

### 4.4.2 Optimisation of nitrogen removal

The objectives of design optimisation for nitrogen removal activated sludge processes are:

- To produce an effluent with a minimum total nitrogen concentration;
- To carry out this nitrogen removal at minimum construction and operational costs.

Before starting with the optimisation procedure, it is necessary to remember that there are several constraints to single sludge activated sludge processes:

- (1) The anoxic sludge mass fraction is limited by two independent criteria: (a) the nitrification efficiency must be high, which implies a certain minimum for the sludge mass fraction in the aerobic zones and a corresponding maximum for the anoxic sludge fraction and (b) the mechanic properties and the kinetic constants can be adversely effected by an excessive anoxic sludge mass fraction. With regard to the second imposition, it is suggested that the anoxic sludge mass fraction should not be larger than sixty percent.
- (2) The value of the recirculation factor “a” for the mixed liquor from the aerobic reactor to the pre-D reactor and the value of the return sludge factor “s” have upper constraints from a viewpoint of energy efficiency. As the headloss in the “a” recirculation is always smaller and since the nitrate concentration in the aerobic reactor at least as high as in the settler, the “a”-recycle is always more cost-efficient than the “s” recycle to introduce nitrate into the pre-D reactor.

For that reason, the value of the sludge recycle factor “s” will be dictated by the requirements for efficient settling only. In practice this often means an “s”-recycle with a value of  $0.5 < s < 1$  (refer also to Chapter 6).

- (3) The value of the “a”-recycle is more difficult to assess. Ideally, the size of the mixed liquor recirculation flow must be such that the available nitrate in the pre-D reactor is exactly equal to its denitrification capacity. Considering that the denitrification rate in the pre-D reactor is always larger than in the post-D reactor (Fig. 4.17) it is, at least in principle, advantageous to have a large pre-D reactor and hence a high value of the “a”-recycle would be required. On the other hand, even if the head loss is low, the high recycle flow will lead to increased operational costs. Furthermore when a high “a” recycle is imposed, the amount of oxygen recycled to the anoxic zone may be considerable. In this section the optimal value of the “a”-recycle is evaluated.

A variable of great importance that has not yet been discussed is the proportion between nitrogenous and organic material in the waste water:  $N_i/S_i$ . The value of this ratio is very dependent on the origin of the waste water. Low values ( $< 0.02 \text{ mg N.mg}^{-1} \text{ COD}$ ) are found for waste water from agricultural industry, such as distillage from alcohol plants, black liquor from cellulose production and effluent from breweries. High values (up to  $0.16 \text{ mg N.mg}^{-1} \text{ COD}$ ) are typical for waste water from industries processing animal products like tanneries, slaughterhouses and dairy factories.

In the case of municipal waste waters, the  $N_i/S_i$  ratio is closely associated with the protein consumption of the population. For example, in the United States (where meat consumption per capita is high), the ratio  $N_i/S_i$  is about  $0.12 \text{ mg N.mg}^{-1} \text{ COD}$ , whereas in the cities with a predominance of vegetarians (India, certain regions in Africa), the ratio is found to be only  $0.04$  to  $0.06 \text{ mg N.mg}^{-1} \text{ COD}$ .

In general there is a linear correlation between the wealth of a contributing population and the  $N_i/S_i$  ratio in the sewage. The equations that define the nitrification and denitrification capacities show that  $N_c$  is proportional with the influent TKN concentration, whereas  $D_c$  is proportional to the influent COD concentration.

When the  $N_{ii}/S_{ii}$  ratio is low, it is easy to create a denitrification capacity large enough to completely remove the nitrate formed in the system. However, for complete nitrogen removal, a Bardenpho system is required.

#### 4.4.2.1 Optimised design for complete nitrogen removal

If it is assumed that complete denitrification occurs in both anoxic reactors, it can be seen from Fig. 4.13 that a fraction  $a/(a+s+1)$  of the nitrification capacity will be denitrified in the pre-D reactor, while the remaining fraction  $(s+1)/(a+s+1)$  will be removed in the post-D reactor. Hence, for complete denitrification it is necessary that:

$$D_{c1} = (f_{dn} \cdot f_{sb} + K_2 \cdot C_r \cdot f_{x1}) \cdot S_{bi} = N_c \cdot a / (a + s + 1) \quad (4.67)$$

$$D_{c3} = K_3 \cdot C_r \cdot f_{x3} \cdot S_{bi} = N_c \cdot (s + 1) / (a + s + 1) \quad (4.68)$$

Writing the sludge mass fractions explicitly in Eqs. (4.67 and 4.68) one has:

$$f_{x1} = (N_c / S_{bi}) \cdot a / (a + s + 1) - f_{dn} \cdot f_{sb} / (K_2 \cdot C_r) \quad (4.69)$$

$$f_{x3} = (N_c / S_{bi}) \cdot (s + 1) / (a + s + 1) / (K_3 \cdot C_r) \quad (4.70)$$

The largest  $N_{ii}/S_{ii}$  ratio for which complete denitrification is possible, indicated as  $(N_c / S_{bi})_o$ , can be calculated knowing that for this  $N_{ii}/S_{ii}$  ratio the anoxic sludge mass fraction will be maximum. Hence, with the aid of Eqs. (4.69 and 4.70) for  $f_{x1}$  and  $f_{x3}$ :

$$f_m = f_{x1} + f_{x3} \text{ or}$$

$$f_m = \frac{(N_c / S_{bi})_o \cdot [a / (a + s + 1)] - (f_{dn} \cdot f_{sb})}{K_2 \cdot C_r + [(N_c / S_{bi})_o \cdot (s + 1) / (a + s + 1)] / K_3 \cdot C_r}$$

After rearranging, the ratio  $(N_c / S_{bi})_o$  can be written explicitly:

$$(N_c / S_{bi})_o = \frac{(a + s + 1) \cdot (f_{dn} \cdot f_{sb} + K_2 \cdot C_r \cdot f_m)}{a + (K_2 / K_3) \cdot (s + 1)} \quad (4.71)$$

Once the value of the  $(N_c / S_{bi})_o$  ratio has been determined, the corresponding  $N_{ii}/S_{ii}$  ratio in the influent  $(N_{ii}/S_{ii})_o$  can be calculated using Eqs.(3.3 and 4.44).

$$S_{bi} = (1 - f_{ns} - f_{np}) \cdot S_{ii} \quad (3.3)$$

$$N_c = N_{ii} - N_1 - N_{ad} - N_{oe} \quad (4.44)$$

Which leads to:

$$(N_{ii}/S_{ii})_o = (1 - f_{ns} - f_{np}) \cdot (N_c / S_{bi})_o + (N_1 + N_{ad} + N_{oe}) / S_{ii}$$

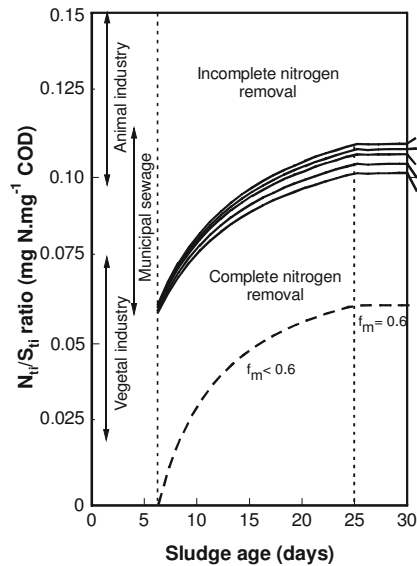
$$(N_{ii}/S_{ii})_o = \frac{(1 - f_{ns} - f_{np}) \cdot (f_{dn} \cdot f_{sb} + K_2 \cdot C_r \cdot f_m) \cdot (a + s + 1)}{a + (K_2 / K_3) \cdot (s + 1) + (N_1 + N_{ad} + N_{oe}) / S_{ii}} \quad (4.72)$$

Equation (4.72) shows that several factors influence the value of the largest TKN/COD ratio for which complete denitrification is feasible:

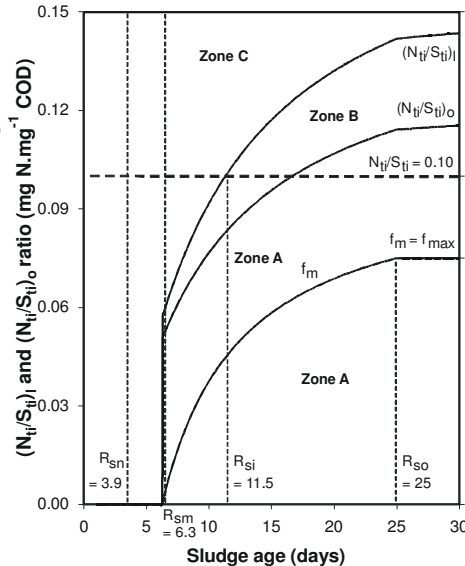
- (1) Composition of the influent organic material ( $f_{ns}$ ,  $f_{np}$  and  $f_{sb}$ );
- (2) Kinetic parameters for denitrification ( $K_2$  and  $K_3$ );
- (3) Kinetic parameters for nitrification ( $\mu_m$ ,  $K_n$ ,  $b_n$ );
- (4) Temperature: influences values of kinetic constants ( $K_1$ ,  $K_2$ ,  $K_n$ ,  $b_n$ ,  $b_n$ ,  $\mu_m$ );
- (5) Organic nitrogen in the effluent  $N_{oe}$ ;
- (6) Specified residual ammonium concentration ( $N_{ad}$ );
- (7) Recirculation factors ( $a$  and  $s$ );
- (8) Sludge age ( $R_s$ ).

The values of factors 1 to 5 listed above cannot be randomly selected in a particular design, but should rather be considered as “given” design values. In principle, the specified residual ammonium concentration  $N_{ad}$  (factor 6) can be freely selected, but in general the activated sludge system will be designed for low  $N_{ad}$  values. Hence, in fact only the recirculation factors  $a$  and  $s$  and the sludge age (factors 7 and 8) are design variables. As shown above, the  $s$ -recycle is determined by the requirements for efficient liquid-solid separation in the settler.

Hence, the factors to be defined in optimising nitrogen removal are the  $a$ -recycle and the sludge age. One of the methods to determine a suitable  $a$ /recirculation factor is to plot the  $(N_{Tf}/S_{Tf})_o$  ratio as a function of the sludge age for different “ $a$ ” values.



**Figure 4.20**  
Maximum TKN/COD ratio in the influent allowing complete nitrate removal as a function of  $R_s$  for different values of “ $a$ ”



**Figure 4.21**  
Values of the ratios  $(N_c/S_{bi})_o$  and  $(N_c/S_{bi})_i$  as a function of the sludge age (for  $a = 4$  and  $s = 1$ )

Figure 4.20 shows as an example of the  $(N_{ti}/S_{ti})_0$  ratio as a function of the sludge age for values of the “a” recirculation factor ranging from 1 to 10. The value of  $f_m$  is indicated as well. The following parameter values were used to construct Fig. 4.20:

$$\begin{array}{lll}
 - T = 20^\circ & - \mu_m = 0.3 \text{ d}^{-1} & - K_n = 1 \text{ mg N.l}^{-1} \\
 - S_{ti} = 500 \text{ mg.l}^{-1} & - b_n = 0.04 \text{ d}^{-1} & - K_2 = 0.10 \text{ mg N.mg}^{-1} X_a \cdot \text{d}^{-1} \\
 - f_{sb} = 0.25 & - s = 1 & - K_3 = 0.08 \text{ mg N.mg}^{-1} X_a \cdot \text{d}^{-1} \\
 - f_{ns} = f_{np} = 0.10 & & 
 \end{array}$$

It can be observed in Fig. 4.20 that the required sludge age for the complete removal of nitrogen tends to increase when the recirculation factor “a” decreases. The choice of the optimal recirculation factor then becomes a question of economics, where the costs for pumping of nitrified mixed liquor to the pre-D reactor (energy and pumps) are compared to the construction and operational costs as a function of the sludge age. In practice the optimal value will almost invariably be less than  $a = 4$ . There are two exceptions:

- (1) Recirculation systems such as carrouseis do not have dedicated nitrification and denitrification reactors, but consist of one or several large “racetrack” loops. They are often designed with surface aerators, double acting as propulsors, allowing higher recirculation factors of up to 10 - 20 to be applied without much additional cost;
- (2) Industrial systems treating waste water with a high  $N_{ti}/S_{ti}$  ratio and a high  $N_{ti}$  concentration, requiring the addition of an external carbon source. Often it is preferred to add this external carbon source to the pre-D zone, to prevent accidental overdosing in the post-D zone with the consequential risk of exceeding the effluent COD limit.

#### 4.4.2.2 Optimised design for incomplete nitrogen removal

For high  $N_{ti}/S_{ti}$  ratios or other unfavourable conditions (low temperature, toxic compounds, low easily biodegradable COD concentration), complete denitrification might not be possible, unless the applied sludge age is so high that the system will be unacceptably large or alternatively, the addition of an external carbon source is required. Should the addition of an external carbon source not be considered as a viable option due to prohibitive costs, the maximum nitrogen removal efficiency may be determined as follows: in the pre-D reactor of the Bardenpho system, nitrate is being introduced with the “a” recycle from the nitrification zone and with the “s” recycle from the settler so that:

$$D_{c1} = (f_{dn} \cdot f_{sb} + K_2 \cdot C_r \cdot f_m) \cdot S_{bi} = a/(a + s + 1) \cdot N_c + s \cdot N_{ne} \quad (4.73)$$

Where  $N_{ne}$  = effluent nitrate concentration (equal to the concentration in the return sludge)

The effluent nitrate concentration is given by the difference between the nitrate concentration in the aerobic reactor and the nitrate removal in the post-D reactor. If Eq.(4.73) is valid, the nitrate concentration in the pre-D reactor will be zero and the concentration in the aerobic reactor will be a factor  $1/(a+s+1)$  of  $N_c$  (the influent is diluted  $(1+a+s)$  times before it reaches the aerobic reactor). The decrease of nitrate concentration in the post-D reactor is  $D_{c3}/(s+1)$ , so that:

$$N_{ne} = N_c/(a + s + 1) - D_{c3}/(s + 1) \quad (4.74)$$

Now, by substituting for  $D_{c3}$  from Eq.(4.63) and knowing that  $f_{x3} = f_m - f_{x1}$  one has:

$$N_{ne} = N_e/(a + s + 1) - k_3 \cdot C_r \cdot (f_m - f_{x1}) \cdot S_{bi}/(s + 1) \quad (4.75)$$

By using Eq.(4.75) in Eq.(4.73) one calculates that:

$$f_{x1} = \frac{(N_e/S_{bi}) \cdot (a+s)/(a+s+1) - f_{dn} \cdot f_{sb} - K_3 \cdot C_r \cdot f_m \cdot s/(s+1)}{C_r \cdot (K_2 - K_3 \cdot s/(s+1))} \quad (4.76)$$

In Eq.(4.76) the calculated value of  $f_{x1}$  is the one that leads to the highest nitrate removal in the Bardenpho system, if complete denitrification is not possible. The residual nitrate concentration is given by Eq. (4.75). In Eq. (4.76), as the  $N_e/S_{bi}$  ratio increases, so does the value of  $f_{x1}$  (while at the same time the value for  $f_{x3}$  decreases), until  $f_{x1} = f_m$  (and  $f_{x3} = 0$ ). For this limiting value of  $N_e/S_{bi}$ , the entire anoxic sludge mass fraction is placed in the pre-D reactor. In other words, the Bardenpho configuration ceases to be advantageous and it is therefore changed into a pre-D system. The value of the ratio  $N_e/S_{bi}$  for which this occurs is obtained by substituting  $f_{x1} = f_m$  in Eq. 4.76):

$$(N_e/S_{bi})_1 = (f_{dn} \cdot f_{sb} + K_2 \cdot C_r \cdot f_m) \cdot (a + s + 1)/(a + s) \quad (4.77)$$

Where  $(N_e/S_{bi})_1$  = limiting ratio for the applicability of the Bardenpho process

The  $(N_i/S_{ti})_1$  ratios corresponding to the  $(N_e/S_{bi})_1$  values can be calculated using a similar expression to the one in Eq.(4.72). In Fig. 4.21 the  $(N_e/S_{bi})_1$  curve is plotted as a function of sludge age for the same conditions specified in Fig 4.20, but with the “a” recycle fixed at a value of four. Now, basically three different situations can be distinguished:

- (1) Zone A: low  $N_i/S_{ti}$  ratio i.e.  $N_i/S_{ti} < (N_i/S_{ti})_0$ . In this particular case the proportion between nitrogenous material and biodegradable organic material is favourable and complete nitrate removal is possible;
- (2) Zone B: average  $N_i/S_{ti}$  ratio, i.e.,  $(N_i/S_{ti})_0 < (N_i/S_{ti}) < (N_i/S_{ti})_1$ . In this case, complete denitrification is not possible, but the minimum effluent nitrogen concentration is obtained in a Bardenpho configuration;
- (3) Zone C: high  $N_i/S_{ti}$  ratio, i.e.  $(N_i/S_{ti}) > (N_i/S_{ti})_1$ . In this case, the proportion between nitrogenous and biodegradable organic material is unfavourable for nitrate removal. The lowest total nitrogen concentration in the effluent is obtained in a pre-D system.

In general, for regions with a warm climate the ratio between the TKN and the COD concentration in raw sewage is such that complete nitrogen removal is feasible, even at relatively short sludge ages (5 to 10 days). A large industrial waste water fraction may lead to a low  $\mu_m$  value and the consequential need to increase the sludge age.

On the other hand some industrial waste waters (especially those of vegetable origin) have a low  $N_i/S_{ti}$  ratio so that complete N removal is relatively easy. Primary and/or anaerobic pretreatment of the raw sewage tends to have a negative effect on the nitrogen removal process, as in such systems more organic than nitrogen material is removed. The  $N_i/S_{ti}$  ratio increases, resulting in a longer sludge age or incomplete nitrogen removal. An analysis of the factors that affect the required sludge age for complete nitrogen removal reveals that the maximum specific growth rate of nitrifiers  $\mu_m$  is the most important one. As it is known that this value tends to vary considerable depending on the origin of the waste water, it is important to determine its value experimentally whenever possible. In Appendix 4 the method used to determine this parameter is explained.