§ 17.6 cont'd

Total Effluent COD from the Process

The total effluent COD from the process consists of the soluble effluent COD and the suspended or particulate COD. The former depends on the efficiency of biological treatment in the aeration basin, whereas the latter depends on the efficiency of solids removal in the secondary clarifier. There are no mechanistic models that can be developed to predict the concentrations of solids in the clarified effluent or in the clarifier underflow. The mixed liquor VSS (MLVSS) influent to the clarifier may contain anywhere from 700 to 5 000 mg/L of VSS and the clarified effluent can contain less than 20 mg/L to higher values depending on the operating conditions of the process. Likewise, the compactibility of the sludge can vary over a wide range. Observations can be used to correlate each of these parameters empirically with system operating conditions (HRT, SRT, temperature, pH, and other variables) and other parameters such as time of year or sewage strength.

Defining the total COD in the clarified effluent as S_{STe},

$$S_{\mathrm{STe}} = S_{\mathrm{e}} + fX_{\mathrm{Ve}} \tag{17.26}$$

where

f is a factor for the COD content of VSS

If the composition of VSS in the system is $C_5H_7NO_2$, the COD content of VSS (f) is 1.42 mg COD/mg VSS (see Section 17.3.2).

Removal of Influent Suspended Organic Matter

Effluent from primary clarifiers normally still contains significant amounts of suspended organic matter. Influent suspended organic matter is removed by two mechanisms in a biological treatment process:

1. Biomass metabolizes some of these organic solids. As for soluble organics, for the portion of suspended organics that is metabolized, there is a fraction that is oxidized, and the other fraction is transformed (synthesized) into biomass.
2. Suspended organics are flocculated with the biomass and settle in the secondary clarifier.

The efficiency of treatment is usually gauged by comparing the total influent COD or BOD to the soluble effluent BOD or COD; S_0 in Eqs. (17.19a) or (17.19b) would be measured on an unfiltered sample of influent. It is reasonable to assess the treatment on this basis because the objective of treatment in the biological reactor is to reduce the soluble degradable organics to a minimum. The separation of suspended solids is a function of the efficiency of the secondary clarifier. Separation of suspended matter from the clarified effluent can be further improved by filtration.

Laboratory studies conducted for research often use a totally soluble waste to avoid complications in modeling the removal rate of influent suspended organics. Modeling the rate of influent suspended degradable organics results in a more complex model. Influent VSS that is not microorganisms which will become part of the biological engine are actually part of the substrate. Substrate removal expressions remain based on the amount of soluble organics remaining in the water but, in fact, substrate removal incorporates hydrolysis and metabolism of suspended organics along with soluble organics. VSS concentrations less accurately reflect the amount of acclimated biomass in the aeration basin as influent VSS rises. It should be noted that some of the influent

VSS is microorganisms that have acclimatized to the waste as the wastewater flows through the sewer system and preliminary treatment operations.

It is possible to use the total influent BOD or COD concentration for S_0 in any of the equations given in this chapter if the kinetic coefficients and other parameters (such as the yield factor or ρ) have been developed on a basis of total influent organics. Regardless of which approach is used, it is necessary to develop treatment parameters for each waste and apply the model consistently.

17.6.3 CM Reactor with Recycle

The assumptions made in the previous section apply to a CM reactor with recycle also. In addition, it will be assumed that the storage of solids in the clarifier is insignificant. As discussed previously, the sludge is essentially dormant in the clarifier and this is equivalent to ignoring its presence (in a biological sense) in the clarifier. Studies have shown that for typical holding times in secondary clarifiers, the sludge is able to recover its activity when returned to the aeration basin (Ford and Eckenfelder, 1967).

Making a mass balance on soluble substrate around the system leads to the same results as given by Eqs. (17.15) and (17.16). Because the sludge is dormant in the clarifier, substrate removal occurs only in the aeration basin and the active volume in the system is V, the volume of the aeration basin. Equation (17.26) is applicable for the total effluent COD from the process.

Biomass Balance

Making the balance around the system,

$$QX_{V0} - Q_w X_{Vr} - (Q - Q_w)X_{Ve} + r_X V = \frac{dX_V}{dt} V = 0$$

There are two exit points for sludge: the clarified effluent and the underflow waste sludge line from the clarifier. Again it is noted that the sludge is only active in the aeration basin.

Because influent biomass VSS is assumed to be negligible,

$$Q_w X_{Vr} + (Q - Q_w)X_{Ve} = r_X V \tag{17.27}$$

The sludge age for this system is given by

$$\theta_X = \frac{X_V V}{Q_w X_{Vr} + (Q - Q_w)X_{Ve}} \tag{17.28}$$

Solving Eq. (17.27) for the inverse of the sludge age, the same equation (Eq. 17.23) obtained for the nonrecycle case is obtained.

Note in this case that the actual residence time of the sludge in the entire system (θ_T) is given by

$$\theta_T = \frac{X_V V + X_{Vc} V_c}{Q_w X_{Vr} + (Q - Q_w)X_{Ve}}$$

where

V_c is the volume of the clarifier

The effective sludge age or SRT is different from θ_T for reasons discussed in Section 17.6.

Substituting the expression for ρ (Eq. 17.15) in place of r_S in Eq. (17.23) allows X_V to be determined.

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

which can be rearranged to

$$X_V = \frac{\theta_X}{\theta_d}\left[\frac{Y(S_0 - S_e)}{1 + k_e \theta_X}\right] \tag{17.29}$$

The difference between Eqs. (17.29) and (17.24) is the θ_X/θ_d term, which is a physical concentration factor resulting from recycling the concentrated sludge. In the nonrecycle case this term equals 1 and so it does not explicitly appear in Eq. (17.24). Because the sludge age is often more than an order of magnitude greater than the HRT, a high degree of concentration can be attained by recycle.

Following the same procedures used for the nonrecycle case, the same expression for the minimum sludge age (Eq. 17.25) can be developed for the recycle case. The same expressions for treatment efficiency defined in Eqs. (17.19a) and (17.19b) also apply.

If influent VSS is significant but does not contain biomass adapted to the process, it is not included in the biomass balance. If the influent VSS is biomass acclimated to the process then it is included in the biomass balance and effectively reduces the sludge age or reproduction time for microorganisms. This is not problematic. Supply of microorganisms from an outside source reduces growth time required for microorganisms in the process.

If a model is developed ignoring influent VSS when it is significant, the model will be limited. More rigorous analysis of the data can be used to develop a more refined and accurate model that will have more validity if the proper data are obtained.

17.6.4 The Rate of Recycle

The design engineer has control over the HRT and the SRT. The operator is able to vary each of these within the design limitations of the system. The recycle ratio r is related to these and other parameters. To derive the relation, consider a mass balance for VSS around the clarifier (Fig. 17.1b).

$$Q(1 + r)X_V = (Q - Q_w)X_{Ve} + rQX_{Vr} + Q_w X_{Vr}$$

It is recognized that the expression for sludge age (Eq. 17.28) can be used to simplify the equation by removing the terms involving Q_w. Q_w is not a primary control variable. It is a function of the sludge age, which influences sludge settleability and the concentration of solids in the recycle line. Rearranging Eq. (17.28),

$$\frac{VX_V}{\theta_X} = (Q - Q_w)X_{Ve} + Q_w X_{Vr} \tag{17.30}$$

Substituting this into the mass balance,

$$(1 + r)X_V = \frac{VX_V}{Q\theta_X} + rX_{Vr}$$

The following relation is obtained:

$$\frac{1}{\theta_X} = \frac{Q}{V}\left(1 + r - r\frac{X_{Vr}}{X_V}\right) \tag{17.31}$$

The term $X_{\mathrm{Vr}}/X_{\mathrm{V}}$ is a measure of the sludge compactibility. A measure of X_{Vr} may be obtained from the SVI test. Solving Eq. (17.31) for r,

$$r = \frac{1 - \dfrac{\theta_{\mathrm{d}}}{\theta_{\mathrm{X}}}}{\dfrac{X_{\mathrm{Vr}}}{X_{\mathrm{V}}} - 1} \tag{17.32}$$

■ Example 17.1 Determination of Parameters for an Activated Sludge Process

The data in the following table have been obtained from bench-scale studies of a continuous flow activated sludge process treating a synthetic waste. The data are the average values determined after steady state conditions have been achieved. Determine the kinetic coefficients and yield factor for this system. Substrate concentration was measured as COD.

Run	θ_{X}, d	θ_{d}, d	S_0, mg/L	S_{e}, mg/L	X_{V}, mg/L
1	12.0	0.25	310	35	2 850
2	8.8	0.25	300	62	2 004
3	6.1	0.25	315	59	1 688
4	12.3	0.33	284	47	1 914
5	8.9	0.33	302	53	1 625
6	6.0	0.33	300	66	997

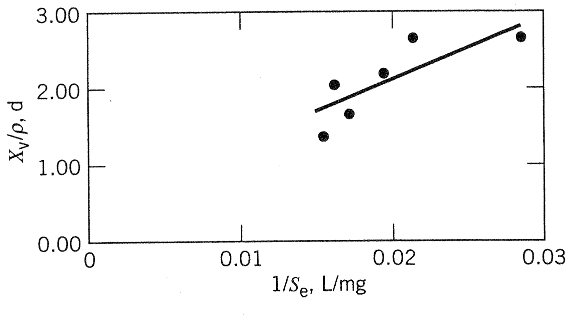
Regardless of whether recycle has been used in the system, Eq. (17.15) applies. Substituting Eq. (17.1a) for r_{S} and rearranging Eq. (17.15) in the linear Lineweaver–Burke form (see Section 4.12):

$$\frac{X_{\mathrm{V}}}{\rho} = \frac{X_{\mathrm{V}}\theta_{\mathrm{d}}}{(S_0 - S_{\mathrm{e}})} = \frac{K}{k}\frac{1}{S_{\mathrm{e}}} + \frac{1}{k}$$

The data were plotted according to this equation and a regression was performed to determine the coefficients. The R^2 value of the regression was 0.60. The values of the intercept and slope were 0.573 and 78, respectively. From this

$$k = 1/0.573 = 1.75\ \mathrm{d}^{-1}$$
$$K = k(78) = (1.75)(78) = 136\ \mathrm{mg/L}$$

The fitted curve is also plotted on the figure below. Equation (17.1b) was also checked as the kinetic model but the R^2 value was much lower than 0.60. Equation (17.1a) was chosen as the kinetic model.



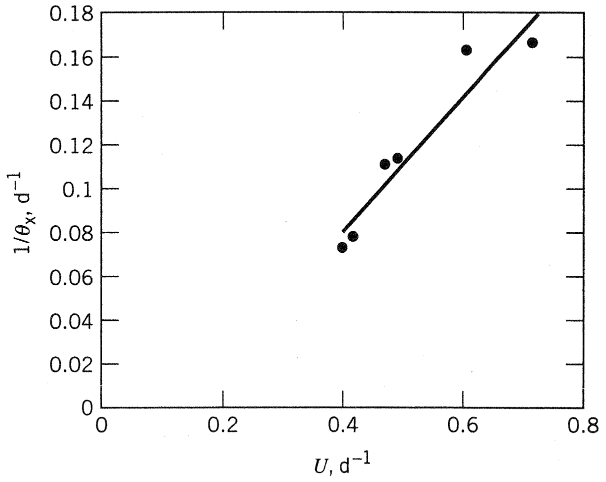
Estimating kinetic parameters of the Monod equation by linearization procedures applied to nonlinear equations is subject to instability and error. For instance, if S_e had been measured as 45 mg/L (this could easily occur in a biological treatment process) instead of 35 mg/L for run 1, the Lineweaver–Burke formulation would lead to a negative K value. Nonlinear parameter estimation techniques are the best choice when possible.

The yield factor and endogenous decay coefficient were determined from Eq. (17.23), which applies to either the recycle or the nonrecycle case (sludge age must be correctly calculated depending on recycle).

From a regression of $1/\theta_X$ against U (r_S/X_V), the slope and intercept were

$$-k_e = -0.019\ \mathrm{d}^{-1} \qquad Y = 0.28 \quad (R^2 = 0.94)$$

The equation and fitted curve are plotted in the accompanying figure.



Similar procedures would be applied to data generated for other variations of the activated sludge process.

If Eq. (17.1a) is used as the substrate removal model, a biomass balance dictates that effluent quality is solely a function of sludge age. MLVSS will vary inversely to the detention time in the system. If Eq. (17.1b) is used as the kinetic model, a substrate balance will show that effluent quality is solely dependent on the detention time in the aeration basin and MLVSS will vary directly with the sludge age. In the former case a minimum detention time is required for mass transfer of substrates and other substances into and out of the microorganisms and metabolism regardless of the concentration of microorganisms. This is illustrated by effluent quality variation with detention time in a contact stabilization basin (discussed in Section 17.8.4).

In the second case, the time (detention time) for organics uptake does not ensure that there is enough time for the microorganisms to reproduce. The sludge age cannot be arbitrarily varied to extremes. The coefficients developed will apply to the model selected and be reasonably constant within a range of operating conditions around the conditions used to generate data for coefficient determination. The models developed here are simple representations of a very complex process and the mathematical constructs must be applied judiciously.