Essential applications of respirometry for an activated sludge process with nitrogen removal performed with a BM respirometer

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Key words: Respirometry, Biodegradable, Respiration rate, COD fractions, Nitrification, Denitrification, Sludge age, Actual oxygen requirement, Oxygen transfer efficiency in process, Fouling factor

Abstract

The slow dynamics of the activated sludge process is one of the main drawbacks when making decisions. Whatever measure is decided to be taken, its effects on the process will not be clearly observed until a few days have passed.
This fact makes it particularly important, on the one hand, to detect problems as early as possible and, on the other hand, to make the right decisions from the very first moment. For this reason, a tool is needed that is capable of performing all these functions in a simple, practical and relatively fast way, and all this is achieved with the BM Respirometry, developed by the company Surcis S.L.

It is important to bear in mind that the active sludge of a treatment plant is a living process with its own respiration; Therefore, a lack of sufficiently rapid information on this aspect can cause serious confusion in the monitoring and control of an activated sludge treatment process, affecting the quality of the effluent and energy consumption.

1. Introduction

The BM Respirometry from Surcis, S.L. combines traditional respirometry, based on the oxygen consumption of the sludge biomass itself, with an exclusive Surcis technology that includes advanced software that allows the automatic measurement and calculation of decisive biological parameters for biological wastewater treatment processes using activated sludge with relatively rapid nitrogen removal. Furthermore, this technology, in addition to being a fundamental tool in the control and protection of activated sludge processes, is presented as an important way towards carrying out studies and R&D activities in the different types of treatment processes. In this article we will describe in a summarized and schematic way the most important applications that allow to clearly justify the use of BM Respirometry, by means of the different models of respirometry (BM Respirometry systems) from Surcis for the control and protection of a biological process of activated sludge in a wastewater treatment plant.

2. BM Respirometry

This type of Respirometry is based on a unique system, which has as its operating principle the modified LFS + LSS type, developed by the company Surcis S.L., which is included in a series of different models of BM respirometers.

This technology allows us to adapt the test to different conditions of pH, temperature, oxygen and sample/sludge ratio during the test's pre-programming and even during its execution.

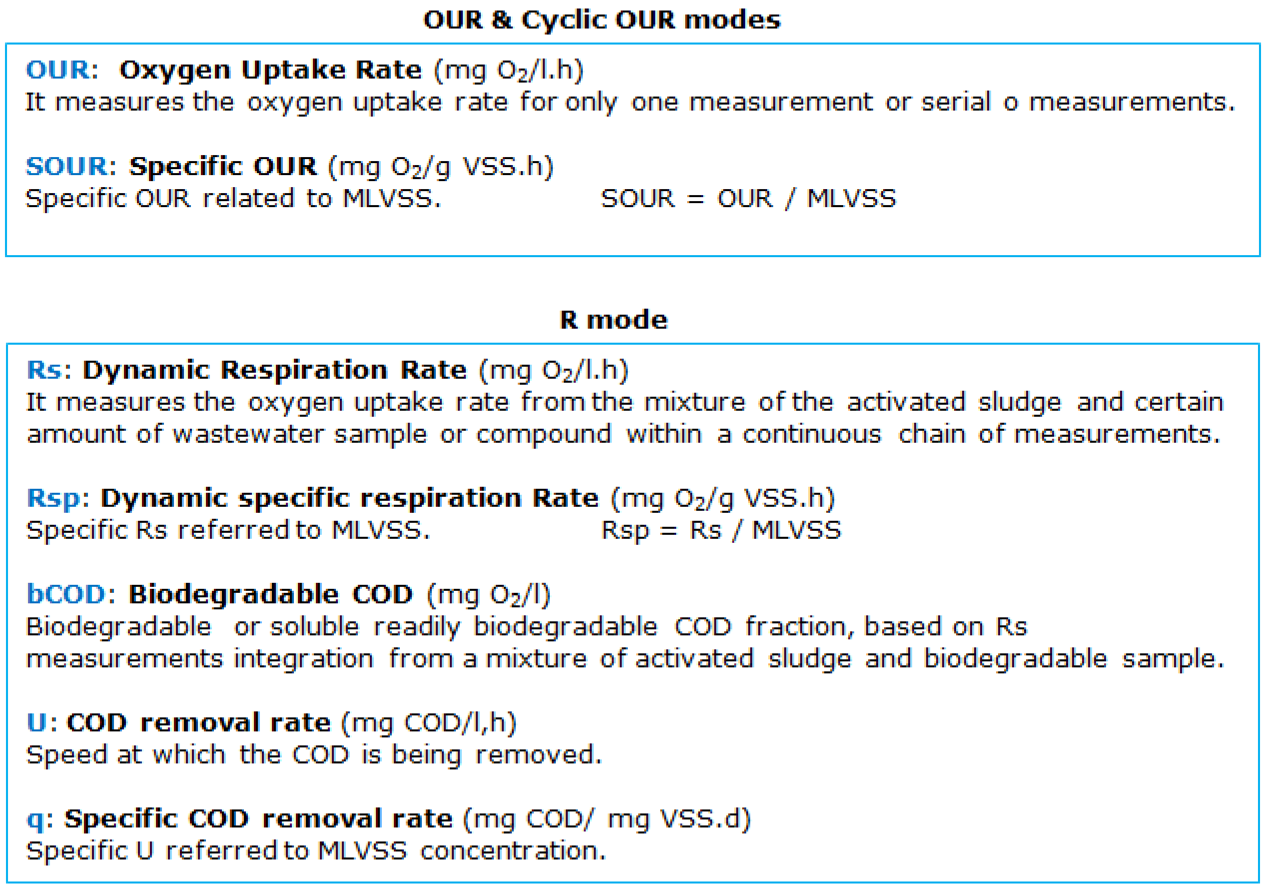
It also allows the possibility of introducing certain data that can participate in the automatic calculations of fundamental parameters in purification processes.

Optionally, using a special reactor (bio-carrier), BM respirometers can carry out respirometry tests with bacterial beds for MBBR and granular biomass type processes.

Figure 1. BM Respirometry System – BM Advance model

1. Automatic pH control system
2. pH sensor
3. Dissolved oxygen sensor
4. Stirrer motor
5. Peristaltic pump
6. Reactor
7. Automatic temperature control system
8. Leeds for devices control
9. Oxygen & temperature controller
10. pH controller
11. PC with BM software

Table 1. Operation modes and main parameters in BM Respirometry



OUR & Cyclic OUR modes

OUR: Oxygen Uptake Rate (mg O_2/l.h)
It measures the oxygen uptake rate for only one measurement or serial o measurements.

SOUR: Specific OUR (mg O_2/g VSS.h)
Specific OUR related to MLVSS. SOUR = OUR / MLVSS

R mode

Rs: Dynamic Respiration Rate (mg O_2/l.h)
It measures the oxygen uptake rate from the mixture of the activated sludge and certain amount of wastewater sample or compound within a continuous chain of measurements.

Rsp: Dynamic specific respiration Rate (mg O_2/g VSS.h)
Specific Rs referred to MLVSS. Rsp = Rs / MLVSS

bCOD: Biodegradable COD (mg O_2/l)
Biodegradable or soluble readily biodegradable COD fraction, based on Rs measurements integration from a mixture of activated sludge and biodegradable sample.

U: COD removal rate (mg COD/l,h)
Speed at which the COD is being removed.

q: Specific COD removal rate (mg COD/ mg VSS.d)
Specific U referred to MLVSS concentration.

3. Some applications that can justify the use of the BM Respirometry

Some of the essential applications that can be carried out in a BM Respirometry System:

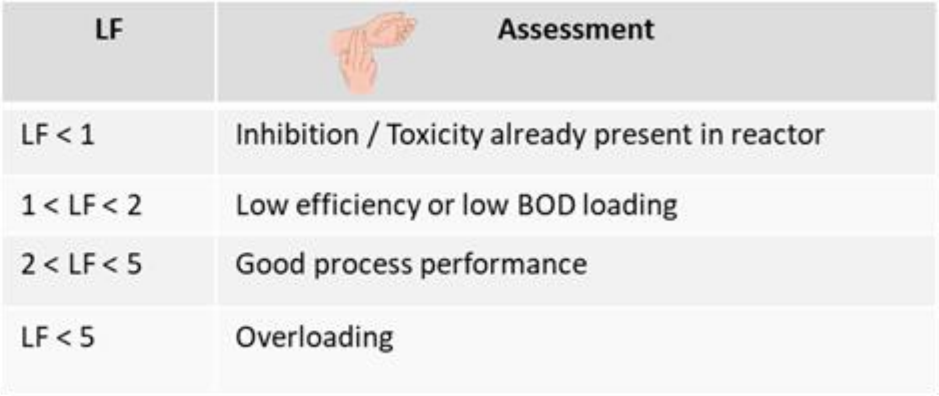
1. Fast pulse to the treatment process.
2. Finding the cause of poor BOD or COD performance.
3. Nitrification rate - Find the possible causes of low nitrification performance.
4. Energy optimization by minimum oxygen in nitrification
5. Denitrification rate – Finding the possible causes of low denitrification performance.
6. Optimum sludge age and F/M in the context of energy optimisation.
7. Actual oxygen requirement (AOR).
8. Evaluation of the diffused aeration systems.
9. Toxicity.

3.1. Taking the pulse of the activated sludge process

The one-day pulse of the process can be taken by means the assessment of the Loading Factor ratio (LF) between the influent sludge (FED OUR) and effluent sludge (UNFED OUR) in the biological reactor.

$$\mathrm{LF} = \frac{\mathrm{FED\ OUR}}{\mathrm{UNFED\ OUR}} \qquad (1)$$

Table 2. Loading factor ranges guide



LF	Assessment
LF < 1	Inhibition / Toxicity already present in reactor
1 < LF < 2	Low efficiency or low BOD loading
2 < LF < 5	Good process performance
LF < 5	Overloading

Ron Sharman - Water and Wastewater Technology, LBCC.

3.2. Finding the cause of poor BOD or COD performance.

In addition to possible inhibition or toxicity (which is also detected by respirometry), the very likely causes of poor performance in the removal of organic matter are the following:

- Low concentration of active biomass
- High inert (non-biodegradable COD (nbCOD) or high slowly biodegradable COD (sbCOD)
- Low concentration of active biomass (X)

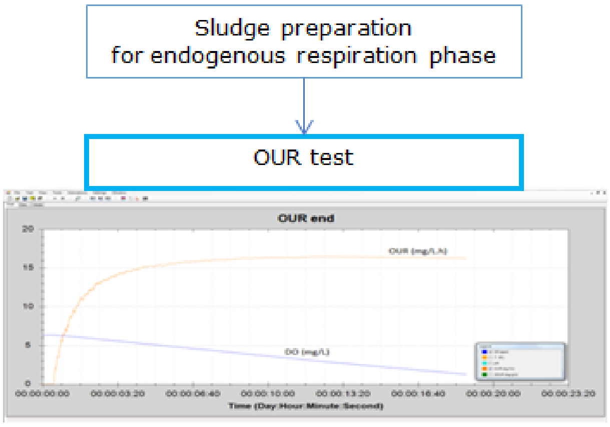
Low concentration of active biomass

The endogenous respiration rate (OUR_{end}) is the rate obtained from the active sludge in the absence of any type of substrate. So, as it depends exclusively on microorganisms, it is directly proportional to the concentration of active biomass (X)

Therefore, when the OUR_{end} is below the normal range, it will indicate that the concentration of biomass is excessively low.

The causes of a low concentration of active biomass could come from lack of nutrients, out-of-range process conditions and recent presence of some toxicant.

Table 3. Guide table for OUR_{end} vs MLVSS



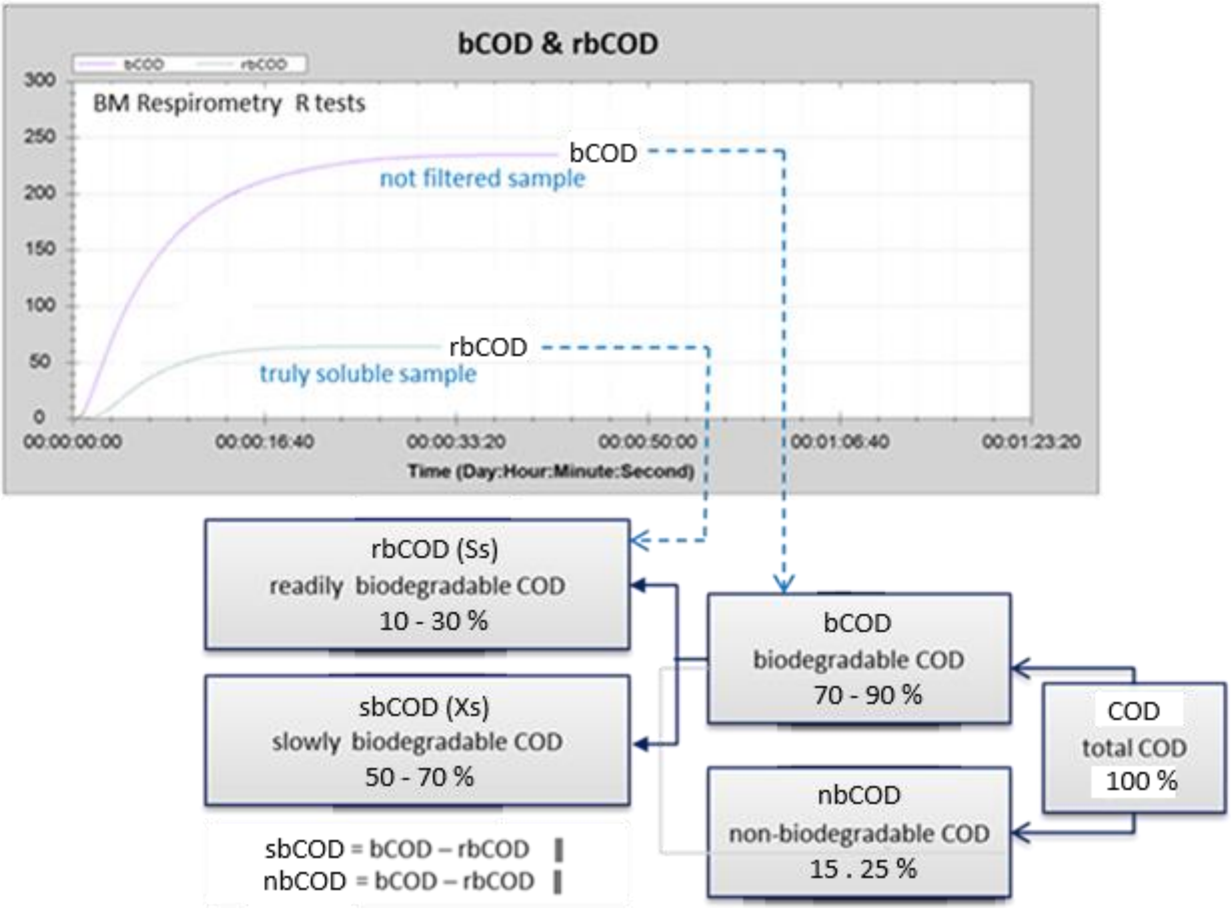
Guide table (20ºC)

MLVSS (mg/l)	Normal range OUR_{end} (mg/l.h)
1000	2 – 3.5
1500	3 - 5
2000	4 - 7
2500	5 – 8.5
3000	6 - 10
3500	7 - 12
4000	8 – 13.5
4500	9 – 15.5

<ins>High values of inert COD and/or slowly biodegradble COD.</ins>

The presence of a high load of slowly biodegradable COD or inert COD can lead to a low elimination of organic matter performance and can also cause a deficiency of organic carbon as a nutrient for the development of active biomass.

Figure 2. Main COD fractions obtained from two BM respirometry tests



By using the operation R mode of the BM Respirometry, the COD fractions of the total readily biodegradable COD (bCOD) and readily biodegradable COD (rbCOD, Xs) can be determined automatically

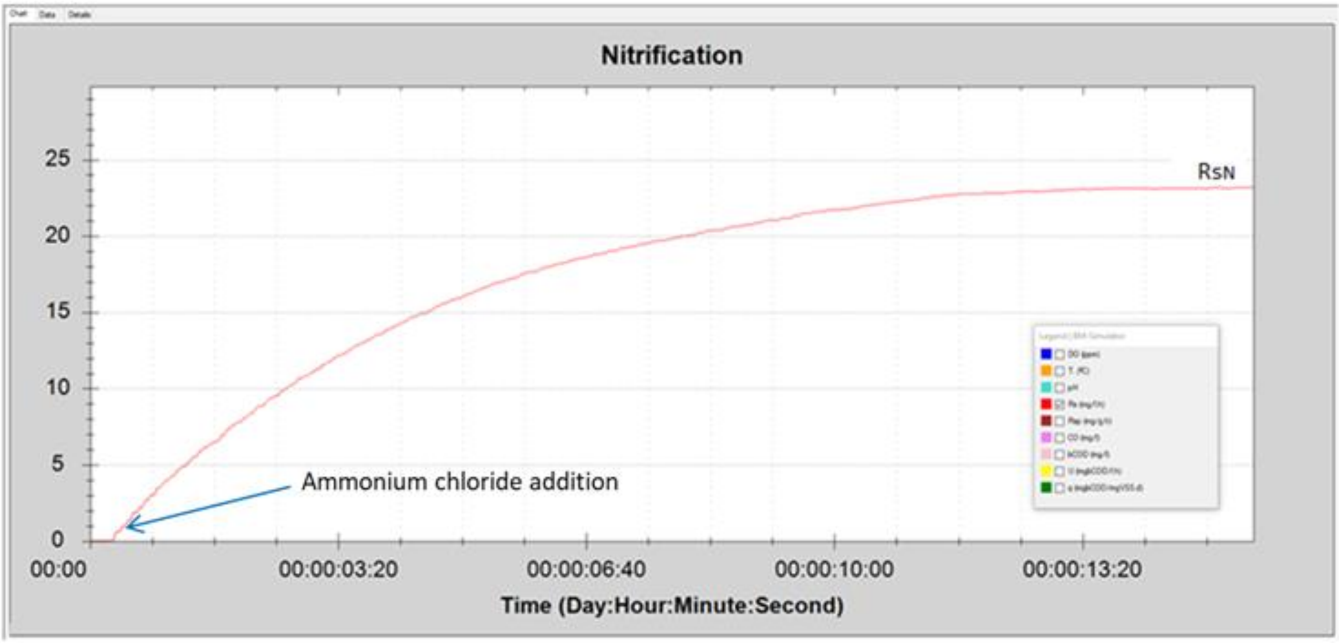
With the result of these fractions and the total COD, sufficient data are available for the determination of the most essential fractions in the COD, where the inert/refractory COD and the slowly biodegradable COD are found.

3.3. Nitrification rate - Possible causes of poor performance in the nitrification process.

3.3.1. Nitrification rate

The key parameter for nitrification is the nitrification respiration rate (Rs_N)
From the Rs_N, the nitrification rate (AUR) and specific nitrification rate (SAUR) can be calculated at the current temperature and pH. The BM software has the ability to modify both temperature and pH and check the different Rs_N values at different conditions.
These parameters measure the rate of nitrifiable nitrogen removal and the nitrifying activity per unit of volatile solids.

Figure 3. R test respirogram of the respiration rate for nitrification (Rs_N)



From Rs_N, the parameters the following parameters can be obtained:

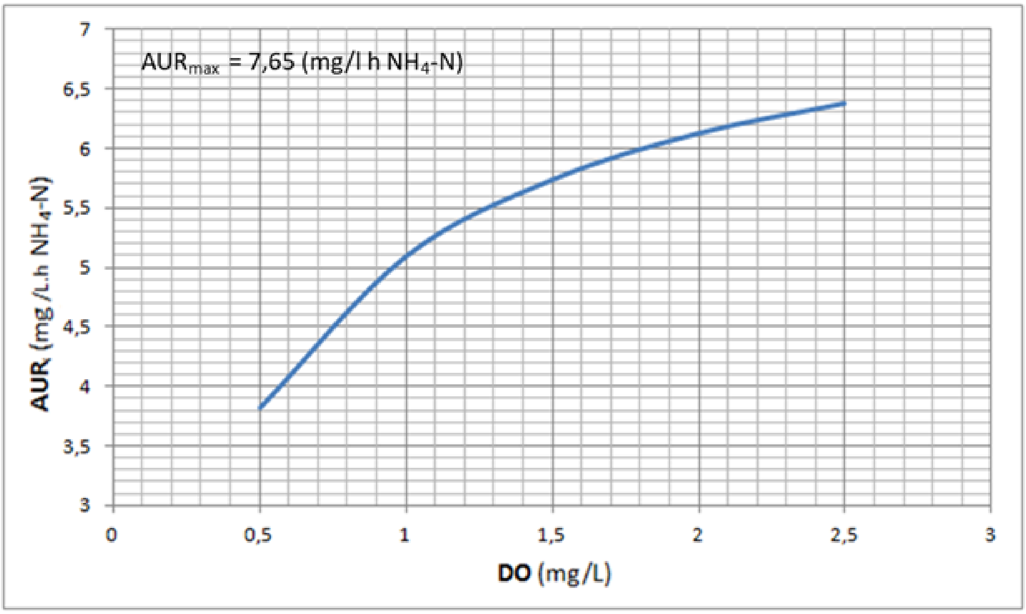
$$\mathrm{AUR} = \frac{\mathrm{Rs_N}}{4.57} * \mathrm{F_{DO}} \qquad (2)$$

$$\mathrm{SAUR} = \frac{24 * \mathrm{AUR}}{\mathrm{MLVSS}} \qquad (3)$$

Where:
AUR: Nitrification rate (mg N/L/h)
4.57: mg O_2 per mg of nitrogen to nitrfy
F_{OD}: Correction factor due to disolved oxygen = DO / (0.5 + OD)
DO: Dissolved oxygen (mg/L)
0.5: Semi-saturation oxygen coefficient: (mg/L) – Habitual value (ASM3) -
SAUR: Specific nitrification rate (g N/g VSS/d)
MLVSS: Mixed liquor volatile suspended solids (mg/L)

As we can see, the nitrification rate depends on dissolved oxygen (DO). So, so we can calculate this parameter for a range of DO values and give way to different AUR and SAUR values.

Figure 4. Graph AUR vs DO



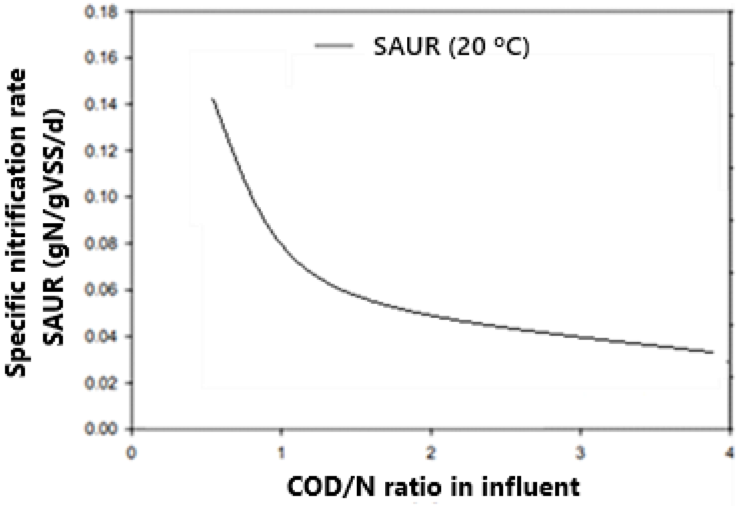
3.3.2. Possible causes of poor nitrification performance

In addition to toxicity, a low nitrification performance may be due to low temperature, low dissolved oxygen or low concentration of nitrifying biomass due to excess COD/N ratio. And through BM Respirometry, all these possibilities can be detected and analysed.

In the reference graph (Figure 5.) we can see the usual values of the SAUR for different values of the COD/N ratio.

Thus, in addition to the temperature, when comparing the SAUR with the reference values, it can be confirmed whether the nitrification rate per unit of volatile solids is normal (equal to or higher than the reference) or, on the contrary, is low (significantly lower than the reference)

Figure 5. Graph of SAUR for reference values



Julian Carrera - 2004

- Low performance due to oxygen deficiency

For the DO criterion, the AUR formula will be used in terms of the influence of the DO on the F_{DO} factor. Since an excessively small value of the DO - due to an oxygen deficiency - will cause a reduction in the nitrification rate (Figure 4.)

- Low performance due to excessive COD/N ratio

To analyse the possibility of a low concentration of nitrifying biomass, the criterion of the COD/N ratio > 5 is normally used as a limit value. Thus, a value above this level would prevent the growth of the nitrifying biomass; and, as a result, the concentration of nitrifying biomass will be excessively low (see Figure. 6)

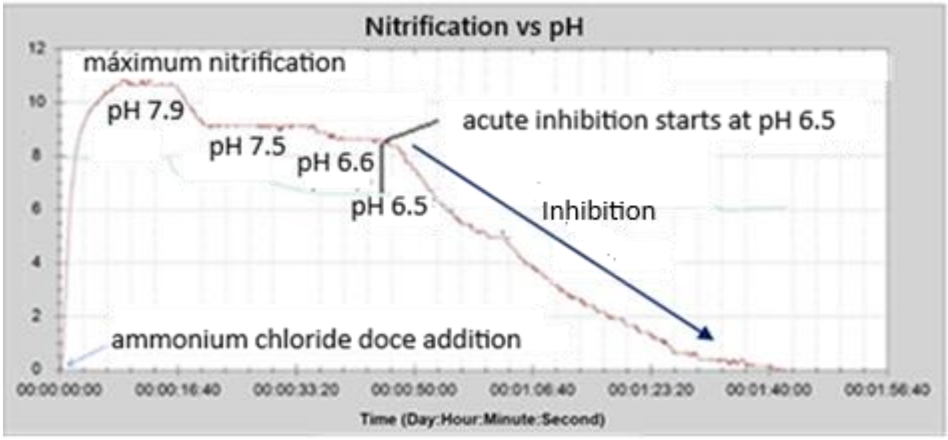
- Low performance due to excessively low pH

pH is a fundamental parameter in the nitrification process, so the reduction of pH with respect to the values of a normal working range (usually between 7 and 8.5) will automatically cause the nitrification rate to decrease, and may even lead to an inhibition of the process.

To detect the influence of pH on the nitrification respiration rate (RsN), an R assay can be carried out with endogenous sludge to which a dose of ammonium chloride with an equivalent ammonia nitrogen concentration is added.

Using the BM software (BM-Advance model), the pH value can be automatically varied and different Rs values obtained due to nitrification. In this way, the different degrees of inhibition caused by the drop in pH can be identified until the limit value from which acute inhibition occurs is detected (Figure 7.)

Figure 6. Example of Rs respirogram due to nitrification at different pH values



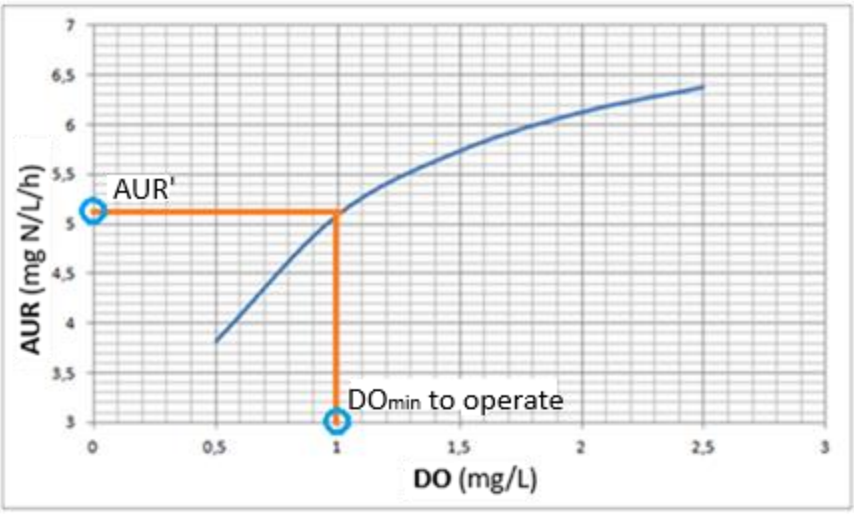
3.4. Energy optimization operating with minimal oxygen in nitrification

The nitrification performance is directly proportional to the nitrification rate value. Therefore, the current performance will be directly proportional to the current AUR.
With this, the desired performance will be proportional to a certain nitrification rate (AUR’) that will directly depend on the OD value (preserving the TRC)

$$\mathrm{AUR}' = \frac{\text{Actual AUR} * \text{ Desired performance}}{\text{Actual performance}} \qquad (4)$$

From the AUR formula, for a serial DO values we get different AUR values until we reach the AUR’.
In this way, the minimum oxygen required is determined and the aeration can be controlled to operate at the minimum level required by the process (Figure 7.)

Figure 7. Graph AUR vs OD to determine the mínimum DO (DO_{min}) for a desired nitrification performance



Similarly, in the BM respirometer reactor, the concentration of SSVLM can be varied and the optimal value for the corresponding sludge age (SRT) couild also be found (see Applications manual for BM Respirometry) Respirometría BM)

3.5. Denitrification rate – Possible causes of poor denitrification performance

3.5.1. Denitrification rate

In the anoxic denitrification process, the removal of nitrate is proportional to the removal of COD from organic matter as a source of organic carbon. Therefore, in practical terms, it is also proportional to the respiration rate (OURDN) of the heterotrophic biomass of the mixed-liquor at the beginning of the anoxic process (*)

(*) Having previously inhibited oxygen demand by nitrification (usually with a dose of Alil-Thiourea)

$$\mathrm{OUR_{DN}} = \mathrm{OUR} - \mathrm{OUR_{end}} \qquad (5)$$

Where:
$\mathrm{OUR_D}$: OUR corresponding to the heterotrophic biomass of the denitrification process (mg O_2/L/h)
OUR: Total OUR (mg O_2/L/h)
$\mathrm{OUR_{end}}$: OUR of the sludge in phase of endogenous respiration (mg O_2/L/h)

Once the OURD has been obtained, the corresponding denitrification rate can be calculated:

$$\mathrm{NUR} = \frac{\mathrm{OUR_{DN}}}{2.86} * \frac{0.2}{0.2 + \mathrm{DO_{DN}}} \qquad (6)$$

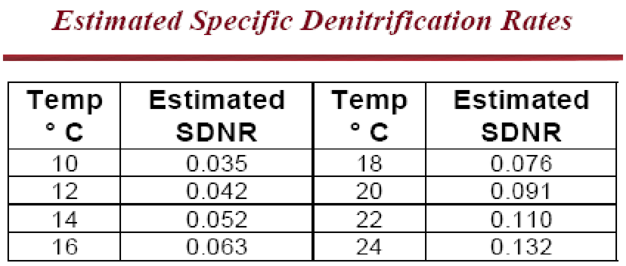
Source: Basado en los principios de E.CHOI and R.DAEHWAN. 2000. Korea University - W.W. Eckenfekder & J.L. Musterman – 1995

Where:
NUR: Denitrification rate (mg N-NO_3/L./h)
0.2: Coefficient for DO presence in the anoxic denitrification process (mg/L)
$\mathrm{DO_{DN}}$: Dissolved oxygen in the anoxic process of denitrification. (mg/L)

3.5.2. Causes of poor denitrification performance

To evaluate the value of the specific denitrification rate we can use a reference table (Table 4.) as a guide:

Table 4. Reference table for SAUR values



Estimated Specific Denitrification Rates

Temp ° C	Estimated SDNR	Temp ° C	Estimated SDNR
10	0.035	18	0.076
12	0.042	20	0.091
14	0.052	22	0.110
16	0.063	24	0.132

SDNR = SAUR

Long Island Sound Training – Nitrogen Removal - 2003 (EPA)

In addition to possible global toxicity or low temperature, the most likely causes of poor denitrification performance may include the following:

- Partial denitrification due to short hydraulic retention time

The hydraulic retention time required for nitrate removal (TRH_{DN}) is calculated as follows:

$$\mathrm{HRT_{DN}} = \frac{\mathrm{S_{NO3}}}{\mathrm{NUR}} \qquad (7)$$

Where:
HRT_{DN}: Hydraulic retention time necessary for a complete denitrification (h)
S_{NO3}: Nitrate to denitrify (mg $N\text{-}NO_3$/L)

With this, poor performance can come as a consequence of the current hydraulic retention time of the anoxic zone being lower than the HRT_{DN}.

- Presence of high dissolved oxygen in the anoxic denitrification process

The presence of dissolved oxygen greater than 0.2 (mg/L) in the denitrification anoxic zone reduces the denitrification rate due to the factor $0.2 / (0.2 + OD_{DN})$ that is applied to the NUR formula.
This increases the required hydraulic retention time of the denitrification process, which opens up the possibility of partial denitrification.

- Lack of biodegradable COD

The ratio of the consumed oxygen from the biodegradable COD (CO_{DN}) to the nitrate removed is 2.86:

$$\mathrm{CO_{DN}} = \mathrm{S_{NO3}} * 2{,}86 \qquad (8)$$

Spanjers, Peter A. Vanrolleghem – 2004

The readilu biodegradable COD necessary for denitrification is calculated as follows:

$$\mathrm{rbCOD_{DN}} = \frac{\mathrm{CO_{DN}}}{1 - \mathrm{Y_{HD}}} \qquad (7)$$

Müller et al., 2003

Where:
$rbCODb_{DN}$: Readily biodegradable COD necessary for the denitrification (mg/L)
Y_{HD}: Yield coefficient for biomass production during denitrification ≈ 0.55 (O_2/COD)

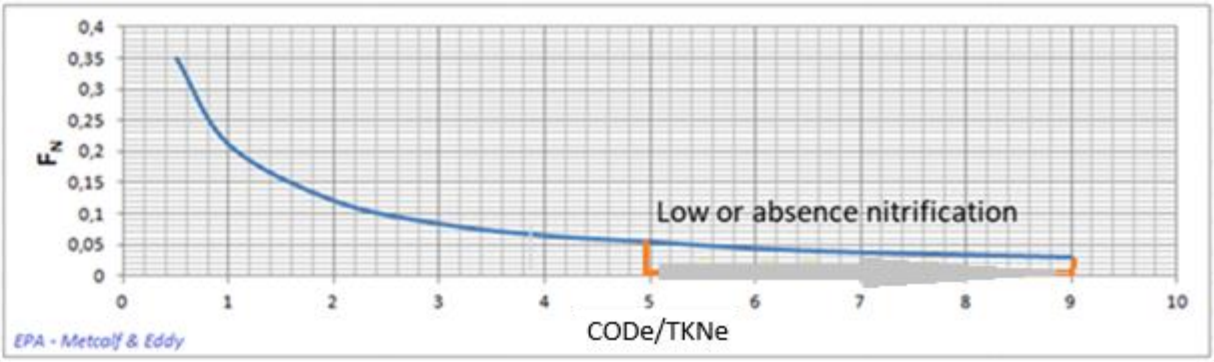
With this, an R test will be carried out with a sample of wastewater from the entrance to the anoxic process for the automatic determination of the rbCOD and then, the calculated value will be compared with the the current rbCOD.

Logically. the condition must be that the current rbCOD must be equal to or greater than the $rbDQO_{DN}$.
And in the event that current COD is below the calculated rbCOD, it will be confirmed that the process needs additional readily biodegradable COD (usually methanol)

3.6. Determination of the sludge age within the framework of energy optimisation

The first step will be the estimation of the nitrifying biomass value, which can be carried out from a graph based on the COD/NTK ratio (Figure 8.)

Figure 8. Graph of the CODe / TKNe vs portion of nitrifier biomass



Metcalf & Eddy – EPA 2006

Where:
CODe: COD eliminated for a determined performance (mg/L)
TKNe: TKN eliminated for a determined performance (mg N/L)

The nitrifier biomass concentration is calculated as follows:

$$X_A = F_N * \text{MLVSS} \qquad (10)$$

Where:
X_A: Autotrophic biomass concentration (mg/L)
F_N: Portion of nitrifier biomass in the total MLVSS.
MLVSS: Mixed liquor volatile suspended solids (mg/L)

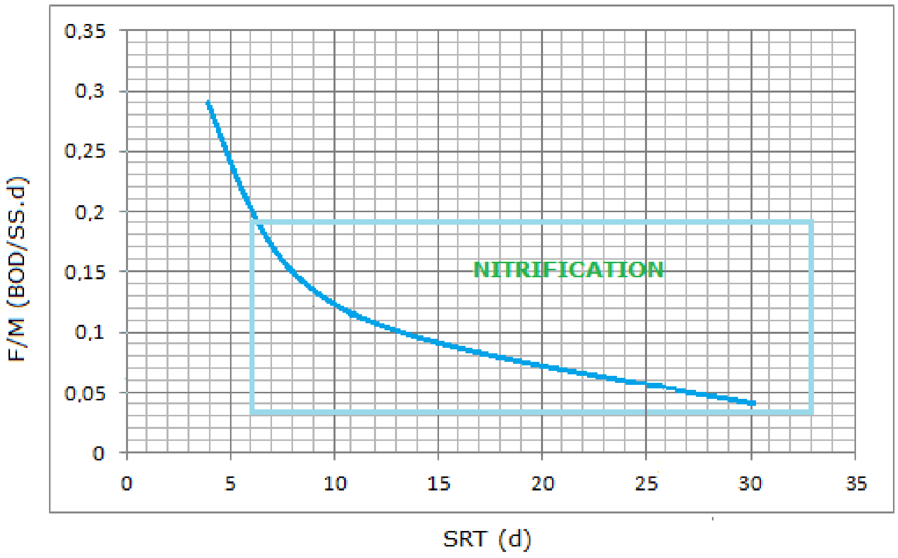
Once the X_A value is known, the value of the optimal sludge age can be calculated from the value of the AUR obtained from the minimum oxygen for a given nitrification process performance (see point 3.4.)

$$\text{SRT} = \frac{X_A}{24 * \text{AUR}'} \qquad (11)$$

Where:
SRT: Minimum sludge age for a given nitrification process performance (d)
AUR': AUR corresponding to the minimum oxygen (see point 3.4.) and calculated from a given desired AUR (mg N/L(h)

Once the age of the sludge has been calculated, we can go to the corresponding loading rate (F/M) (Figure 9.):

Figure 9. Graph F/M vs TRC



E. Ronzano & J.L. Dape

3.7. Actual Oxygen Requirement (AOR) for current sludge age and dissolved oxygen.

The steps to follow:

1. Actual oxygen requirement due to the removal of organic matter

$$\mathrm{AOR_C} = \mathrm{V} * \frac{24 * \mathrm{OUR_C}}{1000} \qquad (12)$$

Where:
AOR_C: Oxygen requirement due to the removal of organic matter (kg O_2/d)
OUR_C: Respiration rate of the heterotrophic biomass in the sludge of the process starts (mg O_2/L/h) (*)
V: Aerobic biological reactor volume (m^3)

(*) OUR_C is automatically determined with the active sludge from the beginning of the process after it has inhibited the possible nitrification (usually with a dose of allylthiourea ATU: 2 to 3 mg ATU/g VSS)

1. Actual oxygen requirement for nitrification

$$\mathrm{AOR_N} = \mathrm{V_N} * \frac{24 * \mathrm{Rs_N}}{1000} * \frac{\mathrm{DO}}{0.5 + \mathrm{DO}} \qquad (13)$$

Where:
AOR_N: Actual oxygen requirement for nitrification (kg O_2/d)
Rs_{NC}: Actaul exogenous respiration rate due to nitrification (mg O2/L) – See point 3.3.1. -
DO: Dossilved Oxygen for a given nitrification performance (mg/L) – See point 3.4. -
V_N: Reactor volume of biological reactor for nitrification (m^3)

2. Actual oxygen requirement for denitrification

$$\mathrm{AOR_{DN}} = \mathrm{Q} * \frac{2.28 * \mathrm{S_{NO3}}}{1000} \qquad (14)$$

Where:
AOR_{DN}: Actual oxygen requirement for denitrification (kg O_2/d)
2,28: mg O_2 needed per each mg of nitrate to denitrify.
Q: Flos in the denitrification zone (m^3/d)
S_{NO3}: Nitrate to denitrify (mg N-NO_3/L)

3. Overall actual oxygen requirement

In the calculation of the overall oxygen requirement, the AOR_{DN} acts as an oxygen credit and therefore enters with the minus sign.

$$\mathrm{AOR} = \mathrm{AOR_C} + \mathrm{AOR_N} - \mathrm{AOR_{DN}} \qquad (15)$$

Where:
AOR: Actual oxygen requirement (kg O_2/d)

3.8. Evaluation of the diffused aeration system

The following parameters must be taken into account for this evaluation:

- SOTE: Standard oxygen transfer efficiency (%)

It is a parameter that can normally be provided by the manufacturer.
But if this is not the case, the following calculation shall be applied: 6.5 % for fine bubble diffusers and 2.46 % for coarse bubble diffusers for each metre of depth in the aeration tank.

Source: Harlan H. Bengtson-2017

- SOR: Standard oxygen requirement (kg O_2/d)

(Standard conditions: 1 atmosphere, 20 ºC, O mg/L of DO)

$$\mathrm{SOR} = \mathrm{Q_{O2}} * \mathrm{SOTE} \qquad (16)$$

Where:
Q_{O2}: Average daily oxygen flow rate proportioned to the process (kg O_2/d)
$Q_{O2} = 0.285 * Q_{air}$
Q_{air}: Average daily air flow rate provided by the aeration system to the biological reactor (m^3/d)

- AOR/SOR ratio

The ratio AOR/SOR is one of the fundamental parameters in the evaluation of diffuser aeration systems. For its valuation, the reference AOR/SOR value will be taken into account:

AOR/SOR_{ref} for fine bubble diffusers: 0,3 to 0,4 (Typical value = 0,33)
AOR/SOR_{ref} for course buble diffusers: 0,4 to 0,6 (Typical value = 0,5)

Source : "Sanitaire - Diffused aeration design guide", University of Idaho, Civil Engineering, 2003

- Evaluation of the aeration system by means the fouling factor: F

$$F = \frac{AOR/SOR}{AOR/SOR_{ref}} \qquad (17)$$

The normal range of the F factor is between 0.7 and 0.9.
Therefore, values lower than 0.7 would indicate wear or lack of maintenance of the diffusers.

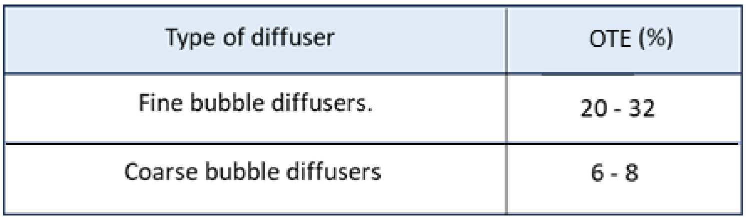
The F factor, especially in fine-pore diffusers, decreases over time due to aging, scale, inorganic scale, or changes due to wastewater quality, sludge characteristics, and operating conditions.

- Follow-up of aeration performance by means of in-process oxygen transfer efficiency: OTE (%)

$$OTE = \frac{100 * AOR}{Q_{O2}} \qquad (18)$$

The determination of OTE allows operators to assess the long-term operating costs of their aeration systems; and to ensure that sufficient capacity is available to meet influent load demand. It is therefore a parameter that can be considered essential for the evaluation and monitoring of aeration systems.

Table 5. Typical OTE ratings for diffused aeration systems.



Type of diffuser	OTE (%)
Fine bubble diffusers.	20 - 32
Coarse bubble diffusers	6 - 8

Wiessman W, & Hammer, 1996

3.8.1. Water Factors Impacting Oxygen Transfer Efficiency

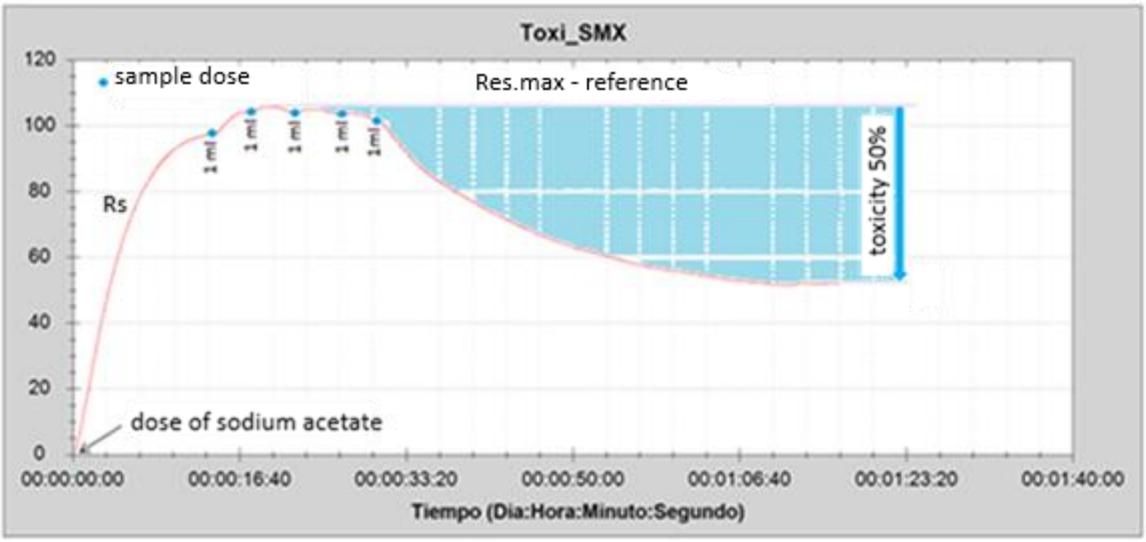
- Temperature – Oxygen is more soluble at lower temperatures
- Air pressure (barometer)
- Water pollutants – BOD/COD especially surfactants impact oxygen transfer efficiency
- MLVSS – higher volatile solids have endogenous respiration but also can impact oxygen transfer to microorganisms.
- The aeration system itself impacts OTE

3.9. Toxicity

- Toxicity analysis by the cumulative sample dose procedure

The objective of the procedure is to analyse a toxic effect that could be produced in the activated sludge by the progressive addition of wastewater sample doses on a healthy activated sludge under the effects of a maximum respiration rate caused by the addition of a reference substrate (sodium acetate, ammonium chloride, or both (Figure 10.)

Figure 10. Rs respirogram by progressive addition of sample doses for toxicity analysis



$$\text{Toxicity (\%)} = \frac{100 * (\text{Rs}_{\text{max}} - \text{Rs})}{\text{Rs}} \qquad (19)$$

In this way, the sample/sludge volume (AS/S) ratio that is needed to initiate toxicity in the activated sludge can also be calculated.

With this, using 1 litter of active sludge, the cumulative sample ratio up to the onset of toxicity/sludge at maximum respiration would be as follows:

$$\text{AS/S} = \frac{\sum \text{ml accumulated sample}}{1000 \text{ ml sludge}} \qquad (20)$$

- There are other procedures for toxicity analysis (see Application Guide Manual of Surcis) -

4. Conclussion

This article has presented a number of applications of BM Respirometry that can be essential in any activated sludge process with nitrogen removal.
However, this does not mean at all that the number of applications is limited, since BM Respirometry is an open programmable system where, in addition to the calculations and applications that are exposed here and in the Surcis Application Manual, the user himself can make other specific applications to his needs (with the technical support of Surcis)

Video of interest: https://youtu.be/UeMvk7U5ZMo

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