

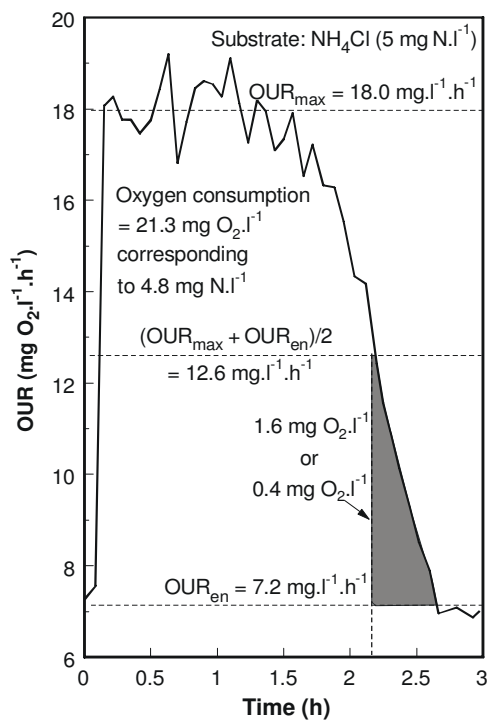
**Example A4.1**

To illustrate the methodology presented in the previous section, an experiment will be analysed where three pilot-scale activated sludge systems were operated on influent received on a large industrial waste water treatment plant (CETREL, Brazil). The dissolved oxygen concentration was controlled by means of a respirometer. The three reactors were operated at different dissolved oxygen concentrations and were identified as R1 (DO between 3.5 and 4.5 mg O<sub>2</sub>.l<sup>-1</sup>), R2 (DO between 1.5 and 2.5 mg O<sub>2</sub>.l<sup>-1</sup>) and R3 (DO between 0.5 and 1.5 mg O<sub>2</sub>.l<sup>-1</sup>). In Table A4.1 the influent and effluent characteristics of the reactors are listed, along with the operational conditions during the experiment. It can be observed that the effluent ammonium concentration in all three systems was low. However, the effluent nitrate concentration decreased at lower average dissolved oxygen concentration. This can be attributed to simultaneous denitrification: at a dissolved oxygen bulk concentration below the critical concentration, anoxic conditions are established inside (part of the) the sludge floc and denitrification will occur.

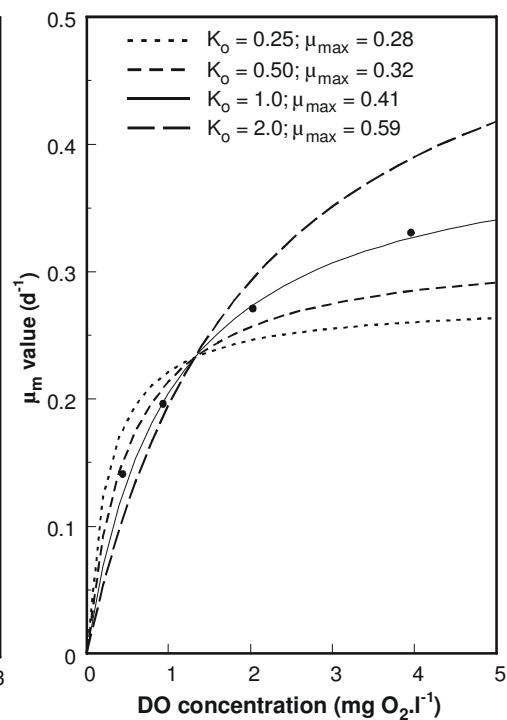
**Table A4.1 Experimental results and operational conditions from the three pilot activated plant systems operated at different dissolved oxygen concentrations ( $V_r = 25$  l;  $Q_i = 17$  l.d<sup>-1</sup>;  $R_s = 20$  d and  $T = 26^\circ\text{C}$ )**

Parameter	UoM	Influent	Effluent R <sub>1</sub>	Effluent R <sub>2</sub>	Effluent R <sub>3</sub>
DO	mg O <sub>2</sub> .l <sup>-1</sup>		4	2	1
COD	mg.l <sup>-1</sup>	1482	296	288	282
TKN / NH <sub>4</sub> <sup>+</sup>	mg N.l <sup>-1</sup>	104 / 58	11.6 / 0.9	14.1 / 0.8	13.3 / 1.2
NO <sub>3</sub> <sup>-</sup>	mg N.l <sup>-1</sup>	<1	51.7	45.0	40.3
X <sub>t</sub> / X <sub>v</sub>	mg SS.l <sup>-1</sup>		4841 / 3098	4530 / 2900	4663 / 2864

Using the data in Table A4.1 and Eq. (A4.3), the concentration of nitrifying bacteria  $X_n$  can be calculated. The excess sludge produced from the reactors was used to determine the kinetics of the nitrification process. Fig. A4.1 presents a respirogram that may be considered as typical for the experiment and that was generated under the following conditions: (1) a high dissolved oxygen concentration (i.e. sludge from system R<sub>1</sub>) and (2) addition of sufficient NH<sub>4</sub>Cl to obtain an ammonium concentration of 5 mg N.l<sup>-1</sup> in the reactor. The interpretation of the respirogram will now be discussed.



**Figure A4.1**  
Typical respirogram after feeding of a sludge batch with ammonium chloride



**Figure A4.2**  
Theoretical curves and experimental values of  $\mu_m$  of the nitrifiers as a function of the dissolved oxygen concentration

#### (1) Verification of the mass balance

In order to confirm that the data is reliable, it is first verified whether the mass balance closes. The area between the maximum OUR curve and the endogenous respiration level is related to the amount of ammonium added as demonstrated in Section A4.1. For the test displayed in Fig. A.4.1, this area is equal to  $21.3 \text{ mg O}_2 \cdot \text{l}^{-1}$ , which corresponds to the oxidation of  $21.3/4.56 = 4.8 \text{ mg N} \cdot \text{l}^{-1}$ . As this value is very close to the added concentration of  $5 \text{ mg N} \cdot \text{l}^{-1}$ , the experimental data is considered to be reliable.

#### (2) Determination of the maximum nitrifier specific growth rate $\mu_{\max}$ and $K_0$

The nitrifier concentration in the batch is estimated as 50% of the value calculated with the data from Table A4.1 (because of the sludge dilution with influent prior to the test):

$$\begin{aligned} X_n &= Y_n \cdot R_s \cdot N_c / ((1 + b_n \cdot R_s) \cdot R_h) \\ &= 0.1 \cdot 20 \cdot 51.7 / ((1 + 0.046 \cdot 20) \cdot 25/17) / 2 = 19.0 \text{ mg } X_n \cdot \text{l}^{-1} \end{aligned}$$

Furthermore the maximum OUR for nitrification can be determined from Fig. A4.1 as:

$$\text{OUR}_n = (\text{OUR}_m - \text{OUR}_{\text{en}}) = (18 - 7.2) = 10.8 \text{ mg O}_2 \cdot \text{l}^{-1} \cdot \text{h}^{-1}$$

Hence the maximum nitrification rate is:

$$r_n = 10.8/4.57 = 2.36 \text{ mg N.l}^{-1}.\text{h}^{-1} = 56.7 \text{ mg N.l}^{-1}.\text{d}^{-1}$$

Now the value of the nitrification constant  $\mu_m$  (or actually  $\mu_m - b_n$ ) for the sludge in reactor R<sub>3</sub> is determined as:

$$\mu_m = Y_n \cdot r_n / X_n = 0.1 \cdot 56.7 / 19.0 = 0.30 \text{ d}^{-1}$$

By calculating the values of  $\mu_m$  for the other reactors ( $\mu_m = 0.27$  for R<sub>2</sub> and  $\mu_m = 0.19$  for R<sub>1</sub>), it becomes apparent that the dissolved oxygen concentration was indeed limiting during the tests. To eliminate the influence of the dissolved oxygen concentration and to determine the true maximum specific growth rate constant  $\mu_{\max}$ , the data are arranged as in Table A4.2. In Table A4.2 an additional batch test with  $\text{DO}_{\text{av}} = 0.5 \text{ mg.l}^{-1}$  has been added.

**Table A4.2 Calculated values of the maximum specific nitrifier growth rate ( $\mu_{\max}$ ) without ammonium or dissolved oxygen limitation, for different  $K_o$  values**

Reactor	$\text{DO}_{\text{av}}$ ( $\text{mg O}_2.\text{l}^{-1}$ )	$\mu_m$ (exp.) ( $\text{d}^{-1}$ ) (from step 2)	$K_o$ values ( $\text{mg O}_2.\text{l}^{-1}$ )			
			0.25	0.50	1.0	2.0
-	0.5	0.15	0.22	0.30	0.45	0.75
R <sub>3</sub>	1	0.19	0.24	0.28	0.38	0.57
R <sub>2</sub>	2	0.27	0.30	0.34	0.40	0.54
R <sub>1</sub>	4	0.30	0.32	0.34	0.37	0.45
Average $\mu_{\max}$ value for each $K_o$ value			0.28	0.32	0.40	0.59
Standard deviation of $\mu_{\max}$			0.05	0.03	0.03	0.12

The values of  $\mu_m$  as calculated above for each batch are listed in column 3. The average dissolved oxygen concentration applied during the batch test is indicated as well (column 2). As the oxygen concentration affects the calculated value of  $\mu_m$ , it has to be corrected for the factor  $\text{DO}_{\text{av}} / (K_o + \text{DO}_{\text{av}})$ . Therefore in the next step, for each of the four  $K_o$  values, the  $\mu_{\max}$  value is calculated for every value of  $\text{DO}_{\text{av}}$  using Eq. (A4.5). The results are listed in columns 4 to 7. As an example, the calculation is presented for a  $K_o$  value of  $1.0 \text{ mg O}_2.\text{l}^{-1}$  and an average dissolved oxygen concentration of  $4 \text{ mg O}_2.\text{l}^{-1}$ :

$$\text{OUR}_m = 4.57 \cdot [\text{DO}_{\text{av}} / (\text{DO}_{\text{av}} + K_o)] \cdot \mu_m \cdot X_n / Y_n \quad (\text{A4.5})$$

$$10.8 \cdot 24 = 4.57 \cdot (4 / (4 + 1)) \cdot \mu_{\max} \cdot 19 \cdot 1 / 0.1 \text{ or}$$

$$\mu_{\max} = 0.3 / 0.8 = 0.37$$

For each of the values of  $K_o$  an average value for  $\mu_{\max}$  is calculated. The results already indicate that the true value of  $K_o$  will be somewhere between  $0.5$  and  $1.0 \text{ mg O}_2.\text{l}^{-1}$ , as the standard deviation of the average  $\mu_{\max}$  value is small in both cases and the individual  $\mu_{\max}$  values do not deviate significantly from the average.

Using the average values of  $\mu_{\max}$  as calculated in Table A4.2, for each  $K_o$  value theoretical curves are generated of  $\mu_m$  as functions of the dissolved oxygen concentration, as shown in Fig. A4.2. Finally, comparing the curves with the experimental data (in column 3 in Table A4.2), the  $K_o$  value resulting in the closest correlation between experiment and theory is selected as the true half saturation value for dissolved oxygen. In Fig. A4.2 it can be observed that the best fit is obtained for  $K_o = 1.0 \text{ mg.l}^{-1}$  and  $\mu_{\max} = 0.4 \text{ d}^{-1}$ . Thus the growth rate of the nitrifiers is reduced by 50 % of its maximum value, if the aeration tank is operated at a dissolved oxygen concentration of  $1 \text{ mg.l}^{-1}$ .

### (3) Determination of the half saturation constant for ammonium $K_n$

To estimate the value of the half saturation constant for ammonium  $K_n$ , the surface of the grey area in Fig. A4.1 is measured at the moment that  $\mu = \frac{1}{2} \cdot \mu_m$  or  $\text{OUR}_n = \text{OUR}_m/2 = (18 + 7)/2 = 12.5 \text{ mg O}_2.\text{l}^{-1}.\text{h}^{-1}$ . The surface of the grey area equals  $1.6 \text{ mg O}_2.\text{l}^{-1}$ , which is equivalent to  $1.6/4.57 = 0.4 \text{ mg N.l}^{-1}$ . It is concluded that the growth rate  $\mu$  is reduced to 50% of its maximum value when the ammonium concentration reaches  $0.4 \text{ mg N.l}^{-1}$ , or  $K_n = 0.4 \text{ mg N.l}^{-1}$ .

The experiment described above was also carried out with sludge batches taken from systems operating at lower dissolved oxygen concentrations. This did not influence the values of  $\mu_m$  and  $K_o$ . This indicates that the decrease of the maximum growth rate  $\mu_m$  as observed at low dissolved oxygen concentrations, is only due to the reduced availability of dissolved oxygen and not to generation of a sludge with a lower metabolic capacity. The value of the nitrifier decay constant has not been determined, instead the value suggested by Marais and Ekama (1976) was accepted:  $b_n = 0.04 \cdot 1.03^{(T-20)} = 0.046 \text{ d}^{-1}$  at  $26^\circ\text{C}$ . For the industrial effluent treated by CETREL and for a temperature of  $26^\circ\text{C}$ , the nitrification kinetics can be summarised as:

$$\begin{aligned} b_n &= 0.046 \text{ d}^{-1} \\ \mu_m &= 0.40 \text{ d}^{-1} \\ K_n &= 0.4 \text{ mg N.l}^{-1} \\ K_o &= 1.0 \text{ mg O}_2.\text{l}^{-1} \end{aligned}$$

Hence the minimum operational sludge age required for this nitrifying system, operating at an average dissolved oxygen concentration of  $2 \text{ mg O}_2.\text{l}^{-1}$  and with a maximum allowed effluent ammonium concentration of less than  $1 \text{ mg N.l}^{-1}$ , can be estimated as:

$$\begin{aligned} R_s &= 1/[(N_a/(N_a+K_n) \cdot \text{DO}/(\text{DO} + K_o) \cdot \mu_m - b_n] \\ &= 1/[1/1.4 \cdot 2/3 \cdot 0.4 - 0.046] = 6.9 \text{ days} \end{aligned}$$