A new overview of the different oxygen uptake rate variants in activated sludge processes with nitrogen removal

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The oxygen uptake rate, also known as the "respiration rate," can be an important tool in the evaluation and control of biological wastewater treatment using activated sludge. In the literature, we can find a large number of articles related to this parameter, which is the main basis of the technology known as “respirometry”.

The respirometry, which was born many years ago, has evolved, and we can currently find a series of variants of oxygen consumption demand that allow us to significantly expand the number of applications by generating key parameters for the control, protection, design, and research of activated sludge biological treatment systems in each of their components, whether for organic matter, nitrification, endogenous respiration, and denitrification.

Another aspect of these variants is that they allow for an oxygen uptake rate that is representative of an aerobic process as a whole. This solves the inconvenient of a trying to get a representative oxygen uptake rate of the entire complex activated sludge process by just a punctual oxygen uptake rater from a mixed liquor from a determined point of the biological reactor (see section 2.10.)

1. Introduction

The oxygen uptake rate is the oxygen (mg O_2/L) consumed by microorganisms per unit of time (h). Thus, the usual units for this parameter become mg/L/hour.

Generally speaking, the classic measurement of the oxygen consumption rate is based on calculating the gradient of oxygen consumption by microorganisms in the sludge with respect to time.

The technology related to the oxygen consumption rate is the respirometry, and devices based on this technology are called respirometers.

In this article, the tests and procedures described are performed using a BM respirometry system from Surcis company, which is equipped with powerful software that allows the automatic calculation of the essential parameters derived from the respiration rate.

Figure 1. BM Respirometry System from Surcis

1. Automatic pH control
2. pH sensor
3. Dissolved oxygen sensor
4. Stirring motor
5. Homogenization peristaltic pump
6. Double chamber Reactor
7. Automatic tempering system
8. Leds for devices control
9. Oxygen & temperature controller
10. Automatic pH controller system
11. PC + BM software

There are several models of BM respirometry systems (see www.surcis.com) and in this article we selected the BM-Advance model (Figure 1), which offers reliable and accurate results when the following conditions are met:

- Uniform stirring.
- Automatic pH control system that allows setting a value equivalent to the actual process pH and maintaining it constant throughout the test (BM Advance models)
- Programmable temperature that remains constant throughout the test.
- Isolation of the measuring chamber from the atmosphere to prevent oxygen absorption from the air due to the centrifugal effect of agitation.
- Slope detection, with sufficient stability to validate the measurement.
- Possibility of measuring an oxygen uptake rate based on a given dissolved oxygen value.
- Graphical representation of simultaneous parameters (respirograms)

The oxygen consumption rate, in general, is a measure of the speed at which microorganisms in a given activated sludge consume oxygen to eliminate a given degradable substrate.

The types of oxygen uptake rates we will present here are as follows:

1. OUR: Punctual oxygen uptake rate.
2. SOUR: Specific oxygen uptake rate related to the concentration of MLVSS.
3. FED and UNFED OUR: Oxygen uptake rate from the start and end of the activated sludge process.
3. OUR_{end}: Oxygen uptake rate by endogenous respiration.
4. OUR_{ex}: Oxygen uptake rate by exogenous respiration.
5. Rs: Dynamic exogenous oxygen uptake rate.
6. Rs_N: Dynamic exogenous oxygen uptake rate by nitrification.
7. Rs_f: Overall exogenous uptake rate of the organic substrate.
8. OUR_f: Overall oxygen uptake rate.

The main difference between the group of oxygen uptake rates that are not exogenous and the oxygen uptake rates that are exogenous is that the exogenous ones refer to oxygen consumption of a certain substrate (organic matter, ammonium nitrogen...) where the endogenous uptake rate is excluded which refers exclusively to the respiration of active biomass (microorganisms).

2.1. Punctual oxygen uptake rate: OUR

It generally refers to a measure of the oxygen uptake rate of a mixed liquor collected from a specific point in the biological reactor.

This OUR is only representative of the point from which the mixed liquor originates and cannot be representative of the entire process.

The OUR test in a BM laboratory respirometer (Figure 1) consists of aerating a mixed liquor collected from a specific point in the biological reactor that is constantly stirred, increasing the oxygen to a starting value (usually above 3 mg/L), then stopping the aeration and fully automatically calculating the maximum stable gradient at which the oxygen is declining as a result of the microorganisms' oxygen consumption as they remove the substrate (Figure 2)

$$\mathrm{OUR} = \frac{\mathrm{Cb} - \mathrm{Cs}}{\mathrm{t}} \qquad [1]$$

Where:
OUR: Oxygen uptake rate - Respiration rate - (mg O_2/L/h)
Cb: Oxygen at the beginning of the measuring period (mg O_2/L)
Cs: Oxygen at the end of the measuring period - DO in respirogram - (mg O_2/L)
t: Time between measurements Cb and Cs (h)

The OUR is composed of the following partial OUR:

$$\mathrm{OUR} = \mathrm{OUR_{end}} + \mathrm{OUR_{ex}} \qquad [2]$$

Where:
OUR_{end}: Oxygen uptake rate from endogenous respiration.
OUR_{ex}: Oxygen uptake rate from exogenous respiration.

Main applications of the punctual OUR

- Oxygen uptake rate at a particular point in the biological reactor,
- Historical monitoring of sludge activity from a single point in the process.
- Detection of symptoms of possible toxicity.
- Detection of possible overload.

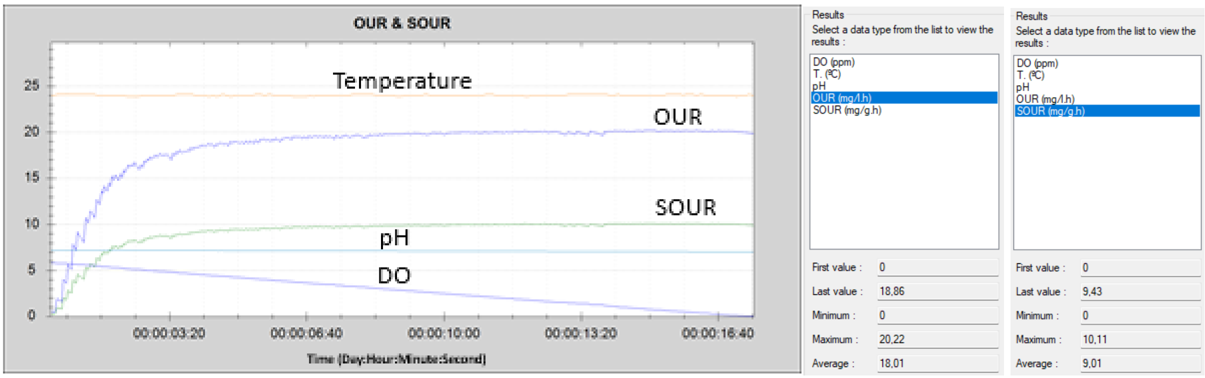
2.2. Specific oxygen uptake rate: SOUR

When the OUR is related to mixed liquor volatile suspended solids it becomes the parameter SOUR (Figure 2):

$$\mathrm{SOUR} = \frac{\mathrm{OUR}}{\mathrm{MLVSS}} \qquad [3]$$

Where:
SOUR: Specific oxygen uptake rate (mg O_2/L/g VSS).
MLVSS: Mixed liquor volatile suspended solids concentration (mg/L)

Figure 2. OUR respirometry test with a BM respirometer for the simultaneous respirograms of OUR, SOUR, DO, Temperature and pH



Respirograms Results

In a BM respirometer, by entering the value of the SSVLM, the software calculates simultaneously and automatically the value of the SOUR together with the values of the test conditions (figure 2)

Main applications of SOUR

- Loading rate evaluation.
- Bioactivity loss detection for the same MLVSS concentration.

2.3. FED and UNFED OUR

FED OUR: It is the OUR of representative mixed liquor collected from the beginning of the process of active sludge (mg/L/h)

UNFED OUR: It is the OUR of the representative mixed liquor collected from the end of the process of active sludge (mg/L/h)

The relationship between the FED OUR and the UNFED OUR is called load factor (FC)

Main applications of the FED & UNFED OUR

Take the pulse at current state of the biological purification process by means of a table in which the load factor is compared with a guide table with a range of normalized values.
The following situations can be detected early on in this comparison:

- Toxicity
- Overall performance
- Overload
- Low load

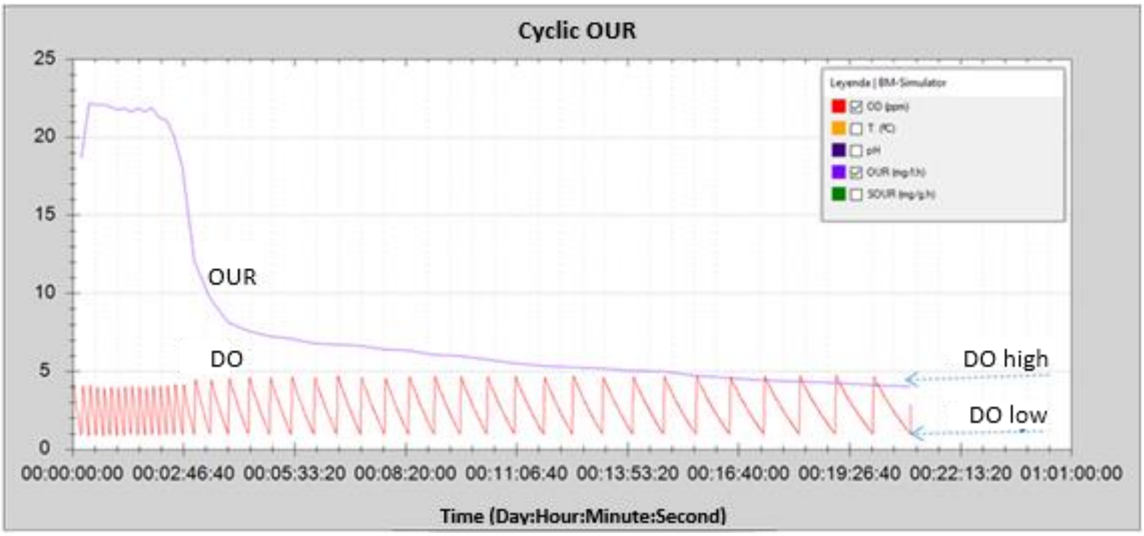
2.4. Cyclic OUR

This is a BM respirometry working mode where OUR and SOUR measurements are performed sequentially within a dissolved oxygen working threshold between two programmable set points (high DO and low DO)

In a cyclic OUR test, it is possible to clearly see how the respiration rate decreases as the degradable substrate is progressively consumed and how the process evolves over time.

The cyclic OUR also allows respirometry tests to be performed with dissolved oxygen values equivalent to those of the actual process.

Figure 3. Respirometry test with a BM respirometer for a cyclic OUR with simultaneous respirograms of dissolved oxygen and OUR.



<u>Main applications of the Cyclic OUR</u>

• Estimation of the HRT required for a given performance.
• Analysis of the evolution of the purification process at different dissolved oxygen (DO) levels

2.5. Oxygen uptake rate by endogenous respiration: OUR_{end}

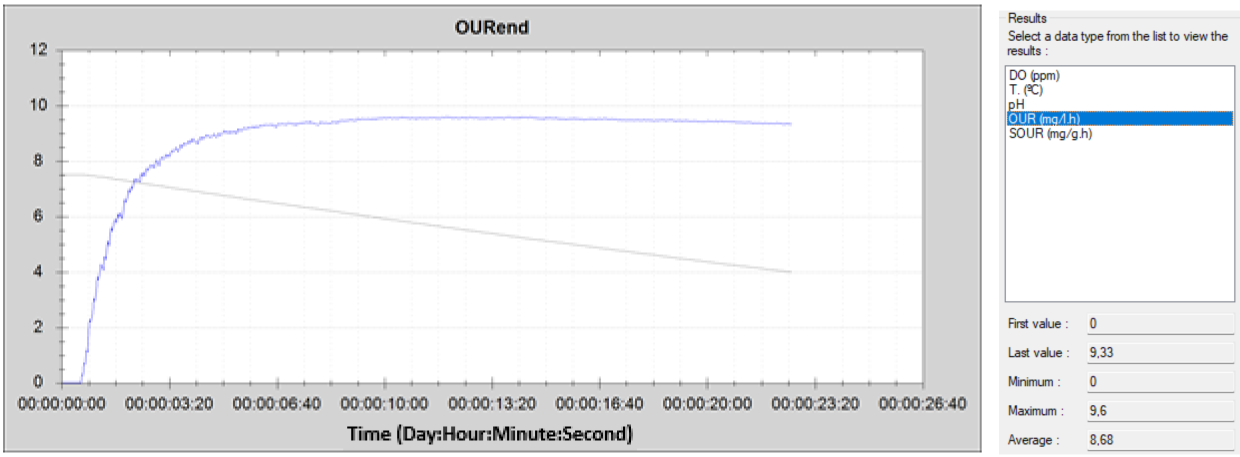
The oxygen uptake rate by endogenous respiration refers to the value obtained in an OUR test with effluent activated sludge on endogenous respiration phase (in the absence of degradable substrate). This is achieved after the sludge has undergone prolonged aeration to eliminate all traces of degradable substrate.

Endogenous respiration in a BM respirometer is recognized when the oxygen value remains sufficiently stable for a representative period of time, with the sludge aerating to saturation in the respirometer reactor.

Endogenous OUR values normally fall within a certain range that depends on the concentration of MLVSS Therefore, the state of the activated sludge can be assessed by comparing the result obtained with a reference table (Table 3)

For calculation purposes, since it depends exclusively on the concentration of microorganisms in the sludge, it is assumed that the OUR_{end} is the same at any point in the aeration tank.

Figura 3. Endogenous OUR test



In addition to serving as a starting point for exogenous respiration assays, the main application of OURend is to assess the concentration of active biomass.

2.6. Oxygen uptake rate by exogenous respiration: OUR_{ex}

Once the results of the total OUR and the endogenous OUR have been obtained, the exogenous OUR referring exclusively to the elimination of the substrate is obtained by the difference between both:

$$OUR_{ex} = OUR - OUR_{end} \qquad [4]$$

The OUR_{ex} is related to the dynamic exogenous oxygen consumption rate (Rs), which is the parameter on which most of the most important applications of Respirometry lie.

2.7. Dynamic exogenous oxygen uptake rate: Rs

Unlike the punctual oxygen uptake rates explained above, BM respirometry systems provide this parameter through an R-mode test performed with endogenously respiring sludge. The oxygen level of the sludge under endogenous state (Cb) acts as a baseline, to which a substrate sample is added to generate a chain of Rs values over time as the degradable substrate is eliminated.

As the rest of the other respirometry tests in a BM respirometer, its can be performed under equivalent conditions of the actual activated sludge process regarding temperature and pH (in BM Advance models)

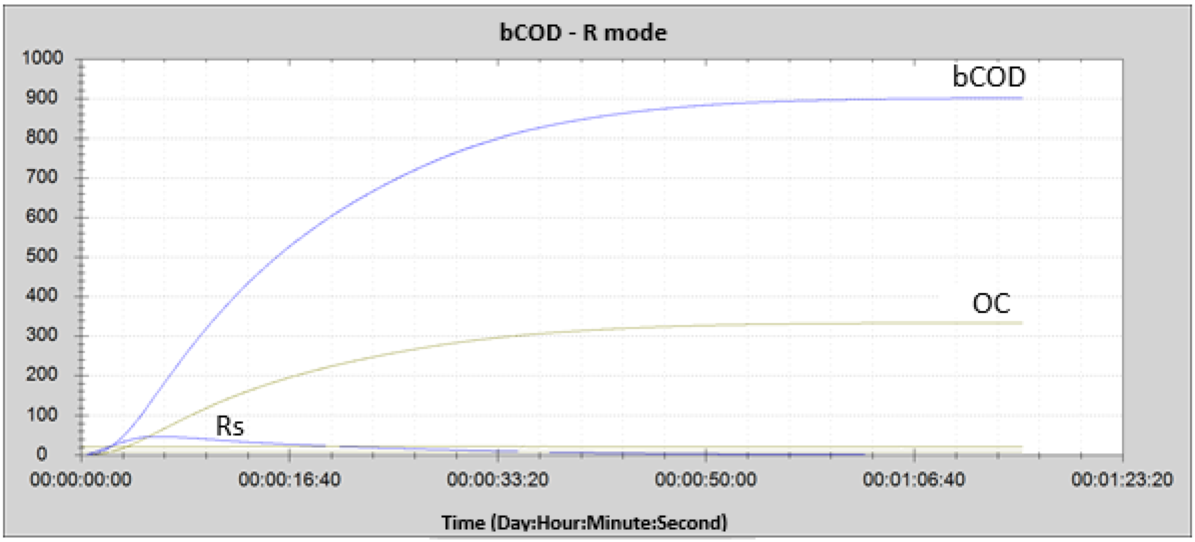
From the progressive series of Rs values, the software automatically and simultaneously calculates several essential parameters in an activated sludge process:

Rs: Dynamic exogenous oxygen uptake rate (mg O_2/L/h)
Rsp: Specific dynamic exogenic respiration rate (mg O_2/L/gVSS)
CO: Oxygen consumed (mg/l)

bCOD: Biodegradable COD (mg/L)
rbCOD: Readily biodegradable COD (mg/L)
U: COD utilization rate (mg COD/L/h)
q: Specific COD utilization rate (mg COD/mg SSV/d)

These parameters give way to a wide range of applications that can be seen in the column "Articles - Presentations, Manual of Applications-Case Studies" in the Surcis website.

Figura 3. Simultaneous respirogram on R test performance in a BM respirometer



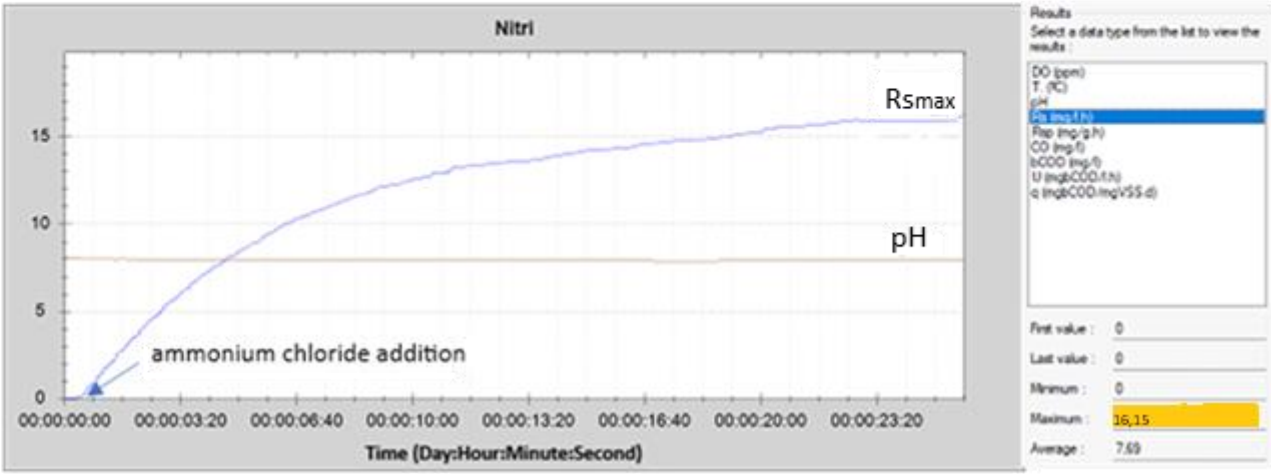
Main applications of Rs

- Yield coefficient calculation.
- COD fractionation.
- Non-biodegradable COD determination.
- Total Consumed oxygen (CO)
- Toxicity.
- Operational parameters.
- Biokinetic parameters.
- Nutrients ratio.
- Organics actual oxygen requirement.
- Others.

2.8. Oxygen uptake rate by nitrification: Rs_N

To determine this oxygen uptake rate by nitrification, a dynamic test is used using endogenously respiring sludge to which an equivalent dose of ammonium chloride is added. The test is run until the maximum respiration rate is automatically achieved.

Figurea 4. R test for Rs_{max} in nitrification



By adding ammonium chloride to the endogenous sludge as the only substrate, the respirometry test acquires the ability to calculate oxygen demand without interference from any oxygen demand per organic substrate. To do this, the maximum dynamic exogenous respiration rate is selected.

Due to the great influence that dissolved oxygen exerts on nitrification, a correction factor for this concept must be applied to the maximum respiration rate.

$$Rs_N = Rs_{max} * F_N \qquad [5]$$

Where:
Rs_N: Oxygen uptake rate by nitrifying nitrogen removal (mg O_2/L/h)
Rs_{max}: Maximum exogenous respiration rate (mg O_2/L/h)
F_N: Dissolved oxygen correction factor = DO / (K_{OA} + OD)
K_{OA} = 0.5 by default. Source: ASM3, Henze *et al.* (2000)

Main applications of the RsN

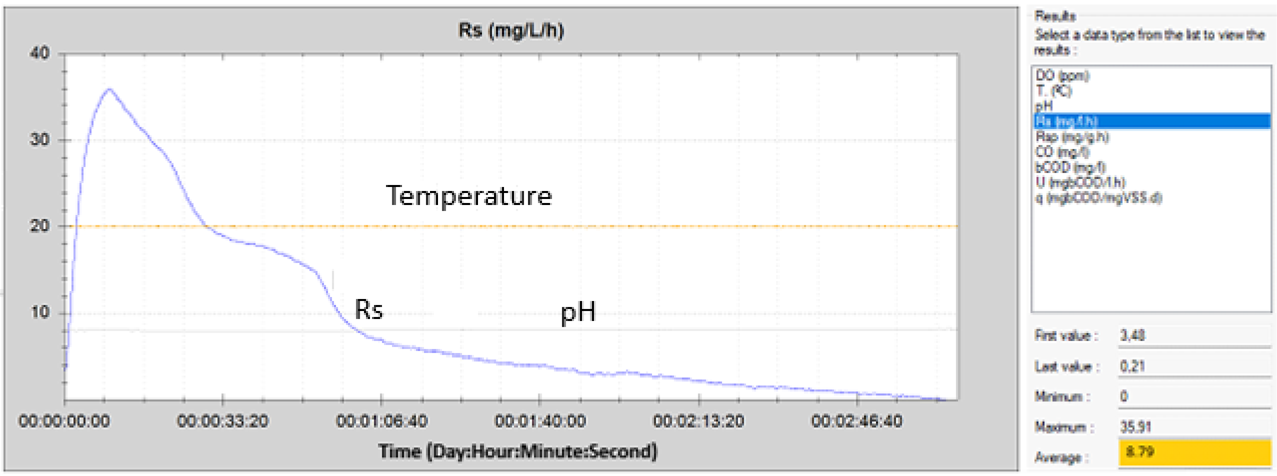
- Detection of nitrifying activity.
- Calculation of the nitrification rate (AUR).
- Detection of specific toxicity to autotrophic biomass for nitrification.
- Calculation of the actual oxygen requirement for nitrification (AOR_N).

2.9. Exogenous oxygen uptake rate for carbonaceous organic matter removal: Rs_f

This parameter is obtained from the exogenous dynamic respiration rate coming from the organic matter removal in the activated sludge (Rs)
The BM respirometer obtains Rs automatically by mean a R test type.
For this it is required a volume of activated sludge in its endogenous respiration phase, a dose of aliltiourea (ATU) to inhibit nitrifying activity and a sample of inlet wastewater.

The representative Rs coincides with the mean value (Rs_m), which is automatically obtained by the BM software, avoiding the dilution factor (fd = 1), which divides the consumed oxygen (CO) in the organic matter sample removal by the time invested in this consumption.

Figura 4. Ensayo de respirometría con un respirómetro BM del parámetro Rs



With this, once the Rs_m is obtained, the Rs_f is then calculated with the following equation:

$$Rs_f = Rs_m * F_S \qquad [7]$$

Where:

Rs_f: Overall oxygen uptake rate for total organic substrate removal (mg/L/h)

F_S: Correction factor for the effect of the actual dissolved oxygen = OD / (K_{OD} + OD)

OD coefficient: K_{OD} = 0.2 when average DO < 2 mg/, and K_{OD} = 0 when average OD es > 2 m

2.10. Global oxygen uptake rate of the entire activated sludge process: OUR_f

When the process operates with dissolved oxygen limitations and a relatively high rbCOD/N ratio, the simultaneous organic matter and nitrogen removal cycles become unbalanced, so that a single specific oxygen consumption rate can only be representative of the mixed liquor at a specific point in the biological reactor, but cannot represent the entire aerobic activated sludge process.

However, the variants here explained that generate the oxygen uptake rate for the different process cycles give rise to a simple procedure that allows an overall oxygen consumption rate to be obtained.

This global oxygen uptake rate, which we have named OUR_f, can be considered as a respiration rate representative of the aerobic biological treatment in its integral concept; that is, including the current rate of oxygen per organic matter (Rs_f), the current rate of oxygen by nitrification (Rs_N) and the oxygen uptake rate of oxygen by endogenous respiration (OUR_{end}). And its calculation will logically be the sum of each of them (equation 8)

$$OUR_f = Rs_f + Rs_N + OUR_{end} \qquad [8]$$

Main applications of the OUR_f

- Calculation of the actual oxygen requirement (AOR)
- Evaluation of the aeration system by AOR/SOR vs reference values.
- Evaluation of the current state of the diffusers by the fouling factor (F)
- Field oxygen transfer efficiency (OTE_f)

3. Conclusion

This paper describes a series of oxygen uptake rate variants within three groups: total uptake rate, endogenous uptake rate and exogenous uptake rate.

These variants translate into parameters that open the door to important applications for the evaluation and control of activated sludge processes. Many of these parameters are automatically obtained using a Surcis BM respirometer.

This demonstrates that a punctual OUR cannot normally be used as a basis for calculating parameters representing a global process, but the calculation of a global OUR (OUR_f) can be.

The punctual OUR, however, has important applications, such as the current state of process operation when sludge is collected at the beginning and end of the biological reactor to calculate the loading factor (LF).

On the other hand, regardless of the point from which the sludge is collected, we also have the endogenous OUR (OURend) as a representative of the oxygen uptake rate in the absence of substrate. This endogenous OUR gives rise to the important application related to assessing the current state of biomass and calculating the concentration of active biomass and early detection of possible toxic that is progressively reducing the concentration of the active biomass.

Regarding the global OUR, a procedure is described based on the sum of the dynamic exogenous respiration rate by organic matter (Rs_f), the endogenous respiration rate (OUR_{end}), and the nitrification respiration rate (Rs_N) – parameters that are obtained thanks to the software incorporated in the BM respirometry system -.

With the global OUR, the important application of calculating the current oxygen requirement (AOR) can be introduced, which is the fundamental basis for evaluating the current state of the aeration system (AOR/SOR), the state of the diffusers (F), and the oxygen transfer efficiency (OTEf).

All these applications are described in detail in the "Articles - Presentations - Applications Manual - Case Studies" column on the Surcis website: www.surcis.com

In addition, BM Respirometry is based on an open, programmable system and is therefore capable of generating an unlimited number of applications. Therefore, the applications listed are only a small part of a wide range of applications that BM respirometry can offer.

Logically, the entire form presented in this article can be incorporated into a spreadsheet (Excel-type)

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"To teach is to learn twice"