8.2.3 Aerobic digester design

Aerobic digesters are usually constructed as completely mixed reactors. The reactor may be fed continuously or intermittently with excess sludge. The objective of the digestion is to reduce the fraction of biodegradable organic material to such a level that the digested sludge can be disposed of without problems. In practice this means that the active sludge fraction f_{av} should be reduced to a value between 0.10 to 0.20 of the volatile sludge mass. For the design of the aerobic digester the following factors are important:

(1) Flow and composition of the sludge to be digested;
(2) Maximum allowable fraction of active sludge remaining after digestion;
(3) Digestion temperature;
(4) Configuration of the aerobic sludge digester: i.e. the number of digesters in series.

With respect to the sludge composition, a distinction must be made between the digestion of combined primary- and secondary excess sludge and that of secondary sludge only. In the former case, at first the primary sludge will be metabolised by the active sludge, which is an oxygen consuming process and leads to the production of more active sludge. Thus the advantages of having primary sedimentation (i.e. smaller aeration tank and less oxygen consumption) are lost to a large extent when aerobic sludge digestion is applied, because the digester will be large and will consume a considerable amount of oxygen.

Therefore in practice, primary settling is almost always combined with anaerobic sludge digestion. The composition of the excess sludge, the desired composition of the stabilised sludge and the temperature will normally be known, thus the only variable that the designer is able to optimise is the reactor configuration.

The influence of the configuration on the digester performance can be evaluated by using basic principles of chemical reactor engineering. Knowing that aerobic digestion is a first order process with respect to the active sludge concentration and that a digester operates as a completely mixed reactor, the decrease of the active sludge concentration in the case of continuous feeding can be expressed as (Levenspiel, 1972):

$$X_{ae} = X_{ai}/(1 + b_h \cdot R_d) \tag{8.27}$$

Where:

X_{ae} = active sludge concentration in the digester and its effluent
X_{ai} = active sludge concentration of the digester feed
R_d = retention time in the digester

In the case of a series of completely mixed digesters, the effluent from the first digester serves as the influent for the second and so on, until stabilised sludge is discharged from the last digester of the series. Equation (8.27) remains valid for each digester individually so that:

$$X_{an} = X_{a(n-1)}/(1 + b_h \cdot R_n) \tag{8.28}$$

Where:

X_{an} = active sludge concentration in digester n and its effluent.
$X_{a(n-1)}$ = active sludge concentration in digester (n-1)
R_n = retention time in the n-th digester

For a series of N digesters Eq. (8.28) leads to:

$$X_{aN}/X_{ai} = \sum_{n=1}^{N} 1/(1+b_h \cdot R_n) \qquad (8.29)$$

X_{aN} = active sludge concentration in the discharge from the last digester

It is well known that for a first order process the highest efficiency is obtained when a series of completely mixed reactors all have the same retention time (Levenspiel, 1972) so that:

$$R_n = R_d/N \qquad (8.30)$$

For a very long series of reactors the behaviour of a plug flow reactor is approximated as can be observed from Eq. (8.29):

$$X_{ae}/X_{ai} = \lim_{n \to \infty} 1/(1 + b_h \cdot R_n)^N = \exp(-b_h \cdot R_d) \qquad (8.31)$$

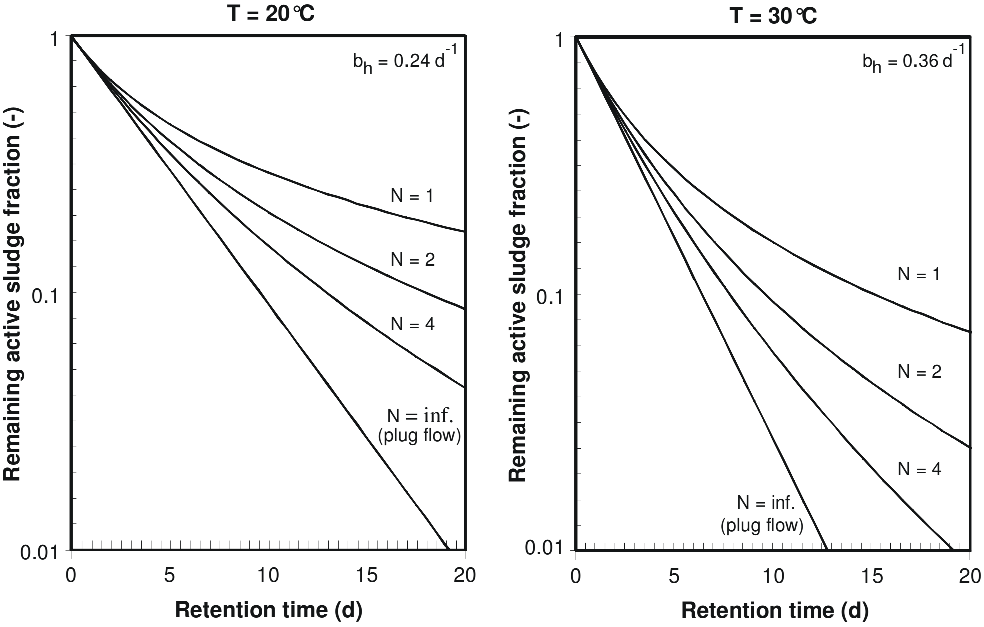

Figure 8.6 Residual active sludge fraction as function of the retention time in aerobic digesters for different configurations and temperatures

Equation (8.31) shows that the relationship between the active sludge concentration and the retention time in a plug flow reactor is the same as in a batch reactor with a digestion period equal to R_d. Equation (8.29) permits an evaluation of the influence of the number of digesters on the digestion efficiency. To compare the performance of a single digester with a series of digesters, it is convenient to calculate the ratio X_{ae}/X_{ai} as a function of the total retention time R_d.

In Fig. 8.6a and b this relationship is presented for the single digester ($n = 1$), for two ($n = 2$) and four ($n = 4$) digesters in series as well as for the plug flow reactor ($n = \infty$) at temperatures of 20 and 30°C. It can be observed that a higher temperature accelerates the digestion process significantly and that for any value of the retention time, the digester is more efficient as it has more reactors in series.

In practice, the objective of an aerobic digester is to reduce the active sludge fraction from a fraction f_{ai} in the excess sludge to a specified fraction f_{ae} in the stabilised sludge. The influence of the digester configuration on the performance can be evaluated by deriving an expression for the relationship between the retention time and the values of the incoming and outgoing active sludge fractions f_{ai} and f_{ae}. In the case of a single digester, the retention time to reduce the active sludge fraction from f_{ai} to f_{ae} is calculated as follows:

(1) The active sludge fraction in the influent of the digester is given by:

$$f_{ai} = X_{ai}/(X_{ai} + X_{nai}) = 1/(1+X_{nai}/X_{ai}) \quad (8.32)$$

Where:

X_{ai} = incoming active sludge concentration
X_{nai} = incoming inactive sludge concentration ($X_i + X_e$)

(2) In the aerobic digester the active sludge concentration decreases to X_{ae}. Consequently, an endogenous residue mass will be formed with a concentration of:

$$X_{ee} = f\cdot(X_{ai} - X_{ae}) \quad (8.33)$$

Where X_{ee}= endogenous residue concentration formed in the digester.

(3) Thus the active sludge fraction in the outgoing sludge is given by:

$$f_{ae} = X_{ae}/(X_{ae} + X_{nae} + X_{ee}) = 1/(1 + X_{nae}/X_{ae} + X_{ee}/X_{ae}) \quad (8.34)$$

Where X_{nae} = inactive sludge concentration in the outgoing sludge

(4) Considering that the inactive sludge concentration remains constant in the digester one has:

$$X_{nae}/X_{ae} = X_{nai}/X_{ae} = (X_{nai}/X_{ai})\cdot(1 + b_h\cdot R_d) \quad (8.35)$$

(5) Now using Eq.(8.32) in Eq. (8.35) gives:

$$1/f_{ae} = X_{nae}/X_{ae} = (1/f_{ai} - 1)\cdot(1 + b_h\cdot R_d) \quad (8.36)$$

(6) Finally, by substituting Eqs. (8.33 and 8.36) in Eq.(8.34) the following relationship is established:

$$R_d = 1/b_h\cdot\left[\frac{1/f_{ae} + f - 1}{1/f_{ai} + f - 1} - 1\right] = 1/b_h\cdot\left[\frac{1/f_{ae} - 1/f_{ai}}{1/f_{ai} + f - 1}\right] \quad (8.37)$$

In order to calculate the required retention time in a series of digesters (with equal volumes) to reduce the active sludge fraction from f_{ai} to f_{ae}, first the n-th digester of the series is considered. For this reactor Eq. (8.37) is valid so that:

$$R_n = 1/b_h \cdot \left[\frac{1/f_{an} + f - 1}{1/f_{a(n-1)} + f - 1} - 1 \right] \text{ or}$$

$$1/f_{an} + f - 1 = (1/f_{a(n-1)} + f - 1) \cdot (1 + b_h \cdot R_n) \qquad (8.38)$$

f_{an} = active sludge fraction in the sludge leaving the n-th digester
$f_{a(n-1)}$ = active sludge fraction in the sludge entering the n-th digester

Applying Eq. (8.38) for a series of N digesters one has:

$$1/f_{ae} + f - 1 = (1/f_{ai} + f - 1) \cdot (1 + b_h \cdot R_n)^N \text{ or}$$

$$R_n = 1/b_h \cdot \left[\frac{1/f_{ae} + f - 1}{1/f_{ai} + f - 1} \right]^{1/N} - 1 \qquad (8.39)$$

Now the total retention time can easily be calculated as:

$$R_d = N \cdot R_n = N/b_h \cdot \left[\frac{1/f_{ae} + f - 1}{1/f_{ai} + f - 1} \right]^{1/N} - 1 \qquad (8.40)$$

The minimum retention time for a large number of digesters ($n \rightarrow \infty$) can be calculated from Eq. (8.40) as:

$$R_{d,min} = \lim_{n \rightarrow \infty} R_d = 1/b_h \cdot \ln \frac{1/f_{ae} + f - 1}{1/f_{ai} + f - 1} \qquad (8.41)$$

Fig. 8.7 shows the relationship between the retention time and the active sludge fraction in the excess sludge for different reactor configurations (N = 1, 2, 4 and ∞) and for active sludge concentrations of 10 and 20 percent in the stabilised sludge at 20°C. The required retention time is significantly influenced by the chosen digester configuration, especially when the active sludge fraction in the excess sludge is high and/or if a very low active sludge fraction in the stabilised sludge is to be obtained. It can be observed that the required retention time for $f_{ae} = 0.10$ is always very much longer than for $f_{ae} = 0.20$. Therefore it is important to establish the maximum permissible value of the active sludge fraction in the stabilised sludge. In practice the maximum f_{ae} value will depend on the method for final sludge disposal. The active sludge fraction affects the rheological and mechanical properties of the sludge as well as its biological and hygienic quality. The higher the degree of stabilisation, the more favourable mechanical properties (good settleability, low specific filter resistance) can be expected.

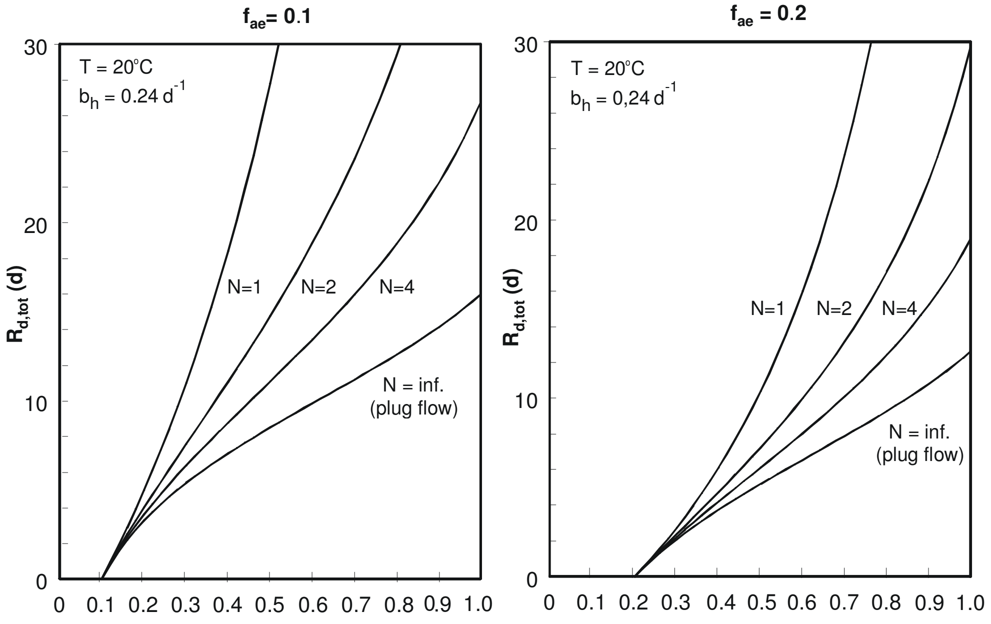

Figure 8.7 Minimum required retention time as function of the active sludge concentration in the excess sludge for different digester configurations (N = 1, 2, 4 and ∞)

In so far as the biological properties are concerned, the most important parameters are the rate and extent of putrefaction (acid fermentation), when the stabilised sludge is placed in an anaerobic environment. The hygienic quality is of great importance when the stabilised sludge is used as a fertiliser in agriculture. Several researchers have shown that aerobic digestion is not a very efficient method to eliminate pathogens in sludge and often physical (drying) or chemical (lime treatment) are required to obtain an acceptable hygienic quality.

The active sludge fraction can be evaluated from OUR or BOD tests with stabilised sludge. The relationships between the OUR and the volatile sludge concentration can be derived from Eq. (8.13).

$$O_t = (f_{cv} + 4.57 \cdot f_n) \cdot (1 - f) \cdot b_h \cdot X_a = (f_{cv} + 4.57 \cdot f_n) \cdot (1 - f) \cdot b_h \cdot f_{av} \cdot X_v \text{ or}$$

$$O_t/X_v = (f_{cv} + 4.57 \cdot f_n) \cdot (1 - f) \cdot b_h \cdot f_{av} = f_{av} \cdot 15.7 \cdot (1.04)^{T-20} \text{ (mg } O_2.g^{-1} \text{ VSS.h}^{-1}) \tag{8.42}$$

Using Eq. (8.21) in Eq. (8.42) the BOD per unit volatile sludge mass is calculated as:

$$BOD_{vss} = BOD/X_v = (f_{cv} + 4.57 \cdot f_n) \cdot (1 - f) \cdot 0.7 \cdot f_{av} = 1.10 \cdot f_{av} \text{ (mg BOD.mg}^{-1} \text{ VSS)} \tag{8.43}$$

Equations (8.42 and 8.43) show that the active sludge mass fraction can be calculated easily if the OUR or the BOD per unit mass of volatile sludge are determined experimentally. Fig. 8.8 shows the relationship between the BOD per unit mass of volatile sludge and the active sludge mass fraction. It can be observed that the BOD of stabilised sludge ($0.1 < f_{av} < 0.2$) is in the range of 0.10 to 0.25 mg O_2.mg^{-1} VSS. In the same figure the relation between the OUR and the active sludge fraction is given for several temperatures. At 20°C the OUR per gram stabilised sludge is between 1.5 and 3.0 mg O_2.g^{-1} VSS.h^{-1}.

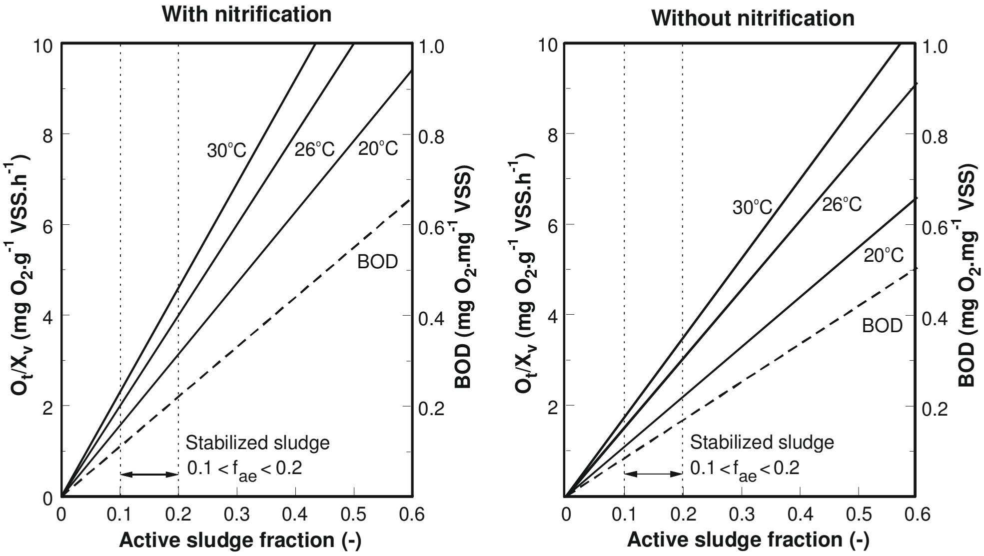

Figure 8.8 Theoretical OUR and BOD values per unit volatile sludge mass as a function of the active sludge fraction, with (left) or without (right) nitrification of mineralised ammonia