Using respirometry for energy optimization in a nitrifying biological wastewater treatment system

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ABSTRACT

Many wastewater treatment plants use more than 50% of their total energy budget in the aeration basin and, when nutrient removal is included in the activated sludge process, it is very common that the majority of oxygen uptake goes to the nitrification process. For that reason, in most wastewater treatment plants, energy optimization is focused on nitrification management. This information can be obtained in different ways, but perhaps the most direct way is based on the correct control of the minimum dissolved oxygen (DO_{min}) and sludge retention time (SRT) without impairment of process efficiency.

The present paper describes a relatively simple, fast procedure whereby the use of an advanced and high sensitivity respirometry system, both parameters are obtained throughout a novel method to accurately determine values of the half-saturation DO constant (K_{OA}) and active nitrifier concentration (X_A) from the results of a single respirometry test.

The procedure and methods here described do not aim to be a scientific document. On the contrary, one of its aims is to be accessible to any plant operator with access to a respirometer provided with necessary features to quickly obtain information about critical parameters on which the nitrification process can be calibrated so that it can be developed in the framework of its best energy optimization.

Keywords: respirometry, activated sludge process, dissolved oxygen, oxygen uptake rate, nitrfiers, nitrification, nitrification rate, nitrification capacity, half-saturation coefficient, minimum oxygen, sludge residence time, sludge age, energy optimization, respirometer, heterotrophic biomass, autotrophic biomass.

1. INTRODUCTION

The influence of dissolved oxygen (DO) on nitrification is well known. Nitrification increases with the DO concentration until reaching a limiting-DO (between 3 and 4 mg/L) where the maximum nitrification rate is achieved (Figure 1).

It is understood that nitrification can take place within different DO ranges; but the approach of many plant operators is to select the minimum DO range and operate within a sludge retention time (SRT) to get the maximum energy optimization in the aeration tank corresponding to the process temperature, pH and effluent ammonium requirements.

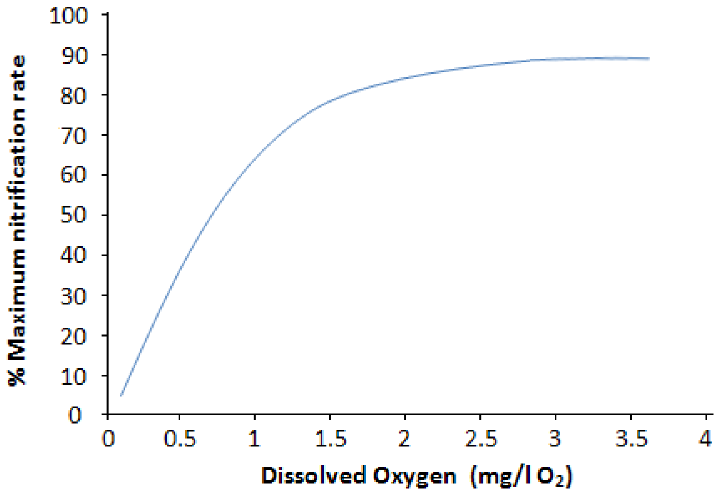

Figure 1. Effect of DO on the % maximum nitrification rate

Historically, the influence of dissolved oxygen on the nitrification rate has been controversial. One of the main reasons comes from evidence that the half-saturation coefficient (K_{OA}) applied in kinetic parameters determination, despite being critical, is not a well-defined value. This is evidenced by reported concentrations ranging between 0.15 and 2 mg/L O_2.

Table 1 – Example of some reported half saturation values

Source	K_{OA} (mg/L)		Source	K_{OA} (mg/L)
USEPA	1.3		ASM1	0.4
IAW	0.4		ASM2	0.5
BioWin	0.25		ASM3	0.5
GPS-X	0.5		Henze *et al.* (2000)	0.5
Beccari *et al.* (1999)	0.83		Contreras *et al.* (2008)	0.75

According to Monod kinetics, the specific growth rate (μ_A) and the maximum nitrification rate (AUR_o) for any nitrification limiting DO concentration is dependent on temperature, pH and DO. But when those parameters are obtained under equivalent conditions of substrate, temperature, pH and oxygen to the actual process, this correlation only relies on the DO and half-saturation coefficient (K_{OA}). Therefore, it is evident that K_{OA} plays a critical role, but due to the variability in reported ranges (see Table 1), in many cases it can be too risky to use the default values from bibliography or simulation software. For that reason, it is more than justifiable to develop an affordable method that could calculate the K_{OA} value for a specific nitrification process.

The major nitrification driver is the SRT. This value can be obtained from the reciprocal value of the actual autotrophic growth rate and is dependent on the nitrification rate (AUR) and active nitrifier concentration (X_A). Therefore, to determine the corresponding SRT it is necessary to determine the X_A beforehand; this is possible by taking advantage of the principle that the endogenous respiration rate is directly proportional to the biomass concentration (James C. Young. 2004; Peter A. Vanrolleghem. 2002).

2. BM RESPIROMETER

The methods and case study described in this paper were carried out with parameters and calculations resulting from a test performed using an advanced respirometer. This respirometer is able to conduct tests within different ranges of temperature, pH and DO. It also gives the option to change these variables, if required, during the test.

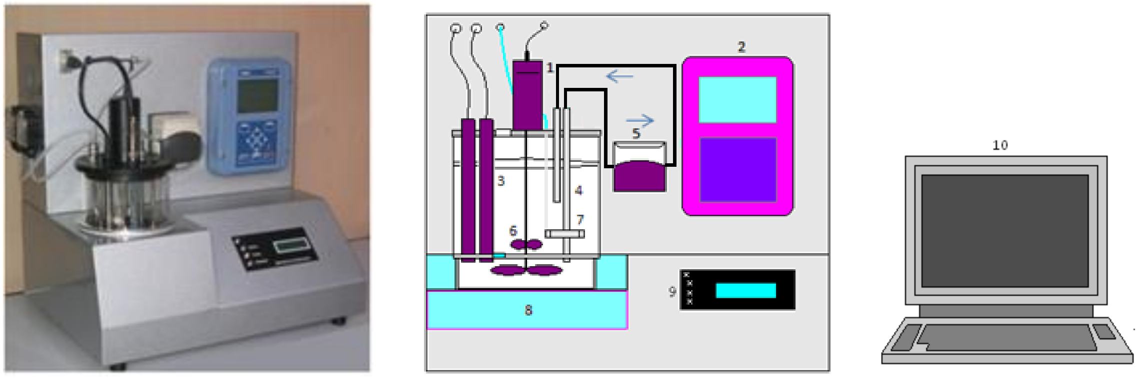

Figure 2. BM-Advance respirometry system

1. Stirring motor - 2. Oxygen & pH controller - 3. Oxygen & pH sensors - 4. Inlet & Outlet recirculation tubes - 5. Peristaltic pump. 6. Stirring paddles - 7. Air diffuser - 8. Automatic cooling & heating system - 9. Console display - 10. PC with BM software

The BM respirometer is programmed with three different operation modes: OUR, Cyclic OUR and R; in the present study the operation mode utilized was R.

The R mode is based on a modified LFS batch respirometry type where the dissolved oxygen is measured in liquid which is continuously aerated, stirred and recirculated. The respirometer is already calibrated from the factory to run in R mode. The exclusive feature of this operation mode is based on the fact that, when sludge under endogenous respiration is used, the stable resultant dissolved oxygen of the sludge without adding any substrate is taken as base line. Then, when substrate is added, the test actually begins and the software is able to calculate the exogenous respiration rate directly related to the biological substrate removal for a maximum DO concentration over time. In our case, the substrate is ammonium and therefore the exogenous respiration rate is exclusively related to nitrification.

3. MAIN APPROACH AND OBJECTIVES

Approach:

1. Energy optimization by operating within minimum DO range and SRT.

Objectives:

1. Calculation of the specific K_{OA}
2. Calculation of the minimum and maximum DO in which nitrification can operate in its actual ammonium range.
3. Calculation of the SRT in which the process should operate.

The common condition for all of them is to get a short, simple and reliable method.

4. METHOD TO DETERMINE K_{OA}, MINIMUM DO AND SRT BY RESPIROMETRY

To get reliable results for any procedure related to nitrification, it is important to confirm that the process is running within normal conditions and operating parameters (Table 2 and Figure 3).

Table 2. Normal conditions for nitrification

Nutrient ratio C/N/P - High & medium load	100/5/1
Nutrient ratio C/N/P - Low load	100/3/0.7
pH	7.3 to 8
T	> 15 to 28°C
DO	1 to 3 mg/L
SRT	5 to 35 days
No nitrification inhibitors in the wastewater	
Sufficient HRT for nitrification	

Respirometry test

The R test must be set at equivalent conditions to the actual process in regard to temperature and pH. Begin by measuring the dissolved oxygen and its stability in the actual activated sludge under endogenous respiration. Once the oxygen is enough stable the software stores it as a baseline and a dose of ammonium chloride for equivalent ammonium substrate can be added. The test, remaining continuously aerated, starts to directly measure the exogenous respiration rate that, in our case, is the one provoked by the nitrification of the ammonium- nitrogen contained in the ammonium chloride (Fig. 3).

Once the maximum oxygen uptake rate (OUR) is reached, a serial doses of allyl thiourea (ATU) are added until the OUR starts to decrease. In that way, it is added the exact amount of ATU to avoid the risk of inhibition of the heterotrophic biomass

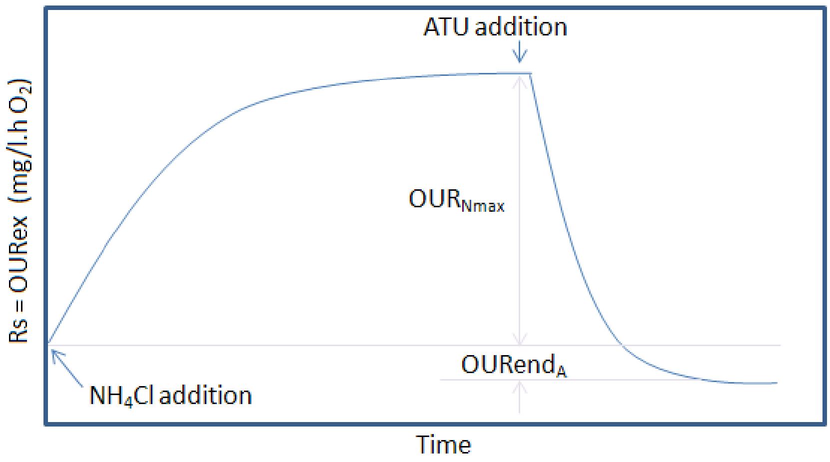

Figure 3. Respirogram for the nitrification of ammonium chloride and its inhibition after ATU addition

The test allows for the respiration rate to cross below the base line and, because of the nitrification inhibition, this will display negative oxygen uptake.

Once the negative respiration rate has stabilized, the test can be stopped.

This negative respiration is that which corresponds to the absence of nitrifiers in the global biomass and therefore it represents its endogenous respiration.

In this way, in the same test, the maximum oxygen uptake rate and the endogenous oxygen uptake rate of the nitrifiers are obtained.

K_{OA}

Ammonium to nitrify

Because of the ammonification process, where part of the organic nitrogen is transformed into ammonium (Figure 4), the effective ammonium to nitrify must be calculated from the eliminated TKN from which we have to subtract the corresponding nitrogen directed to cell synthesis.

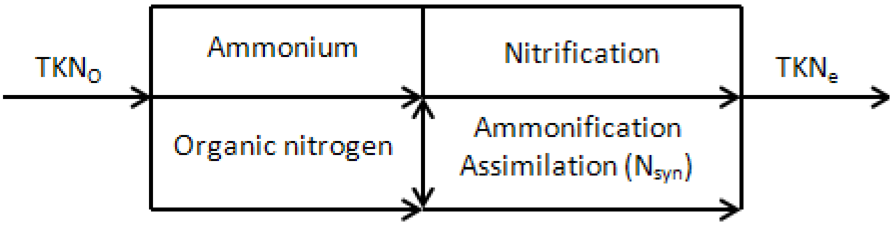

Figure 4. TKN in the nitrification

$$S_N = TKN_O - TKN_e - N_{syn} \quad (1)$$

Where

- S_N: Typical ammonium concentration to nitrify (mg/L NH_4-N)
- TKN_O: Influent TKN (mg/L N)
- TKN_e: Effluent soluble TKN (mg/L N)
- N_{syn}: Nitrogen directed to cell synthesis (mg/L N) ≈ 0.04 * BOD utilized

Actual ammonium uptake rate

The actual ammonium uptake rate is calculated by applying a mass balance equation from the data of the actual process under current conditions and for its specific average DO value.

$$AUR = S_N / HRT \quad (2)$$

Where

- AUR_{act}: Actual ammonium uptake rate (mg/L.h NH_4-N)
- HRT: Actual aerobic hydraulic retention time (h)

Ammonium uptake rate for maximum DO

This ammonium uptake rate is calculated from the maximum oxygen uptake rate in a respirometry test performed under equivalent conditions but for a maximum DO oxygen:

$AUR_o = OUR_{No} / 4.57$ (3)

where

AUR_o: Maximum ammonium uptake rate (mg/L.h NH_4-N) for maximum DO.
OUR_{No}: Maximum oxygen uptake rate due to nitrification for maximum DO, measured in the respirometry R test (Figure 3)
4.57: mg of oxygen needed to nitrify 1 mg of ammonium-nitrogen

K_{OA} calculation

With the AUR_o and AUR_{act} results, we use the equation below based on Monod kinetics.

$AUR = AUR_o * [DO / (K_{OA} + DO)]$ (4)

Then, from equation (4) the K_{OA} coefficient can be calculated to get its actual value:

$K_{OA} = DO\ (AUR_o – AUR) / AUR$ (mg/L) (5)

Minimum DO range

Ammonium uptake rate for a set of different DO values

Once the K_{OA} value is obtained for a set of different representative DO values at which the nitrification process could operate, the equation (6) is performed to calculate the corresponding ammonium uptake rate for each of them.

$AUR_n = AUR_o * [DO_n / (K_{OA} + DO_n)]$ (6)

Where

AUR_n: Ammonium uptake rate corresponding to DO_n (mg/L.h NH_4-N)
DO_n: One of the DO values set at which the process could operate (mg/L)

Nitrification capacity

Using data on the actual hydraulic retention time for nitrification and the concentration of ammonium to nitrify, the nitrification capacity can be obtained for each of the theoretical DO values.

$NC_n = AUR_n * HRT$ (7)

Where

NC_n: Nitrification capacity corresponding to DO_n (mg/L NH_4-N)

DO range to operate

Once we obtain the set of different values for NC_n for each DO_n, compare the results with the concentration of ammonium range to nitrify (S_N range) and then select the minimum DO which corresponds to the NC_n required to complete nitrification.

The concentration of the corresponding NC_n must be equal to or higher than S_N.

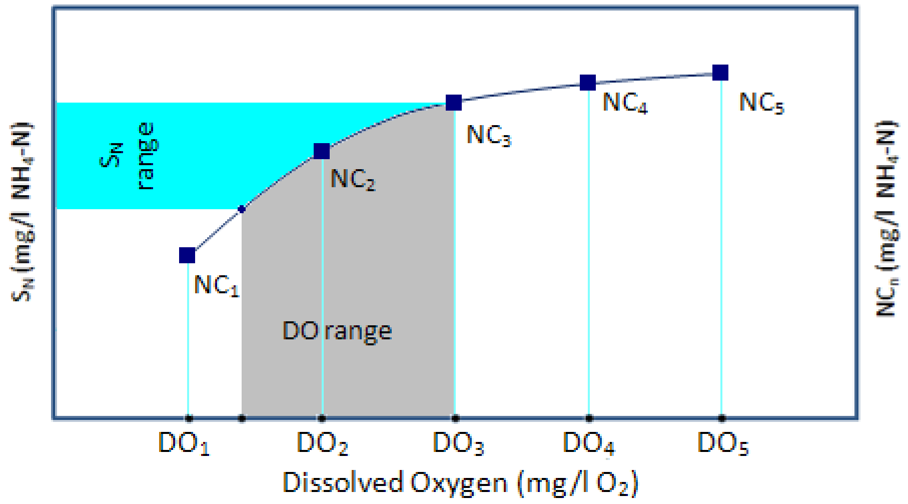

Figure 5. DO range vs S_N range from NC_n curve

Minimum SRT

Nitrifier biomass concentration

The nitrifier concentration is calculated based on two principles: 1) the endogenous respiration rate is directly proportional to the total active biomass and 2) the maximum exogenous respiration rate due to nitrification is directly proportional to the nitrifier concentration.

Research confirmed that the endogenous respiration rate has a direct proportionality with the active biomass (Michael W. Barnett et al. 1998, Vanrolleghem & W. Verstraetet et al 1992) and, based on the equation formulated by James C. Young (2004), a mathematical equation that links the active nitrifier biomass with its endogenous respiration can be derived.

$$X_A = 24 * OURend_A / (f_{cv} * b_{A,T}) \qquad (8)$$

Where

X_A: Active concentration of nitrifiers
$OURend_A$: Endogenous OUR from nitrifiers (mg/L.h) from R test (Figure 3)
f_{cv}: Oxygen uptake per unit of biomass = 1.48 (O_2/X)
$b_{A,T}$: Endogenous decay coefficient for nitrifiers at temperature T = $0.17 * 1.029^{T-20}$ (Melcer, 2003)

Autotrophic biomass growth rate

The autotrophic biomass growth rate is calculated from the actual AUR.

$$\mu_A = Y_A * 24 * AUR / X_A \qquad (9)$$

Where

Y_A: Autotrophic yield coefficient = 0.13 (estimated)

Sludge retention time

$$SRT = 1 / \mu_A \qquad (10)$$

5. CASE STUDY: APPLICATION TO A REAL ACTIVATED SLUDGE PROCESS

The procedures explained above were applied to an actual activated sludge process. The system consisted of a two-lane parallel plug-flow activated sludge system. Currently, aeration is controlled by an ammonium probe installed at the reactor outlet in combination with upper and lower DO set-points.

Table 3. Process data

Parameter	Average value
DO (mg/l O_2)	1.5 Range: 0.5 – 2.5
pH	7.5
T (ºC)	23
F/M (BOD/SS.d)	0.17
SRT (d)	13
HRT_N (h)	7
Qr/Qo	1
BOD_O (mg/L) to b. reactor	340
BOD_e (mg/L)	42
TKN_O (mg/L N)	54 Range: 20 – 83
$STKN_e$ (mg/L N)	7 Range: 1.5 – 26
BOD / TKN	5.67
MLSS (mg/L)	3700
MLVSS (mg/L)	3145

By means of a BM respirometer, the R test is set to be performed on equivalent temperature and pH conditions and the values of OUR_{Nmax} and $OURend_A$ are obtained.

The R test is set to be able to record negative respiration rate readings.

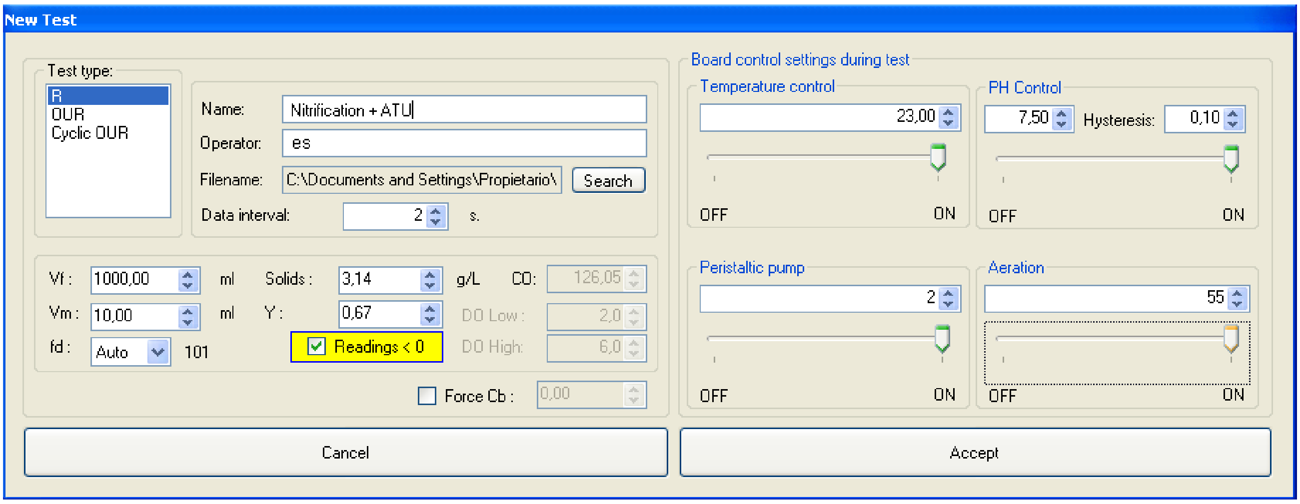

Figure 6. Settings board for R test

The test starts when the dose of ammonium chloride is added to a volume of 1000 ml of endogenous sludge. The test is carried out as described above. When it reaches the minimum respiration rate it is stopped. At any time throughout the test it is possible to get the current results and analyze the evolution of the ammonium reaction in the activated sludge.

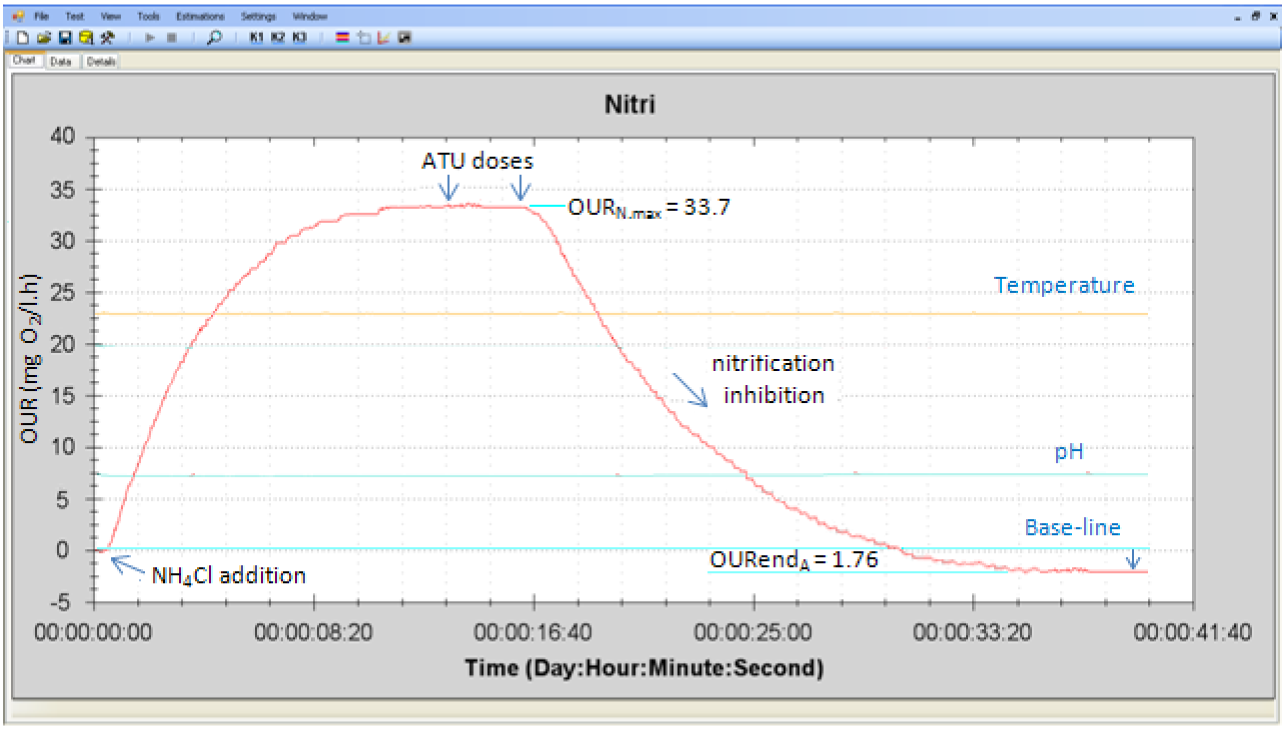

Figure 7. Respirogram for the R test to get the OUR_{Nmax} and $OURend_{A}$

The results can be seen any time during the test at any point of the respirogram or by opening the Details tab of the results.

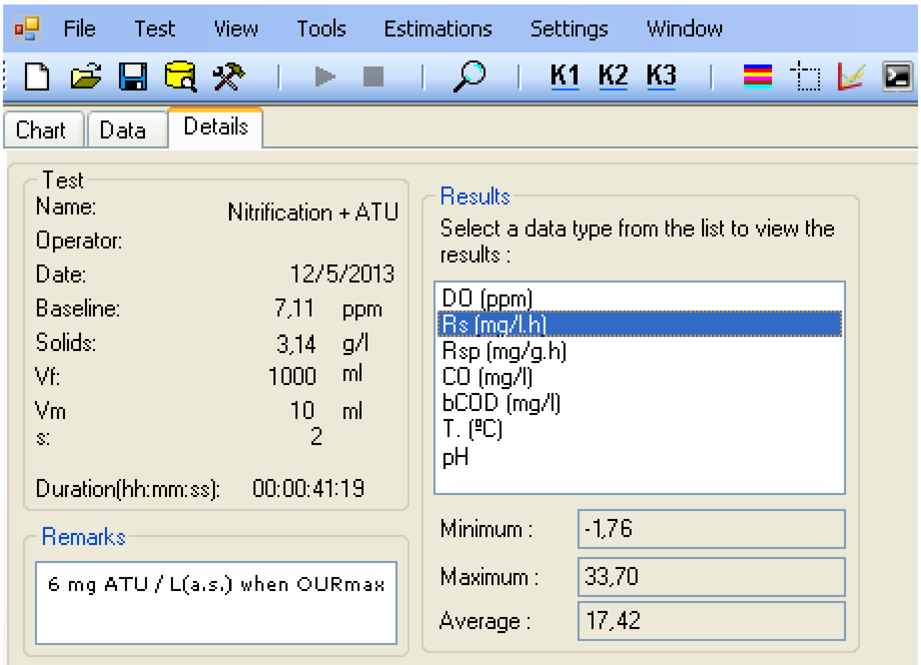

Figure 8. Final results from the R test

From the process data in Table 3 and respirometry test (Figure 7 and 8) the results of equations (1), (2), (3), (4), (5), the basic key parameters, have been calculated and are shown in Table 4.

Table 4. Basic key parameters

Parameter	Values
S_N typical (mg/l NH_4-N)	35
S_N range (mg/l NH_4-N)	15 - 40
OUR_{No} (mg/l.h O_2)	33.7
$OURend_A$ (mg/l.h O_2)	1.76
AUR (mg/l.h NH_4-N)	5.14
AUR_o (mg/l.h NH_4-N)	7.37
K_{OA} (mg/l O_2)	0.65

Then, by making use of K_{OA}, S_N and equations (6) and (7), a table of the AUR_n and NC_n was made using a set of different representative DO_n values.

Table 5. AUR_n and NC_n for different DO levels

Parameters	Values				
DO_n (mg/l)	0.5	1	1.5	2	2.5
AUR_n (mg/l.h NH_4-N)	3.20	4.42	5.14	5.56	5,84
NC_n (mg/l NH_4-N)	22.4	30.94	36	39	41

Table 5 is graphically represented in Figure 9. Here, it is observed that the DO of 0.5 mg/L has enough NC to surpass the minimum S_N range.

However it is assumed that below this level the nitrification activity can decrease excessively and for this reason the value of 0.5 has been established as the minimum DO.

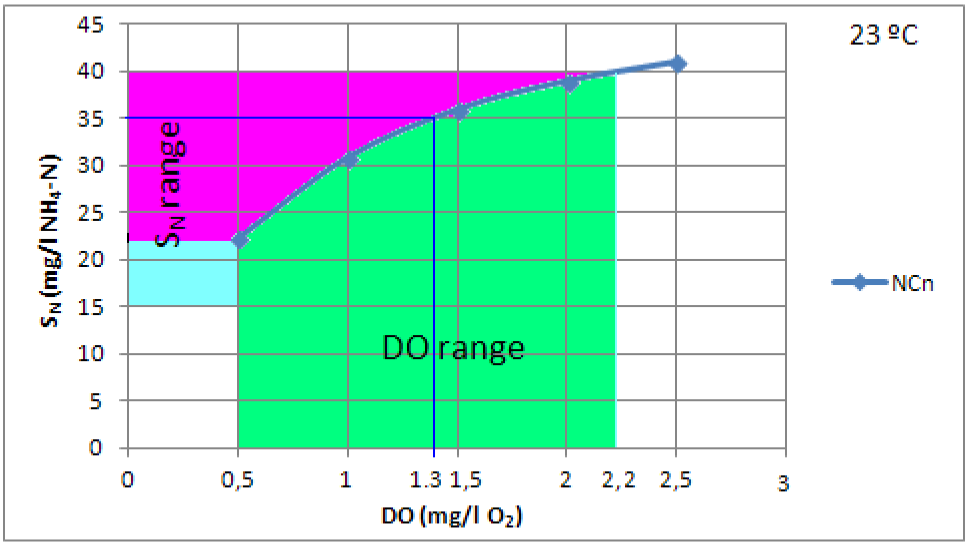

Figure 9. DO range vs S_N range – Minimum DO for S_N reference

In Figure 9, the maximum value of the DO operating range is determined by simply drawing a horizontal straight line from the maximum S_N until reaching the NC curve and then, from this point, down to the corresponding DO. In this way, the operational DO range is found to be between 0.5 and 2.2 mg/L O_2. For the typical S_N value, the typical DO is 1.3 mg/L O_2.

The values of X_A, μ_A, and SRT are calculated and presented in Table 6.

Table 6. Final results for X_A, AUR and μ_A

Parameter	Value
X_A (mg/L)	154
μ_A (d^{-1})	0.10
SRT (d)	10

Finally, a summary of the calculated parameters on which the aeration and activated sludge control can be based are presented in Table 7.

Table 7. Summary of parameters for energy optimization - Comparison vs current values

Parameter	Values from the study	Current values in the process
Temperature ºC	23	23
DO operative range (mg/L O_2)	0.5 - 2.2	0.5 - 2.5
DO typical (mg/L O_2)	1.3	1.5
SRT (d)	10	13

Table 7 shows that results from the study are not very different from the current conditions at which the process is currently operating. This means that the treatment process was running at operative parameters and conditions approaching optimal energy optimization.

6. DISCUSSION

In the method here described, the key point is to create a diagram (Figures 5, 9) that links the DO range with the nitrification capacity (N_C) for a specific ammonium range to nitrify (S_N). Once we obtain this diagram, we will have a tool to control the nitrification process within the appropriate DO range and minimum DO as a basis to optimize energy in the aeration control. The plant operator could also make up a diagram for each representative daily average temperature and know the corresponding minimum and DO range for each situation. In this way, permanent efficient process operation within an energy optimization framework is possible.

Although it was not explained here, it is important to realize that this method could also be used for modeling a new process. For this application, by taking advantage of the different operational modes of the BM respirometer, we would make use of Cyclic OUR mode and equivalent ammonium chloride concentration in a representative activated sludge to get a new AUR for the DO we expect in the nitrification process and then follow the same steps as above.

In this novel method, we explain how to calculate the respiration rate for maximum DO ($OUR_{N.max}$) and nitrifier endogenous respiration rate ($OURend_A$) in the same test. Most importantly, both parameters are directly calculated from the existing nitrifier biomass. For this reason, the procedure to calculate the active nitrifier biomass concentration (X_A) can be considered realistic and it could be added to others described in the bibliography (Metcalf & Eddy, Eckenfelder, Dupont & Sinkjer, etc.) which are indirect calculations depending on other parameters in the process.

Another important point in the respirometry test is the determination of the precise amount of Allyl Thiourea (ATU) to be added to inhibit nitrification. This is because ATU kills autotrophic microorganisms (nitrifying bacteria) because they are much more sensitive to toxic compounds than heterotrophic microorganisms; but, if we add too much ATU to the activated sludge, we will also kill part of the heterotrophic biomass and get an erroneous respiration result. However, in the method here described, the progressive and controlled doses of ATU added upon the maximum respiration rate provoked by the addition of ammonium chloride, are highly precise and avoid the risk of affecting the heterotrophic microorganisms. In that way, we get a reliable result for the nitrifier endogenous respiration rate and further calculations.

7. CONCLUSIONS

The use of an advanced multifunction respirometry system able to run a constantly aerated R test at equivalent conditions of substrate concentration, pH, and temperature allows one to obtain the actual maximum respiration rate and endogenous respiration rate due to nitrification.

By making use of those parameters obtained in the respirometry test, the method described in this paper is able to calculate a diagram for the different values of nitrification capacity (N_C) corresponding to different representative oxygen levels and, from this curve, to determine the minimum DO range and SRT in which the activated sludge process could operate.

These values of minimum DO, DO range and SRT can be used as the basis to implement an energy efficient strategy of aeration and activated sludge control. In this way, when process conditions allow, there is the real possibility to save energy without any detriment to treatment efficiency.

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