

MODELING OF COMBINED ACTIVATED SLUDGE AND BIOFILM PROCESS FOR THE REMOVAL OF NITROGEN AND PHOSPHORUS

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**MODELING OF COMBINED ACTIVATED SLUDGE AND BIOFILM PROCESS
FOR THE REMOVAL OF NITROGEN AND PHOSPHORUS**

by

Yutaka Suzuki

Synopsis:

A simulation model was developed for a combined activated sludge and biofilm process which was developed in Japan to achieve nitrogen and phosphorus removal without extending the existing treatment facilities. The process consists of an activated sludge process of three zones (anaerobic, anoxic and aerobic) and a biofilm process in the form of fluidized bed in the aerobic zone, in which nitrification is carried out by the nitrifiers on the fluidized media and denitrification and phosphorus removal are performed by the activated sludge.

Firstly a biofilm model was developed by modifying an existing model in terms of components, biological processes and a detachment mechanism, using the experimental results of the fluidized bed process.

Secondly the biofilm model was incorporated into the IAWQ Activated Sludge Model No.2 with an addition of a mechanism of transferring detached biofilm to the activated sludge. The parameter values of this model were fitted using the data of a pilot plant during the term without rainfall. The model, then, was evaluated with the pilot plant data with a successive rainfall.

The model developed for the combined activated sludge and biofilm process expressed the water quality of the pilot plant well. Necessary improvement was also discussed.

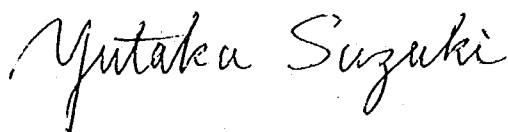
Key Words: Wastewater treatment, Nitrogen and phosphorus removal, Activated Sludge, Biofilm, Immobilization, Model

Preface

This research work was carried out as a part of Germany-Japan Joint Research Project on Phosphorus Removal from Wastewater during the author's stay in the Institute of Sanitary Engineering and Solid Waste Management, University of Hannover, Federal Republic of Germany, from April 1995 to September 1995.

The stay was realized by the effort of Mr. D. Fuhrmann, Project Manager of the Project Agency for WaterTechnology and Sludge Treatment, Research Center Karlsruhe, and Professor Dr.-Ing. C.F. Seyfried, the former Director of the Institute. Financial aid was provided by the Federal Ministry of Education, Science, Research and Technology.

Tsukuba, December 15, 1995

A handwritten signature in cursive script that reads "Yutaka Suzuki".

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1 Introduction

1.1 History and status of wastewater treatment in Japan

There was no sewerage system in Japan when the country closed itself from foreign countries. At that time, night soil was stored in a tank just below the toilet in each house, and farmers came and collected the night soil to use it for fertilizer. Wastewater from a kitchen or a bath was discharged directly to ditches or rivers.

After Japan opened itself to foreign countries, sewer systems started to be constructed in large cities and in 1922 the first wastewater treatment plant was operated in Tokyo. The constructions of sewerage systems were accelerated after World War II, because the night soil was no more used as fertilizer because of the production of chemical fertilizer and also rivers in cities were polluted with the wastewater discharged from private houses.

Served ratio by the sewerage systems at present is 51% as the whole country, but the ratio differs according to the size of the population of municipalities. As shown in Fig. 1.1, big cities whose population is more than 1 million have almost completed their sewerage systems, but smaller cities, especially whose population is lower than 50 thousand, still need sewerage construction.

Percentage Population Served by
Public Sewerage
System

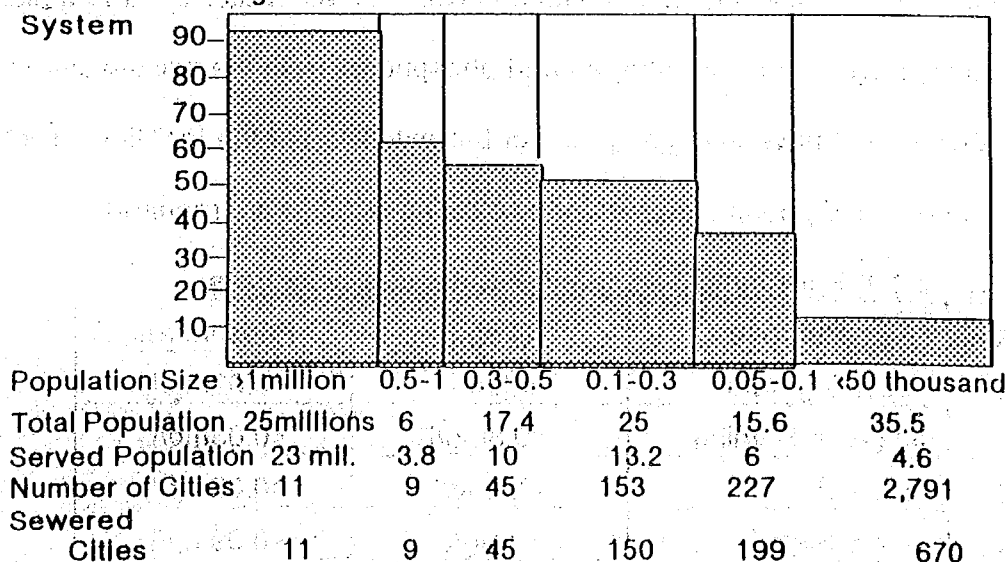


Figure.1 Percentage of population by served sewerage systems
classified by city size

1.2 Requirements for removal of nitrogen and phosphorus from wastewater

Counter measures to prevent eutrophication are taken only in the areas of lakes, because the laws to prevent eutrophication are regulated only for lakes.

Among the measures, sewerage systems are thought most efficient in reducing nutrients load to the lakes. Two ways are taken with sewerage systems, one is by-passing of wastewater with sewer pipes, and the other is advanced treatment of wastewater. There are 5 lakes where wastewater is treated with the advanced treatment processes to remove nitrogen and phosphorus. Fig. 1.2 shows the target of the nitrogen and phosphorus concentration of the advanced treatment. As for phosphorus, the peak concentration is 0.5mg/L, and that for nitrogen is 10mg/L. Typical concentration of raw sewage in Japan is 35mg/L for nitrogen and 3.5mg/L for phosphorus, therefore, typical removal ratio is 70% for nitrogen and 85% for phosphorus.

As the first step to protect bays, environment standards of water quality for bays were regulated in 1993 (Table 1.1). The government is now going to apply one of the standards to each eutrophic bay, which may be followed by a new regulation of effluent water quality from wastewater treatment plants.

The eutrophic bays in Japan are faced with big cities, for instance, Tokyo bay with Tokyo and Yokohama, and Osaka bay with Osaka and Kobe. Wastewater treatment plants in big cities, therefore, have to remove nitrogen and phosphorus from the wastewater in the near future, but they do not have enough space for the extension of the facilities. Technologies to remove nitrogen and phosphorus within the existing facilities are required.

Table 1.1 Environment standard of water quality for bays

Class	Purpose	Nitrogen	Phosphorus
1	Preserving nature	<0.2mg/L	<0.02mg/L
2	Fishery-1, Bathing	<0.3mg/l	<0.03mg/L
3	Fishery-2	<0.6mg/L	<0.05mg/L
4	Fishery-3 etc.	<1mg/L	<0.09mg/L

Fishery-1: Multi-species of aquatic life including the life at the bottom of water can be maintained

Fishery-2: An abundance of fish can be captured

Fishery-3: Fish which has resistance against pollution can be captured

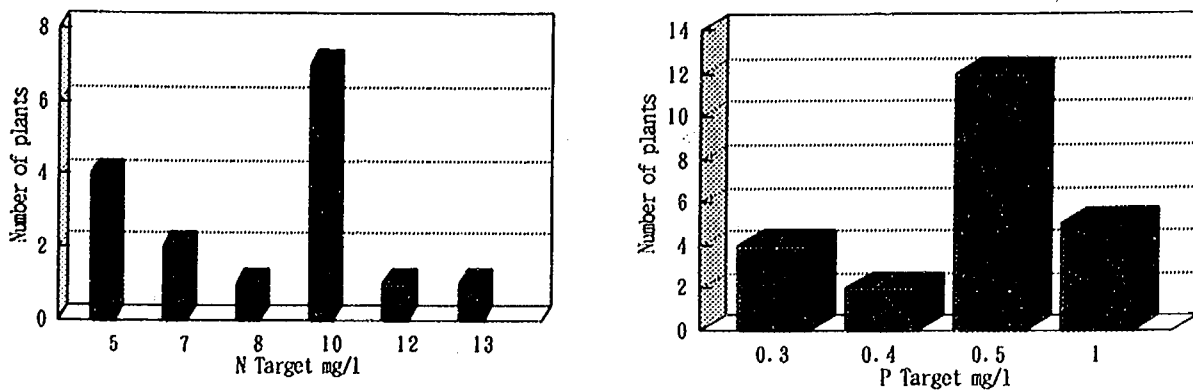


Fig.1.2 Distribution of target of N and P concentration for treated wastewater

1.3 Development of new process

In the activated sludge process, nitrification can be maintained only when solids retention time (SRT) is sufficient for the growth of nitrifying bacteria. This condition can be expressed as follows;

$$SRT > 1/\mu_N$$

SRT : solids retention time
 μ_N : specific growth rate of nitrifiers

The specific growth rate of nitrifiers (μ_N) is much smaller than that of heterotrophic bacteria, therefore, SRT must be kept long for the nitrification to occur. This long SRT, then, requires of bigger reactor volume.

In the big cities in Japan, it is very difficult to enlarge the reactor volume because land is limited around the treatment plants, therefore, a process which can accomplish nitrification with the existing reactor volume, or at short SRT, is required.

In the new process developed, nitrification is carried out mainly by the nitrifiers attached on media, which enables nitrification at short SRT, and denitrification and phosphorus removal are carried out by the activated sludge. Because of the allocation of the roles, the new process has a form of combined process of activated sludge and biofilm. Fig. 1.3

shows the outline of the process. The basic configuration is the three-zone (anaerobic - anoxic- aerobic) biological nutrients removal process, to whose aerobic tanks immobilization media are added for the attachment of nitrifiers.

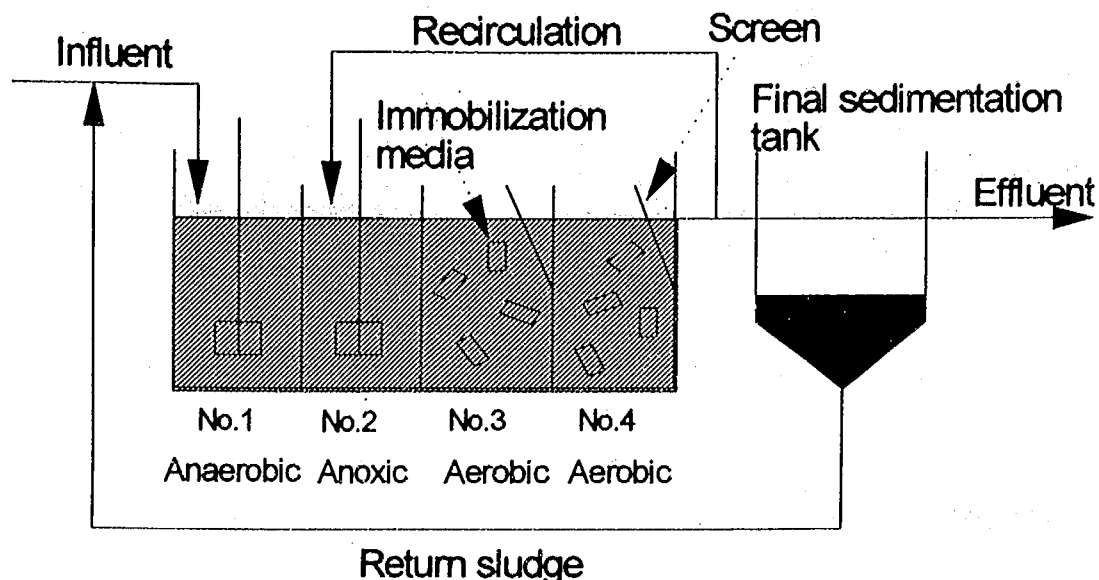


Fig. 1.3 New process for the removal of nitrogen and phosphorus (Combined activated sludge and biofilm process)

1.4 Basics of biological phosphorus and nitrogen removal

1) Biological phosphorus removal

Biological phosphorus removal can be achieved if the conditions of a reactor are preferable for the phosphorus accumulating bacteria. The bacteria accumulate phosphate in the form of polyphosphate in their cells with the consumption of organic acid. The metabolisms of the bacteria are thought as listed in Table 1.2.

Three conditions are important for the biological phosphorus removal, 1) maintaining the anaerobic condition in the anaerobic tank, 2) enough quantity of organic acid inflow to the anaerobic tank and 3) proper hydraulic retention time for the anaerobic and aerobic zone.

Table 1.2 Metabolisms of phosphate accumulating bacteria

Anaerobic zone	Aerobic zone
Hydrolysis of polyphosphate and release of phosphate into water	Oxidation of PHA
↓ Energy	↓ Energy
Uptake of organic acid and synthesis of PHA	Excess uptake of phosphate and formation of polyphosphate in the cell
	Cell growth

2) Biological nitrogen removal process

A biological nitrogen removal process needs two steps, nitrification ($\text{NH}_4^+ \rightarrow \text{NO}_3^-$) and denitrification ($\text{NO}_3^- \rightarrow \text{N}_2$). The nitrification is carried out by the nitrifiers under aerobic condition and the denitrification is carried out by the heterotrophs with the consumption of organic matter under anoxic condition.

In the new process, nitrifiers are accumulated on the media in the aerobic tanks, and the activated sludge denitrifies nitrate using the organic matter in the influent.

1.5 Needs for simulation model of new process

The pilot plant of the combined activated sludge and biofilm process has been operated for over 3 years, and it showed good efficiencies of N and P removal if the conditions of the process are kept proper. The process is ready for the application to the real treatment plants. Also, a new rule for the nitrogen and phosphorus concentration in the treated wastewater is expected to be regulated in the near future in bay areas. The development of designing methods, therefore, is an urgent task.

On the other hand, a better understanding of the process is needed. It is possible when the process is examined with a model composed of recent research results. With the model, it will be made clear what is not clarified and what should be investigated.

2 Theoretical background

2.1 Activated sludge process

In 1994, the IAWQ task group on mathematical modeling for design and operation of biological wastewater treatment published a report on **Activated Sludge Model No. 2** (Henze *et al.*) which can express biological removal of organic matter, nitrogen and phosphorus.

Components and biological processes of the model are briefly summarized here.

1) Components

Components consist of two groups, soluble and particulate.

Soluble components are defined as follows;

S_A ($M_{COD}L^{-3}$) : Fermentation products (Acetate)

S_{ALK} ($MOl_{HCO_3}L^{-3}$) : Alkalinity

S_F ($M_{COD}L^{-3}$) : Fermentable, readily biodegradable organic substrates, which is directly available for biodegradation by heterotrophic organisms.

S_I ($M_{COD}L^{-3}$) : Inert soluble organic material

S_{N_2} (M_NL^{-3}) : Dinitrogen

S_{NH_4} (M_NL^{-3}) : Ammonium plus ammonia nitrogen

S_{NO_3} (M_NL^{-3}) : Nitrate plus nitrite nitrogen

S_{O_2} ($M_O L^{-3}$) : Dissolved oxygen

S_{PO_4} ($M_P L^{-3}$) : Inorganic soluble phosphorus (Ortho phosphate)

Particulate components are defined as follows;

X_{AUT} ($M_{COD}L^{-3}$) : Nitrifying organisms, which perform nitrification ($S_{NH_4} \rightarrow S_{NO_3}$)

X_H ($M_{COD}L^{-3}$) : Heterotrophic organisms, which grow aerobically and anoxically (denitrification) on S_A and S_F and perform both hydrolysis of X_S to S_F under all environmental conditions and fermentation of S_F to S_A under anaerobic condition

X_I ($M_{COD}L^{-3}$) : Inert particulate organic material

X_{MeOH} ($M_{TSS}L^{-3}$) : Metal-Hydroxides

$X_{MeP} (M_{TSS}L^{-3})$: Metal-Phosphate

$X_{PAO}(M_{COD}L^{-3})$: Phosphate accumulating organisms

$X_{PHA} (M_{COD}L^{-3})$: Cell internal storage product (poly-hydroxy-alkanoates, glycogen, etc.)
of X_{PAO}

$X_{PP} (M_P L^{-3})$: Cell internal poly-phosphate storage in X_{PAO}

$X_S (M_{COD}L^{-3})$: Slowly biodegradable substrate

$X_{TSS} (M_{TSS}L^{-3})$: Total suspended solids

2) Biological processes

Hydrolysis : Transformation of X_S to S_F by X_H under all environmental conditions

Fermentation : Transformation of S_F to S_A by X_H under anaerobic condition

Growth of X_H : Growth of X_H on S_A and S_F with either S_{O_2} consumption or S_{NO_3} reduction under anoxic condition (denitrification)

Growth of X_{PAO} : Growth of X_{PAO} on X_{PHA} with the consumption of S_{O_2}

Growth of X_{AUT} : Growth of X_{AUT} on S_{NH_4} with the consumption of S_{O_2}

Storage of X_{PHA} : Uptake of S_A and formation of X_{PHA} at the hydrolysis of X_{PP} into S_{PO_4} under anaerobic condition

Storage of X_{PP} : Uptake of S_{PO_4} and formation of X_{PP} at the consumption of X_{PHA} and S_{O_2}

Lysis of X_H , X_{PAO} and X_{AUT} : Transformation of X_H , X_{PAO} and X_{AUT} to X_S and X_I with the release of S_{NH_4} and S_{PO_4}

Lysis of X_{PHA} and X_{PP} : Transformation of X_{PHA} or X_{PP} to S_A or S_{PO_4}

※In the growth processes, uptake of S_{NH_4} and S_{PO_4} must be added.

※Stoichiometric coefficients and kinetic expressions are omitted here.

3) Chemical process

In the chemical processes precipitation of phosphate is included. This process, however, is ignored in this research because the biological processes are of concern.

2.2 Biofilm process

Many biofilm processes exist in the field of wastewater treatment, such as a trickling filter, a rotating biological contactor and a fluidized bed. These biofilm processes differ from the activated sludge process in that the microorganisms are not dispersed but are attached on some supporter with some thickness. This feature is important when a model for a biofilm process is developed.

Biofilm models have been developed by many researchers to predict the treatment efficiency of these processes. The history of developing biofilm models is reviewed below.

Firstly models were developed to predict a substrate (organic matter) removal rate. The basic model was of Williamson and McCarty(1976), the concept of which was 1)substrate transportation from bulk water to biofilm surface and 2)substrate diffusion and substrate utilization in the biofilm. It required, however, a try and error method with numerical computation, because the substrate removal rate was not obtained explicitly. Harremoës (1978) presented a model in which the substrate utilization rate can be expressed explicitly as a function of the substrate concentration in the bulk water, assuming some conditions for the substrate concentration and biological kinetics. Rittmann and McCarty (1978) also presented a model consisted of variable-order equations in terms of the bulk substrate concentration, which could predict the substrate utilization rate explicitly for the wide range of bulk substrate concentration.

No consideration having been made for the biomass growth in the models above, Rittmann and McCarty (1980) presented a steady-state model in which the biomass growth and decay was incorporated. Later, Rittmann (1982) presented a model in which the loss of the biomass by detachment is considered.

Arising the necessities to predict a nitrification efficiency of a biofilm in later years, Kissel *et al.* (1984) and Wanner and Gujer (1984) developed multispecies models which predicted both the organic matter removal and nitrification efficiency. The basic concept was not changed from the single species model of Rittmann and McCarty (1980), but they extended

the model by employing two kinetic equations to express the growth of heterotrophs and autotrophs which grow on an electron acceptor (O_2) and electron donors (organic matter or NH_4-N). A new aspect was that they had to deal with the biomass movement toward the biofilm surface in the biofilm, which is caused by the biomass growth, if they wanted to calculate the distribution of each microorganisms in the biofilm. In this model, only the method of implicit numerical calculation was possible for the prediction.

The multispecies models succeeded in expressing both the biomass distribution in a biofilm and the substrate utilization rate of the process, however, they could not express the steady-state of the biofilm, because the detachment process, which surely occurs in a real process, was not considered. Wanner and Gujer (1986), Rittmann and Manem (1992) and Furumai and Rittmann (1994) incorporated detachment processes into their multispecies models, but they differed in how to express the detachment process. Little is known at present about the mechanisms of the detachment, therefore, further researches are needed to express the biofilm processes more precisely.

In the followings, more detailed descriptions of each biofilm model are listed.

2.2.1 Single species model

(1) Substrate utilization model

Biofilm model was firstly presented to predict organic matter removal rate of biofilm processes (Williamson and McCarty(1976)). There are several assumptions for the model as listed in from 1) to 6) in the following and the conceptual basis for the model is illustrated in Fig. 2.1.

1) Biofilm is attached to a flat plate with infinite length and width. Therefore changes of concentration is only in the z direction which is perpendicular to the plate and from the biofilm surface to the bottom.

2) Biofilm has a uniform cell density (X_f (g/m^3)).

3) The rate of reaction is limited by a single substrate S (g/m^3) (other nutrients are in

excess concentration)

4) Substrate is transported from bulk water to biofilm through the diffusion layer by molecular diffusion. In the bulk water mixing intensity is so strong that the substrate concentration is uniform, while in the diffusion layer the water is stagnant and change of the concentration exists because in the diffusion layer the substrate is transported only by molecular diffusion whose rate is proportional to the substrate concentration gradient. The diffusion rate is expressed as $-D_w (dS/dz)$ where D_w is the diffusion coefficient (m^2/d). The concentration change as time by the molecular diffusion can be expressed as follows.

$$\partial S / \partial t = D_w (\partial^2 S / \partial z^2) \quad \text{----- (1)}$$

5) Substrate is transported within biofilm by molecular diffusion, the rate of which is lower than that in water (diffusion coefficient : D_f (m^2/d), $D_f < D_w$)

$$\partial S_f / \partial t = D_f (\partial^2 S_f / \partial z^2) \quad \text{----- (2)}$$

S_f : substrate concentration in biofilm (g/m^3)

6) Substrate utilization at any point in the biofilm is assumed to follow a Monod relation.

$$\partial S_f / \partial t = -(\mu/Y) X_f S_f / (K_s + S_f) \quad \text{----- (3)}$$

μ : maximum growth rate of microorganisms ($1/d$)

Y : yield coefficient (-)

K_s : saturation coefficient (g/m^3)

Summing eqs.(2) and (3) gives the total $\partial S_f / \partial t$ for any point in the biofilm. Assuming that the substrate concentration profile is at steady state ($\partial S_f / \partial t = 0$), eqs.(1) can be integrated into eq.(4), and eqs.(2) and (3) become eq.(5).

$$J = D_w (dS/dz) = D_w (S_0 - S_s) / L_w \quad \text{----- (4)}$$

$$D_f (d^2 S_f / dz^2) = (\mu/Y) X_f S_f / (K_s + S_f) \quad \text{----- (5)}$$

J : substrate flux per unit area parallel to the concentration gradient ($g/(m^2 d)$)

S_0 : substrate concentration in bulk water (g/m^3)

S_s : substrate concentration at biofilm surface (g/m^3)

L_w : thickness of diffusion layer (m)

Substrate concentration profile in both the diffusion layer and the biofilm becomes as shown in Fig. 2. 1. Substrate concentration decreases from S_0 to S_s through the diffusion layer because of the substrate transport from the bulk water to the biofilm by the molecular diffusion. It also decreases in the biofilm toward the bottom, because the substrate must be transported into the deeper part of the biofilm and also the substrate is utilized by the microorganisms.

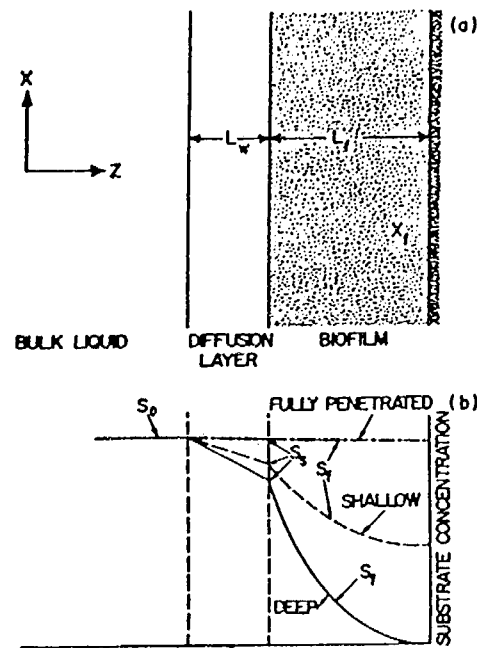


Fig. 2.1 Conceptual basis for biofilm model. (a)Physical concepts; (b)Substrate concentration profiles

To know a substrate utilization rate of the biofilm, the substrate profile in both the diffusion layer and the biofilm must be calculated taking the following procedures.

Firstly S_f at $z=L_f$ is assumed, then eq.(5) is integrated in small steps toward the biofilm surface numerically (because the equation is nonlinear) with a boundary condition of $dS_f/dz=0$ at $z=L_f$ (biofilm bottom) which means no substrate flux at the bottom of the biofilm. When the integration reaches the biofilm surface, substrate flux can be calculated in two ways. One is with eq.(4) which calculates the flux from the bulk water to the biofilm surface through the diffusion layer, and the other is with eq.(6) which calculates the flux from the biofilm surface into the deeper biofilm caused by the substrate utilization of the whole

biofilm.

$$J = -Df (dSf/dz) \text{ at } z=0 \text{ (biofilm surface)} \quad \text{----- (6)}$$

If the two substrate fluxes calculated with eqs.(4) and (6) meet, then the substrate utilization rate is calculated correctly. If not, new S_f at $z=L_f$ is assumed and the same calculation must be repeated until the two substrate flux meet.

Harremoës (1978) presented a simpler model which predict a substrate utilization rate if $K_s \ll S_0$ and L_w is negligible. On these conditions S_s is equal to S_0 and eq.(5) becomes as follows.

$$Df (d^2Sf/dz^2) = (\mu/Y) X_f \quad \text{----- (7)}$$

For a thick biofilm in which S_f decreases to 0, eq.(7) can be solved with boundary conditions of $dSf/dz=0$ and $S_f=0$ at $z=L_{fe}$ (L_{fe} : biofilm thickness where $S_f>0$), and gives following equations.

$$-Df (dSf/dz) = (\mu/Y) X_f (L_{fe} - z) \quad \text{----- (8)}$$

$$S_f = (\mu X_f / (2 Y Df)) (L_{fe} - z)^2 \quad \text{----- (9)}$$

The substrate utilization rate of the whole biofilm can be expressed in terms of S_0 using eqs.(6), (8) and (9).

$$J = (2 \mu X_f Df / Y)^{1/2} S_0^{1/2} \quad \text{----- (10)}$$

Eq.(10) shows that the total substrate utilization rate is proportional to the square root of the substrate concentration in the bulk water (Fig. 2.2).

For a thin biofilm in which $S_f>0$, the boundary condition is $dSf/dz=0$ at $z=L_f$. In this case the total substrate utilization rate is expressed as a function of biofilm thickness using eqs.(6) and (8).

$$J = (\mu/Y) X_f L_f \quad \text{----- (11)}$$

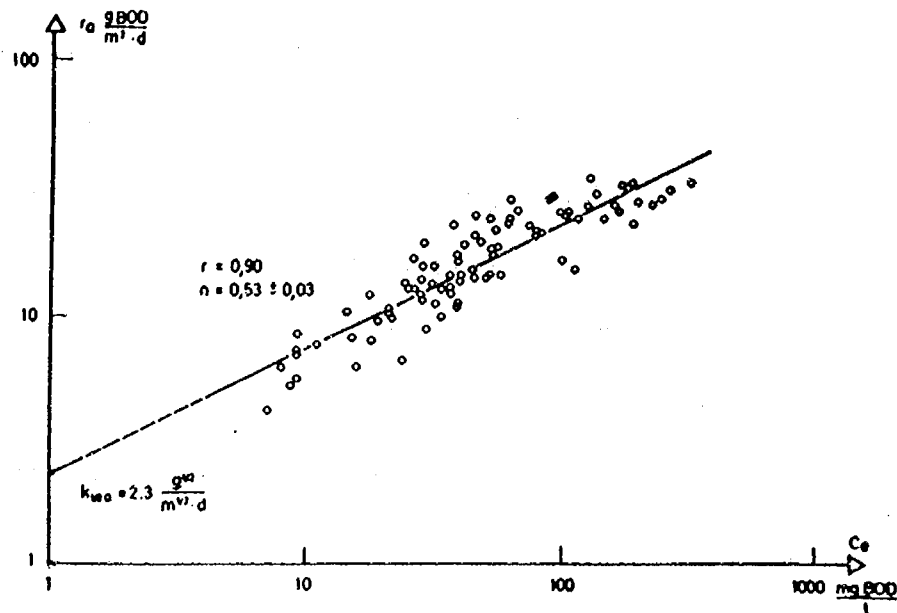


Fig. 2.2 Relationship between substrate concentration and substrate utilization rate

Rittmann and McCarty(1978) derived variable order equations which can express substrate utilization rate for wide range of bulk concentration. The rate of the equations becomes first order of S at low S and half order at high S (Fig. 2.3).

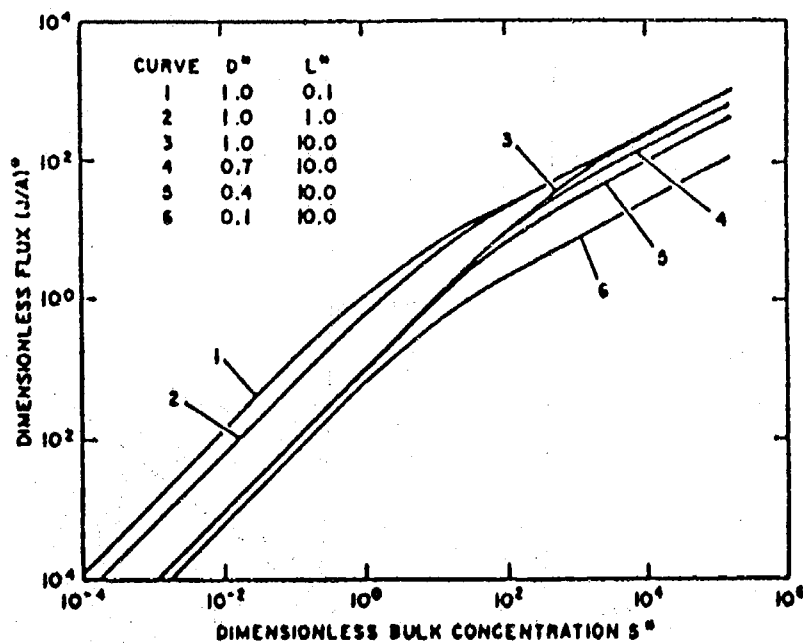


Fig. 2.3 The relation between the dimensionless bulk substrate concentration and dimensionless substrate flux with D^* (dimensionless diffusion coefficient) and L^* (dimensionless diffusion layer thickness) as parameters

(2) Steady state biofilm model

The substrate utilization models did not consider the biofilm growth which occurs together with the substrate utilization. Rittmann(1980) presented a steady state biofilm model which took into account the biofilm growth and decay. Basic equations are eqs.(4), (5) and a new one expressing biomass growth and decay.

$$\partial X_f / \partial t = \mu X_f S_f / (K_s + S_f) - b X_f \quad \text{----- (12)}$$

b : decay coefficient (1/d)

For a steady state biofilm, total biofilm growth (YJ) must be equal to total biofilm decay ($b X_f L_f$) and a following equation is derived.

$$L_f = YJ / (b X_f) \quad \text{----- (13)}$$

Rittmann (1982) also showed that loss of a biofilm due to sloughing is proportional to the biofilm thickness and $w^{1.16}$ (w : rotational speed of annular reactor (rpm)) (Fig. 2.4 and 2.5), and proposed that sloughing occurs at the rate of ($b_s X_f L_f$) (b_s : sloughing coefficient (1/d)) at every depth of the biofilm, though b_s is dependent on the biofilm depth.

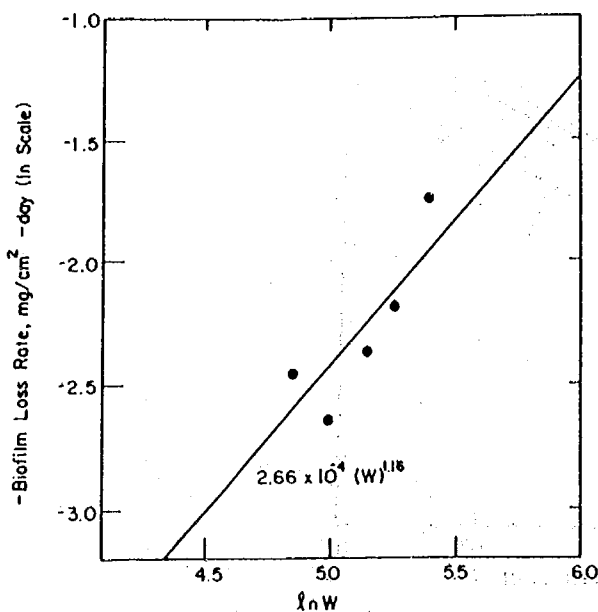


Fig. 2.4 Biofilm loss rate as a function of rotational speed w (rpm)

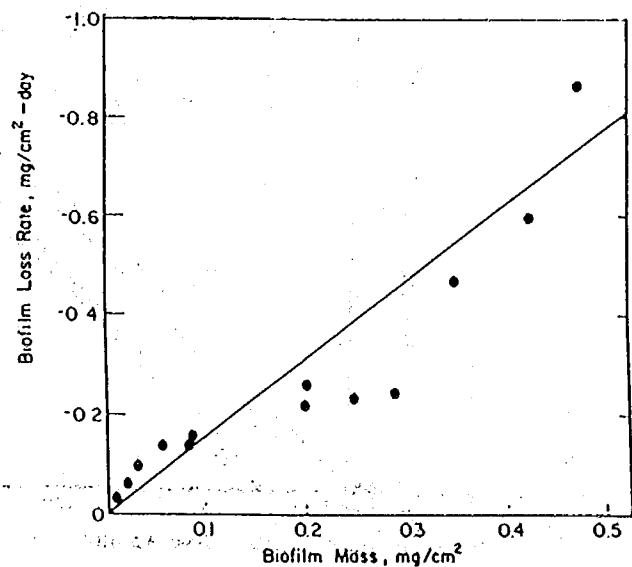


Fig. 2.5 Biofilm loss rate as a function of biofilm mass per area

For $L_f < 3 \times 10^{-5} \text{ m}$

$$b_s = 8.42 \times 10^{-2} \sigma^{0.58} \text{ ----- (14)}$$

For $L_f > 3 \times 10^{-5} \text{ m}$

$$b_s = 8.42 \times 10^{-2} \left(\sigma / (1 + 4.332 \times 10^4 (L_f - 3 \times 10^{-5})) \right)^{0.58} \text{ ----- (15)}$$

σ : shear stress (dyn/cm^2)

2.2.2 Multispecies model

In wastewater usually both organic matters and reduced inorganic matters are contained, and heterotrophs and autotrophs grow on these substrates. Autotrophs must reduce inorganic carbon for their growth and this reaction is energy intensive, therefore, the values of yield coefficient (Y) and maximum specific growth rate ($\mu_{\max}$) for autotrophs are low. On the other hand, heterotrophs grow faster utilizing organic matter as the substrate.

Within a biofilm, competition between heterotrophs and autotrophs occurs, and the autotrophs can easily be outgrown because of the slow growth rate. Among the autotrophs nitrifier is the most important because it is concerned with nitrogen removal. Multispecies models were presented to explain the competition between heterotrophs and autotrophs within biofilm and to predict the nitrification efficiency of the biofilm process.

In 1984 two groups presented multispecies models (Wanner and Gujer (1984), Kissel *et al.* (1984)). Both of groups made the same assumptions, which are that the growth of microorganisms is expressed with double Monod equations of electron acceptor (O_2) and electron donor (organic matter or NH_4^+), biomass decay is proportional to the biomass concentration (eqs.(15) and (16)), certain part of the biomass which has undergone the decay is turned into inert substances (eq.(17)) and the net biofilm concentration, which is the sum of the concentrations of heterotrophs, autotrophs and inert substances, is constant (eq.(18)).

$$\partial X_A / \partial t = \mu_A (S_{NH_4} / (K_{NH_4} + S_{NH_4})) (S_{O_2} / (K_{O_2} + S_{O_2})) X_A - b_A X_A \text{ ----- (15)}$$

$$\partial X_H / \partial t = \mu_H (S_{COD} / (K_{COD} + S_{COD})) (S_{O_2} / (K_{O_2} + S_{O_2})) X_H - b_H X_H \text{ ----- (16)}$$

$$\partial X_I / \partial t = f b_A X_A + f b_H X_H \text{ ----- (17)}$$

$$X_f = X_A + X_H + X_I \text{ ----- (18)}$$

X_A : nitrifiers concentration (g/m^3)
 X_H : heterotrophs concentration (g/m^3)
 X_I : inert matter concentration (g/m^3)
 X_f : net biofilm concentration (constant) (g/m^3)
 S_{NH_4} : NH_4 -N concentration (g/m^3)
 S_{COD} : organic matter concentration (g/m^3)
 S_{O_2} : dissolved oxygen concentration (g/m^3)
 μ_A : specific maximum growth rate of nitrifiers (1/d)
 μ_H : specific maximum growth rate of heterotrophs (1/d)
 b_A : decay rate of nitrifiers (1/d)
 b_H : decay rate of heterotrophs (1/d)
 f : fraction of cell which is turned into inert substances (-)

By using eqs.(15) to (18) together with equations for substrate consumption, substrate concentration profiles and biomass growth rates within the biofilm can be calculated. The two groups differ how to describe the net biomass growth in a control volume within the biofilm. As shown in Fig. 2.6, Kissel *et al.* consider the control volume increases as a consequence of biofilm growth, on the other hand, Wanner and Gujer consider the biomass flux is produced beyond the control volume.

Biomass distribution within a biofilm calculated with the multispecies model shows that fast growing heterotrophs tend to be accumulated near the surface, while slow growing nitrifiers tend to reside more in the depth (Fig. 2.7).

With the multispecies model, however, a biofilm grows infinitely as shown in Fig. 2.8, because the biomass is lost only by decay and detachment of the biomass is not considered.

For the detachment of biomass, Wanner and Gujer (1986) presented a model which incorporated a mechanism of shearing of biofilm, which assumes biomass is detached at the biofilm - water interface continuously at the rate dependent on the biofilm thickness. On the other hand, Rittmann and Manem (1992) presented a steady-state, multispecies model,

in which every part of the biofilm is detached at the rate of $(b_s \times f \times L)$ (b_s : detachment coefficient ($1/d$)). Furumai and Rittmann (1994) proposed a simplified multispecies model in which the biofilm layer of $30 \mu m$ thickness at the biofilm surface is detached at a high rate (b_s), while other biofilm layer has the detachment coefficient of $0.01 d^{-1}$. They assumed within the surface layer the detachment coefficient (b_s) decreases linearly along the biofilm depth and becomes $0.01 d^{-1}$ at $z = 30 \mu m$.

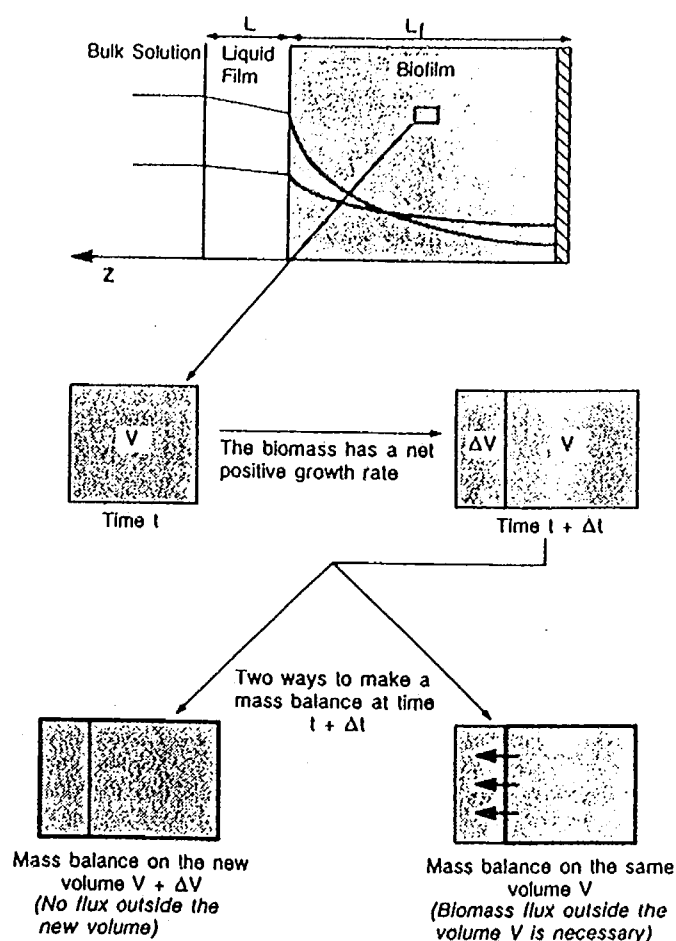


Figure 2.6 Two different approaches for the description of net growth at a position within the biofilm. Kissel et al. used the $V + \Delta V$ approach, while Wanner and Gujer used the biomass flux approach.

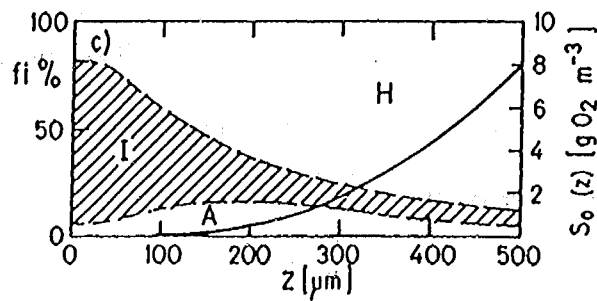


Fig. 2.7 Relative biomass distribution over the depth of a biofilm and oxygen concentration profile (H : heterotrophs, A : autotrophs, I : inert biomass)

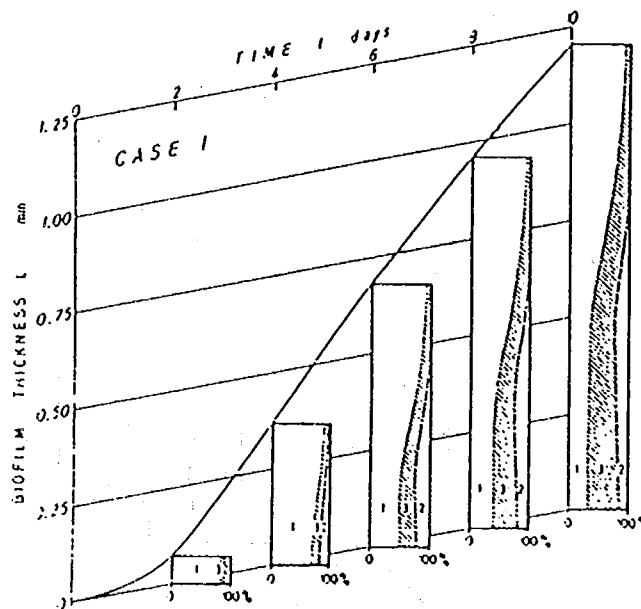


Figure 2.8 Development of biofilm thickness and volume fractions for unrestricted growth of microbial species with time. Volume fractions indicate relative abundance of heterotrophic (1), autotrophic (2), and inert (3) mass. Lower end, film-support interface; upper end, film-water interface.

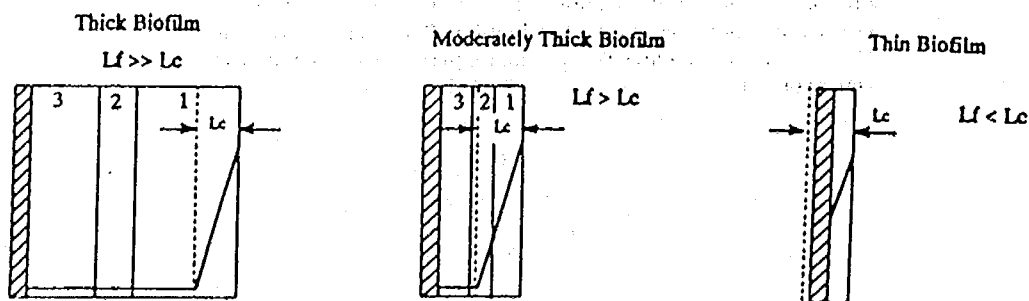


Fig. 2.9 Apportionment of the specific detachment rate (b_d) for biofilms of different thicknesses relative to L_c , the critical thickness, or the thickness of the biofilm layer having a high detachment rate.

3 Process description

The combined activated sludge and biofilm process is described here.

3.1 Three-zone biological nutrients removal process with immobilized nitrifiers

Fig. 3.1 shows the outline of the three-zone biological nutrients removal process with immobilized nitrifiers, which has anaerobic, anoxic and aerobic cells with immobilization media in the aerobic cells. The hydraulic retention time is 8 h, and the solids retention time (SRT) and the aerobic SRT are 14 d and 7d respectively.

Biological excess phosphorus removal can be achieved by the phosphate accumulating bacteria which accumulate phosphate in their cells to a high concentration. For the good removal of phosphate, having the bacteria in great quantity in the process is important. The bacteria uptake organic acid under the anaerobic condition and grow on it aerobically, therefore, high concentration of organic acid in the influent and the anaerobic condition in the anaerobic cell are the requisites for the phosphorus removal.

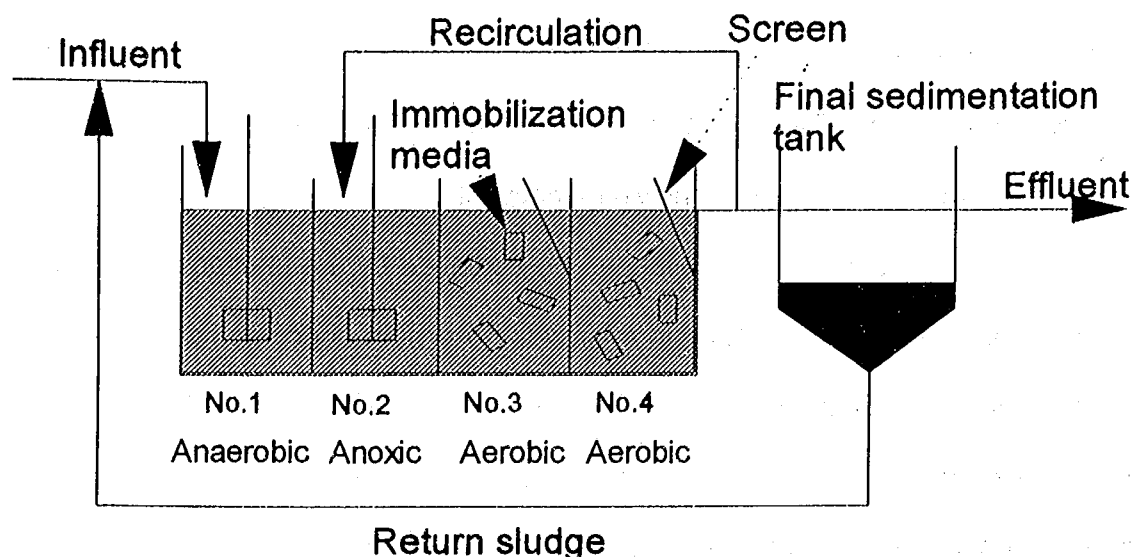
Biological nitrogen removal must take two steps, nitrification (oxidation of ammonia to nitrate) by nitrifiers, and denitrification (reduction of nitrate to nitrogen gas with the consumption of organic matter) by heterotrophs. In this process nitrification is carried out mainly by the nitrifiers attached on the media in the aerobic cells, because nitrifiers can not grow in the activated sludge because of the short solids retention time. The nitrate produced in the aerobic cells is recirculated to the anoxic cell and denitrified there.

The influent to the process is the effluent of a primary sedimentation tank of a municipal wastewater treatment plant which receives wastewater from both separated and combined sewer areas.

3.2 Immobilization media

The characteristics of the media used for the immobilization of nitrifier are listed in Table 3.2. The media can be easily fluidized in the aeration tank with air diffusion. The volume ratio of the media to the reactor has to be lower than 40 % to prevent sedimentation of the

on the bottom of the reactor.



	Anaerobic	Anoxic	Aerobic
Volume of aeration tank	: 10 m ³ (2.5m ³ 2.5m ³ 5m ³)		
Inflow rate	: 30 m ³ /d		
Return sludge ratio	: 0.5		
Recirculation ratio of nitrified mixed liquor	: 1.5		
Solids retention time	: 14d		
Volumetric ratio of media in aerobic cell	: 40%		

Fig. 3.1 Three-zone nutrients removal process with immobilized nitrifiers

TABLE 3.2 Characteristics of Immobilization Media

Material	: Polypropylene
Specific gravity	: 1.025 g/cm ³
Configuration	: Cylinder with empty inside (diameter : 4 mm, length : 5 mm)
Specific surface area when the media are packed densely	: 1410 m ² /m ³
Specific gravity when the media are packed densely	: 0.271g/cm ³

4 Experiments for model development and evaluation

The results of two experiments which had been carried out in Japan as a part of Germany-Japan joint research project were used for the model development and evaluation. One of the experiments is a basic research to investigate the effect of the organic and ammonium load on the performance of the biofilm formed on the immobilization media, and the other is a pilot plant experiment of the new process for nitrogen and phosphorus removal from municipal wastewater.

The methods and the results are described below.

4.1 Experiment on biofilm formed on immobilization media (Experiment 1)

(1) Purpose

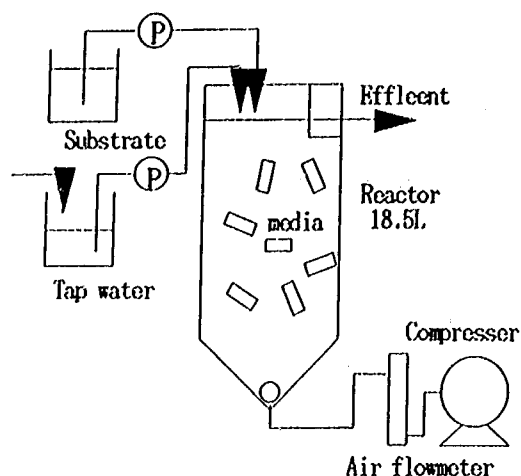
This experiment was carried out to investigate the effect of organic and ammonium loading on 1) removal rates of nitrification and organic matter by the biofilm formed on the fluidized media 2) mass of nitrifiers and heterotrophs on the media.

The results of this experiment were used to develop a model for the biofilm formed on the media.

(2) Methods

The reactor is shown in Fig. 4.1, which was used for the continuous flow experiment.

Three reactors which differed in the organic matter concentration in the inflow were used in parallel, corresponding to the reactor A, B and C in Table 4.1. Four runs were carried out, first the lowest load then higher loads in turn. When the steady state was reached after about one month of the treatment, batch experiments were conducted to obtain the maximum substrate utilization rates for the evaluation of the mass of the nitrifiers and the heterotrophs.



Reactor volume : 18.5 L
 Volume ratio of media : 30 %V/V
 Surface area of media : 7.83 m²
 Specific surface area of media : 423 m²/m³
 in the reactor

Fig.4.1 Experimental apparatus

TABLE 4.1 Conditions for Continuos Flow Experiment

Reactor.	Influent water quality (g/m ³)			
	BOD	TOC	T-N	NH ₄ -N
A	0.3	5	25	25
B	12.5	20	27.5	25
C	125	120	25	3

	Run 1	Run 2	Run 3	Run 4
HRT(h)	8	4	2	1
Qin (m ³ /d)	0.0554	0.111	0.222	0.444

(3)Results

The results of the experiment are shown in Table 4.2.

For the reactor A, almost complete nitrification was achieved in Run 1 through 3, but some ammonia remained in the effluent in Run 4. The reactor B showed almost the same tendency as the reactor A, but the nitrification rate in Run 4 was lower than that of the reactor A. In the reactor C, though complete nitrification was possible in Run 1 and 2, the nitrification rates were reduced in Run 3 and 4.

TABLE 4.2 Results of Experiment

1) Steady state of continuous flow experiment

		A				B				C			
		Run1	2	3	4	Run1	2	3	4	Run1	2	3	4
IN	Org-N (g/m ³)	-	-	-	-	-	1.5	2	1.5	23.0	22.0	21.0	23.2
	NH ₄ -N	22.8	21.4	20.9	22.3	24.1	20.7	21.6	21.6	5.4	4.2	4.7	2.5
	NO ₃ -N	0.6	0.6	0.9	0.6	0.8	0.5	0.8	0.6	0.6	0.5	0.8	0.5
	S-CODslow **	-	-	-	-	21.2	19.6	19.6	17.0	292	222	206	214
	S-CODinert **	-	-	-	-	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
OUT	Org-N (g/m ³)	-	-	-	-	0.2	1.3	0.6	0.7	1.4	2.3	2.9	6.6
	NH ₄ -N	0.3	0.3	1.0	7.0	0.3	0.4	1.2	12.5	0.5	0.8	2.2	9.5
	NO ₃ -N	23.5	20.3	22.8	16.0	26.5	21.9	24.4	11.8	17.3	12.0	7.1	0.5
	S-CODslow **	-	-	-	-	0.8	0.6	1.6	4.0	2.6	7.4	25.2	56.4
	S-CODinert **	-	-	-	-	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	VSS	0.9	1.2	1.0	0.6	5.1	5.5	6.6	5.8	117	204	160	186
	DO	7.1	6.8	4.8	6.4	6.7	6.1	4.5	6.1	6.3	5.2	4.7	4.8
Bio-film	Conc. (gVS/m ²) *	0.35	0.52	0.83	0.87	1.33	2.11	3.46	3.86	3.50	4.78	6.16	5.04
	Thickness (μm)	14	21	33	35	53	84	138	154	140	191	246	202

2) Batch experiment

(g/m ² /d)	A				B				C			
	Run1	2	3	4	Run1	2	3	4	Run1	2	3	4
COD removal rate (R _H) *	-	-	-	-	1.4	2.2	4.2	5.9	4.6	5.9	5.4	6.2
Nitrification rate (R _N) *	0.41	0.45	0.97	0.98	0.43	0.59	0.68	0.70	0.36	0.44	0.28	0.28

* Biofilm concentration, COD removal rate and Nitrification rate are expressed as the ones per unit surface area of media.

** S-CODslow : soluble slowly biodegradable COD, S-CODinert : soluble inert COD

3) Parameters obtained from batch experiments

a) Maximum specific growth rate of nitrifier

The reactor A was operated with only inorganic substrate, therefore, the data of the batch experiment can be used to calculate the maximum specific growth rate of nitrifiers.

$$\mu_N = Y_N R_N / (M_N \cdot i_{\text{COD/VS}}) \quad \text{----- (19)}$$

μ_N : maximum growth rate of nitrifiers (1/d)

Y_N : yield coefficient of nitrifiers (= 1/4.17) (gCOD/gN)

R_N : maximum nitrification rate (gN/m²/d)

M_N : mass of nitrifiers per unit area (gVS/m²)

$i_{\text{COD/VS}}$: ratio of COD/VS for biomass (= 1.3) (gCOD/gVS)

μ_N calculated with eq.(19) are listed in Table 4.3. A little higher value of 0.25 d⁻¹ was chosen for μ_N , because the biomass contained some inert mass.

TABLE 4.3 Calculated Maximum Specific Growth Rate of Nitrifiers (μ_N)

Run	1	2	3	4
μ_N (d ⁻¹)	0.16	0.16	0.22	0.20

b) Maximum hydrolysis rate constant

The reactor C was operated under a high organic load, therefore, almost all of the biomass was thought to be heterotrophs. The rate limiting process of the substrate utilization was the hydrolysis process because the substrate was of high molecule. The maximum substrate utilization rate, therefore, was interpreted as the maximum substrate hydrolysis rate, which was calculated with eq.(20) to give the value of 1.5 d⁻¹.

$$r_h = R_H / (M_H * i_{COD/VS}) \quad \text{----- (20)}$$

r_h : maximum hydrolysis rate constant (d⁻¹)

R_H : maximum substrate utilization rate (gCOD/m²/d)

M_H : mass of heterotrophs per unit area (gVS/m²)

$i_{COD/VS}$: ratio of COD/VS for biomass (= 1.3) (gCOD/gVS)

The ratio of nitrogen to COD of the organic substrate was also calculated to be 0.1 gN/gCOD from the experiment data.

c) Detachment rate of biofilm

The detachment rates of the biofilm are shown in Fig. 4.2 as a function of the biofilm thickness, which were calculated from VS concentration in the effluent assuming the biofilm concentration is 25,000gVS/m³. The lower figure is the magnified one of the upper figure.

The biofilm began to be detached when the biofilm thickness exceeded 12 μm , and the detachment rate increased as the biofilm thickness increased. Beyond the thickness of 120 μm the increasing rate became much higher, and the biofilm stopped gaining its thickness at 240 μm because of the very high detachment rate. These detachment rates can be

expressed in formulas as follows;

$$L_f < 12 \times 10^{-6} \text{ m}$$

$$r_{\text{detach}} = 0$$

$$12 \times 10^{-6} < L_f < 120 \times 10^{-6} \text{ m}$$

$$r_{\text{detach}} = 1.11 \times 10^3 \cdot (L_f - 12 \times 10^{-6})$$

$$120 \times 10^{-6} < L_f < 240 \times 10^{-6} \text{ m}$$

$$r_{\text{detach}} = 4.18 \times 10^4 \cdot (L_f - 120 \times 10^{-6}) + 0.12$$

$$240 \times 10^{-6} \text{ m} < L_f$$

$$r_{\text{detach}} = 2.5 \times 10^4$$

L_f : Biofilm thickness (m)

r_{detach} : Biofilm detachment rate (gVS/(m² · d))

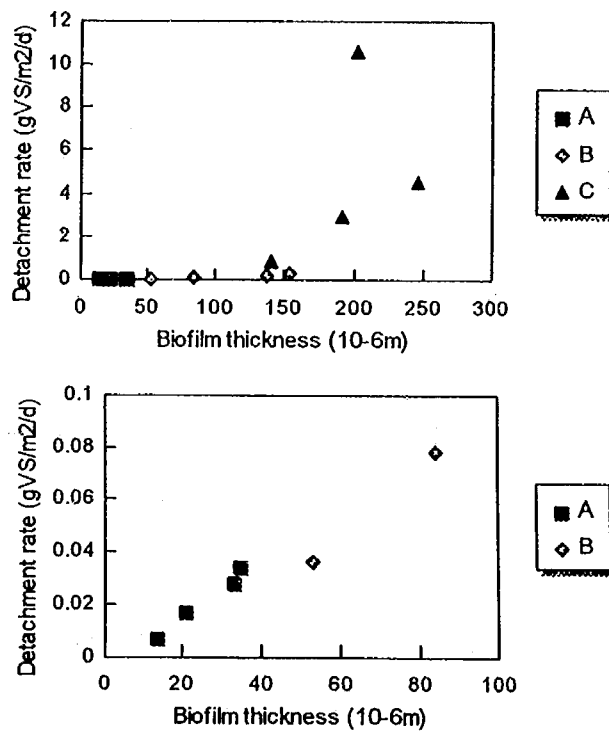


Fig. 4.2 Biofilm detachment rate

Yield coefficient for the heterotrophs in this experiment was also calculated from the data of the reduced COD concentration of substrate and the produced suspended solids concentration in the reactor. The value was around 1.0 g-biomassCOD/g-substrateCOD, but 0.8 gCOD/gCOD was chosen for the calculation because the value of 1.0 is theoretically impossible.

4.2 Pilot plant of three-zone biological nutrients removal process with immobilized nitrifiers (Experiment 2)

(1) Purpose

Performance and stability of the new process for the removal of nitrogen and phosphorus from municipal wastewater were investigated. The results of this experiment were used for the development of the model.

(2) Method

The process outline and the experiment conditions are already described in the chapter 3.1 Three-zone biological nutrients removal process with immobilized nitrifiers. In some cases, however, the media were taken out from the first aerobic cell to investigate the effects of reducing media volume.

In addition to the treatment experiment, two kinds of batch tests and one continuous flow experiment were conducted. One of the two batch tests was to determine the readily biodegradable COD (RBCOD) concentration in the influent according to Scheer and Seyfrieds' method (1994). The other batch test was for the measurement of the maximum nitrification rates of the activated sludge or the biofilm on the media to evaluate the mass of nitrifiers. The continuous flow experiment was carried out to determine the maximum growth rate of nitrifiers against the wastewater according to the method described in Activated Sludge Model No. 1 (Henze *et al.* 1986).

(3) Results

1) Treatment experiment

The results of the treatment experiment are shown in Fig. 4.2 and Fig. 4.3.

The data of Fig. 4.2 were obtained when the water temperature was 20 °C and there had been no effect of rainfall over weeks. The concentration of phosphorus increased in the anaerobic cell to a very high level because phosphorus was released from the phosphorus

accumulating organisms. In the following cells it decreased because of the dilution with the recirculated nitrified mixed liquor and the uptake by the organisms. Very low concentration of phosphorus was attained in the effluent.

Nitrification occurred in the two aerobic cells, and the nitrate was denitrified well in the anoxic cell after recirculated from the aerobic cell. The nitrate concentration in the return sludge was also low because of the denitrification in the sedimentation tank.

The influent soluble COD was removed 67 % in the anaerobic cell and 30% in the anoxic cell, leaving little amount to the aerobic cells.

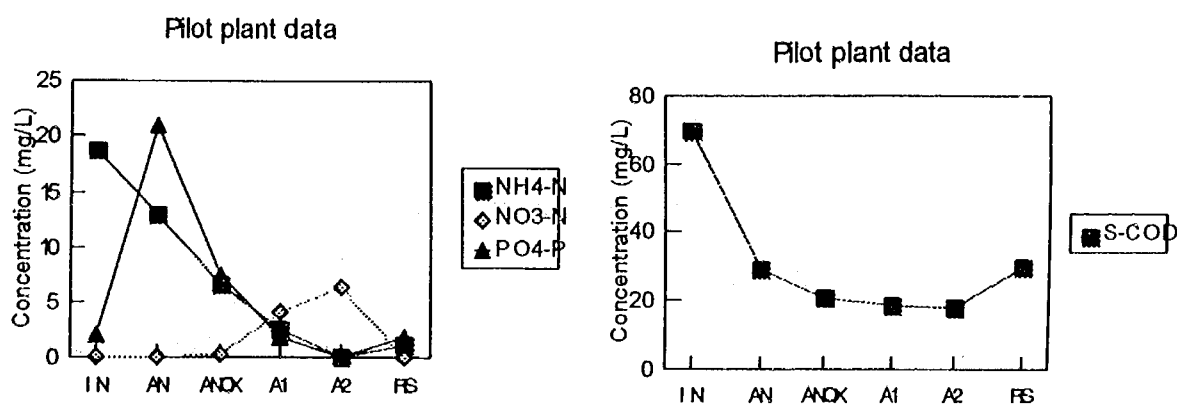


Fig. 4.2 Experimental results of pilot plant at 20 °C without the effect of rainfall
(Data of 18 October 1993)

The data of Fig. 4.3 were obtained when there had been a successive rainfall and the water temperature was 20 °C. In this case, the media were taken out from the first aerobic cell.

Compared with the Fig. 4.2, the phosphorus release in the anaerobic cell is not remarkable, and the denitrification in the anoxic cell is not enough. The nitrate was mainly produced in the second aerobic cell, indicating the high nitrification ability of the biofilm on the media and the low one of the activated sludge.

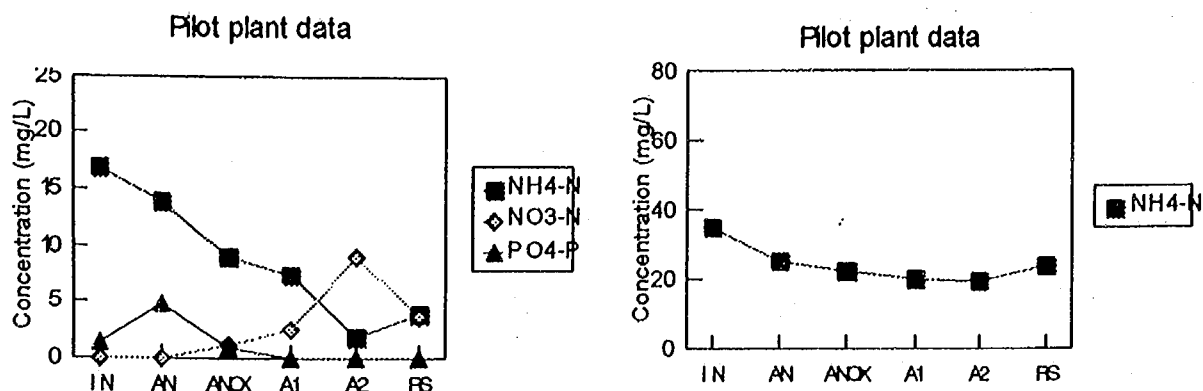


Fig. 4.2 Experimental results of pilot plant at 20 °C without the effect of rainfall
(Data of 21 May 1995)

2) Batch test for RBCOD measurement

A batch test was conducted to measure the readily biodegradable COD (RBCOD) concentration in the influent. From the experiment the RBCOD concentration was calculated to be 60 % of the soluble COD concentration in the influent.

Acetate, an important substrate for biological phosphorus removal, was also measured with GC, which showed 46 % of the soluble COD concentration.

3) Batch test for maximum nitrification rate

Maximum nitrification rates of the activated sludge and the biofilm on the media were measured by batch tests on October 20, 1993, when the water temperature was around 20°C.

Table 4.4 Maximum nitrification rate measured by batch tests

	Maximum nitrification rate
Activated sludge	7.8 mgN/(m ³ ·h)
Biofilm in the first aerobic cell	26.1 mgN/(m ² -media surface·h)
Biofilm in the second aerobic cell	11.8 mgN/(m ² -media surface·h)

4) Continuous flow experiment for maximum growth rate of nitrifiers

A continuous flow experiment was conducted to obtain the maximum growth rate of nitrifiers. The reactor, however, was not the single aerobic one, but the anoxic(40L) - aerobic(60L) reactors with recirculation.

Table 4.5 Results of experiment for calculating maximum growth rate of nitrifiers

Time (t)(d)	Water Temp.	Nitrate produced (q _N) (gN/d)	ln(q _N)	Δt(d)	$(\ln(q_N)_{t+\Delta t} - \ln(q_N)_t) / \Delta t$ $\approx 0.6 \mu - b - (1/\theta_x)$	SRT (θ _x)(d)	0.6 μ - b (d ⁻¹)	μ at 20 (d ⁻¹)
9	8	2.05	0.718					
				21	-0.00567	16.9	0.053	0.39
30	8	1.82	0.599					
				14	-0.0781	9.35	0.029	0.25
44	8	0.61	-0.494					

μ (d⁻¹) : Maximum specific growth rate of nitrifiers

b(d⁻¹) : Decay rate of nitrifiers

The calculated value of (0.6 μ - b) was obtained at the water temperature of 8 °C. To calculate μ at 20 °C, firstly, the temperature coefficient for μ and b was assumed to be 0.105 d⁻¹, and (0.6 μ - b) at 20 °C was calculated. μ at 20 °C, then, was calculated to be 0.39 d⁻¹ and 0.25 d⁻¹ with the assumption of b as 0.05 d⁻¹.

The value of 0.25 d⁻¹ for μ is more reliable because the control of SRT was more accurate for the latter case, and 0.25 d⁻¹ was chosen as μ at 20 °C.

5 Procedure of modeling

The procedure of modeling the combined activated sludge and biofilm process consists of two steps. The first step is modeling the biofilm formed on the surface of the media. The results of **Experiment 1**, which are described in **4.1**, were used for this modeling. The second step is modeling the combined process, in which the biofilm model was incorporated in an activated sludge model. The data of **Experiment 2**, which are described in **4.2**, were used for the modeling.

5.1 AQUASIM as a simulation tool

Aquasim, developed by P. Reichert (1994), is a simulation software for aquatic systems. It can deal with a treatment system composed of activated sludge processes and biofilm processes.

Three types of **compartment** are defined in the Aquasim, a mixed reactor, a biofilm reactor and a river section. Using those compartments together with **links** which connect the compartments one another, a configuration of a system is made up. For the calculation, **variables** such as water qualities or specific growth rates of microorganisms must be defined, and **biological reactions** must be written in formulas.

5. 2 Modeling of biofilm process

5. 2. 1 Model description

(1) Components

Components used in this model are based on the **Activated Sludge Model No. 2**, which are listed in Table 5.1.

One component, however, differs from the Activated Sludge Model No. 2 in terms of the definition. In the Model No. 2 the slowly biodegradable COD is defined as particulate (X_s), but in this model, it is divided into two parts, soluble (S_s) and particulate (X_s), because some

part of the slowly biodegradable COD is really soluble and it can diffuse into the biofilm. Particularly the organic substrate in Experiment 1 was defined as the soluble slowly biodegradable COD because it was composed of high molecular organic matter such as dextrin and peptone.

The component of inert soluble organic material (S_i) is omitted in this model, because it has no relation to other components.

(2) Biological process

The expression of the biological processes in the **Activated Sludge Model No. 2** are used in this model.

Parameter values used in the simulation are summarized in Table 5.1, of which the nitrogen content in the slowly biodegradable COD, the hydrolysis rate constant, the yield coefficient for heterotrophs and the maximum specific growth rate of nitrifiers are the obtained data in the Experiment 1. The saturation coefficient for S_s in the hydrolysis process was introduced in this model, because S_s is soluble and the hydrolysis mechanism is different from that of X_s . The rate expression for the aerobic hydrolysis of S_s was formulated as follows;

$$r_h \cdot S_{O_2} / (K_{O_2} + S_{O_2}) \cdot S_s / (K_s + S_s) \cdot X_H \quad \text{-----} \quad (21)$$

The mechanisms of adsorption and degradation of particles at the biofilm surface are not fully understood, therefore, the mechanisms are not considered in this model.

Table 5.1 Parameter values used for simulation
(artificial substrate is used in the experiment)

* Values of bold letters are different from the values listed in IAWQ model No. 2

Conversion Factors

Nitrogen:

Soluble Material:

i_{NSF} N content of fermentable substrate S_F **0.03** $g_N g^{-1} COD$

i_{NSS} N content of slowly biodegradable substrate S_s **0.1** $g_N g^{-1} COD$

Particulate Material:

i_{NXI} N content of inert particulate COD X_i **0.03** $g_N g_{COD}^{-1}$

i_{NXS} N content of particulate substrate X_S	$0.04 \text{ g}_N \text{ g}_{COD}^{-1}$
i_{NBM} N content of biomass X_H, X_{PAO}, X_{AUT}	$0.07 \text{ g}_N \text{ g}_{COD}^{-1}$

Phosphorus:

Soluble Material:

i_{PSF} P content of soluble substrate S_F	$0.01 \text{ g}_P \text{ g}^{-1}_{COD}$
--	---

Particulate Material:

i_{PXI} P content of inert particulate COD X_I	$0.01 \text{ g}_P \text{ g}_{COD}^{-1}$
i_{PXS} P content of particulate X_S	$0.01 \text{ g}_P \text{ g}_{COD}^{-1}$
i_{PBM} P content of biomass X_H, X_{PAO}, X_{AUT}	$0.02 \text{ g}_P \text{ g}_{COD}^{-1}$

Stoichiometric Constants

Hydrolysis:

f_{SI} Fraction of inert COD in particulate substrate	$0.00 \text{ g}_{COD} \text{ g}^{-1}_{COD}$
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Heterotrophic Organisms X_H

Y_H Yield coefficient	$0.8 \text{ g}_{COD} \text{ g}^{-1}_{COD}$
f_{XI} Fraction of inert COD generated in biomass lysis	$0.10 \text{ g}_{COD} \text{ g}^{-1}_{COD}$

Nitrifying Organisms X_{AUT}

Y_{AUT} Yield coefficient (Biomass/Nitrate)	$0.24 \text{ g}_{COD} \text{ g}^{-1}_N$
f_{XI} Fraction of inert COD generated in biomass lysis	$0.10 \text{ g}_{COD} \text{ g}^{-1}_{COD}$

Kinetic constants

Hydrolysis:

r_h = Hydrolysis rate constant	1.5 d^{-1}
η_{NO_3} = Anoxic hydrolysis reduction factor	0.60 -
η_{f_6} = Anaerobic hydrolysis reduction factor	0.10 -
K_{O_2} = Saturation/inhibition coefficient for oxygen	$0.20 \text{ g}_{O_2} \text{ m}^{-3}$
K_{NO_3} = Saturation/inhibition coefficient for nitrate	$0.50 \text{ g}_N \text{ m}^{-3}$
K_X = Saturation coefficient for particulate COD (X_S)	$0.10 \text{ g}_{COD} \text{ g}^{-1}_{COD}$
K_S = Saturation coefficient for soluble COD (S_S)	$4.0 \text{ g}_{COD} \text{ m}^{-3}$

Heterotrophic Organisms:

μ_H = Maximum growth rate on Substrate	6.00 d^{-1}
η_{NO_3} = Reduction factor for denitrification	0.80 -
b_H = Rate constant for lysis	0.10 d^{-1}
K_{O_2} = Saturation/inhibition coefficient for oxygen	$0.20 \text{ g}_{O_2} \text{ m}^{-3}$
K_F = Saturation coefficient for growth on S_F	$4.00 \text{ g}_{COD} \text{ m}^{-3}$

K_{Fe}	= Saturation coefficient for fermentation of S_F	20.00 $g_{COD}m^{-3}$
K_A	= Saturation coefficient for S_A (Acetate)	4.00 $g_{COD}m^{-3}$
K_{NO_3}	= Saturation/inhibition coefficient for nitrate	0.50 g_Nm^{-3}
K_{NH_4}	= Saturation coefficient for ammonium (nutrient)	0.05 g_Nm^{-3}
K_P	= Saturation coefficient for phosphorus (nutrient)	0.01 g_Pm^{-3}
K_{ALK}	= Saturation coefficient for alkalinity	0.10 $mole_{HCO_3}m^{-3}$

Nitrifiers:

μ_{AUT}	= Maximum growth rate	0.25 d^{-1}
b_{AUT}	= Decay rate	0.05 d^{-1}
K_{O_2}	= Saturation coefficient for oxygen	0.50 $g_{O_2}m^{-3}$
K_{NH_4}	= Saturation coefficient for ammonium	0.20 g_Nm^{-3}
K_{ALK}	= Saturation coefficient for alkalinity	0.10 $mole_{HCO_3}m^{-3}$
K_P	= Saturation coefficient for phosphorus	0.01 g_Pm^{-3}

Biofilm:

X_f	= Biofilm concentration	25,000 gVS/m^3
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(3) Mass transfer in biofilm

Substrates are transported in the biofilm by molecular diffusion. The values of the diffusion coefficient used for the model are listed below.

Table 5.2 Values of molecular diffusion coefficient

Symbol	Substrate	Diffusion coefficient (m^2/d)	
		in Water	in Biofilm
D_A	Acetate	1×10^{-4}	0.8×10^{-4}
D_{ALK}	Alkalinity	1×10^{-4}	0.8×10^{-4}
D_F	S_F	6×10^{-5}	4.8×10^{-5}
D_S	S_S	1×10^{-5}	0.8×10^{-5}
D_{NH_4}	NH_4	1.6×10^{-4}	1.3×10^{-4}
D_{NO_3}	NO_3	1.2×10^{-4}	1.0×10^{-4}
D_{O_2}	O_2	2.2×10^{-4}	1.8×10^{-4}
D_{PO_4}	PO_4	1.5×10^{-4}	1.2×10^{-4}

(4) Calculation of biofilm growth

Aquasim incorporates a calculation procedure for the biofilm growth, the theory of which is based on Wanner and Gujers' model (1984).

This model also utilizes this procedure for the calculation of the biofilm growth.

(5) Biofilm detachment

The mechanism and the rate of biofilm detachment are peculiar to a biofilm process, therefore, they have to be formulated to each treatment process.

The total detachment rate was obtained in the Experiment 1 (Fig. 4.2). However, it is necessary that the detachment rate at every biofilm depth is formulated, because a biofilm has thickness and the detachment rate may not be uniform through the depth.

Four assumptions were made as the detachment mechanism as follows;

a) Surface detachment

Very thin layer of biofilm is detached from the biofilm surface

b) Depth detachment

b-1) Certain depth of biofilm is detached at a gradient rate

b-2) Certain depth of biofilm is detached at a constant rate

b-3) Whole depth of biofilm is detached at a constant rate

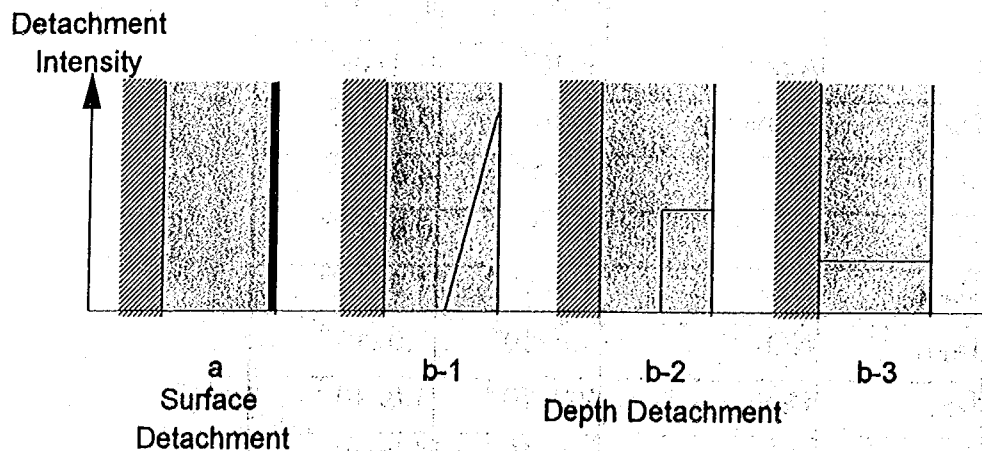


Fig. 5.1 Four assumptions of the mechanism of biofilm detachment

5. 2. 2 Calculation results

(1) Biofilm without organic load

The case without the organic load corresponds to Run 1 to Run 4 of the **reactor A** in the Experiment 1. The experiment results and the calculation results are listed in Table 5.3.

The biofilm model could not express the biofilm thickness and the effluent water quality of the experiment correctly, if the detachment rate was set at the experiment value of 0.0444 d^{-1} . A higher detachment rate, about five times of that of the experiment, was needed for the model to meet the experiment data. A possibility that the effluent suspended solids concentration was not measured correctly because of the very low SS concentration (1mg/L) and the low coagulation ability of nitrifiers might be the reason.

In this case, the difference in the detachment mechanism did not cause any difference in the calculation results, because most of the biomass were the nitrifiers.

Table 5.3 Calculation results of the reactor A in Experiment 1

	Detachment rate (d^{-1})	Biofilm thickness (μm)				$\text{NH}_4\text{-N}$ (mg/L)			
		Run 1	Run 2	Run 3	Run 4	Run1	Run2	Run3	Run4
Experiment	0.0444	14	21	33	35	0.3	0.3	1.0	7.0
Model calculation	0.0444	28	45	80	120	0.1	0.1	0.2	0.5
	0.25	15	20	26	34	0.2	0.5	2.0	7.0

(2) Biofilm with low organic load

The case with the low organic load corresponds to Run 1 to Run 4 of the **reactor B** in Experiment 1. Detachment mechanisms were defined in four ways in the model, as described in 5. 2. 1 (4) **Biofilm detachment**, and calculation was carried out. Depth of the biofilm subject to detachment was assumed to be $50 \mu\text{m}$ for the case b-1 and b-2 in Fig. 5.1. The results of the calculation are shown in Fig. 5.2.

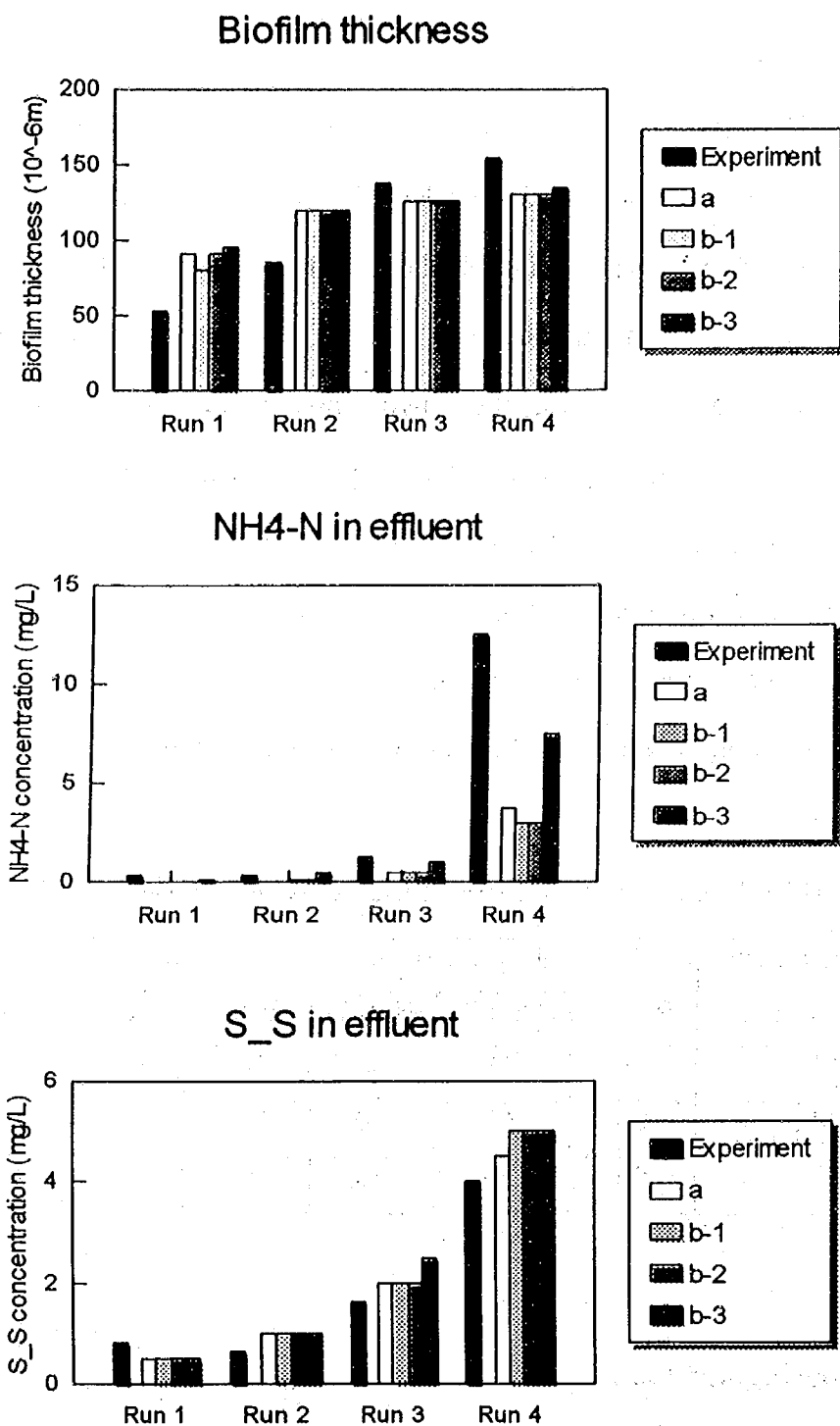


Fig. 5.2 Comparison of calculation results with four different detachment mechanisms

a : surface detachment

b-1 : depth (50 μ m) detachment at a gradient rate, maximum at the surface

b-2 : depth (50 μ m) detachment at a constant rate through the depth

b-3 : whole depth detachment at a constant rate through the film thickness

As for the calculation of the biofilm thickness and S_s (soluble slowly biodegradable COD), each model with different detachment mechanism could express the experimental results well. However, concerning NH_4-N concentration, only the model with the detachment mechanism of **b-3** (whole detachment at a constant rate through the film) could calculate the high concentration of NH_4-N in Run 4.

Biomass distributions in the biofilm calculated with each detachment mechanism for Run 4 are shown in Fig. 5.3. When the detachment mechanisms are **a** (surface detachment), **b-1** and **b-2** (certain depth detachment), nitrifiers can exist throughout the biofilm, which causes the higher nitrification rates and the low NH_4-N concentration in the effluent. On the other hand, with the detachment mechanism of **b-3**, nitrifiers can not exist in the upper layer of the biofilm, which results in the lower nitrification rate and the higher NH_4-N concentration in the effluent.

If a biofilm is thinner than 150 μm with a low organic load, the biofilm seems to be detached from every depth equally.

(3) Biofilm with high organic load

The case with the high organic load corresponds to Run 1 to Run 4 of the reactor C in Experiment 1, and the results of calculations are shown in Fig. 5.4.

Firstly, a calculation was carried out assuming the mechanism of whole biofilm detachment, but it could not express the NH_4-N and NO_3-N concentrations of Run 2 and Run 3 correctly. The calculated NH_4-N concentration became higher than the experiment, because the detachment rate of the nitrifiers might be calculated higher.

As the second trial, the mechanism of 100 μm depth detachment was assumed in the model to reduce the detachment of nitrifiers. With this assumption, NH_4-N and NO_3-N concentrations of Run 2 were calculated correctly, but the concentrations of Run 3 were not.

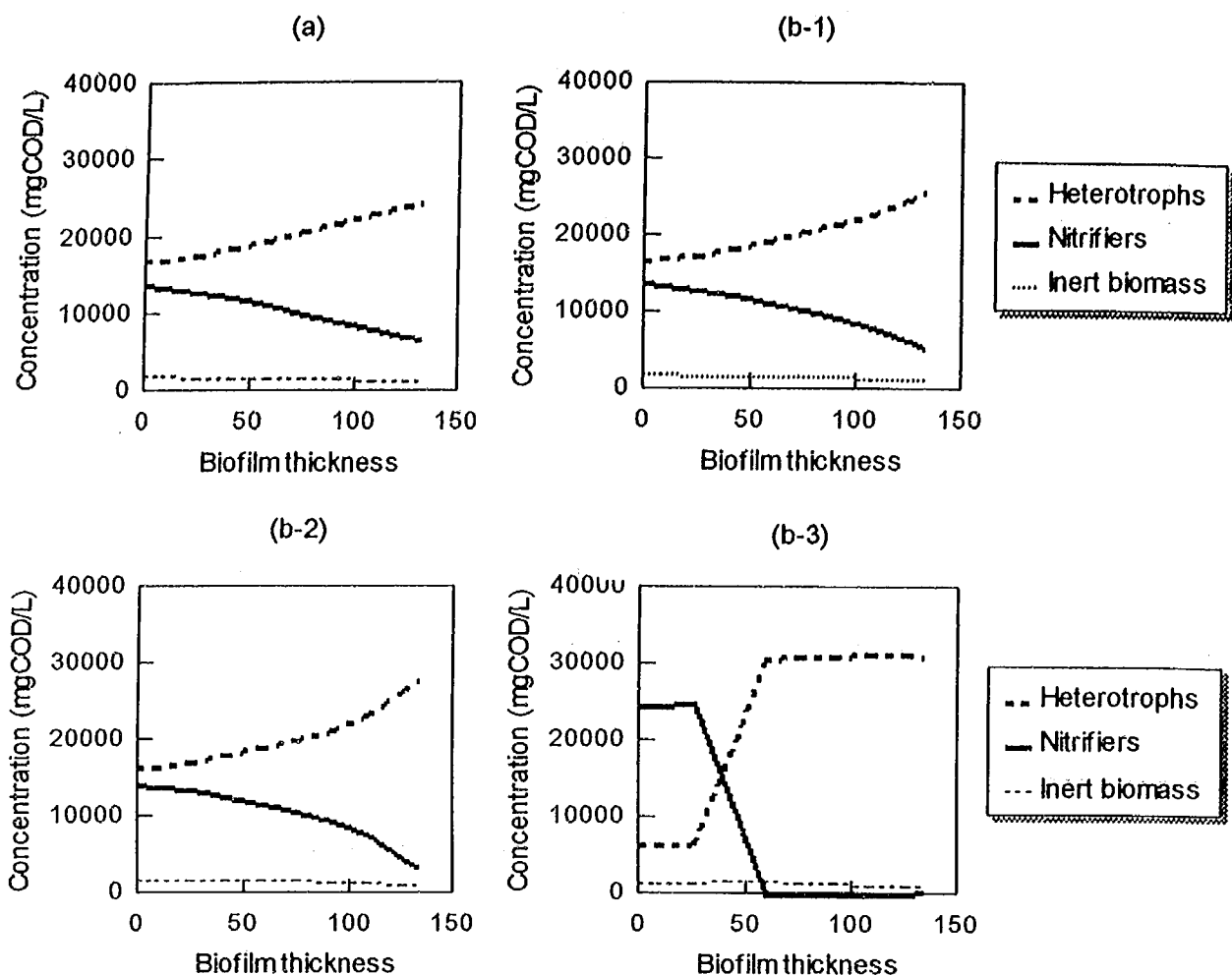


Fig. 5.3 Distributions of biomass in biofilms in Run 4 of the reactor B
with four detachment mechanisms
(Biofilm thickness of 0 means the bottom of biofilm)

The detachment mechanism with a high organic load must be investigated more precisely, because the detachment rate is much higher than that with a low organic load and the difference in the detachment mechanism causes a big difference in the calculation results.

The purpose of this research is to develop a model for the combined activated sludge and biofilm process which has a comparatively low organic load to the aerobic cell where biofilms exist, therefore, further model development for the high organic load was not pursued here.

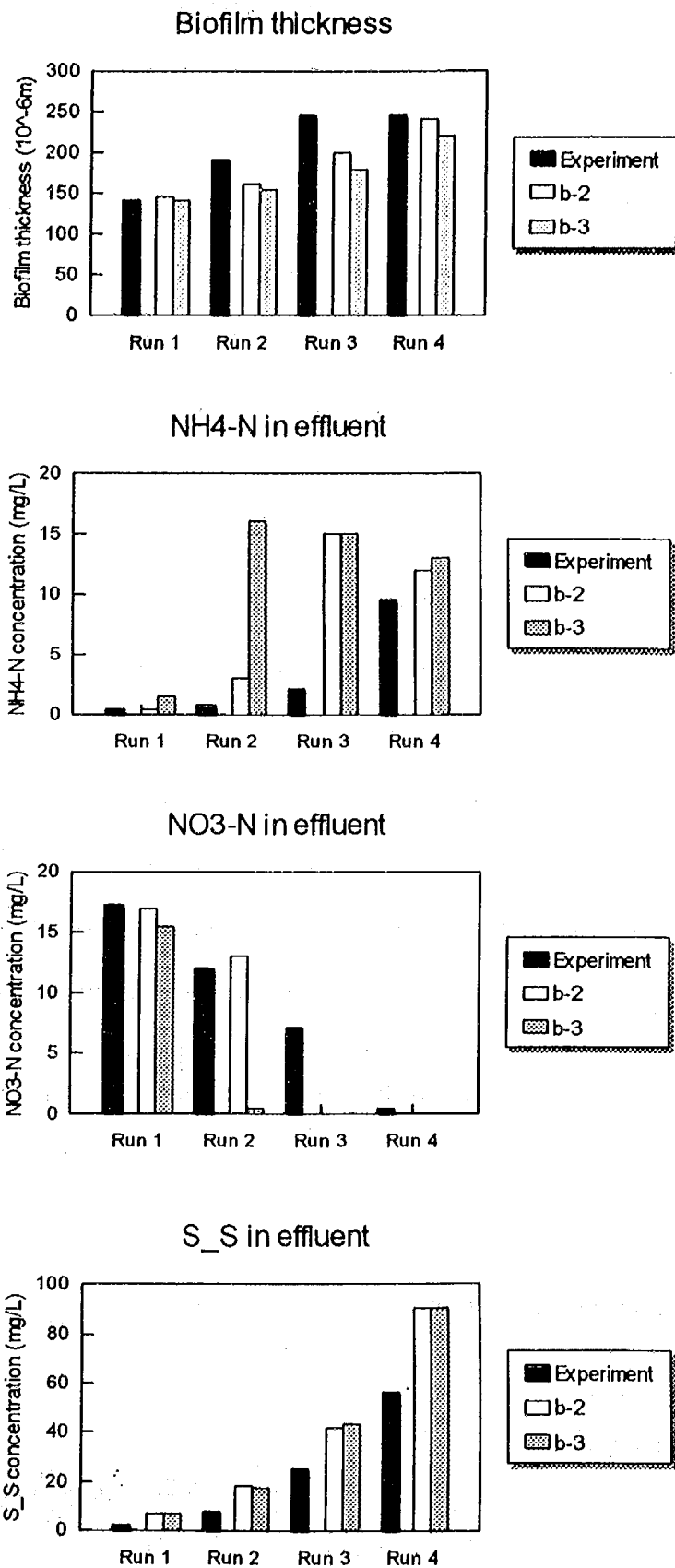


Fig. 5.4 Calculation results in the case with high organic load

5.3 Modeling of combined activated sludge and biofilm process

5.3.1 Model description

(1) Components

Components used in the model are basically the same as those used in the biofilm model. However, the activated sludge microorganisms had to be distinguished from the biofilm microorganisms, when the mechanism of transferring detached biofilm to the activated sludge was incorporated in the model. The details are described in (5) Additional processes 2) Transfer of detached biofilm to activated sludge.

The concentration of soluble slowly biodegradable COD (S_S) in the influent was calculated by subtracting both the concentration of readily biodegradable COD ($S_A + S_F$) and the inert soluble organic matter (S_I) from the soluble COD concentration.

(2) Biological process

Biological phosphorus removal processes were added to the model with some arrangement that the PHA storage process is inhibited by the existence of dissolved oxygen and nitrate. Also, the values of some parameters were changed from the biofilm model because the influent was changed from the artificial sewage to municipal wastewater.

Table 5.4 Parameter values used in model
(Only the values changed from Table 5.1 or added newly are listed)

Conversion Factors

Nitrogen:

Soluble Material:

i_{NSS} N content of slowly biodegradable substrate S_S **$0.04 \text{ g}_N \text{ g}^{-1}_{\text{COD}}$**

Stoichiometric Constants

Heterotrophic Organisms X_H

Y_H Yield coefficient **$0.63 \text{ g}_{\text{COD}} \text{ g}^{-1}_{\text{COD}}$**

Phosphorus Accumulating Organisms X_{PAO}

Y_{PAO} Yield coefficient(Biomass/PHA) **$0.63 \text{ g}_{\text{COD}} \text{ g}^{-1}_{\text{COD}}$**

Y_{PO4} PP requirement(S_{PO4} release) for PHA storage **$0.40 \text{ g}_P \text{ g}^{-1}_{\text{COD}}$**

Y_{PHA} PHA requirement for PP storage **$0.20 \text{ g}_{\text{COD}} \text{ g}^{-1}_P$**

f_{XI} Fraction of inert COD generated in biomass lysis 0.10 $\text{g}_{\text{COD}} \text{g}^{-1}_{\text{COD}}$

Kinetic constants

Hydrolysis:

r_h = Hydrolysis rate constant 6 d^{-1}
 K_X = Saturation coefficient for particulate COD (X_S) 0.05 $\text{g}_{\text{COD}} \text{g}^{-1}_{\text{COD}}$

Heterotrophic Organisms:

q_{fe} = Maximum rate for fermentation 3.00 $\text{g}_{\text{COD}} \text{g}^{-1}_{\text{COD}} \text{d}^{-1}$

Phosphorus Accumulating Organisms:

q_{PHA} = Rate constant for storage of PHA (base: X_{PP}) 3.00 $\text{g}_{\text{COD}} \text{g}^{-1}_{\text{PAO}} \text{d}^{-1}$
 q_{PP} = Rate constant for storage of PP 1.50 $\text{g}_{\text{PP}} \text{g}^{-1}_{\text{PAO}} \text{d}^{-1}$
 μ_{PAO} = Maximum growth rate 1.00 d^{-1}
 b_{PAO} = Rate constant for lysis of X_{PAO} 0.20 d^{-1}
 b_{PP} = Rate constant for lysis of X_{PP} 0.20 d^{-1}
 b_{PHA} = Rate constant for lysis of X_{PHA} 0.20 d^{-1}
 K_{O_2} = Saturation coefficient for S_{O_2} 0.20 $\text{g}_{\text{O}_2} \text{m}^{-3}$
 K_A = Saturation coefficient for S_A (Acetate) 4.00 $\text{g}_{\text{COD}} \text{m}^{-3}$
 K_{NH_4} = Saturation coefficient for ammonium 0.05 $\text{g}_{\text{N}} \text{m}^{-3}$
 K_P = Saturation coef. for phosphorus in PP storage 0.20 $\text{g}_P \text{m}^{-3}$
 K_P = Saturation coef. for phosphorus in growth 0.01 $\text{g}_P \text{m}^{-3}$
 K_{ALK} = Saturation coefficient for alkalinity 0.10 $\text{mole}_{\text{HCO}_3} \text{m}^{-3}$
 K_{PP} = Saturation coefficient for poly-phosphate 0.01 $\text{g}_{\text{PP}} \text{g}^{-1}_{\text{PAO}}$
 K_{MAX} = Maximum ratio of $X_{\text{PP}} / X_{\text{PAO}}$ 0.34 $\text{g}_{\text{PP}} \text{g}^{-1}_{\text{PAO}}$
 K_{IPP} = Inhibition coefficient for X_{PP} storage 0.02 $\text{g}_{\text{PP}} \text{g}^{-1}_{\text{PAO}}$
 K_{PHA} = Saturation coefficient for PHA 0.01 $\text{g}_{\text{PHA}} \text{g}^{-1}_{\text{PAO}}$

(3) Mass transfer in biofilm

Mass transfer coefficients used in the model are the same as those used in the biofilm model as listed in Table 5.2.

(4) Biofilm detachment

The biofilm detachment rates in Experiment 1 were also used in this model. The whole depth detachment mechanism (case b-3 in Fig. 5.1) was employed, because the soluble organic load to the biofilm in the combined process is low as shown in Fig. 4.2.

(5) Additional processes

1) Control of oxygen concentration in aerobic cell

In the pilot plant experiment, dissolved oxygen (DO) concentration in the aerobic cells was controlled by an automatic control system. Therefore, the mechanism of controlling DO concentration in the aerobic cell was added to the model.

The DO control process was defined only in the bulk water, not inside of the biofilm.

2) Transfer of detached biofilm to activated sludge

In the real treatment system, detached biofilm becomes a part of the activated sludge after the detachment, therefore, a mechanism of adding the detached biofilm to the activated sludge is necessary.

In the model, biomass which was detached from every part of the biofilm must be transferred from inside of the biofilm to the bulk water to be added to the activated sludge. For this purpose, detached biomass was defined as soluble, which enables the biomass to diffuse through the biofilm to the bulk water. The detached biofilm, then, becomes a part of the activated sludge, which requires the activated sludge should also be soluble because there must not be any difference between the detached biofilm and the activated sludge.

The imaginary diffusion coefficients for the detached biomass were set at $0.001\text{m}^2/\text{d}$.

In the model defined above, the detached biofilm and the activated sludge can exist in the biofilm in the form of soluble matter, but those soluble substances must not perform any reaction in the biofilm. The reactions concerned with the suspended biomass, therefore, were inactivated inside of the biofilm.

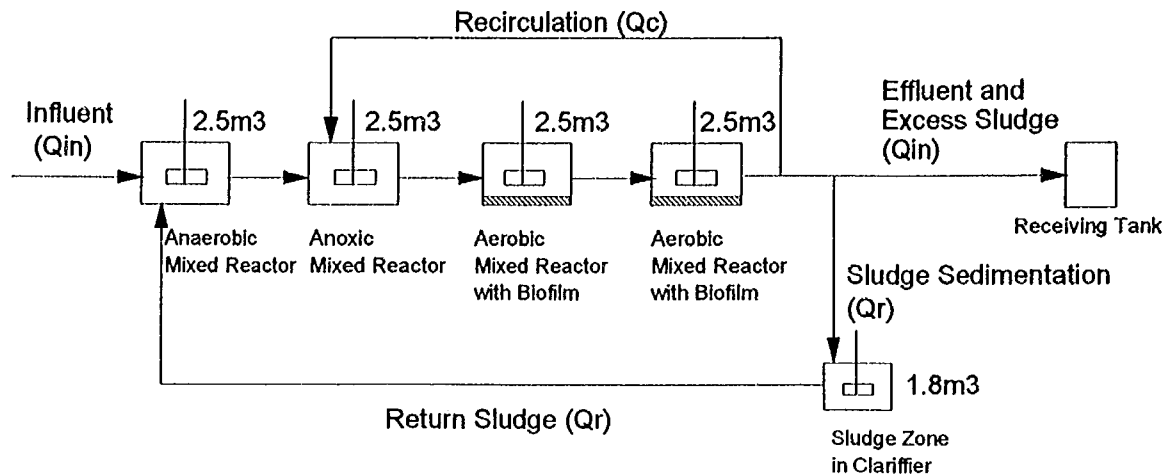
(6) Structure of the model

The structure of the model is shown in Fig. 5.5, which consists of six compartments. Four out of them represent the aerobic, anoxic and aerobic cells of the reactor. The sludge zone in the clarifier is also defined as a reactor because biological reactions can take place

in the zone.

Excess sludge is separated from the treatment process at the line between the second aerobic cell and the clarifier, and it runs away together with the effluent. The purpose of this is to reduce the model size.

The receiving tank is necessary only for the flows of the effluent and the excess sludge to be defined.



Name of Flow	Flow rate (L ³ /T)	Flux of Soluble matter (M/T)	Flux of Particulate matter (M/T)
Recirculation	Q_c	$Q_c C$	$Q_c X$
Sludge Sedimentation (or Return Sludge)	Q_r	$Q_r C$	$(Q_{in} + Q_r - Q_{ex}) X$
Effluent and Excess Sludge	Q_{in}	$Q_{in} C$	$Q_{ex} X$

C: concentration of soluble matter (M/L³)
X: concentration of particulate matter (M/L³)

Fig. 5.5 Structure of the model of three-zone biological nutrients removal process with immobilized nitrifiers

Active processes for each compartment were defined as listed in Table 5.5. To select the active processes, impossible processes in each compartment were erased from the total processes and the remaining processes were defined active. Therefore, the aerobic processes are inactive in the aerobic cell and the phosphorus removal processes are inactive for the biofilm process.

Table 5.5 Active processes for each compartment

	Activated sludge	Biofilm
Anaerobic cell	Anoxic, Anaerobic	-
Anoxic cell	Aerobic, Anoxic, Anaerobic	-
Aerobic cell	Aerobic	Aerobic (Heterotrophs, Nitrifiers, Inert biomass)
Sludge zone in Clarifier	Aerobic, Anoxic, Anaerobic	-

5. 3. 2 Calculation results

(1) Parameter fitting

Parameter fitting was carried out mainly for the hydrolysis process, using the pilot plant data during the term without rainfall. The results of the fitting are shown in Fig. 5.6 for the water quality, and in Fig. 5.7 and Fig. 5.8 for the biomass concentration.

The model with the fitted parameter values could express the water quality, the total biomass concentration and the high value of poly-phosphate concentration well. The tendency of nitrifier concentration was also calculated well, higher in the biofilm and lower in the activated sludge. The concentration itself, however, was predicted lower, which might be caused by higher temperature of the preceding term of Experiment 2.

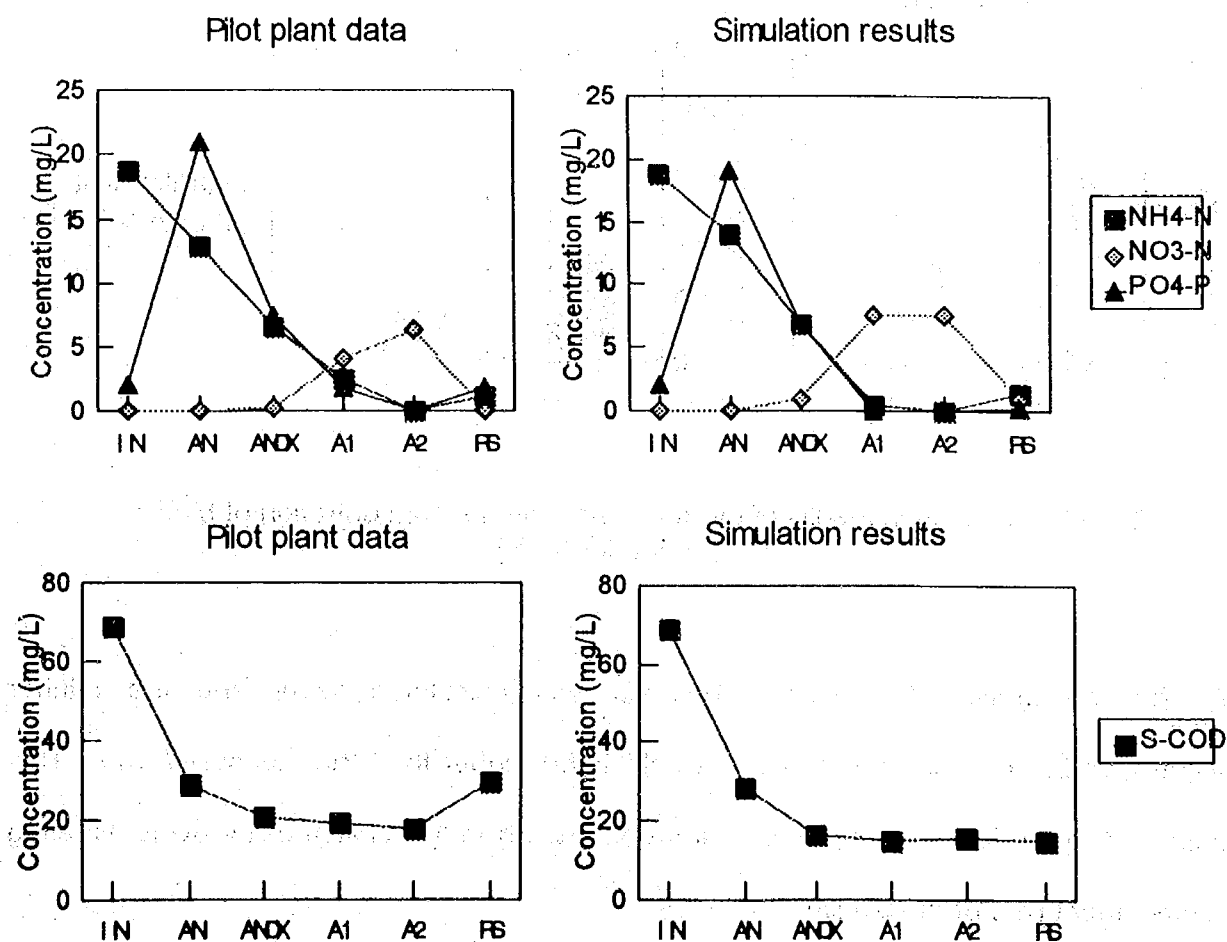


Fig. 5.6 Calculation results of water quality after parameter fitting

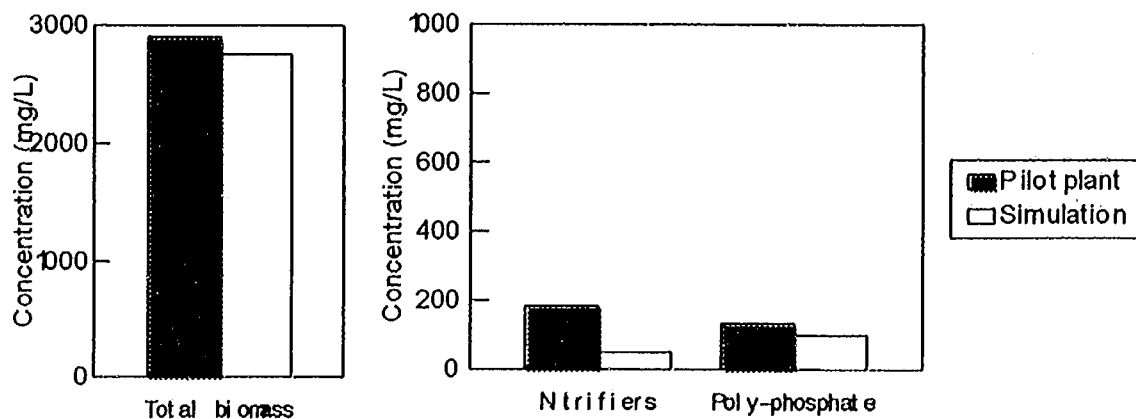


Fig. 5.7 Calculation results of biomass concentration in activated sludge after parameter fitting (concentration : COD)

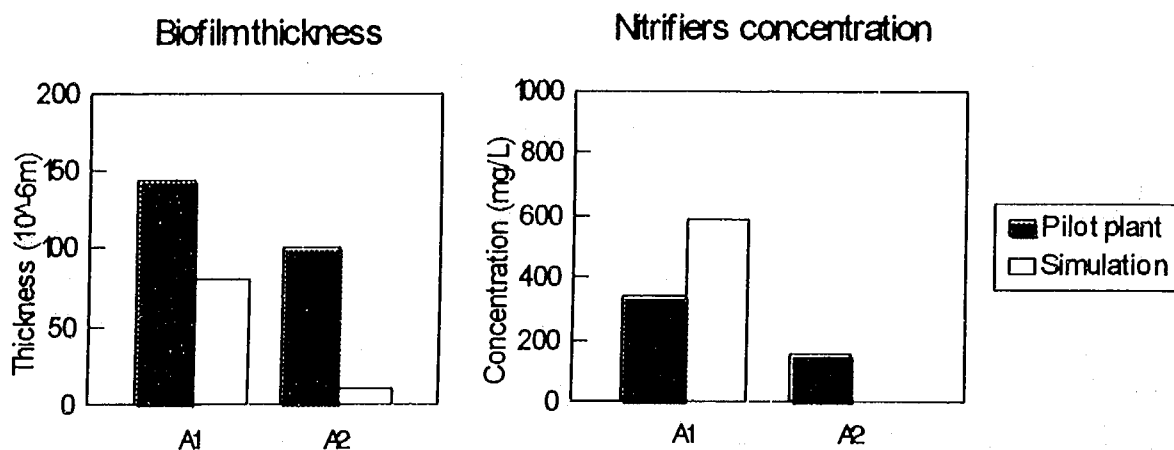


Fig. 5.8 Calculation results of thickness and nitrifier concentration of biofilm after parameter fitting

As for the biofilm, the biofilm thickness was calculated lower and the nitrifier concentration in the first aerobic cell was calculated higher than the measured one. This was caused by underestimating the heterotroph growth in the biofilm or by overestimating the detachment rate of the biofilm.

If the former assumption is true, a possible reason for that is particulate slowly biodegradable COD (P-SBCOD) is not treated as a substrate for the biofilm because the

processes of the attachment and the hydrolysis of P-SBCOD at the biofilm surface are not considered. Little is known about the mechanisms of those two processes, therefore, the mechanisms must be clarified first for the improvement of the model.

There is also a possibility that the detachment rate of the biofilm in Experiment 2 is lower than that in Experiment 1. Further investigation is needed concerning the detachment rate of the biofilm.

(2) Model evaluation

The model with the parameter values fitted above was evaluated using the pilot plant data during the term with much rainfall. The influent concentration was diluted by a successive rainfall, therefore, the treatment condition was quite different from that of Fig. 5.6 through 5.8.

The results of the simulation are shown in Fig. 5.9 for the water quality and in Fig. 5.10 for the biomass concentration. The relatively low nitrate concentration in the first aerobic cell and the high concentration in the second aerobic cell were calculated well, which means this model could simulate the high nitrification rate of the biofilm and the low nitrification rate of the activated sludge.

The calculated phosphorus concentration in the anaerobic cell also showed a good agreement with the pilot plant data, but the effluent phosphorus concentration was lower than the real value. The reason of this might be that the pilot plant had not reached the steady state though the calculated value was of the steady state. One month later, the effluent phosphorus concentration increased because of successive diluted influent. Unfortunately, the data could not be used for the evaluation because of higher water temperature.

The thick biofilm in spite of the diluted influent was not expressed at all by the model. It seems that biofilm doesn't lose its strength for the attachment easily after the reduction of organic load. Further research is needed for the attachment mechanism.

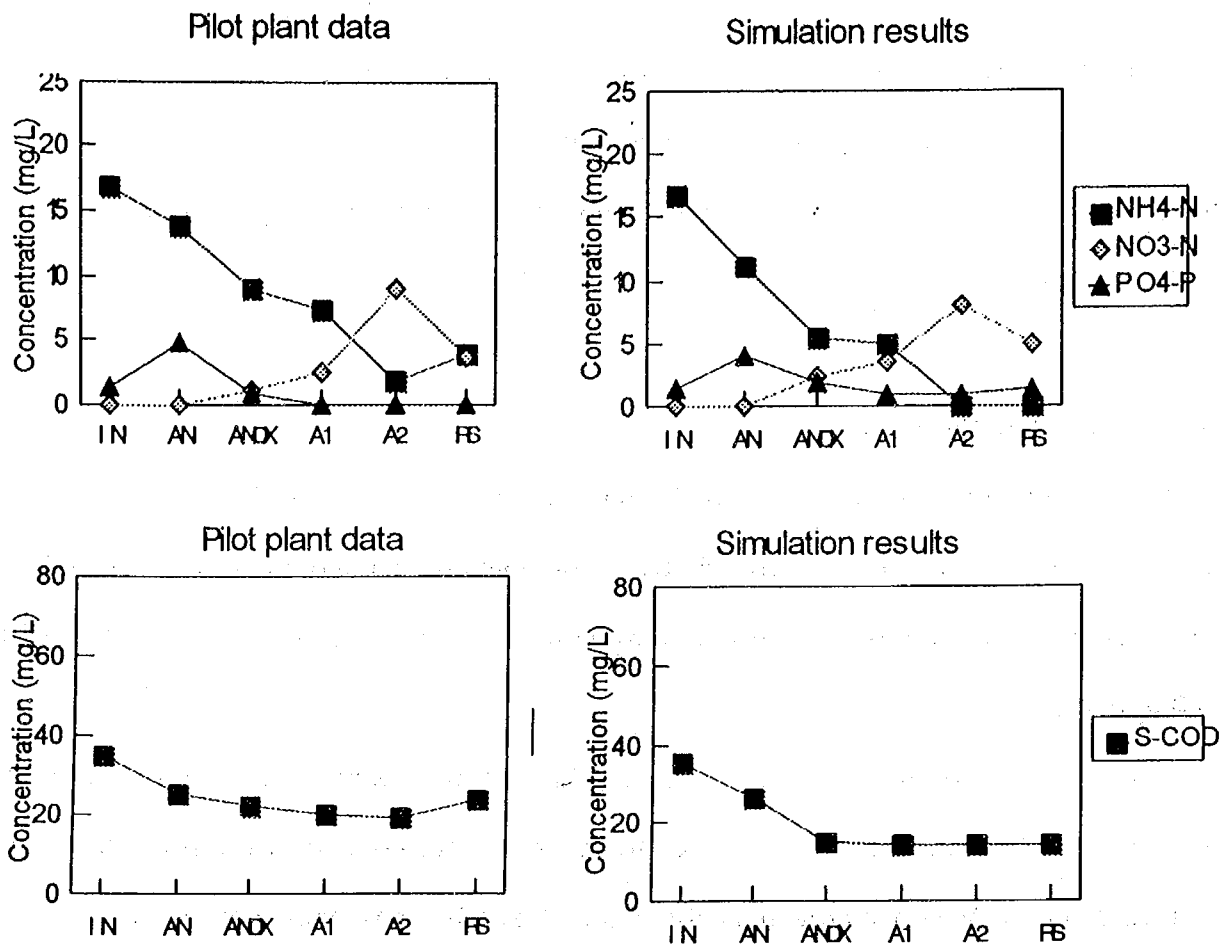


Fig. 5.9 Calculated water quality in the case of diluted influent with parameter values fitted for normal influent

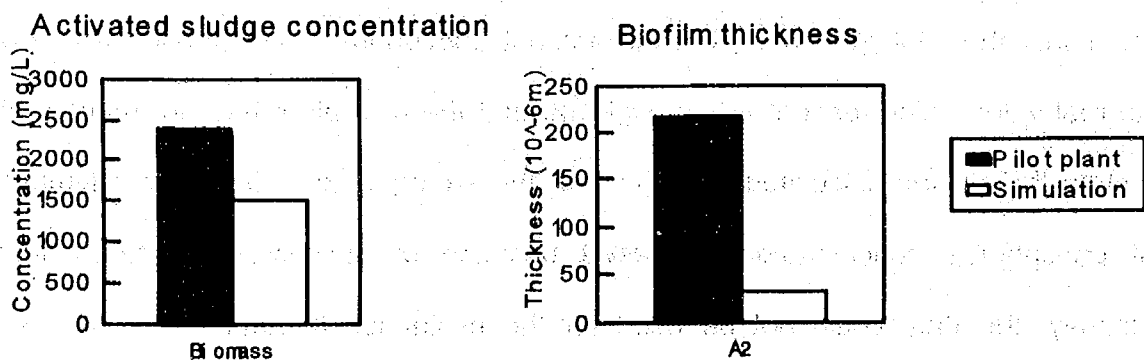


Fig. 5.10 Calculated biomass concentration in the case of diluted influent with parameter values fitted for normal influent

6 Prediction of other processes with model developed

Treatment efficiencies without the media were calculated for two cases using the model developed. One is the process which has the same reactor volume as the one shown in Fig. 3.1 but doesn't have the media in the aerobic cells. The other is the process which has big enough aerobic volume to achieve nitrification but doesn't have the media in the aerobic cells. The withdrawal rate of excess sludge from these process was set the same as that of the combined new process.

The calculation results are shown in Fig. 6.1. If the reactor volume is as same as the combined new process, no nitrification occurs because of the too short aerobic solids retention time (≈ 7 days) for the growth of nitrifiers, but phosphorus removal is good. On the other hand, if the aerobic volume is big enough for the nitrifier growth, nitrogen removal is good, but phosphorus cannot be removed to a low level, which is caused by the longer solids retention time (28 days).

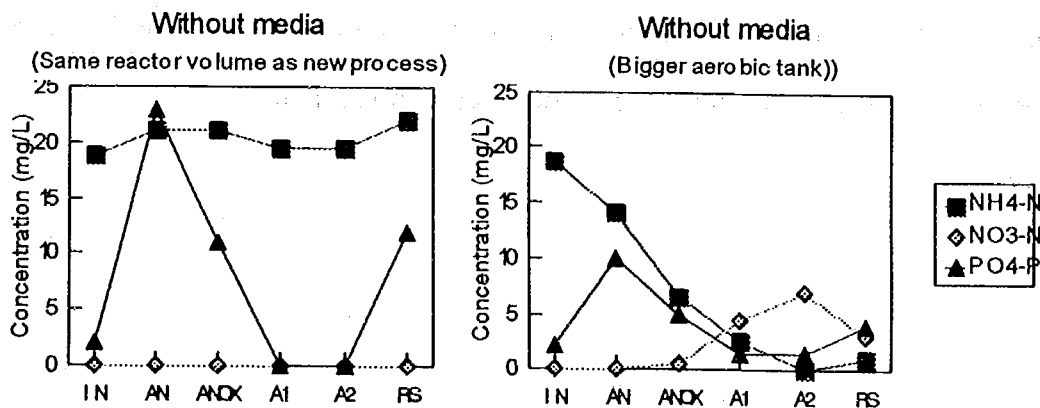


Fig. 6.1 Calculation results of the processes without media in the aerobic cells

7 Conclusions

A simulation model was developed for a nutrients removal process which consisted of an activated sludge process of three zones (anaerobic, anoxic and aerobic) and a biofilm process in the form of a fluidized bed in the aerobic zone.

Firstly a biofilm model was developed by modifying an existing model in terms of components, biological processes and a detachment mechanism, using the experimental results of the fluidized bed process. In the case of the low organic load, the model with biofilm detachment from every part of a biofilm showed a good agreement with the experimental results.

Secondly the biofilm model was incorporated into the IAWQ Activated Sludge Model No.2. Modification was made in terms of components, and a mechanism of transferring detached biofilm to the activated sludge was added. Development and evaluation of the model were made using the data of a pilot plant.

The model of the combined activated sludge and biofilm process expressed the water quality of the pilot plant well. However, improvement was necessary for the calculation of the biofilm thickness and the nitrifier concentration in the biofilm.

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