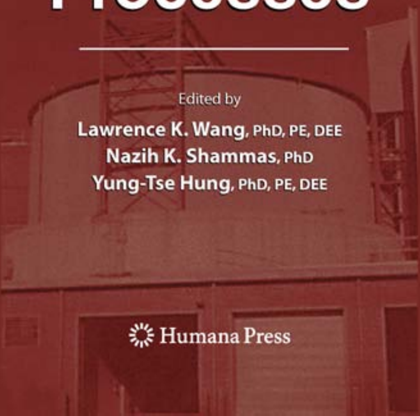
HANDBOOK OF ENVIRONMENTAL ENGINEERING™ VOLUME 9

Advanced Biological Treatment Processes



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Humana Press

Advanced Biological Treatment Processes

Humana Press
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ISBN: 978-1-58829-360-2 e-ISBN: 978-1-60327-170-7

DOI: 10.1007/978-1-60327-170-7

Library of Congress Control Number: 2008931192

Printed on acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

Preface

The past 30 years have seen the emergence of a growing desire worldwide that positive actions be taken to restore and protect the environment from the degrading effects of all forms of pollution—air, water, soil, and noise. Because pollution is a direct or indirect consequence of waste, the seemingly idealistic demand for "zero discharge" can be construed as an unrealistic demand for zero waste. However, as long as waste continues to exist, we can only attempt to abate the subsequent pollution by converting it to a less noxious form. Three major questions usually arise when a particular type of pollution has been identified: (1) How serious is the pollution? (2) Is the technology to abate it available? and (3) Do the costs of abatement justify the degree of abatement achieved? This book is one of the volumes of the *Handbook of Environmental Engineering* series. The principal intention of this series is to help readers formulate answers to the last two questions above.

The traditional approach of applying tried-and-true solutions to specific pollution problems has been a major contributing factor to the success of environmental engineering, and has accounted in large measure for the establishment of a "methodology of pollution control." However, the realization of the ever-increasing complexity and interrelated nature of current environmental problems renders it imperative that intelligent planning of pollution abatement systems be undertaken. Prerequisite to such planning is an understanding of the performance, potential, and limitations of the various methods of pollution abatement available for environmental scientists and engineers. In this series of handbooks, we will review at a tutorial level a broad spectrum of engineering systems (processes, operations, and methods) currently being used, or of potential use, for pollution abatement. We believe that the unified interdisciplinary approach presented in these handbooks is a logical step in the evolution of environmental engineering.

Treatment of the various engineering systems presented will show how an engineering formulation of the subject flows naturally from the fundamental principles and theories of chemistry, microbiology, physics, and mathematics. This emphasis on fundamental science recognizes that engineering practice has in recent years become more firmly based on scientific principles rather than on its earlier dependency on empirical accumulation of facts. It is not intended, though, to neglect empiricism where such data lead quickly to the most economic design; certain engineering systems are not readily amenable to fundamental scientific analysis, and in these instances we have resorted to less science in favor of more art and empiricism.

Because an environmental engineer must understand science within the context of application, we first present the development of the scientific basis of a particular subject, followed by exposition of the pertinent design concepts and operations, and detailed explanations of their applications to environmental quality control or remediation. Throughout the series, methods of practical design and calculation are illustrated by numerical examples. These examples clearly demonstrate how organized, analytical reasoning leads to the most direct and clear solutions. Wherever possible, pertinent cost data have been provided.

Our treatment of pollution-abatement engineering is offered in the belief that the trained engineer should more firmly understand fundamental principles, be more aware of the similarities and/or differences among many of the engineering systems, and exhibit greater flexibility and originality in the definition and innovative solution of environmental pollution problems. In short, the environmental engineer should, by conviction and practice, be more readily adaptable to change and progress.

Coverage of the unusually broad field of environmental engineering has demanded an expertise that could only be provided through multiple authorships. Each author (or group of authors) was permitted to employ, within reasonable limits, the customary personal style in organizing and presenting a particular subject area; consequently, it has been difficult to treat all subject material in a homogeneous manner. Moreover, owing to limitations of space, some of the authors' favored topics could not be treated in great detail, and many less important topics had to be merely mentioned or commented on briefly. All authors have provided an excellent list of references at the end of each chapter for the benefit of interested readers. As each chapter is meant to be self-contained, some mild repetition among the various texts was unavoidable. In each case, all omissions or repetitions are the responsibility of the editors and not the individual authors. With the current trend toward metrication, the question of using a consistent system of units has been a problem. Wherever possible, the authors have used the British system (fps) along with the metric equivalent (mks, cgs, or SIU) or vice versa. The editors sincerely hope that this duplicity of units' usage will prove to be useful rather than being disruptive to the readers.

The goals of the *Handbook of Environmental Engineering* series are: (1) to cover entire environmental fields, including air and noise pollution control, solid waste processing and resource recovery, physicochemical treatment processes, biological treatment processes, biosolids management, water resources, natural control processes, radioactive waste disposal, and thermal pollution control; and (2) to employ a multimedia approach to environmental pollution control because air, water, soil, and energy are all interrelated.

As can be seen from the above handbook coverage, no consideration is given to pollution by type of industry, or to the abatement of specific pollutants. Rather, the organization of the handbook series has been based on the three basic forms in which pollutants and waste are manifested: gas, solid, and liquid. In addition, noise pollution control is included in the handbook series.

This particular book Volume 9, *Advanced Biological Treatment Processes*, is a sister book to Volume 8 *Biological Treatment Processes.* Both books have been designed to serve as comprehensive biological treatment textbooks as well as wide-ranging reference books. We hope and expect it will prove of equal high value to advanced undergraduate and graduate students, to designers of water and wastewater treatment systems, and to scientists and researchers. The editors welcome comments from readers in all of these categories.

The editors are pleased to acknowledge the encouragement and support received from their colleagues and the publisher during the conceptual stages of this endeavor. We wish to thank the contributing authors for their time and effort, and for having patiently borne our reviews and numerous queries and comments. We are very grateful to our respective families for their patience and understanding during some rather trying times.

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1

Principles and Kinetics of Biological Processes

Nazih K. Shammas, Yu Liu, and Lawrence K. Wang

Contents

Abstract Biological technologies can be used to treat a vast majority of organic wastewaters because all organics could be biologically degraded if the proper microbial communities are established, maintained, and controlled. Before environmental engineers design and operate biological treatment systems that create the environment necessary for the effective treatment of wastewater, a sound understanding of the fundamentals of microbial growth and substrate use kinetics is essential. This chapter covers the above including basic microbiology and kinetics, kinetics of activated sludge process, factors affecting the nitrification process, kinetics of the nitrification process, denitrification by suspended growth systems and design examples.

Key Words Activated sludge • biological treatment • denitrification • kinetics • mathematical modeling • allosteric kinetic model • nitrification.

1. INTRODUCTION

Microorganisms are found nearly everywhere in the biosphere and thus are a force in the environment. In the past decades, bacteria have been intensively exploited in wastewater treatment processes. It is therefore the task of the environmental engineer and scientist to understand the role of microorganisms first and then use them to beneficially transform the

From: *Handbook of Environmental Engineering, Volume 9: Advanced Biological Treatment Processes*
Edited by: L. K. Wang, N. K. Shammas and Y-T. Hung, DOI: 10.1007/978-1-60327-170-7_1 © Humana Press, New York, NY 2009

particular environment, such as water or soil. Theoretically, biological technologies can be used to treat a vast majority of organic wastewaters because all organics could be biologically degraded if the proper microbial communities are established, maintained, and controlled. In this regard, many environmental engineering principles have been developed for biological wastewater treatment. Before environmental engineers design and operate biological treatment systems that create the environment necessary for the effective treatment of wastewater, a sound understanding of the fundamentals of microbial growth and substrate utilization kinetics is essential.

2. BASIC MICROBIOLOGY AND KINETICS

Microorganisms are powerful and cheap bioagents of biological wastewater treatment. The performance and stability of a biological treatment system relies on the interaction of different species of living organisms, typically including bacteria, fungi, algae, and protozoa (1).

2.1. Microbial Growth Requirements

Biological processes designed for wastewater treatment must maintain rich microbial populations and enough biomass to metabolize the soluble and colloidal organic wastes. For a successful operation of the biological treatment process, several conditions must be fulfilled, such as the type and concentration of organic waste (as electron donor), electron acceptors, moisture, temperature, necessary nutrients, and the absence of toxic and inhibitory compounds. A sound understanding of these microbial growth requirements is essential for environmental engineers and scientists to design and manage biological wastewater treatment systems.

2.1.1. Electron Acceptors

Aerobic and anaerobic processes are the two main biological technologies used for wastewater treatment. Bacterial respirations for aerobic and anaerobic bacteria need different electron acceptors. The choice of electron acceptors depends on which treatment process is desirable for a specific wastewater (2). For aerobic biodegradation, dissolved oxygen (DO) serves as the terminal electron acceptor. However, under anaerobic conditions, a variety of inorganic compounds can be used as terminal electron acceptors, e.g., NO_3^-, SO_4^{2-}, and so on.

In aerobic systems, the theoretical oxygen demand of an organic compound can be calculated from stoichiometry or determined by laboratory test. The theoretical oxygen demand is the amount of oxygen required to completely oxidize the organic carbon to carbon dioxide and water. As an example, for the complete oxidation of phenol (C_6H_6O) the balanced equation is written as follows:

$$\underset{94}{C_6H_6O} + \underset{224}{7O_2} \rightarrow 6CO_2 + 3H_2O \quad (1)$$

From the molecular weights in Eq. (1) the theoretical oxygen demand of phenol is: $224/94 = 2.38$ mg O_2/mg phenol.

2.1.2. Moisture

Because about 75% of cellular mass is water, and water is a good medium for nutrient transportation, adequate moisture concentration is strongly required in biodegradation of organic chemicals, especially in bioremediation of contaminated soil (3). It is generally accepted that the minimum moisture content necessary for bioremediation of contaminated soil is around 40% of saturation (4). In fact, there is no moisture-associated problem in biological wastewater treatment processes.

2.1.3. Temperature

The performance and response of a biological system depends on temperature variation. The effect of process temperature on microbial activity or the rate of biodegradation can be roughly described by the following simple equation:

$$r_T = r_{20}\alpha^{(T-20)} \tag{2}$$

where
r_T = biodegradation rate at temperature T
r_{20} = biodegradation rate at 20°C
α = temperature-activity coefficient
T = temperature, °C

For most of biological treatment systems, α values are in the range of 1.0 to 1.14 (5). Different groups of bacteria have various temperature optimums. For example, methanogenic bacteria are slow-growing bacteria with a generation time of 3 days at 35°C and 50 days at 10°C, indicating that methane-producing bacteria are very sensitive to changes in temperature (1).

2.1.4. pH

Most bacteria can optimally function only at a relatively narrow pH range of 6 to 8. In biological treatment system, once the reactor pH falls outside the optimal range, the activity of microbial population would drop significantly, and such a decline of activity in turn causes a serious operation problem and may result in the failure of the system (1). Consequently, it is recommended that on-site operators need to regularly monitor the system pH and pay attention to its changes.

2.1.5. Nutrients

Typical elementary composition of bacterial cells based on dry weight is 50% carbon, 20% oxygen, 15% nitrogen, 8% hydrogen, 3% phosphorus and <1% each of sulfur, potassium, sodium, calcium, iron, and magnesium (6). Microbial metabolism requires these elements as nutrients for synthesis and energy generation. The most commonly accepted empirical forms of activated sludge biomass are expressed as $C_5H_7NO_2$ and $C_{42}H_{100}N_{11}O_{13}P$ (7). The empirical formulae of bacterial cells provide a basis for calculation of the N and P requirements for synthesis of biomass from organic waste.

2.2. *Kinetics of Microbial Growth in an Ideal Medium*

Bacteria can grow at high rates under suitable conditions because of their relatively simple structures and growth requirements. However, a particular environment will favor some species more than others.

2.2.1. *Kinetics of Microbial Growth*

The growth of bacteria in an ideal medium can be described by the best-known Monod equation:

$$\mu = \mu_{\max} \frac{S}{S + K_{\mathrm{s}}} \tag{3}$$

where

μ = specific growth rate
$\mu_{\max}$ = maximum specific growth rate
S = waste concentration
K_{s} = half-saturation constant

Thus, the rate of bacterial growth in term of mass per unit volume and time can be written as:

$$\frac{\mathrm{d}X}{\mathrm{d}t} = \mu_{\max} \frac{S}{S + K_{\mathrm{s}}} X \tag{4}$$

where:

X = biomass concentration in the system

In the environmental engineering field, it is accepted that the conversion coefficient of organic waste to new synthesized cells is constant, thus the ratio of the increase in biomass to the decrease in organic substrate is defined as the growth yield coefficient Y,

$$Y = \frac{\mathrm{d}X/\mathrm{d}t}{\mathrm{d}S/\mathrm{d}t} \tag{5}$$

Combination of Eqs. (4) and (5) gives the following expression for the rate of waste degradation:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \frac{\mu_{\max}}{Y} \frac{S}{S + K_{\mathrm{s}}} X = q_{\max} \frac{S}{S + K_{\mathrm{s}}} X \tag{6}$$

or

$$q = q_{\max} \frac{S}{S + K_{\mathrm{s}}} \tag{7}$$

where,

$q_{\max}$ = maximum specific substrate utilization rate = $\mu_{\max}/Y$
q = specific substrate utilization rate defined as follows:

$$q = \frac{\mathrm{d}S}{\mathrm{d}t} / X \tag{8}$$

Equation (7) is one of the most commonly used design equations for biological treatment systems. In addition, it can be deduced from above equations that Y can also be defined as the μ/q ratio.

2.2.2. Microbial Decay and Endogenous Respiration

According to Pirt (8), part of the energy source would be used for maintaining the living functions of microorganisms, which is so-called maintenance metabolism. This includes the energy for turnover of cell materials, active transport, motility, and so on. The importance of maintenance metabolism is that the maintenance-associated substrate consumption is not synthesized to new cellular mass. Thus, the biosolids production should be inversely related to the activity of maintenance metabolism (9, 10). On the other hand, to account for the decrease in biomass production that is usually observed when the specific growth rate decreases, Herbert et al. (11) postulated that the maintenance energy requirement could be satisfied through endogenous metabolism. In this case, part of cellular biomass is oxidized to produce the energy for maintenance functions. It is generally assumed that microbial decay occurs following a first-order pattern as follows:

$$\text{Decay rate} = -K_{\mathrm{d}}X \tag{9}$$

where,

K_{d} = constant decay coefficient

Endogenous respiration has profound effect on the production of excessive biosolids. It has been suggested that the aim of both design and operation is to foster as much of this biological decay as possible. Including the decay in Eq. (6) yields an expression for the net growth of biomass in biological system:

$$\frac{\mathrm{d}X}{\mathrm{d}t} = \mu_{\max}\frac{S}{S+K_{\mathrm{s}}}X - K_{\mathrm{d}}X \tag{10}$$

Equations (3) to (10) provide the basis for detailed kinetic analysis and basic design guidelines of biological treatment systems.

2.3. Kinetics of Biological Growth in an Inhibitory Medium

Some substrates may inhibit their own degradation at increased concentrations. When designing and running a biological system for inhibitory waste treatment, environmental engineers must seriously account for the toxicity and inhibition of waste to bacterial growth. It is obvious that the Monod equation does not include the toxic or inhibitory effect, thus they must be modified for biological treatment of inhibitory waste. Figure 1.1 shows typical growth patterns of bacteria in noninhibitory and inhibitory media. It seems that when the concentration of inhibitory substrate is higher than a critical value, a sharp decline in microbial growth is observed, on the other hand, if the concentration of inhibitory substrate is low enough, the inhibitory effect would not be significant.

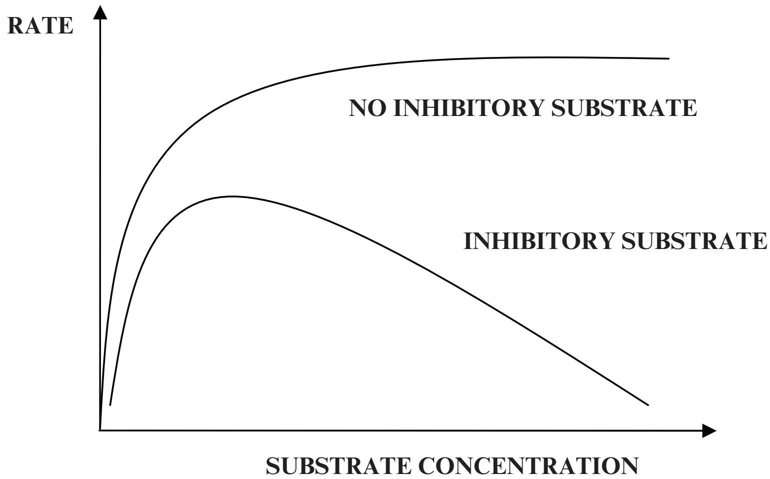

Fig. 1.1. Schematic presentation of inhibitory effect on bacterial growth.

So far, the Haldane equation has been most frequently used to describe the inhibitory effect of a substrate on bacterial growth:

$$\frac{dS}{dt} = q_{max} \frac{S}{S + \frac{S^2}{K_i} + K_s} X \quad (11)$$

where,

K_i = inhibition coefficient

When mixed inhibitory substrates are considered for biological treatment, the expression for inhibitory kinetics will become very complicated because in such a waste mixture, one substrate may inhibit the biodegradation of another.

Current practice shows that for a target inhibitory substrate, its concentration is critical for biological treatment. If the threshold of substrate concentration that bacteria can bear is exceeded, inhibition, and die-off of bacteria in the reactor will start on a continuing and irreversible basis, leading to serious loss or even failure of the system's purification efficiency and capability. Predetermination of inhibitory threshold of substrate concentration is essential for the design of a biological treatment system for inhibitory wastes. In industrial practice, where inhibitory wastes are more common, there are some technical measures that can help to mitigate inhibition, such as acclimation of bacteria, introduction of robust species, or dilution of the waste stream.

2.4. Minimum Substrate Concentration

In many cases, the characteristics of soluble wastes found in soil and wastewater have dual effects on biological treatment processes; one, when the concentrations of waste constituents are generally low and two, when their toxicity to microbial activity is relatively high. A low waste concentration may be risky in case it could not support a sustainable and viable biomass needed for biological treatment. As Eq. (3) indicates, the specific growth rate of microorganisms is proportionally related to substrate concentration. Microbial growth could cease as the substrate concentration diminishes to a certain low unsustainable concentration. For a biological treatment system, a minimum substrate concentration is required to sustain a viable biomass. In the environmental engineering field, the minimum substrate concentration (S_{min}) is defined as the substrate concentration at which formation of new biomass equals its loss by endogenous respiration (3). When the minimum substrate concentration occurs, Eq. (10) shows that

$$\mu_{\text{max}} \frac{S_{\text{min}}}{S_{\text{min}} + K_{\text{s}}} X - K_{\text{d}} X = 0 \tag{12}$$

that is,

$$S_{\text{min}} = \frac{K_{\text{s}} K_{\text{d}}}{\mu_{\text{max}} - K_{\text{d}}} \tag{13}$$

or

$$S_{\text{min}} = \frac{K_{\text{s}} K_{\text{d}}}{Y q_{\text{max}} - K_{\text{d}}} \tag{14}$$

2.5. *Mathematical Approximation for Wastewater Treatment*

In many situations of wastewater treatment, a simple first-order approximation has been used with reasonable accuracy to describe the biodegradation of organic wastewater. This approximation is based on two main assumptions (4):

1. The target substrate or waste is at a relatively low concentration.
2. The biomass concentration in the system is at a steady state, consequently it changes little with operation time and can be regarded as a constant.

Thus, Eq. (6) reduces to:

$$\frac{\text{d}S}{\text{d}t} = \frac{q_{\text{max}}}{K_{\text{s}}} X S \tag{15}$$

or

$$\frac{\text{d}S}{\text{d}t} = k_1 S \tag{16}$$

where,

$k_1 = X q_{\text{max}} / K_{\text{s}}$ = first-order biodegradation rate constant

Integrating both sides of Eq. (16) yields

$$S = S_o e^{-k_1 t} \tag{17}$$

where,

t = reaction time

S_o = initial substrate concentration at $t = 0$

S = substrate concentration at any time t

In case the substrate concentration is relatively higher than K_s and X is considered constant, Eq. (6) can be simplified to

$$\frac{dS}{dt} = q_{max} X \tag{18}$$

Equation (18) shows a zero-order reaction, that is,

$$S = S_o - k_o t \tag{19}$$

where,

$k_o = Xq_{max}$ = zero-order rate constant

Reported examples of zero-order biodegradation kinetics include substances such as glucose, phenol, phthalic acid, aspartic acid, ethanol, and acetate (5).

3. KINETICS OF ACTIVATED SLUDGE PROCESSES

3.1. Brief Description of Activated Sludge Processes

The activated sludge process is the most widely used biological process for treatment of a variety of wastewaters. In the past century many modifications of the basic activated sludge process have evolved for various purposes (2):

1. Complete-mix activated sludge process: A completely mixed system can allow a more uniform aeration of the wastewater in the aeration tank. This process has been applied to handle a variety of wastewaters with great success, especially because the process can sustain shock and toxic loads.
2. Step-aeration activated sludge process: In this modified system, influent wastewater is distributed through several points in the aeration tank. This leads to a relatively homogenous load distribution along the length of the aeration tank resulting in a more efficient use of dissolved oxygen.
3. Contact-stabilization activated sludge: The influent contacts with a high concentration of biomass in a small contact tank for a short period of time (20 to 40 min). The mixture then flows to the secondary clarifier where it gets settled and the resulting biosolids are returned to a stabilization tank with a hydraulic retention time of 4 to 8 h. In this contact tank, a rapid biosorption of organic compounds is expected followed by the oxidation of the organics. This system would need smaller tankage and produce smaller amounts of biosolids.
4. Tapered aeration process: In the basic activated sludge process, organic influent is one-point loaded to the head of aeration tank, thus the oxygen demand is extremely high at the head of the aeration tank, but very low at the exit end. To overcome this problem, in tapered aeration process, the air supply tapers off with distance along the aeration tank so that supply and demand can be balanced throughout the tank.
5. Pure oxygen activated sludge process: The pure oxygen activated sludge process is based on such a simple idea that the rate of oxygen transfer in water is proportional to the partial pressure of oxygen, that is, the rate of oxygen transfer is higher for pure oxygen than for atmospheric

oxygen. Higher availability of oxygen for microorganisms leads to improved treatment efficiency and reduced production of biosolids and reactor volume.

3.2. Kinetics of Completely Mixed Activated Sludge Process

3.2.1. Basic Design Models

Development of design models for a completely mixed activated sludge process is based on a mass balances on microorganisms and substrate around the system together with the kinetics of microbial growth and waste utilization Figure 1.2 shows the items of interest in the mass balance.

To develop a mass balance for the reactor system, some basic assumptions are made (12):

1. Biodegradation of organic wastes takes place only in the aeration tank.
2. No biological reactions take place in the settling tank and the biomass in the secondary clarifier is negligible.
3. No active biomass is present in the influent to the aeration tank.
4. The substrate is soluble so that it cannot settle out in the secondary clarifier.

In Fig. 1.2, X, X_r, X_w, and X_e represent the active biomass concentrations. The following is based on the work by Lawrence and McCarty (12). The mass balance on biosolids is expressed as follows:

$$\text{Accumulation} = \text{in} - \text{out} + \text{generation} \tag{20}$$

According to Eq. (20), the mass balance for microorganisms around the whole system is:

$$V\frac{\mathrm{d}X}{\mathrm{d}t} = 0 - (Q_e X_e + Q_w X_w) + [Y(r_s)V - K_d XV] \tag{21}$$

where,

r_s = rate of soluble substrate utilization
V = Volume
Q = flow rate

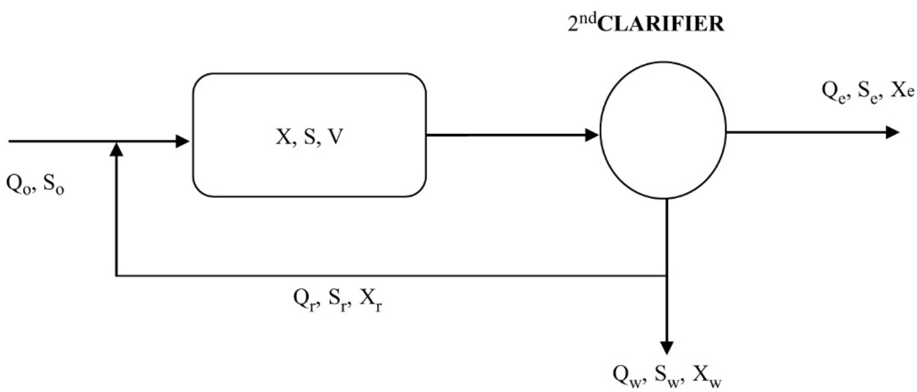

Fig. 1.2. Mass flow chart of completely mixed activated sludge process.

Similarly, the mass balance on substrate yields:

$$V\frac{\mathrm{d}S}{\mathrm{d}t} = Q_o S_o - (Q_\mathrm{e} S_\mathrm{e} + Q_\mathrm{w} S_\mathrm{w}) - r_\mathrm{s} V \tag{22}$$

It should be pointed out that Eqs. (21) and (22) are derived on the basis of a mass balance on biomass and substrate, respectively, thus can be used to describe the operation of the system under nonsteady or steady-state conditions. In practice, activated sludge processes are run under steady-state conditions. At steady state, the changes in accumulation of both biomass and substrate are zero, that is,

$$V\frac{\mathrm{d}X}{\mathrm{d}t} = 0 \text{ and } V\frac{\mathrm{d}S}{\mathrm{d}t} = 0 \tag{23}$$

To facilitate the development of a design model, we need to define some very useful operation and control parameters:

Mean hydraulic retention time for the aeration tank (θ):

$$\theta = \frac{V}{Q_o} \tag{24}$$

Mean cell retention time or solids retention time (θ_x):

$$\theta_x = \frac{\text{biomass in the aeration tank}}{\text{discharge rate of biomass}} \tag{25}$$

That is,

$$\theta_x = \frac{VX}{X_\mathrm{e} Q_\mathrm{e} + X_\mathrm{w} Q_\mathrm{w}} \tag{26}$$

At steady state, Eq. (21) can be rearranged as follows:

$$\frac{X_\mathrm{e} Q_\mathrm{e} + X_\mathrm{w} Q_\mathrm{w}}{XV} = \frac{Y(r_\mathrm{s})}{X} - K_\mathrm{d} \tag{27}$$

Comparing Eqs. (26) and (27) one can deduce that:

$$\frac{1}{\theta_x} = \frac{Y(r_\mathrm{s})}{X} - K_\mathrm{d} \tag{28}$$

Equation (28) is an important design relationship for the completely mixed activated sludge process. It can be applied whatever the form of r_s may be; a Monod equation, a first-order approximation for dilute wastewater or the Haldane equation for high-concentration inhibitory organics. If we assume that for a wastewater the Monod equation is applicable, then

$$\frac{1}{\theta_x} = Y\frac{q_{\max} S_\mathrm{e}}{S_\mathrm{e} + K_\mathrm{s}} - K_\mathrm{d} \tag{29}$$

Solving Eq. (29) for S_e gives:

$$S_\mathrm{e} = K_\mathrm{s}\frac{1 + K_\mathrm{d}\theta_x}{\theta_x(Yq_{\max} - K_\mathrm{d}) - 1} \tag{30}$$

Equation (30) is one of the recognized design equations originally derived by Lawrence and McCarty (12). This equation shows that the efficiency of substrate removal is proportional to the sludge age. Thus, environmental engineers can expect to need a relatively large θ_x to obtain high treatment efficiency; while at the same time have a short hydraulic retention time, which means a small reactor volume.

Similarly, at steady state, Eq. (22) can be rearranged to give r_s as a function of S:

$$r_{\mathrm{s}} = \frac{Q_o S_o - Q_{\mathrm{e}} S_{\mathrm{e}} - Q_{\mathrm{w}} S_{\mathrm{w}}}{V} \tag{31}$$

The substrate concentration in the aeration tank, S, is equal to the concentration in the effluent S_{e} as well as in the waste sludge line, S_{w} because no biological reaction occurs in the settling tank. Also from the continuity equation of fluid flows one can state that:

$$Q_o = Q_{\mathrm{e}} + Q_{\mathrm{w}} \tag{32}$$

Using the above relationships, Eq. (31) becomes

$$r_{\mathrm{s}} = \frac{Q_o (S_o - S_{\mathrm{e}})}{V} = \frac{S_o - S_{\mathrm{e}}}{\theta} \tag{33}$$

Like Eq. (30), Eq. (33) is another general representation of the waste removal rate in terms of system characteristics. Substitution of Eq. (33) into (27) produces,

$$X = \frac{\theta_x}{\theta} \frac{Y (S_o - S_{\mathrm{e}})}{1 + K_{\mathrm{d}} \theta_x} \tag{34}$$

Equation (34) indicates that the biomass concentration in the aeration tank depends on the ratio of solids retention time to the hydraulic retention time, θ_x/θ. This equation is one of the most commonly recognized design formulas (7, 12).

3.2.2. Process Control Parameters

Equations (30) and (34) can be useful in predicting the effects of various changes in system parameters, but they are difficult to use from a design standpoint because of the many kinetic constants involved. Environmental engineers and scientists have developed more usable process design relationships enthatough are widely used in process design practice. These include the specific removal rate of soluble waste (q), mean solid retention time (θ_x), and the food-to-microorganisms, F/M, ratio (7). The following discussion is based on material from Metcalf and Eddy (7).

The specific removal rate of soluble waste, q: The specific removal rate of soluble wastes is defined as,

$$q = \frac{r_{\mathrm{s}}}{X} = \frac{S_o - S_{\mathrm{e}}}{\theta X} = \frac{Q_o}{V} \frac{S_o - S_{\mathrm{e}}}{X} \tag{35}$$

To determine q, the liquid waste flow and the biomass effective in substrate utilized must be known. The substrate utilized can be quantified by the difference between the influent and effluent waste concentrations ($S_o - S_e$). However, the evaluation of the active biomass