BM Respirometry for energy optimization in the aeration system of activated sludge processes

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Nomenclature

ASP: Activated Sludge Process

OUR: Maximum Oxygen Uptake Rate values in the global ASP (mg O_2/L/h)

SOUR: Specific Oxygen Uptake Rate (mg O_2/g VSS/h) = OUR / MLVSS

Unfed SOUR: SOUR corresponding to the ASP effluent (mg O_2/g VSS/h)

Rs: Exogenous respiration rate (mg O_2/L/h)

DO high: DO high set point in the aeration control (mg/L)

SN: Ammonium-nitrogen concentration to nitrify (mg $N-NH_4$/L)

AUR: Nitrification rate (mg $N-NH_4$/L/h)

Y_H: Yield coefficient for heterotrophic biomass (O_2/COD)

bCOD: Biodegradable COD (mg/L)

AOR: Oxygen Requirement in the ASP (kg O_2/d)

K_La_p: Oxygen mass transfer coefficient in the ASP (h^{-1})

K_La: Oxygen mass transfer coefficient in clean water (h^{-1})
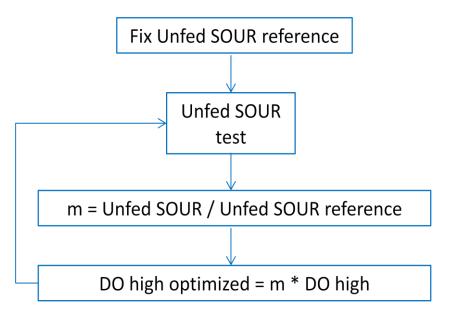
α: Alpha factor = K_La_p / KLa

SOTR: Oxygen Transfer Rate for Standard conditions in clean water (kg O_2/d)

OTR: Oxygen Transfer Rate in the ASP (kg O_2/d)

1. Practical procedure to optimize the DO high set-point in the aeration control for the global activated sludge process

This procedure can be applied to any activated sludge process (ASP) where the aeration us controlled by DO set-points and it is based on the optimization of the DO high set point (DO high)

This is a procedure that can be applied to any ASP

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┌─────────────────────────────┐
│   Fix Unfed SOUR reference   │
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              │
              ▼
      ┌───────────────┐
      │  Unfed SOUR   │
──────▶│     test      │
│     └───────────────┘
│             │
│             ▼
│  ┌──────────────────────────────────────┐
│  │ m = Unfed SOUR / Unfed SOUR reference │
│  └──────────────────────────────────────┘
│             │
│             ▼
│  ┌──────────────────────────────────────┐
└──│    DO high optimized = m * DO high    │
   └──────────────────────────────────────┘
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1.1. Unfed SOUR reference

The Unfed SOUR reference is fixed according to the type of process and desired Performance that we want to select for it. That is to say, for each selected Performance % it correspond one specific Unfed SOUR reference For that purpose we have to go to some SURCIS table based on bibliography.
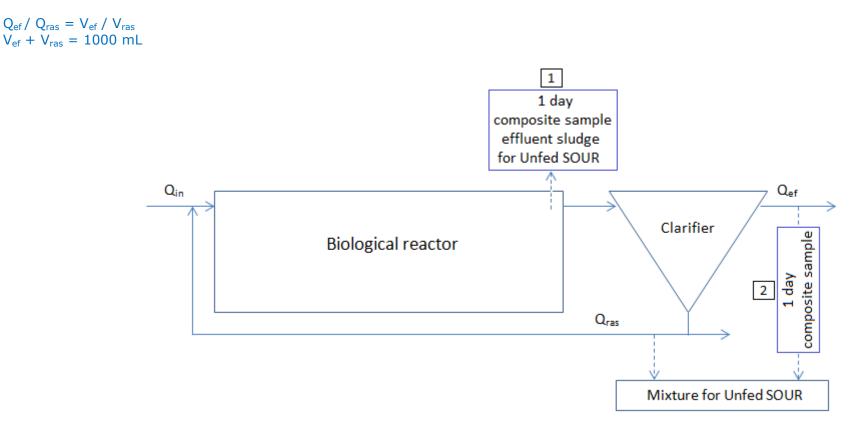
ASP Classification	F/M (kgBOD/kg MLSS.d)	SRT (d)	Unfed SOUR (mg/g.h)	Performance vs Unfed SOUR
High Loading	> 0.4	2 - 4	8 - 18	
Medium Loading	0.2 < F/M < 0.4	4 - 10	4 - 14	
Low Loading	0.7 < F/M < 0.2	10 - 30	2 - 12	
Very Low Loading (Extended Aeration)	> 0.7			

Table to fix de Unfed SOUR reference according to a selected Performance

1.2. Unfed SOUR Test

This is a representative SOUR test of one day composite effluent activated sludge in the biological reactor.
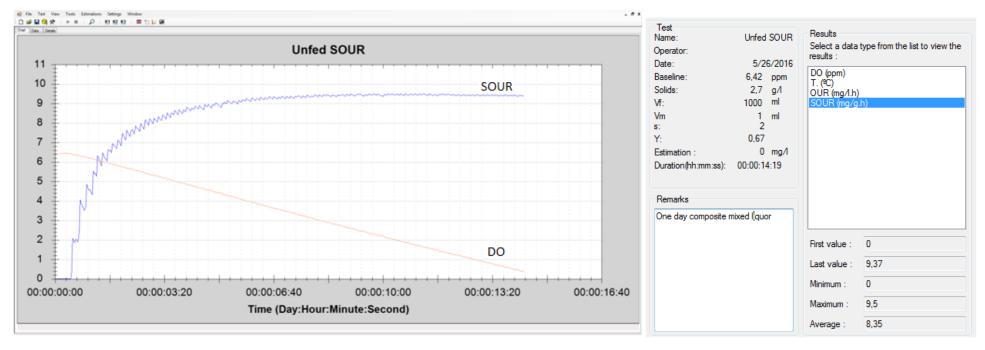
In case that the plant permits to get one liter of one day composite sample of the effluent sludge we can do it with that sludge sample. If not, we can carry out the test with one liter of mixture composed by one day composite sample of effluent (V_{ef}) + returned sludge (V_{ras}) on equivalent volumes to the effluent flow (Q_{ef}) and RAS flow ratio (Q_{ras})

$Q_{ef} / Q_{ras} = V_{ef} / V_{ras}$
$V_{ef} + V_{ras} = 1000$ mL

Two ways of getting the sample for the Unfed SOUR test

1.2.1. Unfed SOUR test performance in a BM respirometer

If the one day composite sample is coming from the effluent sludge, it can go directly to the respirometer.
In case we have to prepare the one litre mixture from one day composite effluent water and returned sludge, then the returned sludge should be continuously aerated during 30 minutes before making the mixture.

Unfed SOUR & DO respirograms in BM respirometer   Results

1.3. Unfed SOUR / Unfed SOUR reference ratio

m = Unfed SOUR / Unfed SOUR reference

1.4. DO high set point optimization

DO high optimized = m * DO high (actual)

1.5. Example

ASP Type = Medium loading
Desired Performance = 86%
Unfed SOUR reference = 12
Actual Unfed SOUR = 9.37
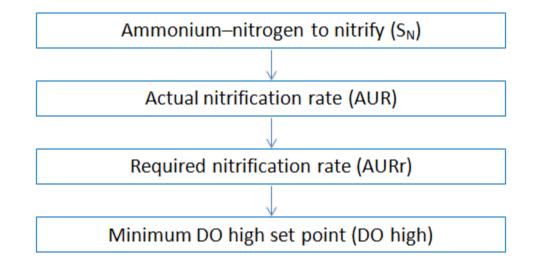Actual DO high = 1.7 mg/L

m = 9.37 / 12 = 0.78

DO high optimized = 0.78 * 1.7 = 1.3 mg/L

The new DO high optimized is about 20% less than the one it was for a performance of 86%.
Although this is not a lineal mathematic correlation, this could represent a significant energy-saving.
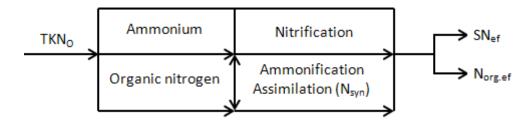
2. Procedure to optimize the minimum DO high set-point in the aeration control for nitrification

The goal in this procedure is to get the minimum DO high set-point (DO high) in the DO control system for a specific ammonium-nitrogen that we want to achieve in the final effluent.

Ammonium–nitrogen to nitrify (S_N)

↓

Actual nitrification rate (AUR)

↓

Required nitrification rate (AURr)

↓

Minimum DO high set point (DO high)

2.1. Ammonium-nitrogen to nitrify

Because of the ammonification process, where part of the organic nitrogen is going into ammonium form, the effective ammonium to nitrify can be calculated as follows:
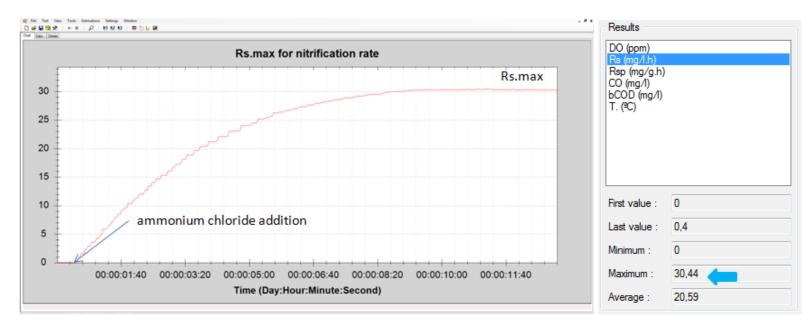

TKN flow diagram in a process with nitrification

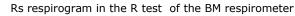$$SN = TKN_o - SNr_{ef} - N_{org.ef}$$

SN: Ammonium-nitrogen to nitrify (mg NH_4-N/L)
TKN_o: Total Kjeldahl Nitrogen in the influent to biological reactor (mg N/L)
SN_{ref}: Required Ammonium-nitrogen in the effluent (mg NH_4-N/L)
$N_{org.ef}$: Soluble organic nitrogen in effluent (mg N_{org}/L)

2.2. Nitrification rate (AUR)

We are getting the actual nitrification rate through a R test by making use of an equivalent (*) dose of ammonium chloride in endogenous sludge, until reaching the maximum exogenous respiration rate (Rs.max)

(*) 1 mg/l of ammonium chloride = 0.26 ammonium-nitrogen

Rs respirogram in the R test of the BM respirometer   Rs results

$$AUR = (Rs_{max} / 4.57) * DO / (K_{OA} + DO)$$

AUR: Nitrification rate (mg NH_4-N/L/h)
Rs.max: Maximum exogenous respiration rate due to nitrification (mg/L/h)
4.57: mg of O_2 for each mg of NH_4- to be oxidized
K_{OA}: Half saturation constant = 0.5 (mg/L)
DO: Daily average of dissolved oxygen on which the process is currently operating (mg/L)

2.3. Required nitrification rate (AURr)

We can assume that the current nitrification performance is a direct consequence of the actual AUR and therefore, to meet any other performance, the first parameter we want to calculate is the required AUR (AURr) that the process would need.

Under that purpose, assuming the nitrification performance is linked to the difference between the influent TKN and effluent ammonium nitrogen, the required AUR could be estimated as follows:

$$AURr = AUR (TKN_o - SNr_{ef}) / (TKN_o - SN_{ef})$$

AUR_r: Required AUR (mg NH_4-N/L/h)
AUR: Actual AUR (mg NH_4-N/L/h)
SNr_{ef}: Required ammonium-nitrogen in the effluent (mg NH_4-N/L)
SN_{ef}: Actual Ammonium-nitrogen in the effluent (mg NH_4-N/L)

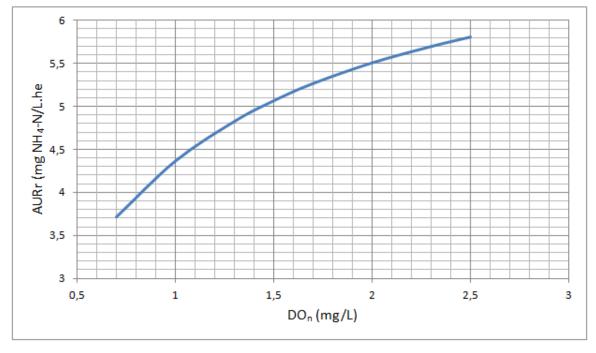To achieve the AURr represents the first goal where control actions should be conducted

2.3.1. AURr vs different DO values

$$AURr = (Rs_{max} / 4.57) * DO_n / (K_{OA} + DO_n)$$

DO_n: Any DO value that could be in the process (mg/L)

2.4. Calculate the minimum DO high set-point (DO high)

The strategy here is to get a set of DOn coherent values on which the process could operate, in order to figure out the corresponding AURr

AURr vs DO$_n$ plot

Then, once we have got the DOn value that fits the AURr, we can fix it in the real process as OD high set-point to make its effect after giving a coherent time to grow its nitrification activity.

The main advantage of this procedure is that making use of it we open the door to the ability of selecting the minimum DO for a sufficient nitrification performance and, in this way, go for the maximum possible energy saving in the aeration system of the biological reactor.

2.5. Example

Current daily average data in the ASP
Rs.max = 30
Current DO = 2.3
SNr_{ef} = 3 mg NH_4-N/L
SN_{ef} = 2 mg NH_4-N/L
TKN_o = 42 mg/L

$AUR = (Rs_{max} / 4.57) * DO / (K_{OA} + DO) = (30 / 4.57) * 2.3 / (0.5 + 2.3) = 5.39$ mgN-NH_4/L/h

$AURr = AUR (TKN_o - SNr_{ef}) / (TKN_o - SN_{ef}) = 5.39 (42 - 3) / (42 - 2) = 5.25$ mgN-NH_4/L/h

$AURr = (Rs_{max} / 4.57) * DO_n / (K_{OA} + DO_n) = (30 / 4.57) * DO_n / (0.5 + DO_n) \rightarrow$ for $DO_n = 0.7 \rightarrow 2.5$
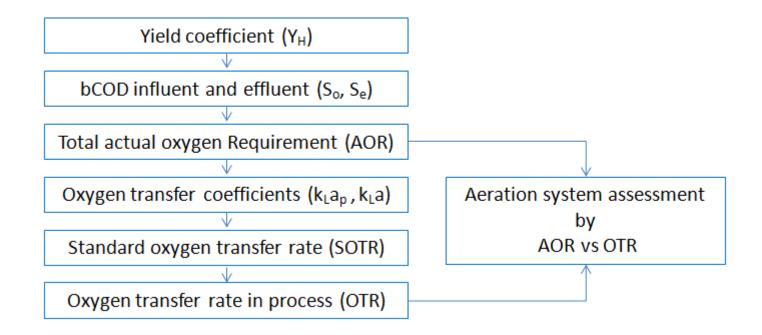

Minimum DO high set-point determination from the AURr vs DO_n plot

Minimum DO high set-point to achieve 4 mg/L ammonium-nitrogen in effluent: DO high = 1.68 ≈ 1.7 mg/L
DO set-point reduction = 1 − 1.7 / 2.3 ≈ 40 %

3. Assessment of the actual aeration system

The assessment of the aeration system follows a procedure to get the AOR and OTR parameters in order to be compared by the corresponding ration between them. In this way, we compare the actual oxygen requirement (AOR) with the oxygen that is currently transferred to the process (OTR)
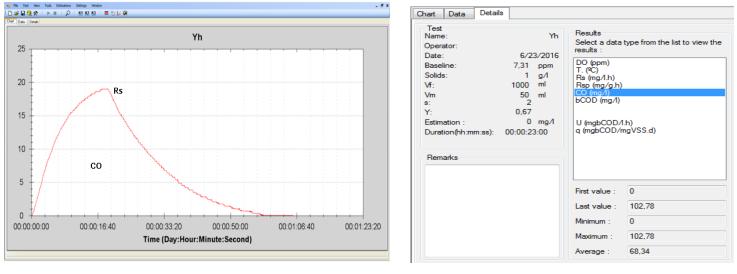
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┌─────────────────────────────────────┐
│      Yield coefficient (Y_H)         │
└─────────────────────────────────────┘
                  ↓
┌─────────────────────────────────────┐
│  bCOD influent and effluent (S_o, S_e) │
└─────────────────────────────────────┘
                  ↓
┌─────────────────────────────────────┐        ┌──────────────────────────────┐
│ Total actual oxygen Requirement (AOR) │────────│                              │
└─────────────────────────────────────┘        │  Aeration system assessment  │
                  ↓                             │             by               │
┌─────────────────────────────────────┐        │         AOR vs OTR           │
│ Oxygen transfer coefficients (k_La_p, k_La) │ │                              │
└─────────────────────────────────────┘        └──────────────────────────────┘
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┌─────────────────────────────────────┐
│ Standard oxygen transfer rate (SOTR) │
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┌─────────────────────────────────────┐
│ Oxygen transfer rate in process (OTR) │──────────────────┘
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3.1. Yield coefficient (Y_H) for heterotrophic biomass

First thing is to make a solution of 400 mg of sodium acetate in 1 litre of distilled water. For this solution, we must obtain (from the lab.) the actual COD value ($COD_{ac} \approx 300$ mg/l

We carry out an R assay in order to determine the consumed oxygen (CO)

CO: Consumed oxygen = ΔO_2 (mg/l)
We can make use of sample volume in between 50 and 100 ml. and pump speed to 2

Rs respirograma for CO determination   CO result

$$Y_{H,COD} = 1 - CO / COD_{ac} \quad \rightarrow \quad Y_{H.VSS} = Y_{H.CO} / 1,42 \quad \rightarrow \quad Y_{obs} = Y_{H.VSS} / (1 + 0.06 * SRT)$$
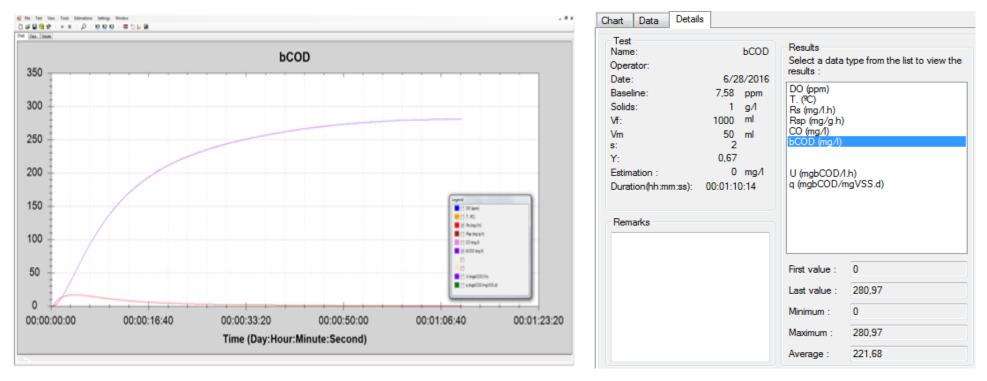
$Y_{H,COD}$: Heterotrophic yield coefficient referred to oxygen demand (mg O_2/mg COD)
$Y_{H,COD}$: Heterotrophic yield coefficient referred to MLVSS (mg VSS/mg COD)
Y_{obs}: Observed yield (mg VSS/mg COD)
SRT: Sludge age (d)

3.2. Influent biodegradable COD (S$_o$)

The BM respirometer automatically calculates the total biodegradable COD (bCOD) of the influent wastewater by means a R test with influent wastewater to the biological reactor and endogenous sludge. To do this, it integrates of the exogenous respiration rate (Rs) to calculate the consumed oxygen (CO) and apply the yield coefficient (Y$_{H.COD}$):

bCOD = CO / (1 − Y$_H$)

Only in case the process has nitrification, you must add a dose o Allyl Thiourea (ATU) to the endogenous sludge (stirring and aerating it) ½ hour before the test (2 to 3 mg ATU / g VSS)

bCOD and Rs respirograms   Result

3.3. Effluent biodegradable COD (S_e)

$S_e = COD_e - iCOD$

CODe: Effluent COD (mg/L)
iCOD: Innert COD (mg/L) = COD_o - S_o
CODo: Infuent COD (mg/L)

3.4. Actual Oxygen Requirement (AOR)

Here we have to distinguish between process without or with nitrification-denitrification.

3.4.1. Actual Oxygen Requirement (AOR) calculation in a process without nitrification

Carbonaceous AOR

$AOR_S = Q (S_o - S_e) / 1000 - 1.42 * P_X$

Q: Influent flow to aerobic biological reactor (m^3/d)
P_X: Sludge production (kg VSS/d) = $Y_{obs} * Q (S_o - S_e) / 1000$

$AOR = AOR_S$

AOR: Total actual oxygen requirement (kg O2/d)

3.4.2. Actual Oxygen Requirement (AOR) calculation in a process with nitrification-denitrification

AOR = Carbonaceous AOR (AOR$_S$) + Ammonium-nitrogen AOR (AOR$_N$) – Oxygen credit from denitrification (AOR$_{DN}$)

AOR: Total actual oxygen requirement (kg O2/d)

Carbonaceous AOR

$$AOR_S = Q \, (S_o - S_e) / 1000 - 1.42 * P_X$$

P$_X$: Sludge production (kg VSS/d) = Y$_{obs}$ * Q $(S_o - S_e)$ / 1000
Q: Influent flow to aerobic biological reactor (m^3/d)

Ammonium-nitrogen AOR

$$AOR_N = Q * 4.57 * S_N / 1000$$

S$_N$: Ammonium-nitrogen concentration to nitrify (mg N-NH$_4$/L)

Oxygen credit from denitrification

$$AOR_{DN} = 2.86 * Q * S_N$$

We assume that all the ammonium is converted into nitrate

3.5. Oxygen transfer coefficient in process (k_La_p)

$k_La_p = $ Unfed SOUR $/ (\beta * DO_{sT} - DO_U)$

k_La_o: Oxygen transfer coefficient at current temperature (1/h)
β: Solubility factor = 0.95
DO_{sT}: DO at saturation level in wastewater at current temperature T (mg/L) → See oxygen solubility table
DO_U: Dissolved oxygen in the sampling point of the effluent sludge just at the time of grabbing the sample (mg/L)

OXYGEN SOLUBILITY TABLE

Solubility of Oxygen (mg/L) in Water Exposed
to Water-Saturated Air at 760 mm Hg Pressure.

Temp °C	Chlorinity 0 Salinity: 0	Temp °C	Chlorinity 0 Salinity: 0
0.0	14.62	25.0	8.26
1.0	14.22	26.0	8.11
2.0	13.83	27.0	7.97
3.0	13.46	28.0	7.83
4.0	13.11	29.0	7.69
5.0	12.77	30.0	7.56
6.0	12.45	31.0	7.43
7.0	12.14	32.0	7.31
8.0	11.84	33.0	7.18
9.0	11.56	34.0	7.07
10.0	11.29	35.0	6.95
11.0	11.03	36.0	6.84
12.0	10.78	37.0	6.73
13.0	10.54	38.0	6.62
14.0	10.31	39.0	6.52
15.0	10.08	40.0	6.41
16.0	9.87	41.0	6.31
17.0	9.67	42.0	6.21
18.0	9.47	43.0	6.12
19.0	9.28	44.0	6.02
20.0	9.09	45.0	5.93
21.0	8.92		
22.0	8.74		
23.0	8.58		
24.0	8.42		

3.6. Oxygen transfer coefficient in clean water at 20 ºC (k_La)

$kLa = (K_La_p / α) * 1.024^{T-20}$

K_La: k_La in standard conditions at 20 ºC
α: Alpha factor → See α table

Aeration systems	α
Fine bubble diffusers	
Medium loading without nitrification	0,50
Low loading with nitrification	0,55
Course bubble diffusers	
Medium loading without nitrification	0,60
Low loading with nitrification	0,70
Mechanical	
Surface	0,85
Submerged turbines	0,90

3.7. Standard oxygen transfer rate in clean water (SOTR)

This parameter is the oxygen transfer rate of the aeration system for clean water in standard conditions.

$SOTR = k_La * DO_{S(20)} * V$

SOTR: Standard oxygen transfer rate (kg O_2/d)
k_La: Oxygen transfer coefficient (1/d) = 24 * k_La (1/h)
$DO_{S(20)}$: DO saturation in clean water at 20ºC (kg/m^3) = 0.001 * $DO_{S(20)}$ (mg/L) → See oxygen solubility table

3.8. Oxygen transfer rate in process (OTR)

$$OTR = \alpha * SOTR * \theta^{T-20} * (\beta * DO_{sT} - DO) * / DO_{s(20)}$$

α: Alpha factor → (α table)
θ: Theta factor for temperature correction = 1.024
β: Solubility factor = 0.95
$DO_{S(20)}$: DO saturation at 20ºC = 9.09 mg/L
DO_{ST}: DO saturation at process temperature (mg/L) → See oxygen solubility table
DO: DO in process (mg/L)

3.9 AOR assessment

Since the AOR and OTR are calculated at 20ºC, the assessment is done at this standard temperature.

To assess the actual oxygen requirement, we calculate the deviation percentage or AOR vs OTR

AOR assessment = 100 (1 – OTR / AOR)

A positive value of the AOR assessment means that the Actual Aeration Requirement is higher than the Oxygen Transfer Rate of the aeration system and then this would be the percentage in which the daily air flow of the aeration system should be increased.
On the contrary, a negative value means that the Actual Aeration Requirement is lower than the Oxygen Transfer Rate of the aeration system and then this would be the percentage in which the daily air flow of the aeration system could be saved.

Example

Data process	Data aeration
Temperature = 23 °C Influent flow: Q = 15,600 m³/d Volume aerobic reactor: V = 7,300 m³ Influent bCOD: S_o = 400 mg/L Effluent bCOD: S_e = 20 mg/L Ammonium-nitrogen: S_N = 40 mg N-NH₄/L Y_{obs} = 0.35 kg VSS/kg COD removed	Alpha factor: $α$ = 0.55 Solubility factor: $β$ = 0.95 Theta factor for temperature correction: $θ$ = 1.024 Unfed OUR = 20 mg/l.h DO in Unfed SOUR: DO_U = 2 mg/L DO saturation in clean water at 20°C: DO_s = 9.09 mg/L DO saturation in wastewater: DO_{sT} = 9 mg/L = 0.009 kg/m³ DO process: DO = 1.7 mg/L = 0.0017 kg/m³

Carbonaceous AOR

$P_X = Y_{obs} * Q (S_o – S_e) / 1000 = 0.35 * 15,600 (400 – 20) / 1,000 = 2,074$ VSS/d

$AOR_S = Q (S_o – S_e) / 1000 – 1.42 * P_X = 15,600 (400 – 20) / 1,000 - 1.42 * 2,074 = 5928 – 2,945 = 2,983$ kg O₂/d

Ammonium-nitrogen AOR

$AOR_N = Q * 4.57 * S_N / 1000 = 15,600 * 4.57 * 40 / 1,000 = 2,851$ kg O₂/d

Oxygen credit from denitrification

$AOR_{DN} = 2.86 * Q * S_N / 1000 = 2.86 * 15,600 * 40 / 1,000 = 1,784$ kg O₂/d

Total AOR

$AOR = 2,983 + 2,851 – 1,784 = 4,050$ kg O₂/d

Oxygen transfer coefficients

k_La_p = Unfed OUR / (DO_S − DO_u) = 20 / (0.95 * 9 − 2) = 3 1/h

k_La = K_La_{p20} / α = 3 / 0,5 = 6 1/h = 144 1/d

Standard oxygen transfer rate

SOTR = k_La * DOs_{20} * V = 144 * 0.0093 * 7,300 = 9,776 kg O_2/d

Oxygen transfer rate in process

OTR = SOTR * α (β * DO_{sT} − DO) * $θ^{T-20}$ / 9.09 = 9,776 * 0.55 (8.55 − 1.5) * $1.024^{(23-20)}$ / 9.09 = 4,474 kg O_2/d

Aeration assessment

AOR assessment = 100 (1 − OTR / AOR) = 100 (1 − 4,474 / 4,050) = - 10 %

Te result of -10% means that in this specific case we could save a 10% of kg O_2/d → -10% of energy

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