Chapter 11

Biological Processes

11.1 INTRODUCTION

The primary objective of biological wastewater treatment processes is the conversion of biodegradable organics into a microbial biomass that can be separated by appropriate solids/liquid separation processes such as sedimentation, flotation, membrane filtration, etc.

Most organic wastewaters contain relatively low concentrations of organic matter and can be dealt with efficiently and economically by aerobic treatment processes, in which part of the organic matter is converted to carbon dioxide through microbial respiration and part is converted to microbial biomass residue.

More concentrated wastewaters and organic suspensions, such as sewage sludge, can also be effectively stabilized anaerobically. Anaerobic wastewater treatment converts organic matter to methane and carbon dioxide and also to an anaerobic biomass residue.

The technology of biological processes is concerned with the design of reactor vessels, that provide an optimum environment for microbial growth and in which a high microbial biomass concentration can be developed. Aerobic process units require a continuous input of oxygen to support microbial respiration, while oxygen must be completely excluded from anaerobic wastewater treatment processes, being acutely toxic to the methanogenic bacteria.

Biological wastewater treatment processes may be of the suspended floc type, the so-called activated sludge processes, or of the attached film type, the so-called biofilter systems. In suspended floc systems (discussed in detail in Chapter 12), the active microbial biomass forms a dispersed aqueous suspension, with which the waste stream is brought into contact by a mixing system. In attached film processes (discussed in detail in Chapter 13), the active biomass is attached as a film to a solid medium of stone or plastic material. The wastewater is brought into contact with the active biomass while flowing over the medium surface as a thin stream. Aerobic filters are typically operated in a trickling downflow mode, which permits free air movement within the filter medium. They can also be operated in submerged downflow mode with a counter-current air flow to provide the necessary oxygen input to meet the microbial respiration demand. Anaerobic filters are generally operated in an upflow flooded mode, effectively excluding air.

11.2 FACTORS AFFECTING MICROBIAL GROWTH

11.2.1 Energy and cell synthesis

Microbial growth results from the conversion of dissolved organic matter plus certain inorganic trace elements into cell protoplasm through a complex train of metabolic reactions. The terms respiration and fermentation are commonly applied to those metabolic reactions that produce the energy required for cell synthesis.

All living organisms use a common firm of energy storage. Whatever the energy source, energy derived from that source is stored in the form of adenosine triphosphate (ATP). The hydrolysis of ATP to adenosine diphosphate (ADP) is an exergonic (energy-producing) reaction, which releases about 7000 calories per mole of ATP. Organisms couple the energy released upon hydrolysis of ATP with the endergonic (energy-requiring) reactions associated with the synthesis of cellular macromolecules such as proteins, lipids, polysaccharides and nucleic acids. This is illustrated in Fig 11.1, which shows the synthesis of a compound AB through the coupling of endergonic reaction $A + B \rightarrow AB$ with the exergonic reaction $ATP \rightarrow ADP + P_i$, where P_i denotes inorganic phosphate.

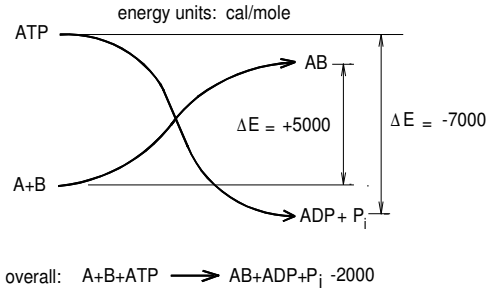

Fig 11.1 Coupling of synthesis with the hydrolysis of ATP

The energy required to form ATP from ADP is derived from the biochemical degradation of organic compounds. In respiring organisms this energy is released through substrate oxidation, the electrons released being passed via electron carriers to terminal electron acceptors. Under aerobic conditions the terminal electron acceptor is oxygen ($O_2 \rightarrow H_2O$), while in non-aerobic respiration the terminal electron acceptor may be nitrate ($NO_3^- \rightarrow N$) or sulphate ($SO_4^- \rightarrow S$).

The generation of ATP through fermentation takes place under anaerobic conditions and involves the production of an energy-rich phosphorylated intermediate, which is capable of donating its phosphate group to ADP to form ATP. Fermentation is an inefficient process for releasing the available energy in the substrate, leaving most of in the fermentation products. For example, in the fermentation of glucose to form lactic acid only about 2% of the potentially available energy in glucose is captured for ATP formation. ATP formation is thus the major growth-limiting factor in fermentation systems.

The large difference in energy production efficiency between respiration and fermentation systems has important consequences in biological wastewater treatment systems. Aerobic systems, served by efficient energy-releasing respiration, generate large amounts of active biomass residue in the form of surplus sludge, while anaerobic processes, deriving their energy by the fermentation route, generate far less biomass and produce energy-rich methane gas as an end-product.

Fig 11.2 shows a schematic representation of biological processes.

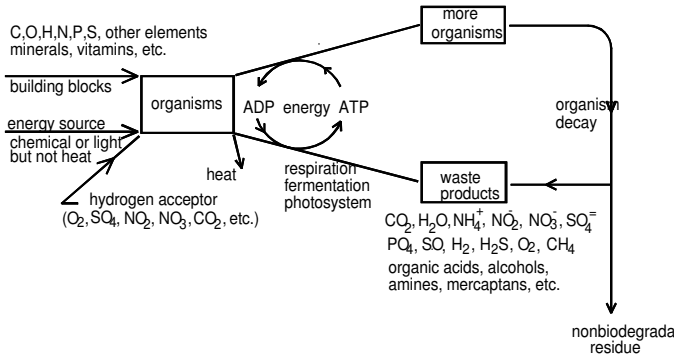

Fig 11.2 Schematic representation of biological processes

11.2.2 Nutrient requirements

Water is the major constituent of microbial cells (75-90% by weight). The elemental composition of the cellular solid fraction varies somewhat, depending on environmental conditions and the species of microorganism. The typical cell composition for the widely distributed bacterium *Escherichia coli* is given in Table 11.1.

Table 11.1
Typical elemental cell composition
For *Escherichia coli*

Element	Dry weight (%)
Carbon	50
Oxygen	20
Nitrogen	14
Hydrogen	8
Phosphorus	3
Sulphur	1
Potassium	1
Sodium	1
Calcium	0.5
Magnesium	0.5
Chlorine	0.5
Iron	0.2
All others	0.3

The four elements , carbon, oxygen, nitrogen and hydrogen, make up more than 90% of the cell dry weight. These elements, plus phosphorus and sulphur, constitute the macromolecules of the cell. The remaining 4% of the cell dry matter includes a large number of elements – potassium, sodium, calcium, magnesium, chlorine, iron, manganese, cobalt, copper, boron, zinc, molybdenum and others. Porges (1956) suggested the formula $C_5H_7NO_2$ for the stoichiometric elemental proportions of a heterogeneous microbial population.

Heterotrophic microorganisms can use a great variety of organic compounds as sources of cell carbon, while autotrophic organisms use carbon dioxide as the sole carbon source. The cell nitrogen requirements may be derived from organic or inorganic nitrogen sources. Inorganic nitrogen forms include ammonia (NH_3), nitrate (NO_3^-), nitrite (NO_2^-) and gaseous nitrogen (N_2). Ammonia is the most readily utilizable form of inorganic nitrogen. A limited number of bacteria are capable of using gaseous nitrogen as the nitrogen source (the nitrogen-fixing bacteria). A general classification of microorganisms by their sources of energy and carbon is given in Table 11.2.

Table 11.2 Classification of microorganisms by energy and carbon source

Designation	Energy source	Carbon source
Autotrophic:		
photosynthetic	light	CO_2
chemosynthetic	inorganic oxidation-reduction reaction	CO_2
Heterotrophic	Organic oxidation-reduction reaction	Organic carbon

The requirements for the major nutrients nitrogen and phosphorus are generally considered to be satisfied (Pipes, 1979: Speece and McCarty, 1964) by the following threshold nutrient ratios:

	BOD_5 : N : P
aerobic processes:	100 : 5 : 1
anaerobic processes:	100 : 0.5 : 0.1

11.2.3 Influence of temperature

Of the physical factors affecting microbial growth in any environment, temperature is one of the most influential in the selection of species. Temperature affects growth in two opposing ways:

(1) According to the Arrhenius relationship (equation (1.5)), an increase in temperature speeds up chemical enzymatic reactions and, therefore, microbial growth and product formation;

(2) With rising temperature, proteins, nucleic acids and other cellular components that are sensitive to temperature, i.e. temperature labile, will tend to become irreversibly deactivated and lysis, death and endogenous metabolism rates will increase. Hydrolysis rates will also increase with temperature.

For every organism there is:

(1) a minimum temperature below which no growth occurs;

(2) an optimum temperature at which organisms grow most rapidly; and

(3) a maximum temperature above which no growth occurs.

The temperature range over which microbial growth can occur is usually considered to be between –12 ^{o}C and +120 ^{o}C (Hamer, 1995; Sonnleitner and Fiechter, 1983). While no single microbe can grow throughout this range, most organisms are eurythermal, i.e. they are capable of growing over a fairly wide temperature range of some 30-40 ^{o}C. The characteristic relationship between the specific growth rate constant μ and temperature is shown in Fig 11.3 (the specific growth μ (d^{-1}) is correlated with the doubling time t_d according to the relation $\mu = \ln (2./t_d)$. This plot is characterized by four growth zones: (a) zone I extends from the lowest temperature of growth to the temperature at which the growth rate increases at a logarithmic rate; (b) zone II is the temperature range of logarithmic growth rate increase, as predicted by the Arrhenius relationship for chemical reactions (equation (1.5)); (c) zone III is the optimum temperature range, which extends from the upper temperature limit for logarithmic growth to the temperature of maximum growth rate; and (d) zone IV is the super-optimum range, in which the growth rate declines rapidly with increasing temperature. The latter range typically does not extend more than about 6 ^{o}C above the temperature of maximum growth rate. For most organisms the growth rate increases two- to three-fold for each 10 ^{o}C rise in temperature in the logarithmic temperature range (zone II in Fig 11.3).

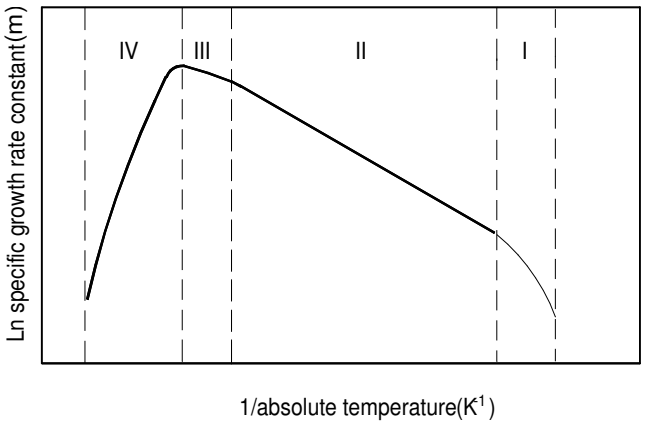

Fig 11.3 Influence of temperature on microbial growth

The main groups of organisms, classified on the basis of temperature, are:

(1) Psychrophiles (temperature optima < 10 ^{o}C)
(2) Psychrotrophs or facultative psychrophiles (grow well below 10 ^{o}C, but have temperature optima > 10 ^{o}C).
(3) Mesophiles (temperature optima 10 ^{o}C – 40 ^{o}C)
(4) Thermotolerant strains (temperature optima 45 ^{o}C–60 ^{o}C)
(5) Thermophiles (temperature optima >60 ^{o}C)
(6) Caldoactive strains (temperature optima >75 ^{o}C)
(7) Barothermotolerant strains (temperature optima <100 ^{o}C, maximum >100 ^{o}C)
(8) Barothermophiles (temperature optima >100 ^{o}C, maximum >100 ^{o}C)

11.2.4 Influence of pH

Each microbial species can grow within a specified pH range, which typically extends over 3 or 4 pH units, with optimum growth rate near the midpoint of the range.

Most bacteria grow in the pH range 5-9 and have an optimum near to neutrality.

Most fungi prefer an acid environment with a pH optimum near 5.

The anaerobic degradation of carbohydrates, producing organic acids, causes a lowering of the environmental pH to the region 4.5-5.0, as a result of which fermentation is inhibited or stopped. In such cases fermentation acts as a preservative process, as for example, in the ensilage of grass to provide winter feed for cattle.

The sulphur-oxidizing bacteria (Thiobacillus), which oxidize reduced sulphur compounds to sulphate (SO_4^-), creating a highly acidic environment (production of H_2SO_4), are capable of growth at pH 1.0 or less.

The anaerobic methane-producing bacteria, which have a particular importance in wastewater treatment, are very sensitive to pH. Their pH growth range is 6.4-7.6, which is unusually narrow.

11.2.5 Oxygen and microbial growth

Organisms that require dissolved oxygen for survival are classified as obligate aerobes. Those that cannot grow in the presence of oxygen are classified as obligate anaerobes. Those that can grow with or without oxygen are classified as facultative anaerobes.

Obligate aerobes and facultative anaerobes are to be found among the bacteria, fungi and protozoa. Bacteria constitute the main group of obligate anaerobes, although some protozoa are also obligate anaerobes.

Dissolved oxygen can be toxic to aerobic microorganisms at supersaturated concentration. Anaerobic microorganisms are usually quite sensitive to oxygen although a few are aerotolerant. Obligate anaerobes are killed by exposure to oxygen. This sensitivity to oxygen may be extreme, as in the case of the methane bacteria.

11.3 KINETICS OF MICROBIAL GROWTH

A knowledge of microbial kinetics, i.e. the rate of conversion of biochemical substrate to end-products and the factors that determine these rates, is essential as a rational basis for process design. The kinetics

of microbial growth in the mixed culture environment, characteristic of biological wastewater treatment reactors, are normally based on an adaptation (Lawrence and McCarty, 1970) of the kinetic model of Monod (1950), which was derived for continuous-growth pure-culture systems.

Consider a suspended microbial biomass growing in a liquid medium containing the necessary nutrients for growth. The rate of change in microbial concentration X (mg l^{-1}) with time (t(d) is the net sum of growth and decay processes:

Net microbial growth rate $$\frac{dX}{dt} = \mu X - k_d X \quad \text{mg } l^{-1} \text{ d}^{-1} \qquad (11.1)$$

Where μ is the specific growth rate coefficient (d^{-1}) and k_d is the decay coefficient (d^{-1}). According to the Monod growth model, the dependence of the specific growth rate coefficient on substrate concentration is expressed as follows:

$$\mu = \hat{\mu}\left(\frac{S}{K_s + S}\right) \qquad (11.2)$$

where $\hat{\mu}$ is the maximum specific growth rate constant at the saturation concentration of the growth-limiting substrate (d^{-1}), S is the substrate concentration (mg l^{-1}), and K_s is the saturation constant, which is the substrate concentration at which the specific growth rate is half the maximum specific growth rate. Combining equations (11.1) and (11.2) results in the following expression for the net microbial growth rate:

net microbial growth rate: $$\frac{dX}{dt} = \frac{\hat{\mu} XS}{K_s + S} - k_d X \qquad \text{mg } l^{-1} \text{ d}^{-1} \qquad (11.3)$$

The rate of reduction of substrate concentration S is related to the microbial growth rate by the mass balance relation:

$$-\frac{dS}{dt} = \frac{\hat{\mu} XS}{Y(K_s + S)} \qquad (11.4)$$

where Y is the yield coefficient.

The dependence of the specific growth rate m on substrate concentration S (equation (11.2)) is illustrated graphically in Fig 11.4. The shape of this curve is influenced by the values of the two regulating constants, the saturation constant Ks and the maximum specific growth rate $\hat{\mu}$. In particular, the saturation constant K_s is a key parameter in relation to microbial competition for food at low substrate concentration, such as might be the case in wastewater treatment processes producing well-stabilised effluents. In such growth-limiting environments, those organisms with the greatest affinity for the substrate (low K_s values, i.e. rapid growth at low substrate concentration) will outgrow those with the least affinity for the substrate (high K_s values), to become the dominant species in the microbial population. At high substrate concentrations, on the other hand, the growth rate is largely determined by the magnitude of the maximum specific growth rate constant, $\hat{\mu}$. These characteristic effects of K_s and $\hat{\mu}$ are illustrated in Fig 11.4, which shows the specific growth rate variations for two heterotrophic organisms, A and B, as a function of substrate concentration. Organism A has a lower K_s value than organism B and hence grows more rapidly than organism B at low substrate concentration. Organism B has a higher $\hat{\mu}$ value than organism A and hence grows more rapidly than organism A at high substrate concentration.

It is important to emphasise that the foregoing mathematical model of the microbial growth process is a gross simplification of what is acknowledged to be a very complex process. The complexity is compounded is biological wastewater treatment processes due to the heterogeneous nature of both the substrate and microbial population. The situation is further complicated by the fact that the model parameters can be expressed in a variety of units. For example, the organic carbon substrate

concentration may be expressed in a number of alternative units, including BOD, COD, TOC and volatile solids.

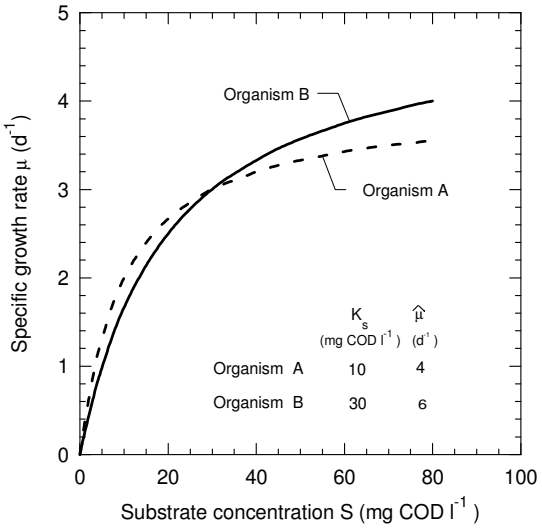

Fig 11.4 **Influence of substrate concentration on specific microbial growth rate**

Substrate nitrogen compounds are conventionally expressed in equivalent nitrogen concentration units, e.g. NH_3-N, NO_3-N. Because it is not feasible to measure the concentration of living organisms in the microbial biomass, the value assigned to the parameter X is usually the volatile fraction of the suspended biomass concentration. It is not surprising, therefore, that the values reported in the literature for the foregoing kinetic coefficients show a wide variation, depending on process environmental conditions and wastewater composition.

Typical model parameter values for the activated sludge process (heterotrophic and autotrophic growth) are given in Table 11.3, while a corresponding set of typical parameter values for the anaerobic digestion process (methanogenic organism growth) are given in Table 11.4.

Table 11.3 Typical model parameter values for the activated sludge process

Parameter	Unit	Value at	
		20 °C	10 °C
Y_A	g cell COD formed per g N oxidised	0.2-0.3	0.2-0.3
Y_H	g cell COD formed per g COD oxidised	0.5-0.7	0.5-0.7
$\hat{\mu}_H$	d^{-1}	4-6	2-4
$\hat{\mu}_A$	d^{-1}	0.6-0.8	0.3-0.4
K_s	g COD m^{-3}	10-80	10-80
K_{NO}	g NO3-N m^{-3}	0.3-0.6	0.3-0.6
K_{NH}	g NH_3-N	0.8-1.2	0.8-1.2
k_d	d^{-1}	0.06-0.1	0.02-0.06

Source: Gray (1990); Horan (1990); IAWPRC (1987)

It is clear from the relative values for the kinetic coefficients presented in Table 11.3 that the heterotrophic organisms grow much more rapidly than the autotrophs ($\hat{\mu}_H >> \hat{\mu}_A$). The low value of $\hat{\mu}_A$ also has implications for the minimum residence time required for autotrophic process

applications, such as nitrification, as discussed in section 11.5. It is also noteworthy that the substrate saturation constants for nitrification and denitrification process, K_{NH} and K_{NO}, respectively, are very low, making these processes virtually zero-order processes with respect to substrate.

Table 11.4 Typical model parameter values for the anaerobic digestion process

Parameter	Unit	Value at 20 °C	Value at 10 °C
$\hat{\mu}_{AN}$	d^{-1}	0.15-0.25	0.30-0.45
K_{AC}	g CH_3COOH* m^{-3}	300-400	100-200
Y	g cell VSS (g $CH_3COOH)^{-1}$	0.04-0.06	0.04-0.06
k_d	d^{-1}	0.01-0.015	0.015-0.02

*Acetic acid

Source: Metcalf and Eddy Inc. (1974); Bailey & Ollis (1986)

The influence of oxygen concentration on aerobic process kinetics may also be modelled by a Monod type function:

$$\frac{dX}{dt} = X(\mu - k_d)\left(\frac{DO}{K_o + DO}\right) \qquad (11.5)$$

where DO is the dissolved oxygen concentration (mg l^{-1}) and K_o is the oxygen saturation constant. K_o has a value of about 0.2 mg l^{-1} for heterotrophs and a value of about 0.4 mg l^{-1} for autotrophs.

Much research effort has been devoted to the development of more comprehensive model descriptions of biological growth processes in wastewater treatment. The Task Group on Modelling of Biological Processes of the International Association for Water Pollution Research and Control has developed multi-parameter activated sludge models (IAWPRC, 1987, 1994), incorporating carbon, nitrogen and phosphorus removal. The modelling approach is based on Monod process kinetics and first-order microbial decay, as outlined above, but is extended to take into account the range of conditions encountered in practice. A total of seven dissolved and six particulate components are used to characterise the wastewater and the sludge. In addition to dissolved oxygen and alkalinity, these include two forms of biomass, seven fractions of COD (organic material) and four fractions of nitrogen. Nine transformation processes are included; three relate to the growth of heterotrophic biomass, two represent decay of biomass and four describe 'hydrolysis' processes, in which complex organic matter is made available for biodegradation in the form of simpler molecules (Gujer and Henze, 1991).

Insert some comments on anaerobic process kinetics

11.4 BIOLOGICAL REACTORS

Biological processes are carried out in tank reactors under controlled conditions. Depending on their flow characteristics, reactors can be classified as being of the plug-flow, mixed-flow or arbitrary-flow type. The ideal plug-flow reactor is completely unmixed, all fluid elements having the same residence time – the influent moves through the tank as a plug. The completely mixed reactor is totally devoid of gradients in composition or temperature. The arbitrary-flow reactor has mixing characteristics which fall between complete mix and plug-flow. Many practical reactors fall into this latter category. Tracer output curves, illustrating the flow characteristics of these reactors, are shown in Fig 11.5.

In plug-flow reactors with a continuous tracer input the first output trace appears after a time interval t_d, where t_d is the nominal detention time, i.e. $t_d = V/Q$; the concentration thereafter is the same as the

influent concentration C_0. Where the input is a tracer slug, the output profile is found from mass balance considerations, as follows:

$$V\frac{dX}{dt} = Q(C_0 - C) \tag{11.6}$$

which integrates to give:

$$C = C_0\left(1 - e^{-t/t_d}\right) \tag{11.7}$$

Where the input to a completely mixed reactor is a tracer slug, the output profile is similarly found from mass balance considerations:

$$-V\frac{dC}{dt} = QC \tag{11.8}$$

which integrates to give:

$$C = C_0 e^{-t/t_d} \tag{11.9}$$

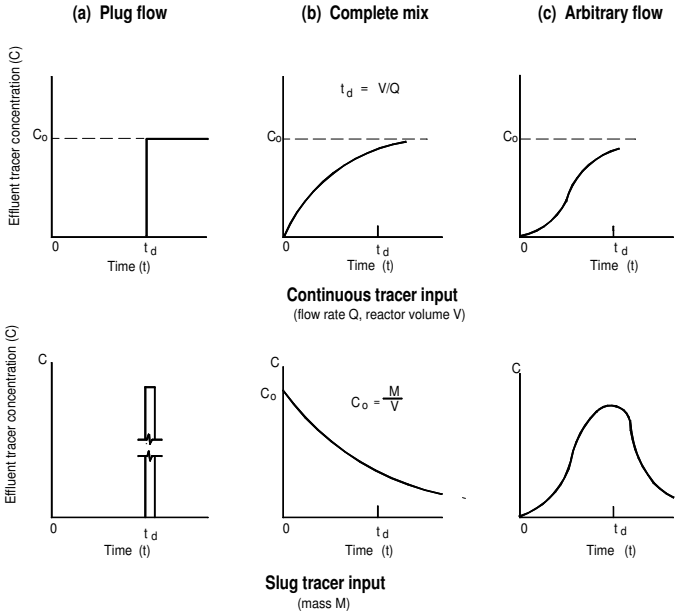

Fig 11.5 **Output tracer profiles for continuous and slug tracer inputs to plug-flow, complete-mix and arbitrary flow reactors**

11.5 APPLICATION OF KINETICS TO A MIXED FLOW REACTOR

A microbial mass balance equation for a completely mixed reactor of volume V (m^3), operating at steady state, may be written as follows:

$$V\frac{dX}{dt} = 0 = VX_t - M_t \tag{11.10}$$

where X_t is the net microbial growth rate and M_t is the rate of removal of microbial biomass from the reactor. Combining equations (11.1), (11.2) and (11.10):

$$M_t = V\left(\frac{\hat{\mu}XS}{K_s + S} - k_d X\right) \tag{11.11}$$

or

$$\frac{M_t}{VX} = \hat{\mu}\left(\frac{S}{K_s + S}\right) - k_d \tag{11.12}$$

hence

$$\frac{1}{\theta_s} = \hat{\mu}\left(\frac{S}{K_s + S}\right) - k_d \tag{11.13}$$

where θ_s is the microbial solids residence time. From equation (11.13) the effluent substrate concentration S may be expressed as a function of θ_s:

$$S = \frac{K_s(1 + k_d\theta_s)}{\theta_s(\hat{\mu} - k_d) - 1} \tag{11.14}$$

Thus θ_s, the microbial solids residence time is identified as a key biological process variable. It will be noted from equation (11.14) that, in a mixed reactor, the substrate concentration S (which is also the effluent substrate concentration) is uniquely determined by θ_s and is independent of the inflow substrate concentration and the hydraulic residence time. S is plotted as a function of θ_s in Fig 11.6 for a mixed aerobic reactor, and in Fig 11.7 for a mixed anaerobic reactor, based on the sets of kinetic and stoichiometric coefficients noted on the diagrams.

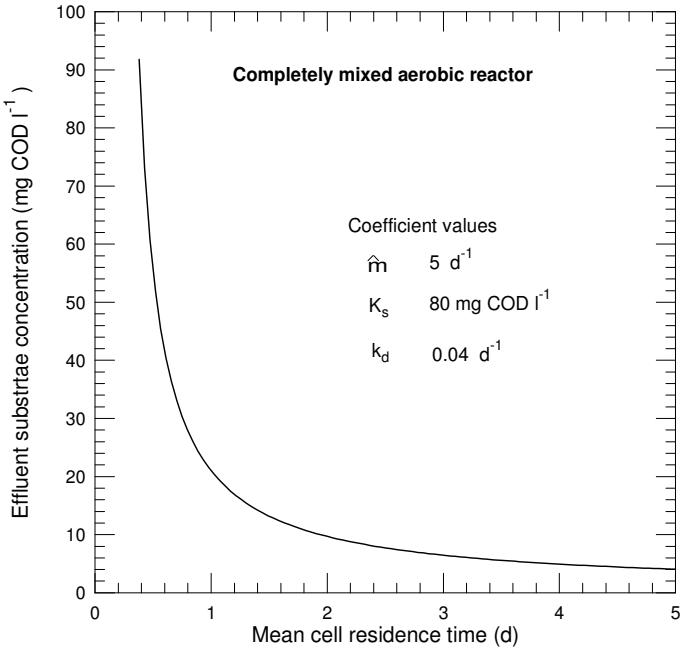

Fig 11.6 **Influence of mean cell residence time on effluent substrate concentration**

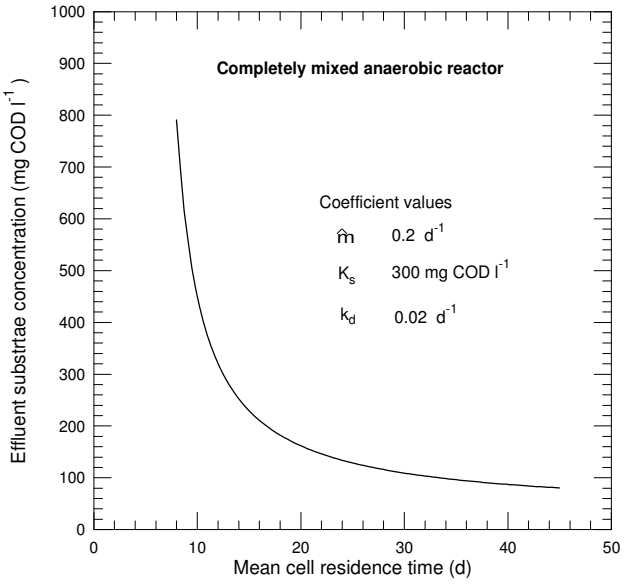

Fig 11.7 **Influence of mean cell residence time on effluent substrate concentration**

The plotted results indicate that the microbial residence time required for stable operation in anaerobic processes is an order of magnitude greater than in aerobic processes and also, because of the much higher K_s value for anaerobic processes, it is not feasible to reduce substrate concentration to a very low level by anaerobic processes. As well as the foregoing kinetic differences between aerobic and anaerobic microbial processes, the stoichiometric differences are also of considerable process significance. The relatively high Y value for aerobic processes means that they produce a much higher yield of microbial biomass than anaerobic processes.

It will be noted from Figs 11.6 and 11.7 that the microbial solids residence time converges to a lower limiting value, approaching which there is a steep increase in substrate concentration. This minimum microbial residence time θ_{sm} can be estimated from equation (11.13) by making the assumption that S is large compared with Ks, resulting in the relation:

$$\frac{1}{\theta_{sm}} = \hat{\mu} - k_d \qquad (11.15$$

On the basis of the kinetic coefficient values for the aerobic and anaerobic coefficient values for the aerobic and anaerobic systems used in Figs 11.6 and 11.7, respectively, the minimum microbial residence times are calculated to be:

aerobic:	θ_{sm} = 0.2 d
anaerobic:	θ_{sm} = 5.6 d

For efficient process operation, it is necessary to have a high microbial population in the reactor. This is commonly achieved by microbial sludge recycle from a downstream sedimentation tank and can also be enhanced by appropriate reactor design so as to maximise microbial biomass retention.

The steady-state microbial biomass concentration X in a mixed reactor of volume V, having a microbial residence time θ_s, an influent volumetric flow rate Q and an influent substrate concentration S_i is derived from the relation:

$$\frac{VX}{YQ(S_i - S) - Vk_dX} = \theta_s \qquad (11.16)$$

which gives:

$$X = \frac{Y(S_i - S)\theta_s}{\theta_H(1 + k_d\theta_s)} \qquad (11.17)$$

where θ_H is the hydraulic retention time equal to V/Q.

The surplus microbial biomass (SS) produced under these operating conditions is:

surplus active biomass: $SS = YQ(S_i - S) - Vk_dX$ (11.18)

Combining equations (11.17) and (11.18):

$$SS = \frac{YQ(S_i - S)}{(1 + k_d\theta_s)} \qquad (11.19)$$

The actual production of excess sludge in an activated sludge process will exceed the foregoing estimate of production of active microbial biomass, owing to the inclusion of inert matter and dead microbial cell residues.

11.6 PLUG-FLOW REACTOR KINETICS

A plug-flow reactor (PFR) differs from a completely mixed reactor (CMR) in that there is a substrate concentration gradient from a maximum value at the inlet end to a minimum value at the outlet end. It follows from this that, where a PFR and a CMR are both producing the same quality effluent under identical operating conditions, the required volume of the PFR will be less than that of the CMR because the average reaction rate in the PFR is higher than the common reaction rate throughout the CMR volume. It is not feasible to quantify the effluent substrate concentration for a PFR in terms of the operational parameters, as has been done for the CMR. However, the hydraulic retention time (V/Q) required in a PFR in order to reduce the substrate concentration to a specified level can be determined by numerical computation as follows:

$$\Delta V = \frac{Q\Delta S}{S_t} \qquad (11.20)$$

where ΔV is the reactor volume required to achieve a substrate reduction of ΔS, S_t is the substrate removal rate, and Q is the flow rate. In a PFR, S_t has a maximum value at the inlet end and a minimum value at the outlet end. The hydraulic retention time θ_H may be expressed in the form:

$$\theta_H = \sum \frac{\Delta V}{Q} = \sum \frac{\Delta S}{S_t} \qquad (11.21)$$

where the summation value for S varies from the influent substrate concentration S_i to the effluent substrate concentration S_e. The corresponding expression for a CMR is

$$\theta_H = \frac{S_i - S_e}{S_t} \qquad (11.22)$$

where the substrate uptake rate S_t is constant and based on the value of S_e.

Fig 11.8 compares the computed relative values of θ_H (and hence also the relative reactor sizes) for PFR and CMR reactors, based on the following assumed values for kinetic coefficients:

$\hat{\mu}$ = 5 d^{-1}; K_s = 80 mg COD l^{-1}; Y = 0.5; and k_d = 0.05 d^{-1}.

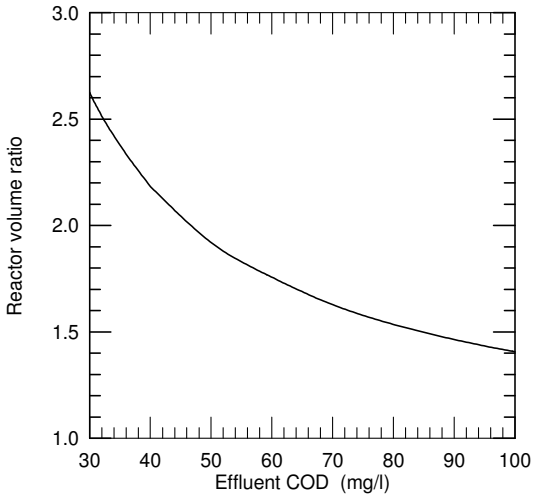

Fig 11.8 **CMR:PFR volume ratio to reduce an influent COD concentration from 600 mg l^{-1} to the indicated effluent value**

Since the mean specific substrate conversion rate in a CMR reactor is proportional to the effluent substrate concentration, it to be expected that the volumetric advantage of the PFR reactor over its CMR counterpart increases as the effluent substrate concentration is reduced. As Fig 11.8 indicates, the calculated reactor volume ratio reduces from 2.6 at a COD concentration of 30 mg l^{-1} to a value of 1.4 at a COD value of 100 mg l^{-1}.

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