17.6 FOOD TO MICROORGANISM RATIO AND SLUDGE AGE

Two important parameters for operating the process are the food : microorganism (F : M) ratio and the sludge age. These parameters originate from mass balances for the systems. The F : M ratio, U, is

$$U = \frac{Q(S_0 - S_e)}{VX_V} = \frac{(S_0 - S_e)}{X_V \theta_d} \tag{17.11a}$$

where

θ_d is the hydraulic retention time (HRT)

The F : M ratio describes the degree of starvation of the microorganisms. Because biological treatment processes should remove nearly all of the influent substrate, the F : M ratio is often expressed as

$$U = \frac{S_0}{X_V \theta_d} \tag{17.11b}$$

Equation (17.11b) also expresses the potential food availability to the microbial population.

The sludge age, θ_X, describes the residence time of the sludge in the system. The sludge or biomass requires a certain amount of time to assimilate the substrate and reproduce. If the sludge is not able to reproduce itself before being washed out of the system, failure will result. Also, the sludge age is related to the F : M ratio describing the relative state of starvation of the microorganisms. Higher sludge ages cause the sludge to undergo more endogenous decay. This has an effect on the settleability of the sludge as well as on the total amount of sludge produced in the system.

Merely storing the sludge under conditions that have a minimal effect on its activity and maintain it in a dormant state will not increase the sludge age. Because the sludge is in an aerobic state in the aeration basin and the small amount of DO in the aeration basin effluent is rapidly exhausted in the clarifier, the sludge is in an anoxic or anaerobic condition in the clarifier. Also, there is no supply of exogenous substrate in the clarifier if the process is operating efficiently. The change in DO and lack of substrate mildly shock the sludge, putting it in an essentially dormant state. Therefore, residence time of the sludge in the clarifier does not contribute to the effective sludge age. It is only in the aeration basin, where a fresh supply of oxygen and substrate is maintained, that the sludge metabolic activity is significant.

Under these conditions, the sludge age or sludge residence time (SRT) is the average amount of time the sludge spends in the aeration basin. The SRT is completely analogous to the HRT, which is the average residence time of a particle of water in the aeration basin, although the two times are not necessarily equal.

$$\begin{aligned} \theta_X &= \frac{\text{mass of solids in aeration basin}}{\text{solids removal rate from the system}} \\ &= \frac{VX_V}{\text{solids removal rate from the system}} \end{aligned} \tag{17.12}$$

The specific expression of the solids removal rate is given below for each system. The concepts of F : M and SRT also become clearer after the mass balance relations are examined.

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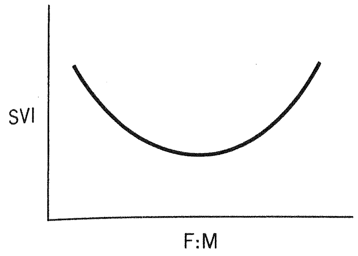

Figure 17.4 SVI as a function of F:M ratio.

17.6.1 Sludge Volume Index

A measure of the settleability and compactibility of sludge is made from a laboratory column settling test. The procedure is outlined in *Standard Methods* (1992). Mixed liquor with a known TSS content (X_T) is mixed and placed in a 1- or 2-L cylinder. The larger cylinder is desirable to minimize bridging of the sludge floc and wall effects. Gentle stirring during the test is also recommended to obtain the most efficient settling. The mixed liquor is allowed to settle for a period of time ranging from 30 min to 1 or 2 h. One-half hour is the more common settling time.

At the end of the settling period the volume of sludge is read from the cylinder. The sludge volume index (SVI) is defined as the volume in milliliters occupied by 1 g of sludge after it has settled for a specified period of time. If a 1-L cylinder is used and the sludge occupies a volume of y mL at the end of the settling period,

$$\text{SVI(mL/g)} = \frac{y}{X_T}(1\,000\ \text{mg/g}) \qquad (17.13)$$

A low SVI is indicative of a sludge that settles well. The SVI can be used to estimate the concentrations of VSS and TSS in the recycle line if the ratio of VSS to TSS in the mixed liquor is known. Typically, the ratio of VSS to TSS in the mixed liquor is in the range of 0.75 to 0.80.

$$X_{Tr} = \frac{10^6}{\text{SVI}} \quad (17.14a) \qquad X_{Vr} = \left(\frac{X_V}{X_T}\right) X_{Tr} \qquad (17.14b)$$

where

X_{Tr} and X_{Vr} are in mg/L

The F:M ratio and the SRT (which is directly related to F:M as shown below) influence the settleability and compactibility of the sludge. When the biomass is in a state of endogenous decay, it tends to form polymers that result in natural flocculation under quiescent conditions. In a CM reactor at low sludge ages the sludge tends to become populated with filamentous organisms that exhibit poor settleability and the sludge does not flocculate well. At the other extreme of highly starved conditions or a very high SRT, the sludge forms pinpoint floc (like the head of a needle) and does not flocculate as well as in intermediate ranges. A typical plot of SVI versus F:M ratio is shown in Fig. 17.4. Using the relations developed below, the F:M ratio can be replaced with the sludge age. Other factors discussed in Section 17.12 affect SVI.

17.6.2 CM Reactor without Recycle

The simplest system to examine is a CM reactor that does not receive recycled sludge from the clarifier. The clarifier is included for the sake of completeness but its operation and efficiency, which are related to conditions in the aeration basin, do not have any influence on phenomena in the aeration basin.

Figure 17.1a is a schematic of the process. Steady state conditions will be assumed. Also, the influent to the reactor will be assumed to not contain any VSS. As noted before, the influent is usually settled; therefore, influent suspended solids tend to be colloidal in nature. These colloidal particles normally contain degradable organic matter and many of the particles may be microorganisms themselves. But these microorganisms will not likely represent a significant contribution to active microorganisms in the aeration basin. The microorganisms that populate the aeration basin are largely adventitious in origin. They survive and reproduce in the conditions existent in the aeration basin. Our analysis will focus on the removal of dissolved organic matter for the moment.

Substrate Balance

$$\text{In} - \text{Out} + \text{Generation} = \text{Accumulation}$$

$$QS_0 - QS_e + r_S V = \frac{dS_e}{dt} V = 0$$

Even though generation (substrate transformation) is, in fact, negative in the case of wastewater treatment, the mass balance should not be incorrectly biased at this stage by putting a negative sign in front of the generation term. The kinetic formulation with the correct sign will be substituted later. Solving for r_S in terms of the physical conditions of the process,

$$r_S = -\frac{Q(S_0 - S_e)}{V} = -\frac{S_0 - S_e}{\theta_d} = -\rho \tag{17.15}$$

where

ρ is the rate of wastewater treatment

The rate of wastewater treatment, ρ, is simply a statement of the substrate mass balance without any kinetic formulation. A kinetic relation will be substituted for r_S and functionally it is related to ρ by Eq. (17.15). It avoids confusion to use ρ and r_S separately.

If a Monod model is substituted for r_S,

$$-\frac{kS_e}{K + S_e} = -\frac{S_0 - S_e}{\theta_d} \tag{17.16}$$

Solving for S_e,

$$S_e^2 + kS_e\theta_d - S_0 S_e + KS_e - KS_0 = 0 \tag{17.17}$$

Defining $b = k\theta_d - S_0 + K$ and $c = -KS_0$ $(a = 1)$,

$$S_e = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \tag{17.18}$$

The negative root will be physically meaningless.

When the form of the kinetic expression is known (i.e., first-order, second-order, Monod, or other model) along with the kinetic coefficients, substitution for r_S in Eq. (17.15) and solving for S_e is fairly routine. This approach is used to predict system behavior under various operating conditions. The other problem is to analyze data to determine the kinetic expression. The rate of wastewater treatment can be determined for any operating condition by measuring the readily determined parameters of θ_d, S_0, and S_e. However, the kinetic expression and the values of the kinetic coefficients should be determined from analysis of a number of operating conditions (see Example 17.1).

It is obvious from Eq. (17.17) that in the case of the two-parameter Monod model, data from at least two operating conditions must be available to solve for k and K. Given the multitude of substrates and microorganisms present in any wastewater, variability is inevitable and more than two operating conditions should be analyzed with regression techniques to establish the best model and its coefficient values.

The efficiency of treatment, η, is defined on the basis of degradable substrate removal. If substrate concentrations are defined on a BOD basis, the efficiency of treatment is

$$\eta = \frac{S_0 - S_e}{S_0} \tag{17.19a}$$

If substrate concentration is defined on a COD basis, there is likely to be a component of the COD that is not removable. The nondegradable component (S_n) is subtracted from the influent COD concentration. The effluent COD consists of the nondegradable component and COD that has not been removed in the process. The equations are based on removable COD only and the nondegradable component is ignored in the formulations for kinetic design of the process.

Defining S_{ST0} as the total soluble influent COD to the process and S_{STe} as the total soluble effluent COD from the process, the efficiency of treatment on a COD basis is defined as

$$\eta = \frac{(S_{\mathrm{ST0}} - S_n) - (S_{\mathrm{STe}} - S_n)}{S_{\mathrm{ST0}} - S_n} \times 100 \tag{17.19b}$$

where

$S_0 = S_{\mathrm{ST0}} - S_n$
$S_e = S_{\mathrm{STe}} - S_n$

It is more usual to compare total influent COD or BOD to soluble effluent COD or BOD, which is discussed later. For now we will work with the definition given in Eq. (17.19b).

The soluble effluent BOD_5 depends on the ease of biodegradation of soluble effluent organics. The organic matter remaining in solution after a biological treatment process is not likely to be as readily degraded as the influent organic matter to the process; therefore, the BOD rate constant will be lower for the effluent compared to the influent. An in situ determination must be performed.

The interpretation of S_n can be difficult and elaborate studies may be required to determine the true concentration of nondegradable components in the influent as opposed to soluble nondegradable components that are actually generated in the reactor. Practically, "correcting" S_0 and S_e with some value S_n simply provides the best correlation for the Monod equation in some circumstances (see for example, Selna and Schroeder, 1978). The lowest value of effluent soluble COD obtained over a wide range of operating conditions would be the maximum value for S_n.

Biomass Balance

The biomass balance applies to biological solids active in the process.

$$QX_{V0} - QX_V + r_X V = \frac{dX}{dt}V = 0$$

Influent biomass VSS is assumed to be negligible.

$$QX_V = r_X V \tag{17.20}$$

If the influent VSS is significant, whether it is incorporated into the biomass balance or not depends on whether the influent VSS are biological solids that will be active in the aeration basin.

The production rate of solids is equal to the net generation rate of solids. Substituting the kinetic relation for r_X (Eq. 17.4),

$$QX_V = (-Yr_S - k_e X_V)V \tag{17.21}$$

The sludge age or SRT for this system is

$$\theta_X = \frac{X_V V}{QX_V} = \theta_d \tag{17.22}$$

The sludge age and HRT are equal in this system but they are not necessarily equal in other systems.

Solving Eq. (17.21) for the sludge age and noting that $-\rho$ or $-UX_V$ can be substituted for r_S (see Eqs. 17.11 and 17.15),

$$\frac{1}{\theta_X} = -\frac{Yr_S}{X_V} - k_e = \frac{Y\rho}{X_V} - k_e = YU - k_e \tag{17.23}$$

Equation (17.23) relates the F:M ratio (also known as the process loading factor) to the sludge age.

Equation (17.23) can be further manipulated by substituting relations for r_S and ρ. First, substituting for ρ, the concentration of VSS in the aeration basin may be determined.

$$\frac{1}{\theta_X} = \frac{Y(S_0 - S_e)}{\theta_d X_V} - k_e \Rightarrow X_V = \frac{Y(S_0 - S_e)}{1 + k_e \theta_X} \tag{17.24}$$

The minimum sludge age, θ_X^m (Lawrence and McCarty, 1969, 1970), is a useful concept in the design of activated sludge systems and other biological treatment processes. The minimum sludge age is determined by the maximum rate at which the sludge can grow in the system. The sludge cannot be washed out of the system at a rate faster than the minimum sludge age or the microorganisms will not be able to sustain themselves in the system unless they are being supplied from an outside source. The maximum rate at which the microorganisms can grow is dependent on the maximum rate of substrate removal. The highest possible substrate concentration in the aeration basin is S_0. Choosing Eq. (17.1b) for the substrate removal expression and substituting it into Eq. (17.23), and replacing S_e with S_0 (to provide the highest rate of substrate removal),

$$\frac{1}{\theta_X^m} = \frac{YkS_0}{X_V(K + S_0)} - k_e$$

Furthermore, if $S_0 \gg K$,

$$\theta_X^m = \frac{X_V}{Yk - k_e X_V} \tag{17.25}$$

Similar expressions can be derived when other substrate removal relations apply.