

4.2.1 Nitrification kinetics

Downing et al (1964) were the first to show that the growth of Nitrosomonas in the oxidation process of ammonium can be described by the Monod equation:

$$\begin{aligned} (dX_n/dt) &= (dX_n/dt)_g + (dX_n/dt)_d \text{ with} \\ (dX_n/dt)_g &= \mu \cdot X_n = \mu_m \cdot X_n \cdot N_a / (N_a + K_n) \text{ and} \\ (dX_n/dt)_d &= -b_n \cdot X_n \end{aligned} \quad (4.28)$$

Where:

- X_n = Nitrosomonas concentration (mg VSS.l⁻¹)
- (dX_n/dt) = rate of change of the Nitrosomonas concentration (mg VSS.l⁻¹.d⁻¹)
- = net growth rate of Nitrosomonas
- $(dX_n/dt)_g$ = Nitrosomonas growth rate (mg VSS.l⁻¹.d⁻¹)
- $(dX_n/dt)_d$ = Nitrosomonas decay rate (mg VSS.l⁻¹.d⁻¹)
- μ = specific growth rate for Nitrosomonas (d⁻¹)
- μ_m = maximum specific growth rate for Nitrosomonas (d⁻¹)
- b_n = decay rate for Nitrosomonas (d⁻¹)
- K_n = Monod half saturation constant (mg N.l⁻¹)

In the Monod equation, the parameter μ represents the growth rate of the micro-organisms per time unit. For example, a value of $\mu = 0.6 \text{ d}^{-1}$ means that the daily rate of micro-organism synthesis is equal to 60 percent of the mass initially present. Equation (4.28) shows that the μ value depends on the substrate concentration N_a . At high N_a concentration (saturation) the maximum growth rate μ_m is attained. The constant K_n is equal to the substrate concentration for which $\mu_m = \frac{1}{2} \mu$, and for that reason is called the “half” saturation constant. The basic equation of Downing et al (1964) can be used to calculate the residual ammonium concentration in a completely mixed, steady state activated sludge process. Under these conditions, there is no variation of the mass of Nitrosomonas in the system: the net growth rate (defined as the growth rate minus the decay rate) is equal to the discharge rate due to abstraction of excess sludge. Hence:

$$(dX_n/dt) = 0 = (dX_n/dt)_g + (dX_n/dt)_d + (dX_n/dt)_e \quad (4.29)$$

The rate of change of the Nitrosomonas concentration due to the discharge of excess sludge $(dX_n/dt)_e$, can be expressed as:

$$(dX_n/dt)_e = -X_n/R_s$$

Now, using Eqs. (4.28 and 4.30) in Eq. (4.29) one has:

$$\begin{aligned} (dX_n/dt) = 0 &= \mu_m \cdot X_n \cdot N_a / (N_a + K_n) - b_n \cdot X_n - X_n/R_s \\ &= \mu_m \cdot N_a / (N_a + K_n) - b_n - 1/R_s \end{aligned} \quad (4.30)$$

Or, by rearranging:

$$N_a = K_n \cdot (b_n + 1/R_s) / [\mu_m - (b_n + 1/R_s)] \quad (4.31)$$

Equation (4.31) gives the ammonium concentration in the mixed liquor of a completely mixed activated sludge process and hence also in the effluent of this process. This residual concentration, which is indicative of the efficiency of the nitrification process, depends on the numerical values of the three kinetic parameters: μ_m , K_n and b_n and one operational variable: the sludge age R_s . It is interesting to note that the residual ammonium concentration does not depend on the initial concentration. The residual ammonium concentration can never be superior to the ammonium concentration that is available for nitrification. Therefore this condition defines the minimum sludge age for nitrification as:

$$N_a = N_p = K_n \cdot (b_n + 1/R_{sn}) / (\mu_m - b_n - 1/R_{sn}) \text{ or}$$

$$R_{sn} = (1 + K_n/N_p) / [\mu_m - b_n \cdot (1 + K_n/N_p)] \quad (4.32)$$

Where:

$$N_p = \text{nitrification potential}$$

$$= \text{ammonium concentration available for nitrification (mg N.l}^{-1}\text{)}$$

In the case of domestic sewage, the ammonium concentration available for nitrification will always be much greater than the half saturation value K_n . In that case the ratio $K_n/N_p \ll 1$ and Eq. (4.32) can be simplified to:

$$R_{sn} = 1/(\mu_m - b_n) \quad (4.33)$$

Equation (4.33) expresses that nitrification will not develop if the sludge age is shorter than a minimum value of $R_{sn} = 1/(\mu_m - b_n)$, because the rate of Nitrosomonas discharge in the excess sludge will exceed the net growth rate. When the sludge age R_s is higher than the minimum value, nitrification will develop and its efficiency will depend on the sludge age and the kinetic constants K_n , μ_m and b_n .

After Downing's work, many research workers have carried out experimental investigations to determine the kinetic parameters for nitrification in the activated sludge process. Table 4.2 a, b and c show experimental values of μ_m , b_n and K_n obtained by different researchers for Nitrosomonas. It can be observed that the numerical values obtained by different authors have a very large spread. This may be attributed partially to differences in the experimental methods, but certainly the fact that different waste waters have been used must have had an influence. Thus it can be concluded that the value of the kinetic parameters of the nitrifiers depends on the origin of the waste water. Ideally these values should be determined for each specific design case.

Table 4.2a Values of μ_m of Nitrosomonas as determined by various authors

μ_{mT} (d ⁻¹)	T (°C)	μ_{m20} (d ⁻¹)	Reference
0.33	15	0.66	Barnard (1991)
0.47	15	0.45	Kayser (1991)
0.33	20	0.33	Downing et al (1964)
0.33 - 0.65	20	0.33 - 0.65	Ekama et al (1976)
0.34 - 0.40	12	0.86 - 1.01	Gujer et al (1974)
0.45	15	0.73	Eckenfelder (1991)
0.40 - 0.50	14	0.80 - 1.00	Gujer (1977)
0.50	20	0.50	Lawrence et al (1973)
0.53	25	0.26	Sutton et al (1979)
0.57	16	0.76	Gujer et al (1974)
0.94	29	0.33	Lijklema (1973)
1.08 - 1.44	23	0.76 - 1.02	Poduska et al (1974)

Table 4.2b Values of b_n of Nitrosomonas as determined by various authors

b_{nT} (d ⁻¹)	T (°C)	b_{n20} (d ⁻¹)	Reference
0.0	20	0.0	Downing et al (1964)
0.0	15	0.0	Downing et al (1964)
0.0	10	0.0	Gujer (1979)
0.04	20	0.04	Ekama et al (1976)
0.12	29	0.09	Lijklema (1973)
0.12	23	0.11	Poduska et al (1974)

Table 4.2c Values of K_n of Nitrosomonas as determined by various authors

K_{nT} (mg.l ⁻¹)	T (°C)	K_{n20} (mg.l ⁻¹)	Reference
0.0	23	0.04	Poduska et al (1974)
0.2	15	0.1	Downing et al (1964)
0.2	20	0.2	Downing et al (1964)
0.2	10	0.6	Gujer (1977)
0.5	14	1.0	Ekama et al (1976)
1.0	20	1.0	Ekama et al (1976)
1.0	20	1.0	Lijklema (1973)

In order to be able to compare the data collected at different temperatures, all values have been corrected to a standard value at 20°C, using the temperature dependencies as determined by Ekama and Marais (1976): $\mu_{nT} = \mu_{n20} \cdot 1.123^{(T-20)}$; $b_{nT} = b_{n20} \cdot 1.04^{(T-20)}$ and $K_{nT} = K_{n20} \cdot 1.123^{(T-20)}$. In order to evaluate the influence of the numerical values of the kinetic parameters for nitrification on the efficiency of the process, the following procedure has been followed: the values in Table 4.2 suggest average values at 20°C of $\mu_m = 0.4 \text{ d}^{-1}$; $b_n = 0.04 \text{ d}^{-1}$ and $K_n = 0.5 \text{ mg N.l}^{-1}$. The influence of the values of these parameters on the residual ammonium concentration is shown in Figs. 4.6a, b and c.

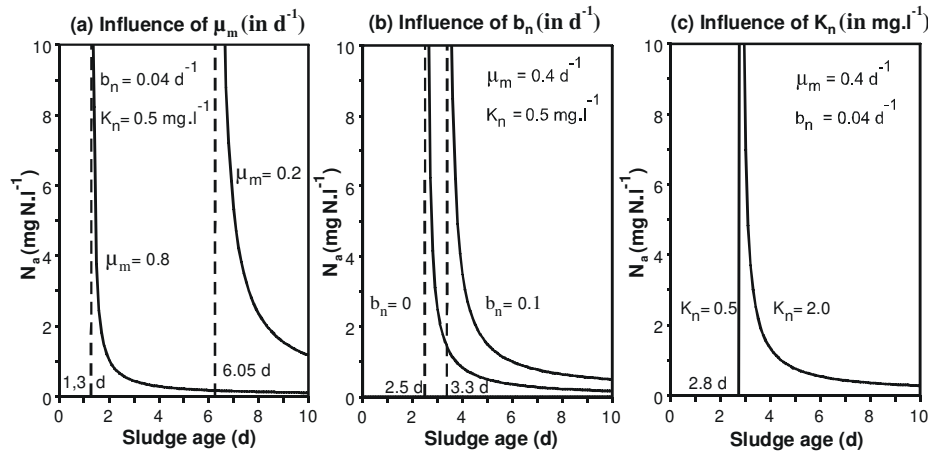


Figure 4.6 Residual ammonium concentration as a function of different values of the kinetic parameters μ_m , b_n and K_n

Figure 4.6a shows the residual ammonium concentration N_a as a function of the sludge age for average b_n and K_n values ($b_n = 0.04 \text{ d}^{-1}$ and $K_n = 0.5 \text{ mg N.l}^{-1}$) and for two values of μ_m , one extremely high ($\mu_m = 0.8 \text{ d}^{-1}$) and the other extremely low ($\mu_m = 0.2 \text{ d}^{-1}$). Hence, the difference between the curves for the residual ammonium concentration in Fig. 4.6a reflects the influence of the different μ_m values (the curves were calculated using Eq. 4.31).

Similarly, in Fig 4.6b, the influence of the value of the decay rate b_n is analysed for average values of the other kinetic parameters: $\mu_m = 0.4 \text{ d}^{-1}$ and $K_n = 0.5 \text{ mg N.l}^{-1}$. The residual ammonium concentration N_a is calculated as a function of the sludge age for a very high value of the decay rate ($b_n = 0.1 \text{ d}^{-1}$) and without decay rate at all ($b_n = 0.0 \text{ d}^{-1}$). The difference between the two curves is due exclusively to the variation of the b_n value.

Finally, in Fig. 4.6c the influence of the K_n value on the residual ammonium concentration is evaluated. For average values of the other two parameters ($\mu_m = 0.4 \text{ d}^{-1}$ and $b_n = 0.04 \text{ d}^{-1}$) curves were drawn for N_a as a function of R_s for $K_n = 2 \text{ mg N.l}^{-1}$ (very high value) and $K_n = 0.00 \text{ mg N.l}^{-1}$ (very low value). From Fig. 4.6 the following conclusions can be drawn:

- The influence of μ_m on the residual ammonium concentration - and hence on nitrification efficiency - is much more pronounced than that of the other two parameters b_n and K_n ;
- For sludge ages of more than 50 percent beyond the minimum sludge age for nitrification R_{sn} , the residual ammonium concentration is so low that for practical purposes nitrification may be considered to be complete.

As the minimum sludge age for nitrification depends mainly on the value of μ_m , it is necessary to analyse why such large differences in the values of μ_m are reported in Table 4.2a. The numerical values of the parameters b_n and K_n are of minor importance. The factors influencing the μ_m value can be divided in two categories: (1) factors related to the origin of the waste water and (2) factors related to the operational conditions in the activated sludge process.

In so far as the origin of the waste water is concerned, there are several compounds that are known to inhibit nitrification. There are clear indications that the μ_m value depends on the fraction of industrial waste in municipal waste water. In the case of a small industrial contribution, the μ_m value is determined in the range of 0.5 to 0.7 d^{-1} at 20°C, but this value decreases to 0.25 to 0.3 d^{-1} or even lower at higher proportions of industrial effluent in the wastewater. Wilson and Marais (1976) measured an μ_m value of 0.17 d^{-1} for a predominantly industrial waste.

In the case of purely industrial waste waters, the μ_m may be very small: a research project at CETREL in Brazil, where petrochemical wastes are processed, showed a μ_m value of less than 0.1 d^{-1} at a temperature of 26 °C, which is equivalent to $\mu_m < 0.05 d^{-1}$ at 20 °C. The dominant influence of the origin of the waste water on the μ_m value indicates that this parameter should be seen as a sewage characteristic rather than a kinetic constant.