CHAPTER 17

AEROBIC BIOLOGICAL TREATMENT

Biological wastewater treatment is primarily used to remove dissolved and colloidal organic matter in a wastewater. Some suspended organics will also be metabolized and because of the natural flocculation and settling characteristics of the biomass formed in biological treatment, the biomass along with other suspended matter can be removed in a sedimentation basin.

Biological treatment is a "natural" process. Organic matter in water will naturally decay as a result of the presence of microorganisms in receiving bodies of water. High organic loads in a wastewater will upset the biocenosis of receiving bodies of water and cause other undesirable effects. Biological treatment is engineered to accelerate natural decay processes and neutralize the waste before it is finally discharged to receiving waters.

Aerobic biological treatment is the focus of this chapter; however, many concepts developed in this chapter apply to any biological treatment process. Further information on other biological treatment processes is given in Chapters 18, 19, and 20.

17.1 MICROORGANISMS IN AEROBIC BIOLOGICAL TREATMENT

Chapter 6 describes general characteristics of microorganisms. Biomass in a reactor is the sum total of all living organisms in the process. Other organic matter present, suspended or dissolved, may have been associated with living biomass at some time but this matter is not part of the biological engine driving the process.

Bacteria are the primary agents of treatment in any biological treatment process. Taken as a whole, their diverse characteristics and minimal growth requirements allow them to proliferate in a wastewater environment. Aerobic processes are usually operated at low dissolved oxygen (DO) concentrations and the microorganisms are subjected to varying periods of time when no DO is present. Therefore, many facultative microorganisms will be found in an aerobic process.

Viruses are present in a biological treatment process but they have no significance in removal of organic compounds.

Protozoans will also be found in large numbers in an aerobic treatment process; however, they will still only account for a small percentage of the biomass. There are some protozoans that are saprophytic, i.e., primary feeders on the raw organics present in the influent. Others are predators of bacteria and other eukaryotes. The presence of ciliated protozoans is usually indicative of good treatment. These protozoans occur in the presence of higher amounts of DO and lower amounts of dissolved organic matter.

Yeast and fungi are not common in wastewater treatment processes. As discussed in Chapter 6, their lower nitrogen requirements and ability to survive at lower pHs can enhance their role in treatment of certain industrial wastewaters. The occurrence of fungi, in particular, is not beneficial for most normally operated biological treatment processes because of their poor settleability, which makes it difficult to separate them from the wastewater and deteriorates final effluent quality as well as causes other operational problems.

Rotifers and crustaceans are the next higher stage of life beyond protozoans. Their role in providing treatment is minimal but their presence is indicative that the treatment process is healthy. Sludge worms are not significant in biological treatment of a wastewater but they will be found.

17.2 THE ACTIVATED SLUDGE PROCESS

Activated sludge is defined as a suspension of microorganisms, both living and dead, in a wastewater. The microorganisms are activated by an input of air (oxygen). The influent to the process is usually settled. The process involves two distinct operations usually performed in two separate basins: aeration and settling.

The aeration basin is the first basin in the process. Microorganisms are mixed with the sewage and oxygen is supplied by aeration. Here the organics in the waste are metabolized to produce end products and new biomass. Mixing must be adequate to prevent the sedimentation of microorganisms and to mix oxygen, sewage, microorganisms, and nutrients. The contents of the aeration basin are known as the mixed liquor (ML).

The second operation is the separation of the biomass and other suspended solids from the wastewater. This is accomplished in a clarifier designed according to type III sedimentation principles (Section 11.5). The clarified effluent is relatively devoid of any suspended particles compared to the clarifier influent. A portion of the sludge from the clarifier underflow is usually returned to the aeration basin, whereas the remainder is discarded or sent for further processing.

The process was developed in the early 1900s by Ardern and Lockett (1914a, 1914b, 1915; Ardern, 1917) who used fill and draw reactors (a batch process) to successfully treat wastes in a short period of time. Continuous flow reactors were designed shortly thereafter and regularly used because of problems in controlling a number of batch reactors throughout fill–react–settle–draw cycles with variable influent flow rates. Although batch treatment was ignored for over 50 years, interestingly, batch treatment systems have been reestablished as a viable treatment alternative in modern times (Irvine and Busch, 1979).

Some of the substrate will be completely oxidized to harmless end products of CO_2, H_2O, and other inorganic substances to provide energy for growth of the microorganisms. Oxygen, which is usually supplied by aeration, must be input continuously or semicontinuously. This is the major energy consuming operation in the process (Owen, 1982). Energy requirements for return sludge pumping from the clarifier to the aeration basin and operation of the clarifier itself are relatively insignificant in the energy balance.

A portion of the substrate is used for synthesis of biomass. The aerobic mode of metabolism is the most efficient in terms of energy recovered by the biomass per unit of substrate processed. This results in a relatively large quantity of sludge production, which is the other primary characteristic of this process. Sludge processing and disposal

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is also a major operating expense (Owen, 1982). It may be possible to use the sludge as a soil conditioner. Whether the sludge can ultimately be applied to crops grown for human consumption or only to land restricted for aesthetic or recreational use or no access at all depends on the sludge's accumulation of heavy metals and other toxicants. The occurrence of metals or other toxicants in the sewage depends on the presence of certain industries discharging untreated or partially treated wastes to the sewer system.

17.3 SUBSTRATE REMOVAL AND GROWTH OF MICROORGANISMS

Substrate removal and growth of microorganisms are closely tied together. Even though starved conditions exist in biological treatment processes there is net growth of microorganisms.

17.3.1 Substrate Removal

The growth cycle of microorganisms and equations to describe substrate uptake have been given in Chapter 6. The Monod (Monod, 1949) equation (Eqs. 17.1a and 17.1b) has been found to suitably describe substrate removal in a wide variety of biological treatment processes. As noted before, the equation is empirical and its constants should be developed for each situation. A wide variety of substrates and microorganisms are involved in a complex dynamic environment when wastewater is being treated. The equation describes the interaction of this large number of variables.

$$r_S = -\frac{kX_VS}{K+S} \tag{17.1a}$$

$$r_S = -\frac{kS}{K+S} \tag{17.1b}$$

where

r_S is the rate of substrate removal ($ML^{-3}T^{-1}$)
X_V is the concentration of volatile suspended solids (VSS)
k and K are the maximum and half-velocity constants (see Section 4.12)
S is concentration of substrate

The maximum velocity constant, k, and the half-velocity constant, K, are functions of environmental variables such as DO concentration, pH, temperature, inhibitory substances, and nutrients as well as the degradability of the substrate.

First-order relations (Eqs. 17.2a and 17.2b) or other expressions such as a retardant model have also been found to provide good correlation of results. The Monod equation reduces to a first-order formulation at low substrate concentrations. The applicability of a first-order model is not surprising because wastewater treatment processes produce an effluent that is low in degradable substrate concentration. The constant k does not have the same value in Eqs. (17.1) and (17.2).

$$r_S = -kX_VS \quad (17.2a) \qquad r_S = -kS \tag{17.2b}$$

The constants in the substrate removal expressions are developed over the range of operating conditions of the process.

The biomass concentration is included in Eqs. (17.1a) and (17.2a). Precisely, the active biomass, X_a, should be used as opposed to VSS, which is only a rough approximation of the concentration of active microorganisms. In addition to viable microorganisms there will be a significant amount of organic debris in the wastewater. Some of this material will come in the influent but a significant amount of suspended organic material will be dead biomass or associated with the decay of biomass (endogenous VSS) because treatment processes are normally operated with a considerable excess of microorganisms to ensure effective treatment. VSS is chosen as a measure of biomass as opposed to total suspended solids (TSS) because biological solids will be primarily composed of organic matter, although there will be an associated inorganic component. Inorganic suspended solids may also be present in the influent.

The measurement of VSS is convenient and practical compared to the assessment of the active biomass (X_a), which may consist not only of viable cells but also of enzymes and other catalytic agents in solution or suspension. As long as conditions in the prototype are similar to conditions in the model the rate constants remain valid. Adenosine triphosphate (ATP) and dehydrogenase activity measurements are the best measures of viable (active) biomass in biological treatment processes (Jørgensen et al., 1992; Weddle and Jenkins, 1971).

Although it has been common practice to incorporate VSS into the substrate removal expression, there is research to demonstrate that it is not always the best relation (Droste et al., 1993; Goodman and Englande, 1974). Substrate removal depends on the active mass present and a given amount of substrate can support only a given amount of active mass when the process is operated under starved conditions for the biomass. This is the common practice to maintain high removal rates and also to maintain the sludge in a state where it flocculates and settles well in the secondary clarifier.

When substrate limited conditions exist, advanced models and studies show that the active mass concentration remains approximately constant but it will decrease as a percentage of the total biomass as the amount of solids in the system is increased (Goodman and Englande, 1974; McKinney, 1962; Weddle and Jenkins, 1971). The direct relation between substrate removal and VSS expressed by Eqs. (17.1a) and (17.2a) becomes doubtful. Therefore, Eqs. (17.1b) and (17.2b) have also been found to give valid results.

The treatment models to be developed in this text will use one of Eqs. (17.1a), (17.1b), (17.2a), or (17.2b) as the descriptor of substrate removal kinetics. Regardless of which equation is used, any of the other models could be substituted and carried through each development. The important point is to apply the models consistently. In practice, the model of choice will be the one that best describes operational data. Regardless of the choice to incorporate VSS into the substrate removal expressions, the models are coarse and, although they have been used satisfactorily time and again, they do not account for many phenomena that are evident. The generation of secondary metabolites through primary substrate metabolism and generation of secondary substrate from decay of the biomass are examples of secondary phenomena that are incorporated into advanced models, which are beyond the scope of this presentation.

Temperature Dependence of Rate Coefficients

The Arrhenius equation is used to describe the temperature dependence of the maximum velocity coefficient k in Eqs. (17.1a) and (17.1b) or the velocity coefficient k in Eqs. (17.2a) and (17.2b).

$$k_T = k_{20}\theta^{(T-20)} \tag{17.3}$$

where

θ is a constant

k_T and k_{20} are the rate coefficients at temperatures of T and 20°C, respectively

Metcalf and Eddy (1991) report a range for θ of from 1.0 to 1.8, with a typical value of 1.04 for activated sludge systems. The temperature dependence of K in Eqs. (17.1a) and (17.1b) has been described by a variety of empirical correlations.

BOD, COD, and TOC Removal

Substrate is usually expressed in terms of BOD, COD, or TOC. Sometimes removal rates of specific compounds are examined such as nitrate or components that are toxic. The removal rates of the nonspecific measures of BOD, COD, and TOC will be different. Organics become more oxidized as biological treatment progresses but there is an accumulation of byproducts of microbial growth and metabolism that are difficult to degrade. This is reflected in the ratios of BOD and COD to TOC shown in Table 17.1, which also shows the effect of primary sedimentation on these ratios. The data in the table are for only a limited number of plants but the variation of the ratios is typical for treatment of domestic wastewater.

17.3.2 Growth of Microorganisms and Biological Sludge Production

Sludge production is another major characteristic of the process. The removal and metabolism of substrate result in the growth of new biomass. This production of biomass can be described by:

$$r_{X\mathrm{p}} = -Yr_{\mathrm{S}}$$

where

$r_{X\mathrm{p}}$ is the production of VSS (biomass) from substrate removal ($\mathrm{ML^{-3}T^{-1}}$ or mg/L/d)

Y (cf. Eq. 6.3) is a yield factor (mass of microorganisms produced per mass of substrate removed)

Because the process is operated in substrate limited conditions, the decay of biomass through starvation, death, predation, and autooxidation becomes significant. These phenomena, collectively known as endogenous decay, can be modeled by a first-order expression.

$$r_{X\mathrm{e}} = -k_{\mathrm{e}}X_{\mathrm{V}}$$

where

$r_{X\mathrm{e}}$ is the rate of decrease of VSS caused by endogenous decay ($\mathrm{ML^{-3}T^{-1}}$ or mg/L/d)

k_{e} is a rate constant (mass removed through endogenous decay/mass present/d, $\mathrm{T^{-1}}$)

The net growth rate of microorganisms is the summation of the above two phenomena.

$$r_X = -Yr_{\mathrm{S}} - k_{\mathrm{e}}X_{\mathrm{V}} \tag{17.4}$$

TABLE 17.1 Organics Variation in Treatment of Municipal Wastewater[a,b]

	BOD_5 mg/L		COD mg/L		TOC mg/L		BOD_5/TOC		COD/TOC	
	Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range
Raw	86	72–105	236	136–304	56	41–70	1.50	1.31–1.88	4.16	3.32–4.68
Primary effluent	58	46–68	204	146–299	52	44–61	1.11	1.00–1.33	3.90	3.19–5.85
Final effluent	15	11–20	84	77–95	35	33–40	0.44	0.20–0.69	2.40	2.02–2.58
Ave. removal (%)	83		64		38					

[a] From Eckenfelder and Ford (1970).

[b] Data are for eight plants. All plants did not necessarily report all three measures.

TABLE 17.2 Yield and Endogenous Decay Coefficients for the Activated Sludge Process[a]

Coefficient	Basis	Range	Typical
Y	g VSS/g BOD_5	0.4–0.84	0.6
Y	g VSS/g COD	0.24–0.4	0.4
k_e	d^{-1}	0.004–0.10	0.06

[a]Derived from Lawrence and McCarty (1970), Metcalf and Eddy (1991), and WEF and ASCE (1992a).

where

r_X is the net growth rate of microorganisms ($ML^{-3}T^{-1}$)

Equation (17.4) accommodates the two phenomena of growth from substrate removal and endogenous decay separately; it is more versatile than simply using a net yield factor times the rate of substrate removal, which is the observed yield (Eq. 17.5). The latter approach does not correlate the data as well as Eq. (17.4).

$$r_X = -Y_{\text{obs}} r_S \tag{17.5}$$

where

Y_{obs} is the observed yield factor

Typical values for Y and k_e are given in Table 17.2. Equation (17.4) describes the net yield of solids from substrate removal. The total production of solids depends on influent solids that are not degradable. These include refractory organics as well as inorganic solids. There is also a fixed (inorganic) component of biological solids, discussed in Sections 17.4.1 and 17.9.

Equation (17.4) shows how sludge production is related to the substrate removal rate and concentration of biomass in the system. In a later section, the biomass concentration will be related to the residence time of sludge in the system or sludge age. Some treatment installations, particularly smaller operations, may not have a primary clarifier. In this case there is a significant deviation from the solids production predicted by Eq. (17.4) because of the input of high solids concentrations. Some of the influent solids will be transformed into biological solids. Schulz et al. (1982) surveyed a number of installations that did not settle sewage entering the activated sludge process. Different modifications of the activated sludge process were included in the survey. The average rate of sludge production was 0.86 kg TSS/kg BOD_5 removed (range: 0.60–1.22 kg TSS/kg BOD_5 removed), with considerable variation for a single plant and among different plants. Good correlations did not exist between solids production and other process parameters. Solids handling facilities should be designed for 150% of design values.

Sludge Composition and Nutrient Requirements

The major nutrient requirements are nitrogen and phosphorus. The amounts of these nutrients required for activated sludge or any biological process depend on the net amount of biomass formed and removed from the process. Typically, sludge has a chemical formula near $C_5H_7NO_2$, determined by Hoover and Porges (1952) in one of the earliest studies of this nature in the field of environmental engineering, and this formula is almost universally used in textbooks and research papers.

Dairy waste was the substrate in the study of Hoover and Porges; there can be significant variations from their formula at different operating conditions and with different waste sources (Burkehead and Waddell, 1969). Incorporating typical biomass phosphorus content, the formulation becomes $C_5H_7NO_2P_{0.074}$. The phosphorus requirement is one sixth of the nitrogen requirement on a mass basis when this formula applies. The rule of thumb that applies to activated sludge processes is that the ratio of influent degradable matter expressed on an ultimate BOD or COD basis to nitrogen and phosphorus should be COD:N:P = 100:5:1 on a mass basis. When nutrient concentrations are less than this value, chemical nutrient supplements of ammonium or phosphate salts are added to the influent.

It is commonly assumed that effluent from an activated sludge process contains a dissolved phosphorus concentration of 1 mg/L. The total phosphorus requirement depends on soluble effluent phosphorus and the amount of sludge produced. Other nutrients are required in trace amounts but they are normally present in excess in most wastewaters.

Writing the chemical equation for the oxidation of biomass, the formula $C_5H_7NO_2$ results in 1.42 mg COD/mg VSS. Different chemical formulas will change the value of the oxygen demand of biomass. It is not necessary to know the chemical composition of biomass to determine its COD. Simply measuring the COD on filtered and unfiltered aliquots from a sample and determining the VSS of the sample is sufficient to determine the COD of the VSS. If this simple exercise were performed more regularly, COD balances for biological processes would exhibit improvement over making the usual assumption that the COD of VSS is 1.42 mg/mg. The value of 1.42 will be commonly used in this textbook but other values will also be used to reflect reality. When no data are available, 1.42 is probably the most reasonable value to use.

17.4 ACTIVATED SLUDGE CONFIGURATIONS

The primary flow and mixing regimes in activated sludge processes are shown in Fig. 17.1. As discussed in Chapter 10, plug flow (PF) and complete mixed (CM) are the extremes in mixing regimes. Many alternative influent addition and effluent withdrawal schemes in the reactor have been used that result in intermediate mixing regimes. The mixing regime is a fundamental process embodiment that influences substrate removal kinetics, settleability of the sludge produced in the process, and conditions in the reactor. Before these various processes are analyzed the symbolic notation scheme is described.

17.4.1 Definition of Symbols for the Activated Sludge Process

The symbols Q, S, and X refer to volumetric flow rate, substrate (measured as BOD_u, BOD_5, COD, or TOC) concentration, and solids concentration, respectively. For Q and S, subscripts indicate the location of the quantity. For X, there are usually two subscripts: the first subscript indicates the type of solids (e.g., TSS, VSS, or inert) and the second subscript indicates the location. X never appears unsubscripted—it must have at least one subscript indicating the type of solids.

Influent

The influent refers solely to the external flow entering the system. Recycled flow (an internal phenomenon) is excluded.

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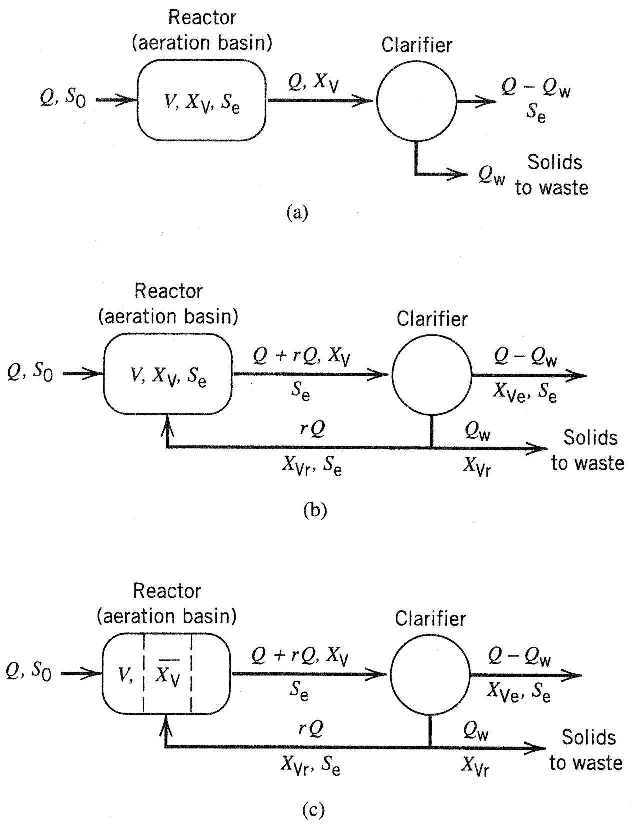

Figure 17.1 Basic configurations of the activated sludge process. (a) Complete mixed, no recycle; (b) complete mixed, biological solids recycle; (c) plug flow, biological solids recycle.

Q = volumetric flow rate
S_0 = substrate concentration (0 refers to influent)
X_{V0} = VSS (V refers to VSS)
X_{Ti0} = inert (inorganic) solids concentration (ISS) (Ti refers to the inorganic portion of TSS)
X_{T0} = TSS

Influent TSS is the sum of influent VSS and influent inert solids defined above:

$$X_{T0} = X_{Ti0} + X_{V0}$$

Reactor

Symbols that designate quantities in the reactor usually have no secondary subscripts associated with them.

S = soluble substrate concentration

This is the major exception to the rule given at the beginning of this section. In a CM reactor, the substrate concentration in the effluent is the same as the substrate concentration in the reactor (see Sections 10.1.1 and 10.1.3); therefore S_e (see the next subsection) is commonly used. In a PF reactor, S (unsubscripted) must be used because substrate concentration is a continuously varying function of time or distance in the reactor. S_e cannot be used because it refers to substrate concentration at a specific location.

X_V = VSS

V = volume

X_T = TSS

X_a = active mass concentration

X_{Ti} = inert (inorganic SS)(ISS) (Note this is in accord with influent notation and Ti, when together, is taken as a primary symbol group.)

There are two components of inorganic SS. Inorganic SS that are present in the influent to the reactor will pass through the process. Biosolids also contain inorganic solids; typically, biomass is composed of 0.75–0.80 VSS and 0.20–0.25 ISS. From a determination of TSS–VSS in the reactor, it is impossible to distinguish between ISS originating in the influent and biomass ISS.

Reactor Effluent

Note that for any reactor without recycle, the reactor effluent flow rate is the same as the influent flow rate.

For a CM reactor, effluent and reactor concentrations of any substance are the same. For a PF reactor, the solids concentration varies along the length of the reactor as shown later. However, for most processes the variation in solids concentration is small. Therefore, the average solids (of any type) concentration in the reactor is approximately the same as the reactor effluent concentration. In PF reactors, often a bar is placed over the symbol to indicate "average" concentration.

S_e = soluble substrate concentration

X_V = VSS

X_T = TSS

X_{Ti} = ISS

System Effluent

No biological treatment is assumed to occur in the clarifier and therefore only solids concentrations change from the influent to the various outflows from the clarifier.

Substrate concentration in clarified effluent and underflow from the clarifier is S_e (There is no soluble substrate removal in the clarifier according to the assumption).

X_{Ve} = VSS in clarified effluent

X_{Te} = TSS in clarified effluent

X_{Tie} = ISS in clarified effluent

Recycled and Waste Flow

The underflow from the clarifier is split into two flow paths. One is the waste flow and the other is the recycled flow. For solids concentrations, the subscripts "w" or "r" are appropriate but "r" is usually employed to describe the solids concentrations.

Q_w = waste sludge flow rate

X_{Tr} = TSS in waste sludge or recycled underflow

X_{Vr} = VSS in waste sludge or recycled underflow

X_{Tir} = ISS in waste sludge or recycled underflow

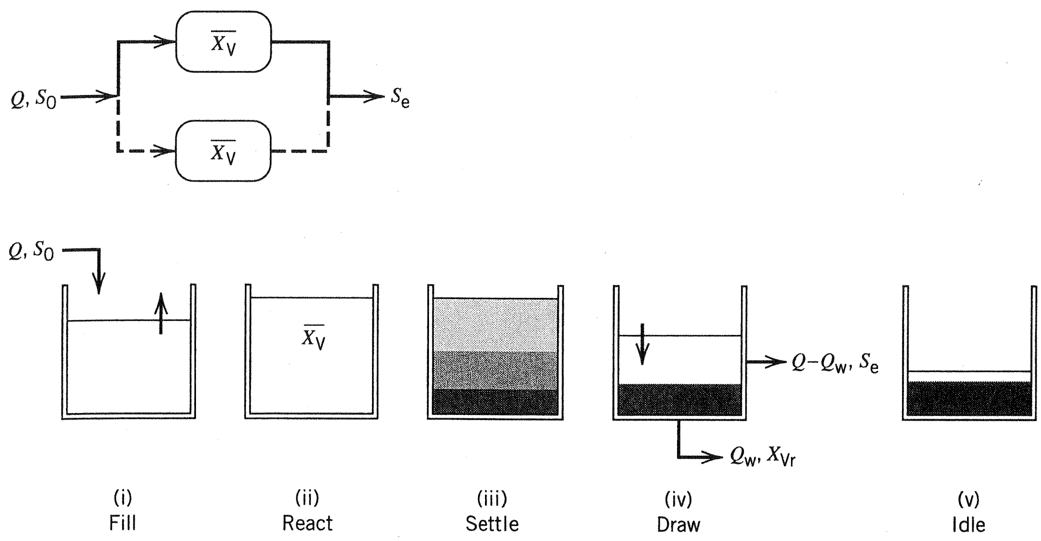

Figure 17.2 Sequencing batch reactor operating cycle.

r = recycle factor (This is the ratio of the recycled flow, Q_r, to the influent flow = Q_r/Q.)

Clarifier

X_{Tc} = average TSS in secondary clarifier
X_{Vc} = average VSS in secondary clarifier
X_{Tic} = average ISS in secondary clarifier

Sequencing batch reactors (Fig. 17.2) are another operational mode. One reactor may be operated in a fill and draw mode. Usually two or more reactors are used and operated in staggered sequences. In a multireactor sequencing batch treatment operation, each reactor cycles through the periods indicated in Fig. 17.2. Depending on influent flow quantity and quality variation, it may not be necessary to have an idle period in the cycle. In a continuous flow situation, it is always necessary to have one reactor filling while the other reactors are staggered throughout other periods of the operating cycle.

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