8.2.4 Optimisation of aerobic sludge digestion

In general when aerobic sludge digestion is applied, a sludge thickener precedes the digester in order to increase the sludge concentration, with the objective to reduce the flow of excess sludge. The thickened excess sludge flow will then be introduced into the aerobic digester. As the required retention time in the digester unit to effect the reduction of the active sludge fraction from f_{ai} to f_{ae} is fixed for a certain excess sludge composition, the volume of the digester will be inversely proportional to the volume of the thickened sludge flow. The objective of the optimisation of the activated sludge system with aerobic digestion is to minimise construction cost of the biological reactor, thickener and digester while producing digested sludge with an active sludge fraction below a specified maximum value (for example $0.1 < f_{ae} < 0.2$).

Two different situations should be considered: (a) the sludge age in the activated sludge process is defined by factors unrelated to sludge stabilisation (in general the sludge age will be set by the requirements for nutrient removal), or (b) the sludge age may be defined by the optimal value for sludge stabilisation. In the first case the optimisation procedure is limited to a calculation for the minimum costs for construction of the thickener and the digester. In the second case, the construction costs of the aeration tank and the final settler must also be taken into consideration. Both cases will now be evaluated.

When the value of the sludge age is given, the composition- and flow of the excess sludge to be digested are known. In this case, the volumes of the thickener and the digester unit required to reduce the active sludge fraction to the desired value f_{ae} can be calculated. To calculate these volumes, the following factors are important: the sludge age, the settling characteristics of the sludge and the number of digesters in series. The sludge age in the activated sludge process determines the composition and flow of the excess sludge. By expressing the variables per unit daily applied COD mass, one has:

$$mX_a = (1 - f_{ns} - f_{np})\cdot C_r$$

$$mX_v = (1 - f_{ns} - f_{np})\cdot C_r\cdot(1 + f\cdot b_h\cdot R_s) + f_{np}\cdot R_s/f_{cv}$$

$$mXt = mX_v/f_v$$

The mass of excess sludge per daily unit applied COD is given by:

$$mE_t = mX_v/R_s$$

The active sludge fraction is equal to:

$$f_{av} = f_{ai} = mX_a/mX_v$$

The settling characteristics determine the concentration of the excess sludge flow after thickening. The required thickener area per unit mass of daily applied COD is given by Eq. (6.45):

$$a_{th} = mE_t/(X_r\cdot v_0\cdot(k\cdot X_l - 1)\cdot \exp(-k\cdot X_l))$$

For a thickener with depth H and a safety factor S_f, the volume of the thickener per unit mass of daily applied COD can now be calculated as:

$$v_{th} = S_f\cdot H\cdot a_{th} \qquad (8.44)$$

The sludge flow per unit mass of daily applied COD after thickening to a sludge concentration X_{th} is calculated as:

$$q_{th} = mE_t/X_{th} \quad (8.45)$$

The digester volume depends on the number of digesters in series, which in turn is dependent on the construction costs. While the combined volume of a series of digesters decreases when the number of digesters increases, the construction costs will not decrease correspondingly, because of the need for additional walls to separate the digesters and the additional equipment and instrumentation. There will be an optimal number of digesters with minimum construction costs. It is interesting to note that for any particular degree of desired stabilisation, the oxygen and alkalinity demands are fixed, so that the operational costs are not influenced by the digester configuration. The total volume of the digestion unit per unit mass of daily applied COD can be calculated with the aid of Eqs. (8.40 and 8.45):

$$v_{da} = q_{th} \cdot R_d = mE_t/X_{th} \cdot N/b_h \cdot \left[\frac{1/f_{ae} + f - 1}{1/f_{ai} + f - 1}\right]^{1/N} - 1 \quad (8.46)$$

Now, the optimal values for the volumes of the thickener and the digester are determined by the criterion of minimal costs. For a particular number of digesters in series N, the only variable is the thickened sludge outlet concentration. The higher this concentration is chosen, the larger will be the required thickener volume, but on the other hand the digester volume will be reduced. The objective function to be optimised can be formulated as:

$$(dC_t/dX_r) = 0 = C_{th} \cdot (dv_{th}/dX_{th}) + C_{da} \cdot (dv_{da}/dX_{th}) \quad (8.47)$$

Where:

C_t = total construction costs per unit mass of daily applied COD
C_{da} = construction costs of the aerobic digester per unit mass of daily applied COD
C_{th} = construction costs of the thickener per unit mass of daily applied COD

As the variables v_{th} and v_{da} are complex functions of the thickened sludge concentration X_{th}, it is convenient to use numerical or graphical techniques to find the optimal solution of Eq. (8.47). In Fig. 8.9 the optimisation procedure described above is shown. The volumes v_{da} of the digester unit and v_{th} of the thickener are shown plotted as functions of the thickened sludge concentration for the following conditions: $f_{ai} = 0.5$; $f_{ae} = 0.1$; $S_f = 1$; H = 4 m; T = 20°C and mE_t= 0.2 mg TSS.mg^{-1} COD.

The calculations were made for both poor settleability (k = 0.46 $l.g^{-1}$ and v_0 = 144 $m.d^{-1}$, top figures) and fair settleability (k = 0.36 $l.g^{-1}$ and v_0 = 216 $m.d^{-1}$, bottom figures). Furthermore, two configurations were considered: a completely mixed digester (n = l, left) and two equally sized digesters in series (n = 2, right).

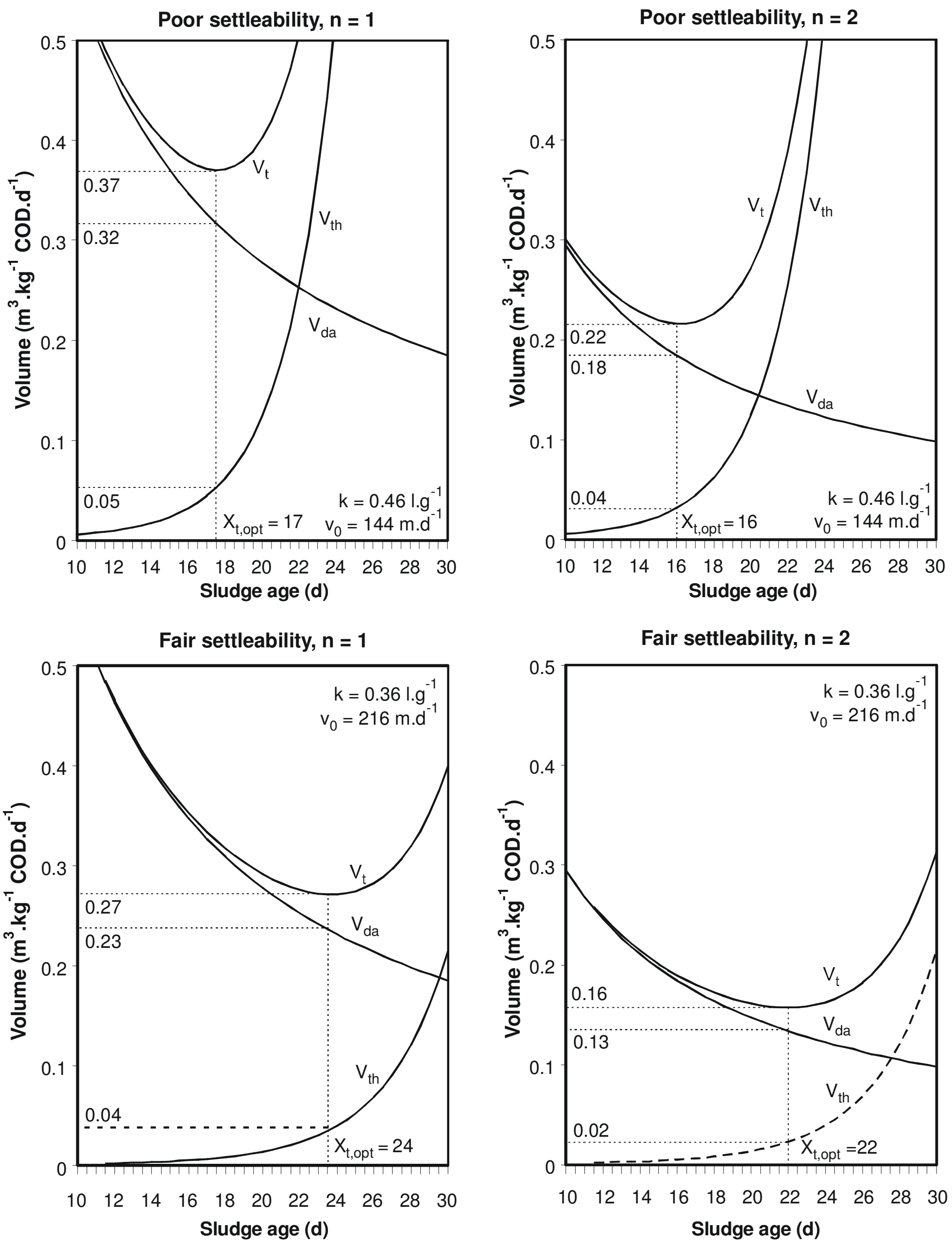

Figure 8.9 Graphical optimisation of a system consisting of an aerobic digester and a sludge thickener

From an analysis of Fig. 8.9, the following may be concluded:

- In all cases the thickener volume is relatively small, but its presence is crucial in order to avoid a very large digester volume. Thus for example, for fair settleability and a series of two digesters (bottom-right diagram of Fig. 8.9), the optimal volume of the thickener is 24 litre.kg^{-1} COD.d^{-1} and produces a thickened sludge concentration of 22 g TSS.l^{-1}.
- If it is assumed that the sludge concentration in the aeration tank was 4.4 g TSS.l^{-1}, the sludge is thickened by a factor 24/4.4 = 5, which means that the digester unit after thickening is 5 times smaller then without thickening. Thus if the thickener with a volume of 24 litre.kg^{-1} COD.d^{-1} were omitted, the digester unit would have to be increased from 134 litre.kg^{-1} COD.d^{-1} in Fig. 8.9 to 5·134 = 670 litre.kg^{-1} COD.d^{-1}. The result would be that the digester is larger than the aeration tank!;
- The influence of the digester configuration on the required volume is considerable. For example, for poor settling (top figures in Fig. 8.9) the optimal digester volume is 320 litre.kg^{-1} COD.d^{-1} for the single digester, but only 190 litre.kg^{-1} COD.d^{-1} for 2 digesters in series and 120 litre.kg^{-1} COD.d^{-1} for a plug-flow digester. At the same time, the required thickener volume is also reduced when the number of digesters in series increases. When the number of digesters increases beyond two, the resulting reduction in digester volume will be relatively small and will probably not compensate for the extra construction costs and operational requirements;
- The settleability has a very marked influence on the required volume for sludge digestion. In Fig. 8.9 the volumes for poor settleability (top) are about twice as big as the volumes in the case of fair settleability (bottom).

When the sludge age in the biological reactor can be selected randomly without limitations imposed by other considerations such as nutrient removal, its optimal value will be determined by the minimal construction costs of the whole treatment system.

In this case it will be necessary to carry out two optimisations at the same time: one for the system consisting of the aeration tank and the settler and the other for the system consisting of the thickener and digester. The procedure can be summarised as follows:

(1) For a particular sludge age the optimal sludge concentration in the aeration tank (using the method described in Section 6.3) is determined and the required volumes of the aeration tank and the final settler are calculated;
(2) For the same sludge age the optimal volumes of the thickener and the digester are calculated, using the method presented above.
(3) The total construction costs are determined for the sludge age under consideration:

$$C_t = C_r \cdot v_r + C_d \cdot v_d + C_{th} \cdot v_{th} + C_{da} \cdot v_{da} \quad (8.48)$$

C = construction cost per unit volume
v = volume per unit daily applied COD mass

(4) Indexes t, r, d, th and da refer to total, aeration tank, final settler, thickener and aerobic digester respectively;
(5) The procedure is repeated for different sludge ages and the total costs are plotted as a function of sludge age. The minimum total costs identify the optimal sludge age in the activated sludge process.

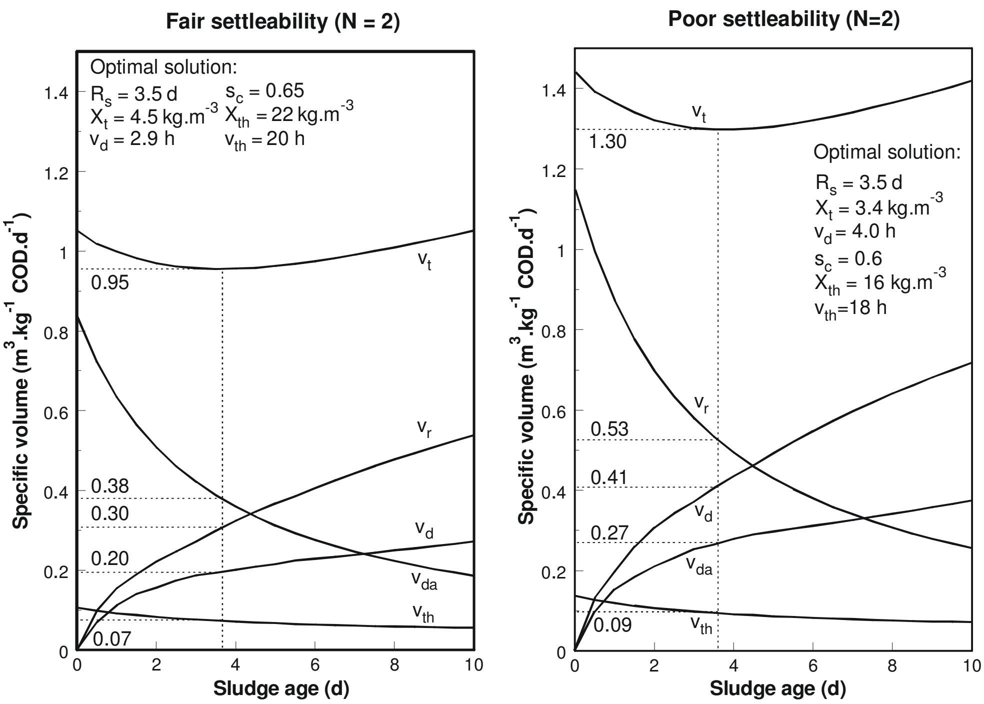

Figure 8.10 Optimisation of the activated sludge process with an aerobic digestion unit without restriction to the applied sludge age

As an example of the procedure described above, the total volume for the treatment system with aerobic sludge digestion is calculated in Fig. 8.10 for fair and poor sludge settleability respectively. To make the necessary calculations, it was assumed that the system has an optimally designed thickener and that the desired active sludge fraction in the stabilised sludge f_{ae} is 0.1. Furthermore the following data were used: non-biodegradable influent fractions f_{ns} and f_{np} are 0.1; the temperature is 20°C (i.e. $b_h = 0.24\ d^{-1}$); H = 4 and S_f = 2 in the settler and H = 4 and S_f = 1.5 in the thickener.

Fig. 8.10 shows that for the specified conditions in both cases, the optimal sludge age in the activated sludge plant is (coincidentally) 3.5 days. If it is assumed that the construction cost per unit of volume is equal for all treatment units, the minimum volume that is obtained for a sludge age of R_s = 3.5 days also indicates the minimum costs. In the case of fair settleability, the volumes would be: v_r = 0.30; v_d = 0.20; v_{th} = 0.07 and v_{da} = 0.38 $m^3.kg^{-1}$ $COD.d^{-1}$, resulting in a total volume v_t = 0.95 $m^3.kg^{-1}$ $COD.d^{-1}$.

For sludge ages beyond the optimal value, the total volume increases gradually and reaches a value of v_t = 1.10 $m^3.kg^{-1}$ $COD.d^{-1}$ for R_s = 10 days. For sludge ages shorter than the optimal value there is a more rapid increase in the required volume, due to the large size of the aerobic digester. Although the same optimal sludge age of 3.5 days is calculated in the case of poor settleability, the reactor volumes are quite different: the total volume increases by 35 percent (from 0.95 to 1.30 $m^3.kg^{-1}$ $COD.d^{-1}$, due to the poor settling characteristics of the sludge.