8.8 Calculation of oxygen requirements
Peder Maribo – 10.08.2009

The oxygen requirement in an activated sludge plant can be divided into four main groups according to the associated microbiological processes:

1. Substrate metabolism – direct degradation of the organic matter in the wastewater
2. Endogenous respiration – The decomposition of dead biomass and slowly degradable organic matter accumulated in the sludge.
3. Nitrification – conversion of ammonia to nitrate
4. Denitrification – conversion of nitrate to atmospheric nitrogen $\text{N}_2$ (leads to reduction in the oxygen requirements as nitrate is used as alternative oxidizing agent).

Substrate respiration is the oxygen consumption related to oxidation of relatively easy degradable organic matter found in the raw wastewater. Endogenous respiration, on the other hand, represents the oxygen consumption related to the degradation of slowly decomposable organic matter, dead microorganisms from the activated sludge, etc. With an increasing sludge age (equivalent to a decrease in F/M ratio), the oxygen consumption for endogenous respiration will increase steadily, whereas the substrate metabolism only increases slightly with an increased sludge age proportional to the (slight) increase in BOD removal efficiency.

The above elements 1 and 2 can be lumped and jointly express the oxygen consumption for aeration of organic matter $\text{BOD}$: $L_{\text{BOD}}$. $L_{\text{BOD}}$ largely depend on the F/M-ratio of the activated sludge system. Table 8.1 shows the relation between F/M ratio and $L_{\text{BOD}}$ from municipal wastewater.

<table>
<thead>
<tr>
<th>F/M-ratio *) [kg BOD/kg VSS-d]</th>
<th>Oxygen consumption for removal of organic matter $L_{\text{BOD}}$ [kg O$_2$/kg BOD removed]</th>
<th>Oxygen consumption for removal of organic matter $L_{\text{BOD}}$ [kg O$_2$/kg BOD in raw sewage]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>0.10</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>0.20</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>0.50</td>
<td>1.0</td>
<td>0.6</td>
</tr>
<tr>
<td>1.0</td>
<td>0.9</td>
<td>0.5</td>
</tr>
<tr>
<td>5.0</td>
<td>0.7</td>
<td>0.35</td>
</tr>
</tbody>
</table>

*Table 8.1 Relation between F/M ratio and the oxygen consumption for removal of organic matter. Data from Winther et al (1998). *) F/M-ratio calculated based on the total volume of process tanks (both aerobic and anoxic tanks)*

The difference between the two columns with oxygen requirement in table 8.1 expresses that more of the supplied BOD quantity is removed at low F/M ratio than at high F/M-ratio. The increase in oxygen consumption with falling F/M ratio is a consequence of a more efficient removal of organic matter from the water, and
increased oxygen consumption for endogenous respiration (slow decomposition of biological sludge and other slowly degradable organic matter in the sludge).

As it can be seen from table 8.1 $L_{BOD}$ for plants with a low F/M ratio has an oxygen consumption for decomposition of organic matter above the inlet quantity of organic matter measured as $BOD_7$. The reason for this is that the sludge age, and the time for decomposition of organic matter, in these plants is above 7 days, hence oxygen consumption above the $BOD_7$ value is experienced.

The oxygen consumption for nitrification is 4.6 kg $O_2$ per kg nitrogen nitrified. In raw sewage the far majority of nitrogen is found in reduced form e.g. as ammonia, urea and protein. The nitrogen accumulated and removed from the WWTP with the excess sludge is also in the reduced form. The nitrogen content of biological sludge is typically in the order of 8 % of the solids weight.

In a WWTP with nitrification, the remaining part of the nitrogen will be oxidized to nitrate in the nitrification process. Assuming that all nitrogen not accumulated in the sludge is nitrified, the oxygen consumption for nitrification can thus be calculated as:

$$L_N [Kg \; O_2/d] = (M_N - 0.08 \times SP_B) \times 4.6 \; [Kg \; O_2/Kg \; N]$$ (8.1)

$SP_B$: the biological excess sludge production [kg SS/d]
$M_N$: the total nitrogen content in the raw wastewater [kg tot-N/d]

The denitrification process removes a part of the formed nitrate from the water. In this process the nitrate acts as an oxidizing agent and consequently reduces the oxygen requirement. For each kg of nitrogen removed by denitrification the oxygen requirement is reduced by 2.86 kg $O_2$. The reduction in oxygen requirement can be calculated as:

$$L_{DN} [Kg \; O_2/d] = 2.86 \; [Kg \; O_2/Kg \; N] \times (L_N/4.6 - Q_{LDW} \; [m^3/d] \times C_{out,NO_3-N} \; [Kg \; N/m^3])$$ (8.2)

$Q_{LDW}$: Peak dry weather flow [m$^3$/d] to the plant
$C_{out,NO_3-N}$: Estimated concentration of nitrate-N in the purified wastewater.

The daily maximum oxygen consumption is thus calculated as:

$$L_{d.tot} = L_{BOD} + L_N - L_{DN}$$ (8.3)

**Eksempel 8.1:**
**Calculation of the oxygen requirement for a WWTP with nitrification and denitrification.**

**Data:**
- $F/M$ ratio: 0.05 kg $BOD$/kg $SS$ · $d$
- $Q_{LDW}$: 2,500 m$^3$/d
- $C_{in,NO_3-N}$: 50 mg N/L
- $C_{out,NO_3-N}$: 8 mg N/L $= 0.008$ kg N/m$^3$ (requirement)
- $C_{in,BOD}$: 300 mg BOD/L
- $C_{out,BOD}$: $< 10$ mg BOD/L (estimated)
- $SP_B$: 525 kg $SS_d$ (equal to a yield constant of 0.7 kg $SS_d$/kg $BOD$)
\[ \begin{align*}
M_N &= Q_{d,DLW} \cdot C_{in, NO_3-N} = 2,500 \text{ m}^3/d \cdot 0.050 \text{ kg N/m}^3 = 125 \text{ kg N/d} \\
M_{BOD} &= Q_{d,DLW} \cdot C_{in, BOD} = 2,500 \text{ m}^3/d \cdot 0.3 \text{ kg BOD/m}^3 = 750 \text{ kg BOD/d}
\end{align*} \]

\[ \begin{align*}
L_{BOD} &= 1.3 \text{ kg O}_2/\text{kg BOD} \cdot 750 \text{ kg BOD/d} = 975 \text{ kg O}_2/d \quad (\text{c.f. table 8.1})
\end{align*} \]

\[ \begin{align*}
L_N &= (125 - 0.08 \times 525) \times 4.6 = 382 \text{ Kg O}_2/\text{Kg N} \\
L_{DN} &= 2.86 \times (382/4.6 - 2.500 \times 0.008) = 180 \text{ Kg O}_2/d \\
L_{d,tot} &= L_{BOD} + L_N - L_{DN} = 975 + 382 - 180 = 1,177 \text{ kg O}_2/d
\end{align*} \]

The calculated daily oxygen consumption is not distributed evenly over the day. The fraction of \( L_{BOD} \) consisting of endogenous respiration can for all practical purposes be calculated as evenly distributed over the day. This is because it originates from decomposition of dead biomass and slowly degradable organic matter captured in the sludge, and with sludge ages of many days the variation in endogenous respiration is slow.

The fraction of \( L_{BOD} \) related to substrate decomposition is more directly dependant on the instant incoming amount of easy degradable substrate. It is more reasonable to assume a variation of this proportional to the variation in incoming wastewater (flow).

The daily variation of \( L_{BOD} \) is thus greater for plants with a high F/M-ratio (low sludge age) and less dominating for plants with low F/M ratios. Further more the variation in incoming organic matter (substrate) is higher for small plants compared to plants with a large contributing sewage area.

For a WWTP with F/M ratio of 0.1 – 0.05 kg BOD/Kg SS \cdot d approximately 60 % of \( L_{BOD} \) is endogenous respiration, and 40 % is substrate respiration. For a F/M-ratio of 0.25 kg BOD/Kg SS \cdot d the ratio is approximately 40 % of \( L_{BOD} \) for endogenous respiration and 60 % for substrate respiration.

\( L_N \) and \( L_{DN} \) varies over the day as \( L_{BOD} \), i.e. equivalent to the variation in incoming wastewater (flow).

**Eksempel**

**Calculation of hourly max oxygen consumption (8.1 continued)**

**Plant size in PE**

\[ \begin{align*}
\text{Plant size in PE} &= Q_{d,DLW} \cdot C_{in, BOD}/0.060 = 2,500 \text{ m}^3/d \cdot 0.3 \text{ kg/m}^3 / 0.06 \text{ kg BOD/D/PE} \\
&= 12,500 \text{ PE} \text{ (population equivalents)}
\end{align*} \]

For a plant of this size an estimate of max hourly factor \( t_{h,d} \) of 14 h/d is chosen.

The peak oxygen consumption can thus be calculated as:

\[ L_{h,tot} = L_{h,BOD} + L_{h,N} - L_{h,DN} \quad (8.3) \]
and  
\[ L_{h,BOD} = L_{BOD}(0.6/24 + 0.4/14) = 975 \text{ kg } O_2/d (0.6/24 + 0.4/14) \frac{d}{h} = 52.2 \text{ kg } O_2/h \]
\[ L_{h,N} = L_{N}/14 = 382 \text{ kg } O_2/d /14 \frac{h}{d} = 27.3 \text{ kg } O_2/h \]
\[ L_{h,DN} = L_{DN}/14 = 180 \text{ kg } O_2/d /14 \frac{h}{d} = 12.9 \text{ kg } O_2/h \]
\[ L_{h,tot} = 52.2 + 27.3 – 12.9 = 66.6 \approx 67 \text{ kg } O_2/h \]

The aeration system thus must be able to transfer 67 kg O₂/h to the mixture of wastewater and activated sludge in order to meet the net requirement of the biomass.

### 8.9 Dimensioning the aeration system

As mentioned in chapter 6 the Aeration can be made with a large variety of aeration equipment. Most equipment can be categorized into two groups: introduction of compressed air via diffusers or other mechanisms, and surface aeration by mechanically mixing the water with atmospheric air.

The capacity of aeration systems are given by the manufacturer under standard conditions: a concentration of dissolved oxygen of 0 mg/L, pure (tap) water, a temperature of 20 °C, and at 1,013 bar of atmospheric pressure.

In the WWTP – e.g. in the aeration basin of the activated sludge plant – the conditions are different, and the aeration capacity of the apparatus is reduced. The reduction in capacity is due to the effect of salts, surfactants, an oxygen concentration of the wastewater higher than zero (hence a lower gradient for diffusion of oxygen into the water), temperature (governing both diffusion speed and saturation level), actual atmospheric pressure etc.

The relation between oxygenation capacity OC at standard conditions and under “actual” conditions can be expressed as follows:

\[
OC_a = OC_{std} \left( \frac{\beta \cdot C_{\text{walt}} - C_L}{9.17} \right) \cdot 1.024^{T-20} \cdot \alpha \tag{8.4}
\]

In which:
- \(OC_a\) = oxygenation capacity at actual conditions
- \(OC_{std}\) = oxygenation capacity at standard conditions
- \(\beta\) = salinity – surface tension correction factor – usually 1.0
- \(C_{\text{walt}}\) = Oxygen saturation concentration for tap water at given temperature and altitude (see appendix and table 8.2)
- \(C_L\) = operating oxygen concentration, [mg/L]
- \(\alpha\) = oxygen transfer correction factor, dependant on the aeration system, and tank design see below

(the 9.17 is the oxygen saturation concentration in [mg/l] at 20 °C.)
<table>
<thead>
<tr>
<th>Elevation, meter above sea level</th>
<th>Oxygen solubility correction factor $F_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>500</td>
<td>0.95</td>
</tr>
<tr>
<td>1000</td>
<td>0.9</td>
</tr>
<tr>
<td>2000</td>
<td>0.75</td>
</tr>
<tr>
<td>4000</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Table 8.2 Correction for reduced oxygen saturation level with increasing altitude.

$C_{W,alt} = C_{W,o} \cdot F_a$

**$\alpha$ values**

Oxygen transfer by a given device in water depend on the quantity and character of suspended solids in the water. Suspended solids change viscosity and density of the liquid and hence affect the mixing capacity of a given aeration device. The $\alpha$-factor express the ratio between the oxygen mass transfer coefficient (often termed $K_{La}$) for wastewater compared to that for the same aeration device in clean water.

Tchobanoglous et al (2003) specify a correction factor $\alpha$ as 0.98 for municipal wastewater (effluent) and surface aeration. $\alpha$ values for surface aerators are generally in the order of 1 – 0.95. Tchobanoglous et al (2003) specify $\alpha$ values of 0.7 – 0.85 for fine bubble aeration. Other references suggest $\alpha$ values of 0.65 – 0.80 for fine bubble diffusers and municipal wastewater.

The requirement for the equipment is that the oxygenation capacity of the installed equipment under actual conditions (i.e. $OC_{a}$) is equal to (or above) the calculated peak oxygen consumption $L_{h,tot}$.

**Example**

**Calculation of $OC_{a}$ (8.1 continued)**

A fine bubble diffuser system is chosen. Diffusers are 100 cm long Ø65 mm rubber hose diffusers units supplied with compressed air. The manufacturer informs us of the following characteristics of the diffusers under standard conditions:

![Fine bubble diffuser X](image)

**Fig 8.1 Relationship between aeration diffuser load, head loss and oxygen transfer.**

*Data for OC is given for standard conditions in the unit g O$_2$ per Nm$^3$ of*
atmospheric air per meter of submersion (until 7 m depth). The head loss is given in units of mbar.

The manufacturer furthermore specifies that alpha values of 0.62 – 0.77 should be used for domestic wastewater according to his experience.

Choosing an aeration tank of 5 m water depth and placing the diffusers 20 cm above the tank bottom, the effective water depth of the diffusers becomes 4.8 m. Choosing a maximum load of the diffuser of 10 Nm$^3$/h, one diffuser can deliver 23 g O$_2$/Nm$^3$ · m · 4.8 m · 10 Nm$^3$/h = 1.1 kg O$_2$/h per unit under standard conditions.

With
$\alpha = 0.7$ (fine bubble bottom diffusers)
$\beta = 1.0$
$C_L = 2$ mg/L (oxygen concentration in the activated sludge)
$T = 15^\circ$C (water temperature)
$C_{walt} = 0.98 \cdot 9.77 = 9.6$ mg/L (plant located 200 m above sea level, salinity 5 g/kg)

\[ OC_a = OC_{std} \left( \frac{\beta \cdot C_{walt} - C_L}{9.17} \right) \cdot 1.024^{15-20} \cdot \alpha \]
\[ L_{h, tot} = 65 \text{ kg/h} = OC_a = OC_{std} \left( \frac{1.96 - 2}{9.17} \right) \cdot 1.024^{15-20} \cdot 0.7 \]

$OC_{std} = 65/0.52 = 126$ kg O$_2$/h.

So, the equipment needs to be able to transfer 126 kg O$_2$/h. at standard conditions to be able to transfer the 65 kg O$_2$/h at actual conditions, and thus covering the peak oxygen need of the activated sludge.

The required number of diffusers is thus 126/1.1 = 115 nos.

The diffusers must be supplied with compressed air at a rate of 115 · 10 Nm$^3$/h = 1150 Nm$^3$/h.

The air blower must supply the air with a pressure corresponding to 4.8 m of water depth (or approximately 485 mbar) + head loss over diffusers of 50 mbar (for a clean diffuser) + increased head loss over a dirty old diffuser (e.g. another 40 mbar) + head loss in the pipe system leading from the air blower to the diffusers (all dependant on the actual pipe system, length, velocity, valves etc.,) – e.g. 100 mbar. Total pressure head for air blower: 675 mbar.

If a surface aerator was chosen (and thus $\alpha = 0.7$) the calculated required $OC_{std}$ would become 90 kg O$_2$/h.

**Power consumption**

The power consumption for surface aerator is generally in the order of 1.7 to 2.2 kg oxygen transferred per kWh used (at standard conditions). For fine bubble bottom aeration the efficiency depends on the submergence, type and loading of diffusers and
air blowers used, but can be up to twice as high as surface aerators (i.e. up to 3 – 4 kg $O_2$/kWh depending on the tank depth).

Power consumption for aeration often constitutes as much as 50 % of the total power consumption in a WWTP so due consideration for a low power consumption for this equipment is significant to the total operation costs of the WWTP.

The power consumption at a number of Danish WWTP is registered as kWh/kg N removed in year 2001 is given in figure 8.2.

![Figure 8.2](image)

**Fig 8.2 Power consumption for all process purposes (excluding inlet pumping of raw wastewater) for 25 Danish WWTP. Blue columns (9 leftmost columns) are for the bigger plants (actual plant load > 50,000 PE), red columns (Randers – OdenseNØ) are intermediate sized plants (load 10,000 – 50,000 PE) and the remaining (green) columns are small plants (actual load < 5,000 PE). The power consumption is expressed as kWh per kg N removed at the plant. From Sørensen and Strandbæk (2002).**

**References:**

Sørensen, John and Helle Strandbæk “Driftsforhold og nøgletal for Spildevandsrenseanlæg 2001”. DANVA, juni 2002. [www.danva.dk](http://www.danva.dk)
