8.2.2 Aerobic digestion in the activated sludge process

Having established a consistent model for aerobic digestion, the question emerges if this model is also applicable in the activated sludge process itself. It is not *a priori* clear, if this question can be answered affirmatively: aerobic digestion was assumed to be a process by which cellular material is oxidised to obtain the necessary energy to maintain the vital functions of the micro-organisms. In an aerobic digester, the only source of organic matter for oxidation is the protoplasm of the active sludge. In contrast, in the activated sludge process there is also extra-cellular organic material present. It could be assumed that the bacteria would "save" their protoplasm and use preferentially the extra-cellular material, so that endogenous respiration would be substituted by exogenous respiration. It will now be shown that the experimental results indicate that the endogenous respiration rate is independent of the exogenous respiration rate.

Fig. 8.4 shows the independence of endogenous and exogenous respiration. In this figure one can observe, plotted as a function of the sludge age, the experimentally determined fractions of the influent COD discharged in the effluent, oxidised and discharged as excess sludge. In the same figure the theoretical COD fractions are also indicated. In order to calculate these theoretical fractions, it was assumed that the value of the kinetic decay rate constant for aerobic digestion (b_h), as determined in the aerobic batch digester, could be used to describe the kinetics of endogenous respiration in the activated sludge process. As there is a very close correlation between the experimental- and the theoretical values of the different COD fractions over the whole range of applied sludge ages, the assumed independence of exogenous and endogenous respiration seems perfectly justified.

The decay constant for active sludge determined in the previous section has a much larger value than the one commonly used in textbooks. This latter "constant" originates from a model in which the aerobic sludge digestion is described as a first order process in relation to the volatile (and not the active) sludge concentration:

$$r_v = (dX_v/dt)_d = -b_v \cdot X_v \qquad (8.22)$$

Where:

r_v = decay rate of volatile solids
b_v = proportionality constant = apparent aerobic digestion constant

The numerical value attributed to b_v shows considerable variation, but generally is within the range of 0.04 to 0.10 d^{-1} for temperatures around 20°C, as compared to a value of $b_h = 0.24\ d^{-1}$ found by Marais and Ekama (1976) and by Van Haandel et al (1985). The reasons for this large difference will be explained below. The following experimental method is often used to determine the b_v value (Ramalho, 1980): if an activated sludge process is operated under steady state conditions, a sludge mass develops that is compatible with the applied organic load. When this sludge mass is established, there is an equilibrium between the sludge growth due to synthesis and the sludge loss due to aerobic digestion and to sludge wastage.

$$(dX_v/dt) = 0 = r_c + r_v + r_e \qquad (8.23)$$

Where:

(dX_v/dt) = rate of change of the volatile sludge concentration (= 0 at steady state)
r_c = growth rate of volatile solids = $Y' \cdot (S_{ti} - S_{te})/R_h$ with Y' as the apparent yield
r_v = decay rate of volatile solids = $-b_v \cdot X_v$
r_e = rate of change due to sludge discharge = $-X_v/R_s$

Substituting the expressions for r_c, r_v and r_e in Eq. (8.23):

$Y'\cdot(S_{ti} - S_e)/R_h - X_v\cdot(b_v + 1/R_s) = 0$ or

$$1/R_s = Y'\cdot(S_{ti} - S_e)/(X_v\cdot R_h) - b_v \qquad (8.24)$$

Using $R_h = V_r/Q_i$, one has:

$$1/R_s = Y'\cdot(S_{ti} - S_{te})\cdot Q_i/(X_v\cdot V_r) - b_v = Y\cdot F/M - b_v \qquad (8.25)$$

The F/M can be calculated by determining the values of S_{te}, S_{ti}, Q_i and V_r (Eq. 3.64). Thus it is possible to determine b_v in the following manner (Fig. 8.4):

(1) For different values of the sludge age the F/M ratio is determined. In the example of Fig. 8.4, for R_s = 2, 3 and 4 days;
(2) The values of l/R_s are plotted as a function of F/M;
(3) A straight line is drawn through the experimental points (line R_l in Fig. 8.4);
(4) With the aid of Eq. (8.25) the apparent yield coefficient Y' is determined graphically. For the straight line R_l the gradient is Y' = 0.40 mg VSS.mg^{-1} COD;
(5) Extrapolate the line to $l/R_s = 0$ to find $(F/M)_{1/Rs=0}$ and the constant b_v can be calculated as $b_v = Y'\cdot(F/M)_{1/Rs=0}$

In the case of the example in Fig 8.4, line R_l intercepts the horizontal axis ($l/R_s = 0$) at $(F/M)_{1/Rs=0}$ = 0.20 mg COD.mg^{-1} VSS.d^{-1}. Hence in this case the value of the constant b_v would be 0.40·0.20 = 0.08 d^{-1}. It must be emphasised that the above method, though much applied in practice, is **incorrect** as becomes apparent from the following analysis.

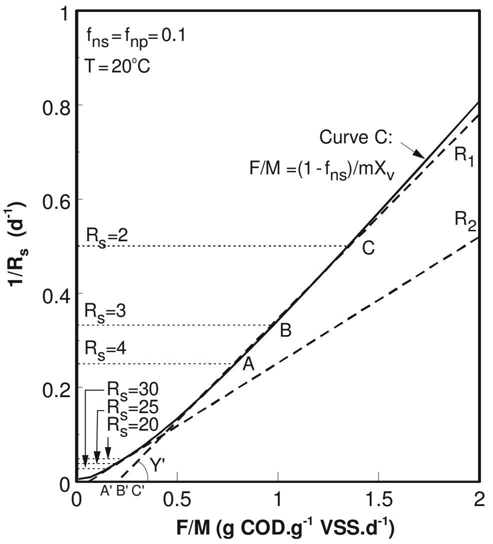

Figure 8.4
Graphical representation of the method to calculate the value of b_v

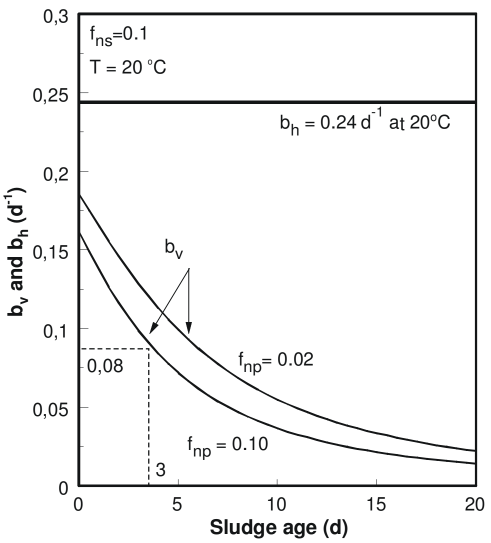

Figure 8.5
b_v and b_h values as function of the sludge age for different f_{np} values

The ratio F/M can be expressed as (refer to Section 3.2.3.5):

$$
\begin{aligned}
F/M &= (S_{ti} - S_t)/(X_v \cdot R_h) \\
&= (1 - f_{ns}) \cdot S_{ti} \cdot Q_i/(X_v \cdot V_r) = (1 - f_{ns})/mX_v \\
&= (1 - f_{ns})/[(1 - f_{ns} - f_{np}) \cdot (1 + f \cdot b_h \cdot R_s) \cdot C_r + f_{np} \cdot R_s/f_{cv}] \qquad (8.26)
\end{aligned}
$$

From Eq. (8.26) it can be noted that the plot of $1/R_s$ as a function of F/M is in fact not a straight line as Eq. (8.23) suggests, but rather a curve that passes through the origin. In Fig. 8.4 it can be clearly observed that the value of b_v is obtained from a linearisation of the experimental relationship between $1/R_s$ and the F/M ratio.

The obtained "straight" line depends heavily on the value of the sludge age used during the experiments. If these values are low (for example R_s = 2 to 4 days), then the corresponding b_v value will be relatively high: $b_v = 0.08\ d^{-1}$ for line R_1. For high sludge ages (for example R_s = 20 to 30 days), then the value of b_v will be small ($0.03\ d^{-1}$ for line R_2).

It can be concluded that the value of the "constant" b_v in fact depends on the value of the sludge age used during the experiment. The reason is that at high sludge ages the active sludge fraction f_{av} will be small, resulting in a small apparent decay rate b_v for the volatile sludge mass as a whole. The opposite is true at low sludge ages: the X_a fraction is large compared to the total volatile sludge concentration resulting in a high apparent decay rate b_v. This also shows that the validity of the value of the b_v parameter is restricted to activated sludge processes that operate under very similar conditions to those used during the investigation (with the same f_{av} value).

It is possible to calculate the theoretical value of b_v as a function of the sludge age. Fig. 8.5 shows the relationship between b_v and R_s for $f_{np} = 0.02$ and for $f_{np} = 0.10$ (at T = 20°C). It can be observed that the value of b_v is influenced considerably by the values of R_s and f_{np} while in contrast the value of b_h does not depend on these variables. The range of values for b_v in Fig. 8.5 covers the range usually found in the literature. Thus, Eq. (8.5) is capable of a correct prediction of the variations of the "constant" b_v.

Evidently, the model based on Eqs. (8.5 and 8.6) is much superior to the model suggested by Eq. (8.23): once the constant b_h has been determined, it can be used for any set of values of the parameters R_s and f_{np}. The value determined for b_v is only valid for similar values of R_s and f_{np} as were applied during the experimental investigation for its determination. For a different set of operational conditions a new determination of the value of b_v will be required.