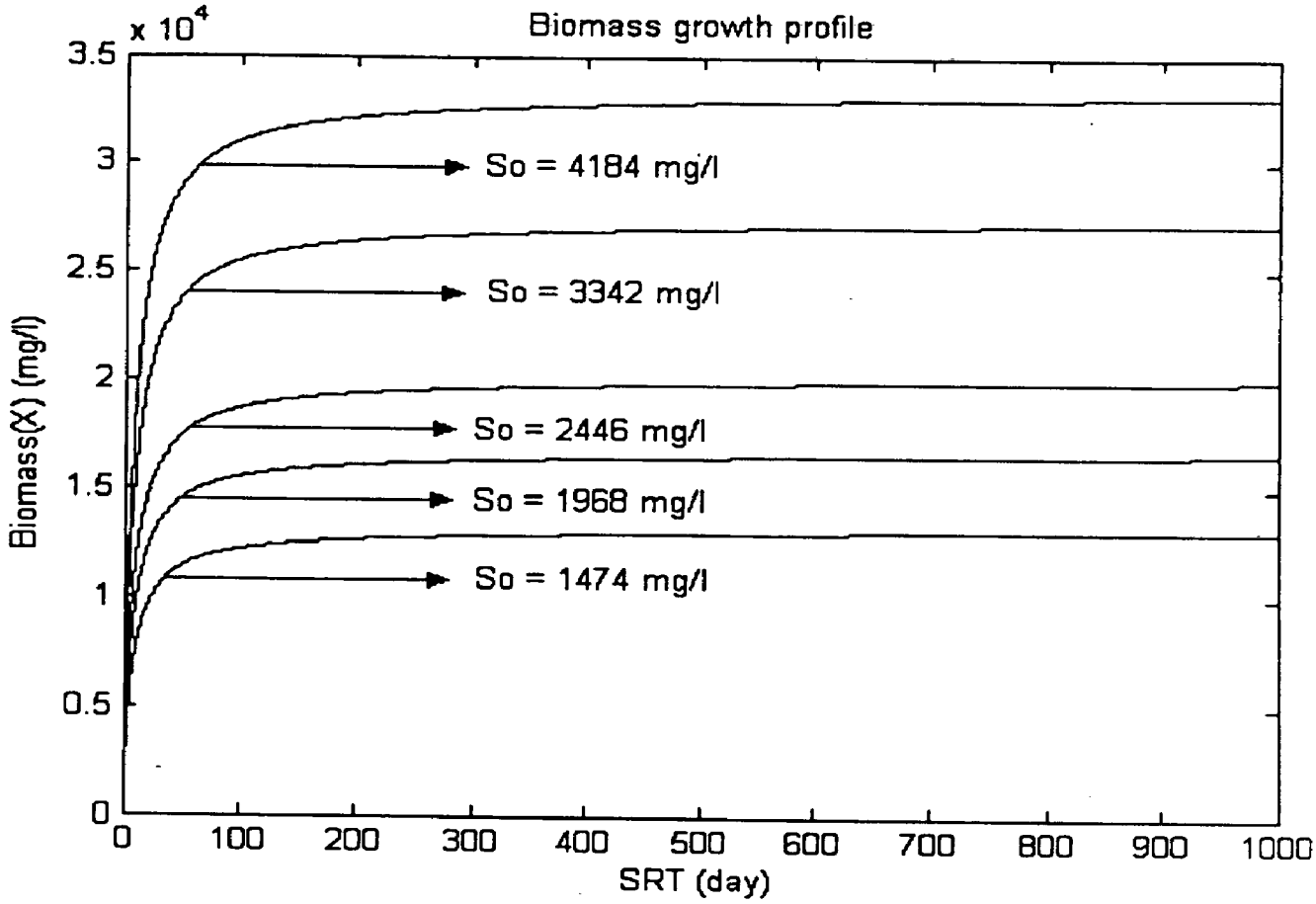

Figure 4.11: Biomass growth for various initial substrate concentrations at MLSS = 10000 mg/l

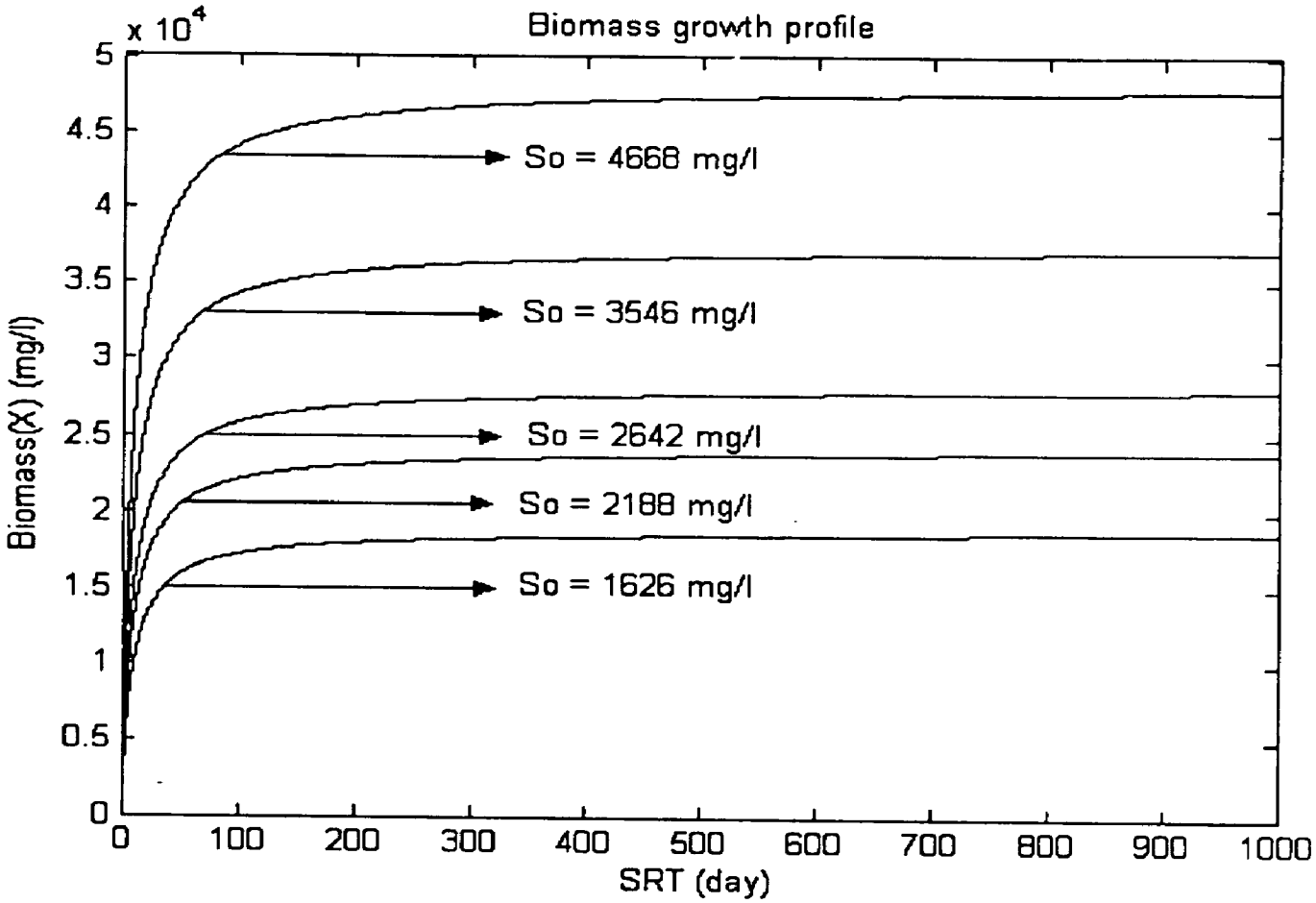

Figure 4.12: Biomass growth for various initial substrate concentrations at MLSS = 15000 mg/l

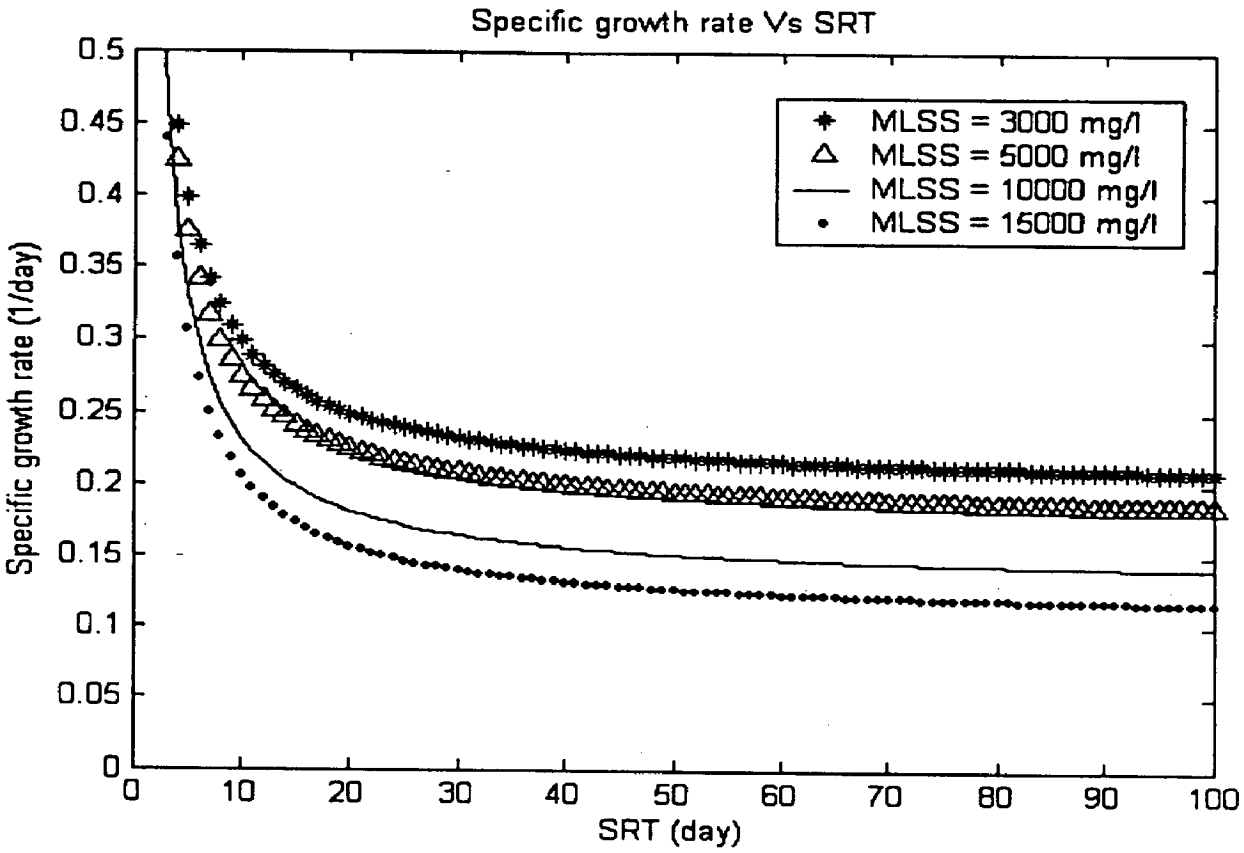

Figure 4.13: Specific growth rate versus SRT at various MLSS concentrations

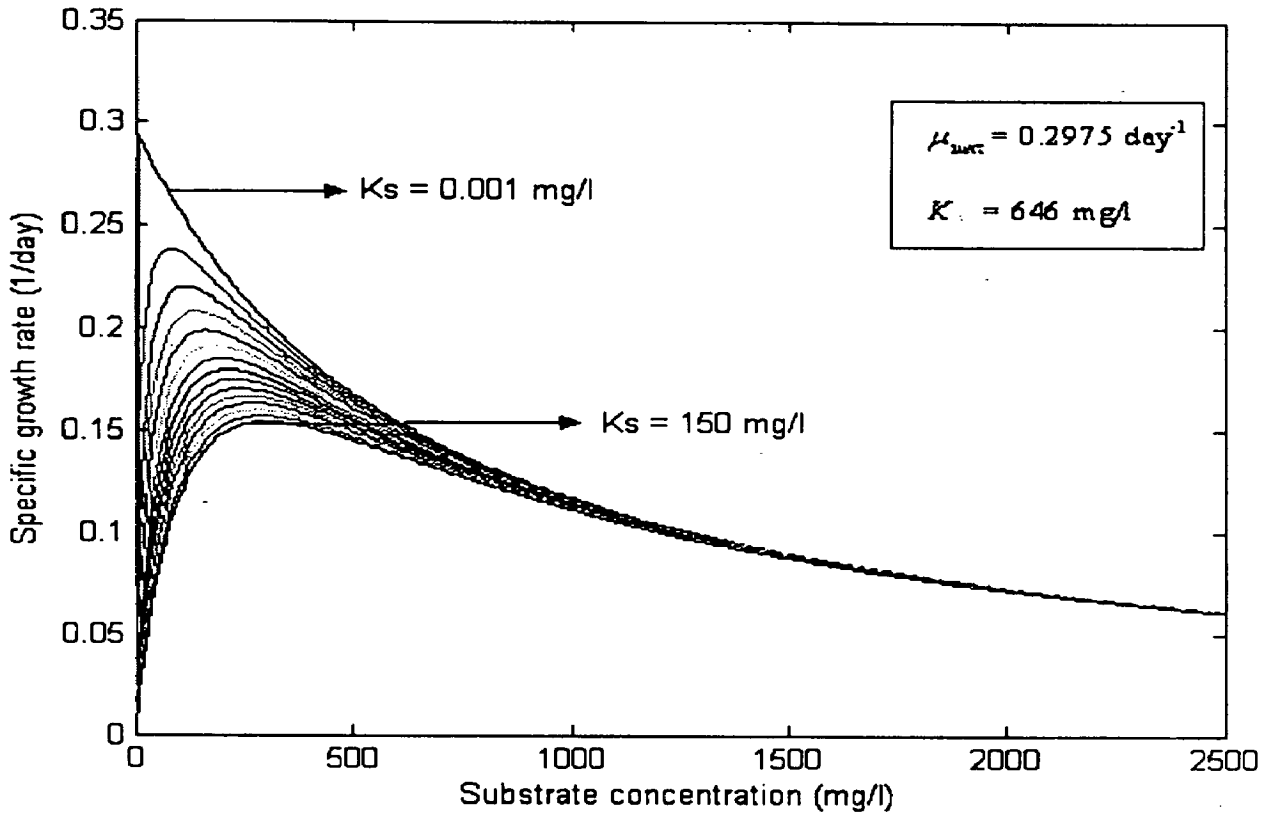

Figure 4.14: Specific growth rate versus substrate concentration profile at MLSS of 3000 mg/l

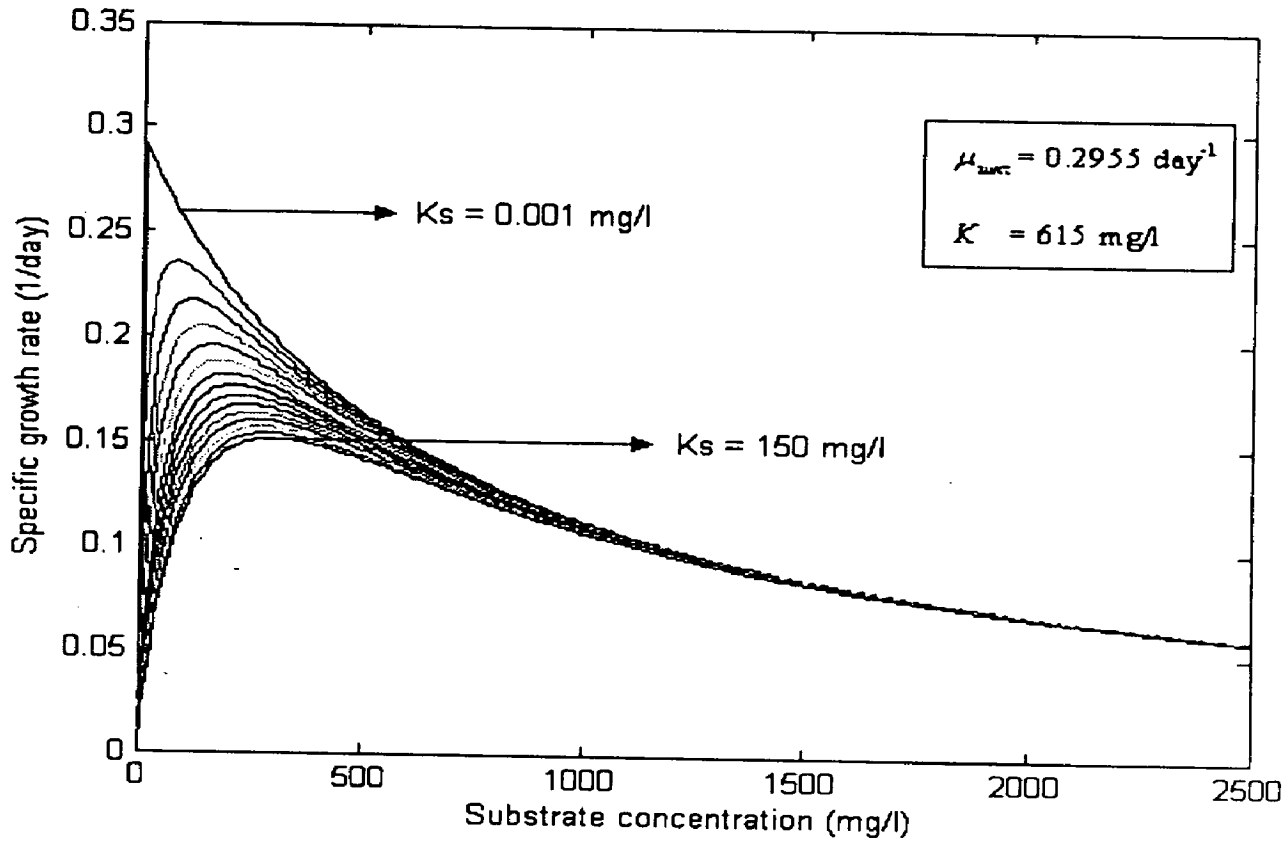

Figure 4.15: Specific growth rate versus substrate concentration profile at MLSS of 5000 mg/l

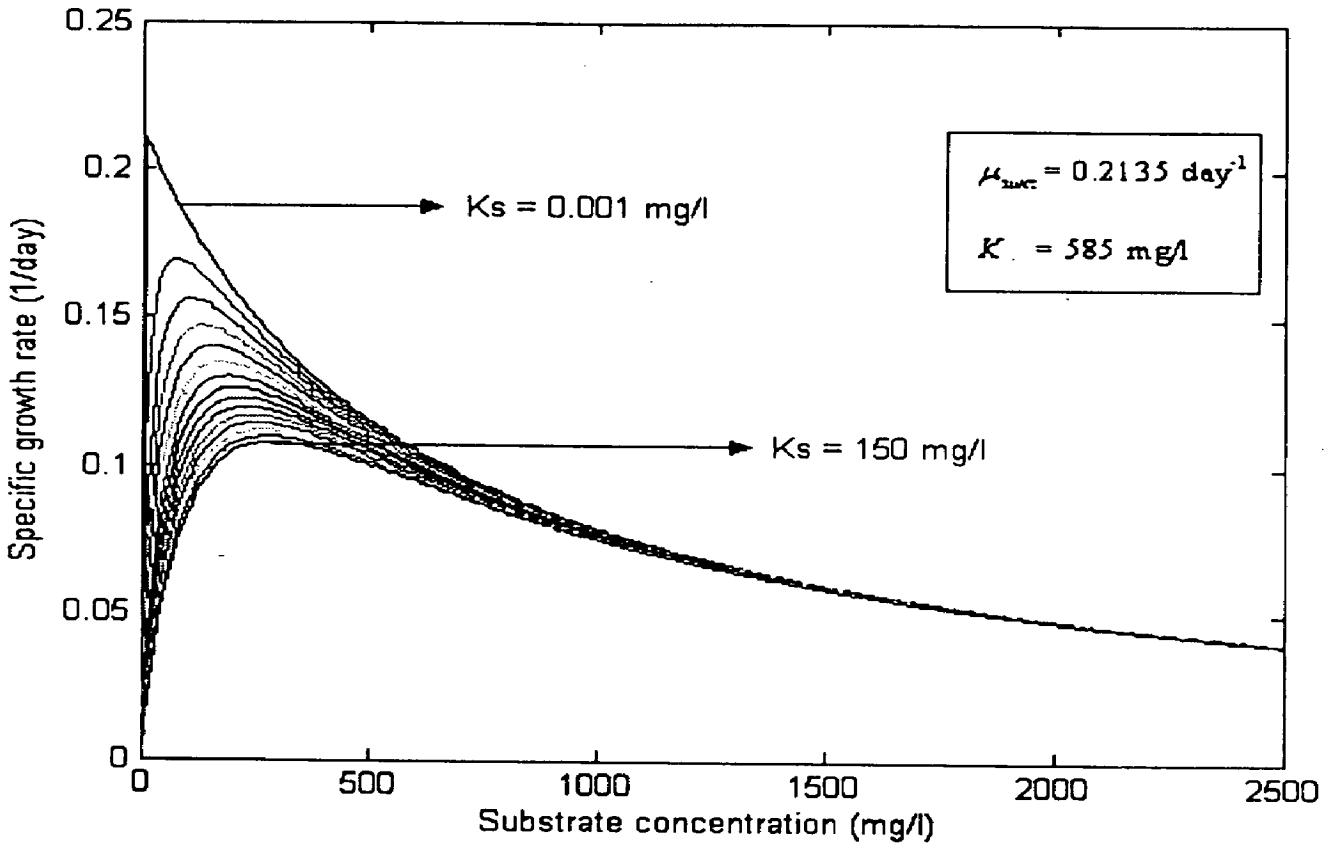

Figure 4.16: Specific growth rate versus substrate concentration profile at MLSS of 10000 mg/l

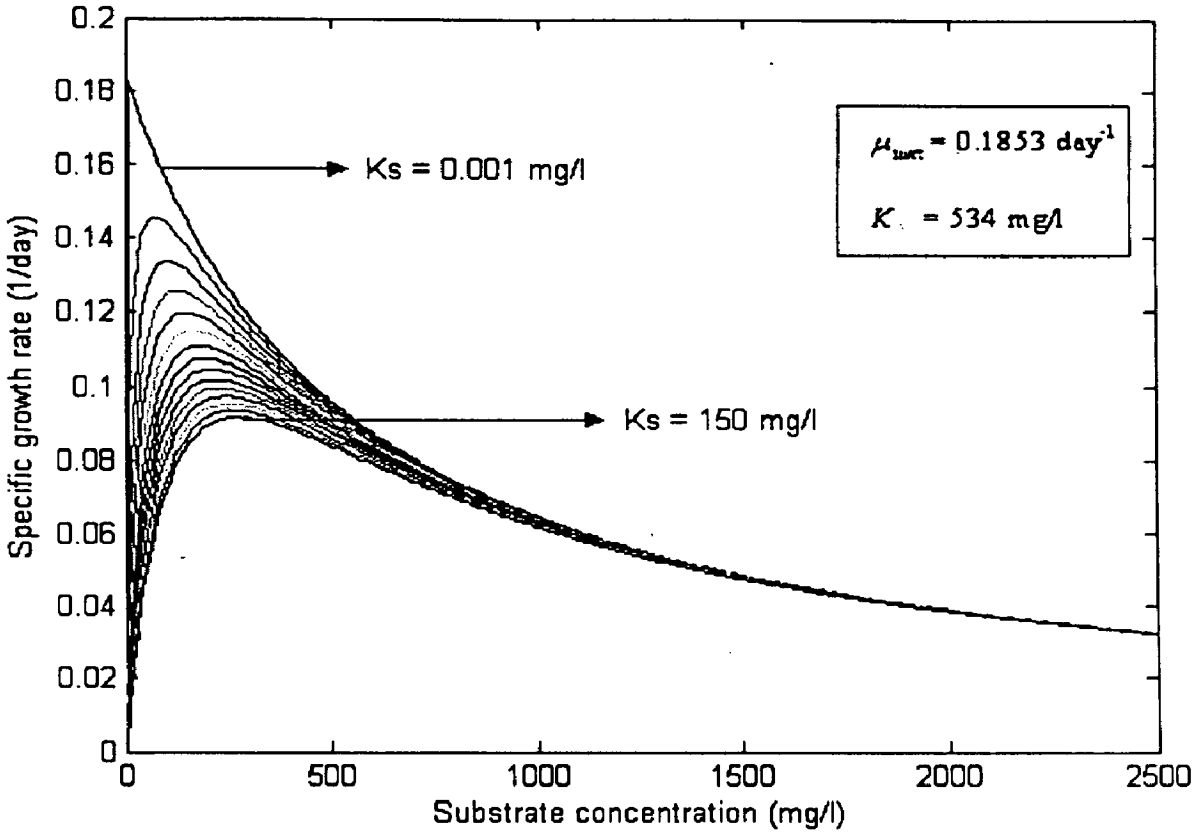

Figure 4.17: Specific growth rate versus substrate concentration profile
At MLSS of 15000 mg/l

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Establishing a structured model for the biological treatment systems of wastewater is a formidable task. This work demonstrates that the outlined modeling concept based on the activated sludge process and microbial products formation can be easily and successfully applied to describe the biological status of the submerged membrane bioreactor (SMBR). In comparison with the conventional activated sludge system, the MBR systems have better removal efficiency and a potential for water reuse. Membrane fouling in the presence of microorganism is linked to microbial products, concentration, and sizes of the particle. The membrane fouling rate increased with STR, due to large amount of foulant.

The mathematical model presented herein includes most of the phenomena occurring in a submerged membrane bioreactor. The model is able to describe the biokinetic coefficients under the inhibition occurring in the continuous mixed flow reactor system. The investigation shows that the values of the coefficients, except that of μ_m, are with in the range of those reported for conventional activated sludge processes. The values of μ_m have been found to be much lower than those reported for the conventional activated sludge processes. Table A5 shows the increase in the value of Y; where as the values of k_d and μ_m have been decreased gradually with the increase in an MLSS concentration. Figures 4.9-4.12 show that the biomass concentrations reach to a steady-state value and which is not affected by SRT after they reached to a steady-state value. Figure 4.13 shows the specific growth rate profile against a certain ranges of SRTs and substrate concentrations. Tables A7 and A8 show the calculated value of the biomass concentration at a particular SRT (1000 days) value. The process provides the benefits of membrane filtration without its usual disadvantages. Moreover, the simulated results could be lead to better values to the other various wastewater treatment processes.

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APPENDIX A

Table A1: Steady-state data at MLSS 3000 mg/l.

Steady-state period (days)	**Q** (l/day)	X_{incr} (mg/l)	X_{avg} (mg/l)	S_0 (mg/l)	**S** (mg/l)	**SRT** (days)
22-31	40	3120	3060	752	12	9.86
45-50	38	3340	3170	1096	102	7.12
56-60	36	3440	3220	1762	342	4.65
127-130	34	3530	3265	2346	478	3.13
136-139	32	3620	3310	2994	552	2.11

Table A2: Steady-state data at MLSS 5000 mg/l.

Steady-state period (days)	**Q** (l/day)	X_{incr} (mg/l)	X_{avg} (mg/l)	S_0 (mg/l)	**S** (mg/l)	**SRT** (days)
70-76	42	5300	5150	896	12	8.52
82-87	40	5520	5260	1296	98	7.45
95-96	38	5680	5340	1686	252	4.87
102-107	36	5800	5400	2182	390	3.45
112-118	34	5880	5440	3014	432	2.18

Table A3: Steady-state data at MLSS 10000 mg/l.

Steady-state period (days)	**Q** (l/day)	X_{incr} (mg/l)	X_{avg} (mg/l)	S_0 (mg/l)	**S** (mg/l)	**SRT** (days)
154-157	40	10320	10160	1474	26	12.25
161-164	38	10580	10290	1968	128	8.33
168-171	38	10900	10450	2446	232	4.8
175-178	36	11080	10540	3342	326	3.37
183-186	36	11270	10635	4184	512	2.24

Table A4: Steady-state data at MLSS 15000 mg/l.

Steady-state period (days)	**Q** (l/day)	$\mathbf{X_{incr}}$ (mg/l)	$\mathbf{X_{avg}}$ (mg/l)	$\mathbf{S_0}$ (mg/l)	**S** (mg/l)	**SRT** (days)
204-208	38	15660	15330	1626	14	13.04
215-219	38	16060	15580	2188	118	8.92
225-229	36	16500	15750	2642	224	5.98
235-239	34	16780	15890	3546	338	3.88
246-250	34	17040	16020	4668	538	2.24

Table A5: Biokinetic coefficients at various MLSS concentrations.

MLSS (mg/l)	Y (mg/mg)	k_d (day^{-1})	μ_m (day^{-1})	K_{s_1} (mg COD/l)
3000	0.5413	0.1984	0.2975	646
5000	0.5597	0.1743	0.2955	615
10000	0.5946	0.1309	0.2135	585
15000	0.6189	0.1061	0.1892	534

Table A6: Range of kinetic coefficients obtained from various sources.

Substrate	Y (mg/mg)	k_d (day^{-1})	μ_m (day^{-1})	K_{s_1} (mg COD/l)	Reference
Phenolic waste	0.627	-	3.8	414.5	33
Synthetic waste	0.49-0.58	-	0.8-6.3	173.0	34
Phenolic waste	0.50-0.62	-	1.34	454	35
Municipal wastewater	0.40-0.80	-	6.48	348	36
Synthetic waste	0.5413-0.6189	0.1089-0.1984	0.1853-0.2975	534-646	This study

Table A7: Steady-state biomass concentrations at various initial substrates concentrations for MLSS = 3000 mg/l and MLSS = 5000 mg/l.

MLSS = 3000 mg/l		MLSS = 5000 mg/l	
S_0 (mg/l)	X (mg/l)	S_0 (mg/l)	X (mg/l)
752	4017	896	5645
1096	5396	1296	7650
1762	7709	1686	9157
2346	10142	2182	11443
2994	13258	3014	16488

Table A8: Steady-state biomass concentrations at various initial substrates concentrations for MLSS = 10000 mg/l and MLSS = 15000 mg/l.

MLSS = 10000 mg/l		**MLSS = 15000 mg/l**	
S_0 (mg/l)	X (mg/l)	S_0 (mg/l)	X (mg/l)
1474	13055	1626	18630
1968	16589	2188	23924
2446	19961	2642	27946
3342	27192	3546	37076
4148	32782	4668	47732