

# Practical procedure aimed at studying energy savings and maintenance of fine bubble diffuser aeration systems by BM respirometry



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## ABSTRACT

In general, the chapter on energy optimization in a treatment plant will always have special relevance, and even more so now with the notable increase in the price of electricity that we are experiencing. With this, the combination of energy savings with the quality of the effluent in many cases means a challenge that plant managers often have to face.

It is well known that most of the energy consumption comes from aeration and that the most used criterion for its evaluation is the level of dissolved oxygen and/or quality of the effluent with which the process is normally operating in contrast to the air flow that the system is supplying. This criterion is still valid. However, in many plants it is not possible to analyze with the effectiveness that the case requires the sufficiency of the aeration system as well as having a representative parameter to follow that indicates the moment in which the membranes of the air diffusers must be cleaned or changed in that kind of system.

To do this, the present paper presents a mathematical model especially aimed at aeration systems of fine bubble membrane diffusers where a solution to these needs can be provided in a relatively simple and effective way.

# 1. INTRODUCTION

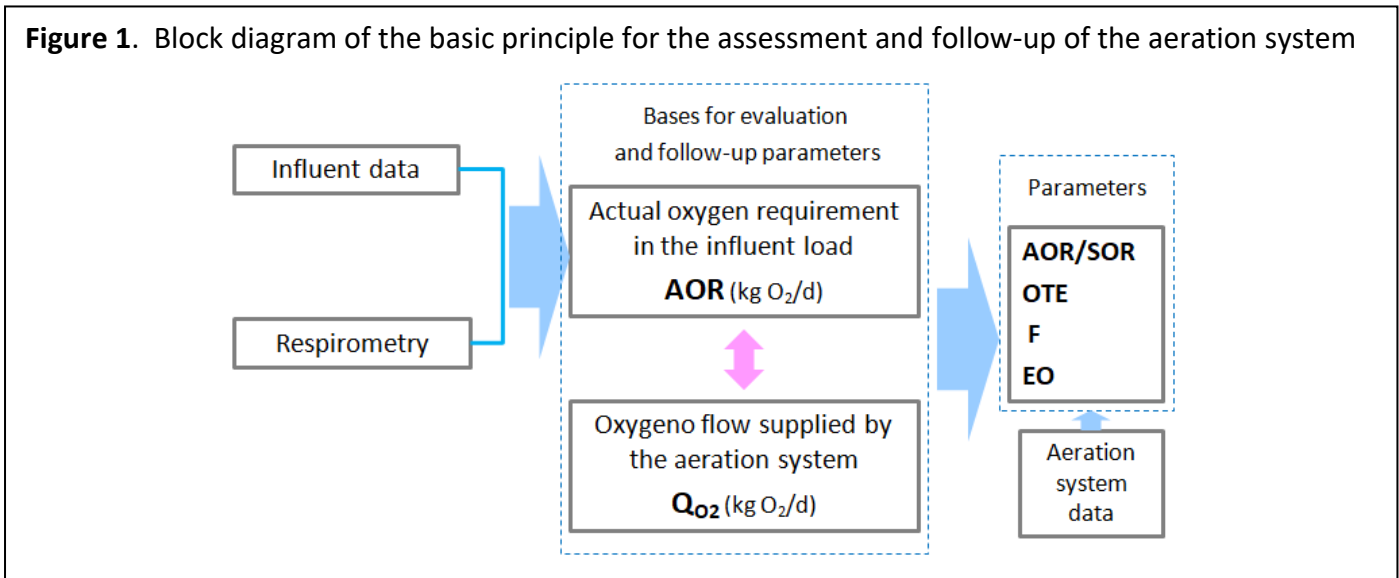
One of the ways to carry out the evaluation of the aeration system is by means of a mathematical model based on the relationship between the average oxygen requirement, derived from the biological input load (AOR), and the average oxygen flow rate being supplied ( $Q_{O_2}$ ). This fundamental principle underlies the development of a simple procedure that will be discussed in detail in this paper.

The potential advantage that this procedure can offer over other methods is that the process is assessed as a whole rather than at selective points in the biological reactor.

For this type of procedure, the reliability of the calculation of the oxygen requirement is of particular importance, as an incorrect result or estimation of this parameter can lead to inappropriate conclusions and actions.

This highlights how, starting from respirometry tests, we can calculate the current oxygen requirement of the organic matter by using the biodegradable COD as the fundamental data in this calculation. From here, we move on to the mathematical model that starts with the relationship between the global oxygen requirement of the process and the requirement under standard conditions (AOR/SOR), which is compared with a duly validated reference value.

The AOR/SOR parameter would be sufficient for a qualitative assessment and follow up of the adequacy and condition of the aeration system. However, in order to open up the range of possibilities of the procedure, the math model is extended to the simplified calculation of the oxygen transfer efficiency in process (OTE), the estimation of the fouling factor (F) as an indication of the condition of the diffusers in terms of dirt or ageing and the calculation of the possible energy optimisation (OE) that may be involved in changing the diffuser membranes or cleaning.



Finally, a real case study of a municipal WWTP operated by the DAM Group is presented. Surcis would like to thank them for their close collaboration in the BM Respirometry tests provided by their laboratory and process data.

## 2. PARAMETERS

The parameters used in the procedure here described are approached to aeration systems with fine bubble membrane diffusers. However, many of them can also be used in other aeration systems.

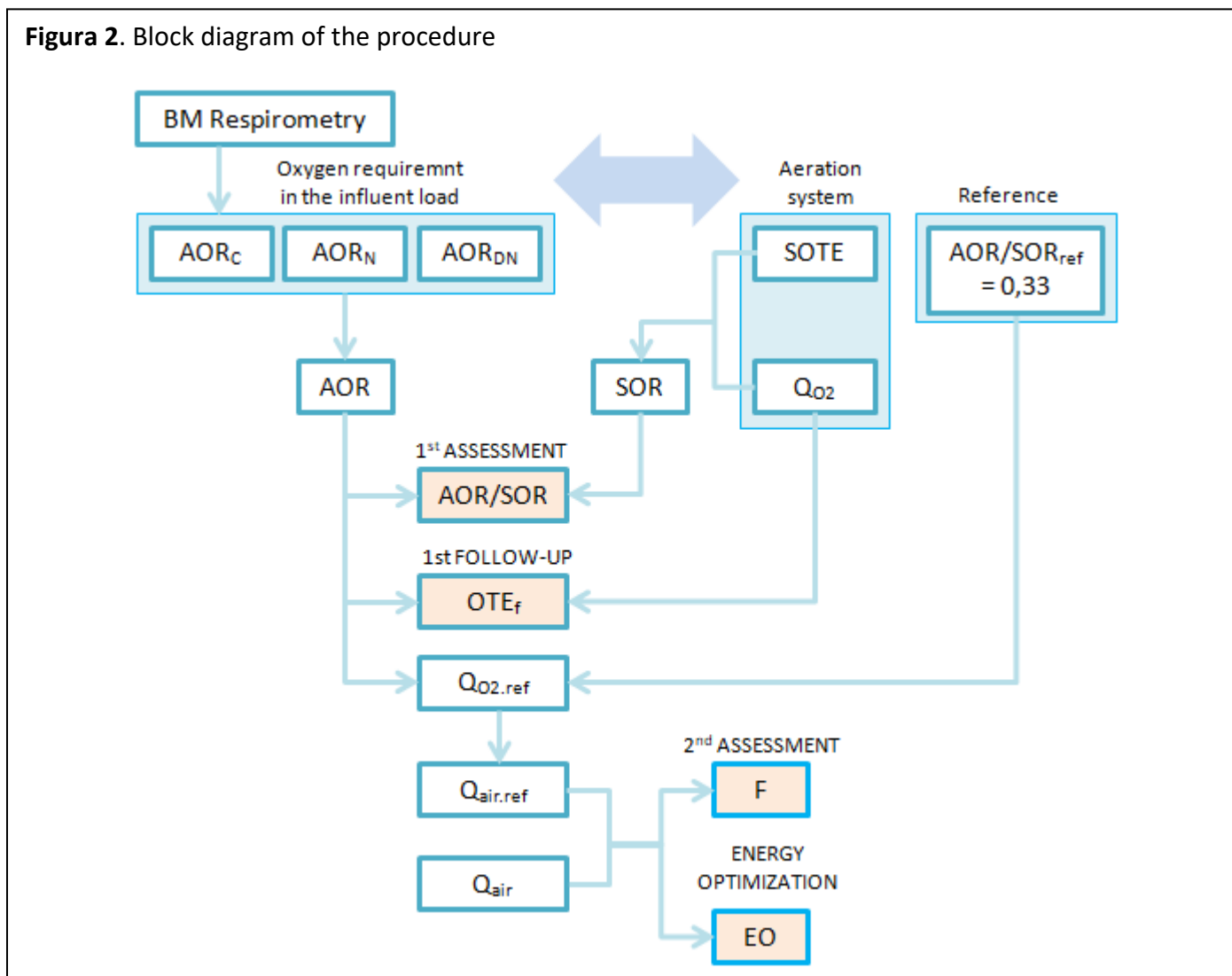
The first group of parameters is derived from the results of a series of BM respirometry tests; and the second is obtained by means of simple equations involving parameters from the first group, data from the current process, the aeration system and reference values.

**Table 1.** Parameter used in the aeration systems evaluation and follow-up

Parameter	Description
Parameters from BM respirometry tests	
SOUR (mg/g/h)	Specific Oxygen Uptake Rate of the endogenous respiration
$Y_{H,O_2}$ ( $O_2/COD$ )	Yield coefficient of the heterotrophic biomass
$Y_{H,obs}$ (VSS/COD)	Observed yield coefficient
bCOD (mg/L)	Biodegradable COD fraction
nbCOD (mg/L)	Non-biodegradable COD fraction
bCOD <sub>e</sub> (mg/L)	bCOD eliminated in the activated sludge process
Parameters from process data, aeration data and respirometry	
AOR (kg $O_2$ /d)	Actual oxygen requirement
SOR (kg $O_2$ /d)	Standard oxygen requirement
OTE <sub>f</sub> (%)	Oxygen transfer efficiency in process
SOTE (%)	Standard oxygen transfer efficiency
AOR/SOR	Ration between actual oxygen requirement (AOR) and standard oxygen requirement (SOR)
$Q_{O_2,ref}$ (kg $O_2$ /d) $Q_{aire,ref}$ ( $Nm^3$ /h)	Reference oxygen flow rate Reference air flow rate
F	Fouling factor
EO (%)	Estimated energy optimization due to diffusers cleaning or membranes replacement.

### 3. PROCEDURE DIAGRAM

This diagram (figure 2) shows the steps to follow in the procedure for the evaluation and follow up of the aeration system.



### 4. BM RESPIROMETER

The BM Respirometry technology is based on a unique system, based on the modified LFS + LSS respirometry, developed by Surcis S.L., which is included in a series of different BM respirometer models.

This technology allows, in the previous test setup and even during its normal performance, the adaptation to different conditions of pH, Temperature, Oxygen and sample / sludge ratio. It also allows the possibility of introducing certain data that can participate in the automatic calculations of fundamental parameters in the treatment process.

The main applications that can be carried out with BM Respirometry are the following: Taking the pulse of the process for its fast assessment, COD fractions, Biodegradability to the sludge, Toxicity, Nitrification rate (AUR), Denitrification rate (NUR), Assessment and monitoring of the aeration system, among many others.

Optionally, by means of a special reactor (bio-carrier), BM respirometers can carry out respirometry tests with moving bed biofilms for MBBR and granular biomass processes.

**Figure 3.** BM Respirometry system and automatic measurements performed by its software



BM-EVO2

**BM Respirometry Operation Modes**

**OUR & Cyclic OUR** modes

**OUR: Oxygen Uptake Rate** (mg O<sub>2</sub>/l.h)

It measures the oxygen uptake rate for only one measurement or serial o measurements.

**SOUR: Specific OUR** (mg O<sub>2</sub>/g VSS.h)

Specific OUR related to MLVSS.       $SOUR = OUR / MLVSS$

**R** mode

**Rs: Dynamic Respiration Rate** (mg O<sub>2</sub>/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<sub>2</sub>/g VSS.h)

Specific Rs referred to MLVSS.       $Rsp = Rs / MLVSS$

**bCOD: Biodegradable COD** (mg O<sub>2</sub>/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.

## 5. PARAMETERS DESCRIPTION

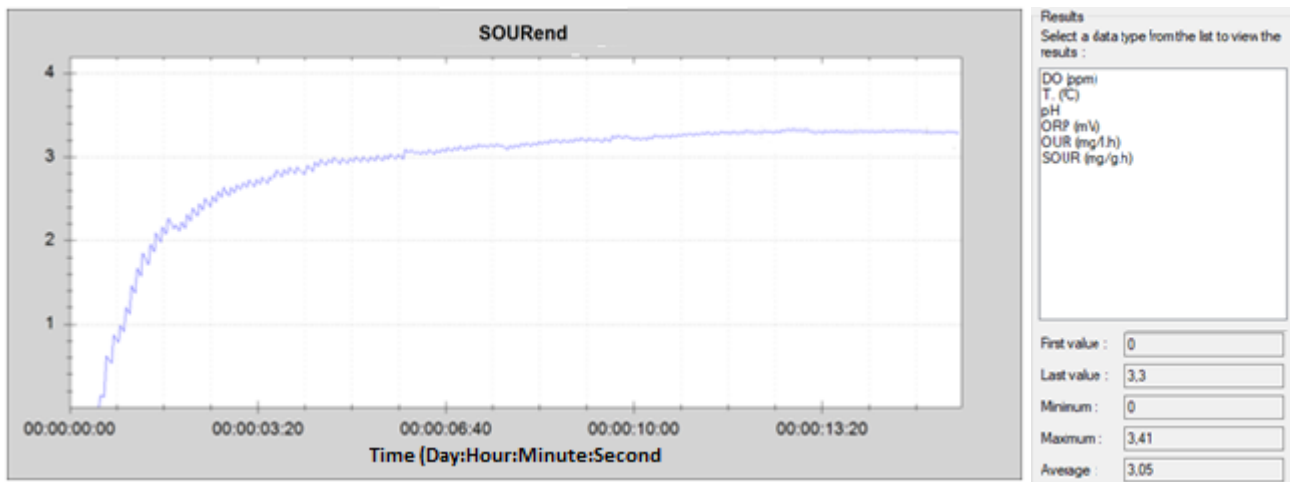
### 5.1. Parameters derived from respirometry tests

It is about the parameters obtained from respirometry tests, either directly calculated automatically by the software or mathematically from the results of tests performed with the respirometry system.

#### 5.1.1. Specific OUR of the activated sludge under endogenous respiration: $SOUR_{end}$ (mg O<sub>2</sub>/g/h)

This is the ongoing specific oxygen consumption rate of the sludge under endogenous respiration phase. By entering the value of the MLVSS concentration, a BM respirometer automatically calculates this parameter by dividing the OUR value by the MLVSS concentration previously entered in the test setup.

**Figure 4.** SOUR<sub>end</sub> respirogram from BM respirometry test



SOUR<sub>end</sub> is involved in the calculation of the K<sub>d</sub> coefficient (equation 1), on units d<sup>-1</sup>.

### 5.1.2. Decay coefficient for endogenous respiration phase: K<sub>d</sub> (d<sup>-1</sup>)

This coefficient accounts for the loss in cell mass due to oxidation of internal storage products for energy for cell maintenance under endogenous respiration phase.

$$K_d = \frac{SOUR_{end}}{1.42} \quad (1)$$

### 5.1.3. Heterotrophic yield coefficient: Y<sub>H</sub> (O<sub>2</sub>/COD), (VSS/COD)

This coefficient represents the part of biodegradable COD that is used in the reproduction of heterotrophic biomass.

It is calculated from the oxygen consumed (OC) value of a known COD standard substrate (COD<sub>ac</sub>) obtained automatically with a BM respirometer.

$$Y_{H.O_2} = 1 - \frac{OC}{COD_{ac}} \quad (2)$$

Where:

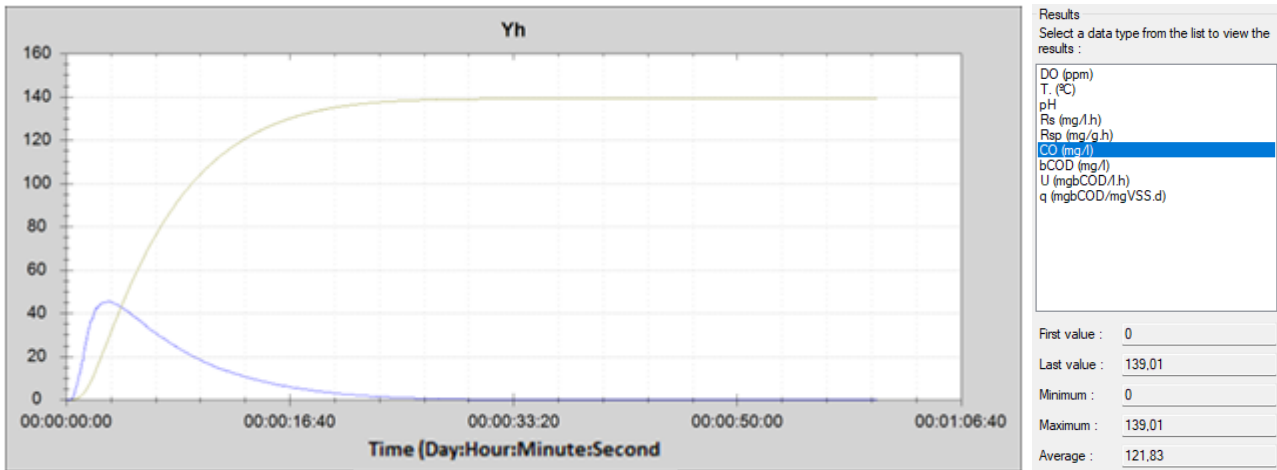
OC: Oxygen consumed (mg/L), calculated from the integration of the set of R<sub>s</sub> values (Figure 5)

COD<sub>ac</sub>: COD of the reference substrate used in the respirometry assay (mg/L)

The Y<sub>H</sub> coefficient is then related to the biomass concentration (MLVSS) with the following equation:

$$Y_{H.VSS} = \frac{Y_{H.O_2}}{1.42} \quad (3)$$

**Figure 5.** Respirogram and result of a BM respirometry test of CO for the determination of the  $Y_H$



#### 5.1.4. Observed stoichiometric biomass production coefficient: $Y_{obs}$ (VSS/COD)

This coefficient relates the biomass produced to the substrate consumed and is mainly calculated for its intervention in the sludge production formula (Equation 7)

$$Y_{obs} = \frac{Y_{H.VSS}}{1 + K_d * SRT} \quad (4)$$

Where:

$Y_{H.VSS}$ : Yield coefficient (VSS/d)

SRT: Sludge Retention Time (sludge age) (d)

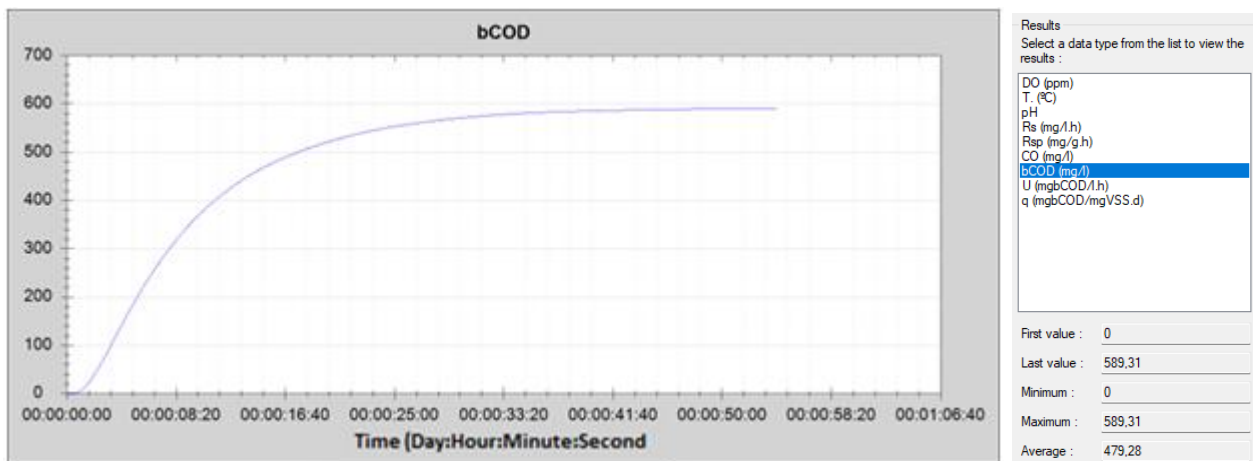
$K_d$ : Biomass fraction per day, oxidized during endogenous respiration ( $d^{-1}$ )  $\approx 0.06$  – Typical value.

#### 5.1.5. bCOD: Biodegradable COD (mg/L)

It is the biodegradable fraction in the total COD.

The bCOD is a key parameter in the calculation of the oxygen requirement of the process. It can be calculated automatically by means of a BM respirometer (Surcis) (Figure 6)

**Figure 6.** Respirogram and bCOD result in a BM respirometry test (Surcis)



### 5.1.6. Non-biodegradable COD : nbCOD (mg/L)

Non-biodegradable or inert Inert COD (nbCOD) is the fraction that is not biologically degradable in the process:

$$\text{nbCOD} = \text{COD} - \text{bCOD} \quad (5)$$

### 5.1.7. bCOD<sub>e</sub>: Eliminated biodegradable COD in the treatment process (mg/L)

$$\text{bCOD}_e = \text{bCOD}_{\text{influent}} - \text{COD}_{\text{effluent}} - \text{nbCOD} \quad (6)$$

## 5.2. Parameters calculated from process data and BM respirometry

This is the name given to the parameters that lead directly to the key equations in the evaluation of the aeration system.

### 5.2.1. Sludge production : P<sub>x</sub> (kg VSS/d)

This parameter represents the net growth of biomass expressed in volatile suspended solids.

$$P_x = \frac{1.42 * Q * \text{bCOD}_e}{1000} \quad (7)$$

Where:

Q : Influent flow rate (m<sup>3</sup>/d)

### 5.2.2. AOR: Actual Oxygen Requirement (kg O<sub>2</sub>/d)

AOR is the oxygen demand required in the biological treatment process.

It is made up of three partial requirements:

- Oxygen Requirement per organic matter:  $\text{AOR}_C = Q * \text{bCOD}_e / 1000 - 1.42 * P_x$
- Oxygen Requirement for nitrification:  $\text{AOR}_N = 4.57 * Q * N_n / 1000$
- Oxygen requirement for Denitrification:  $\text{AOR}_{DN} = 2.28 * Q * N\text{-NO}_3 / 1000$

(Metcalf & Eddy – 2003, Henze, et al 2008)

Where:

N<sub>n</sub> : Nitrifying nitrogen (mg N/L) ≈ NTK removed

N-NO<sub>3</sub>: Nitrate to be denitrified (mg N-NO<sub>3</sub>/L)

The requirement for denitrification, carried out under anoxic conditions, is presented as a credit in the required global oxygen.

$$\text{AOR} = \text{AOR}_C + \text{AOR}_N - \text{AOR}_{DN} \quad (8)$$

### To be taken into account in the calculation of the AOR

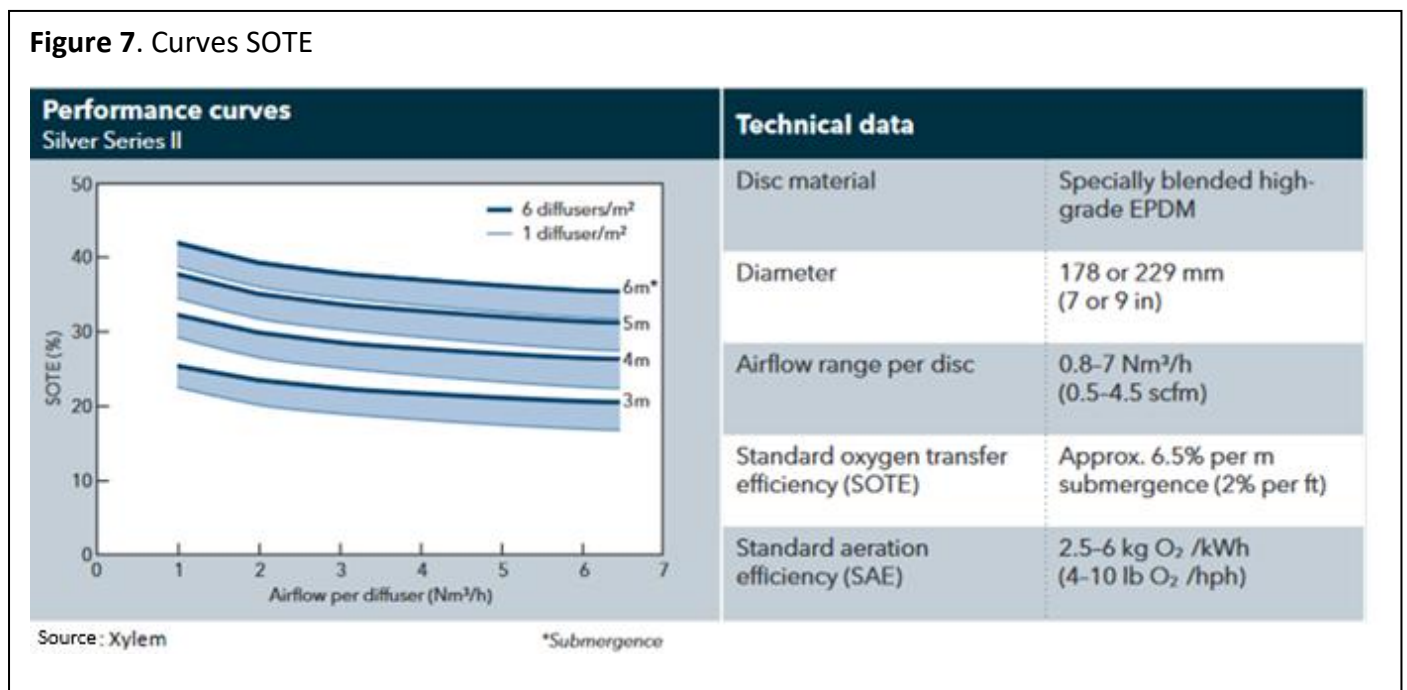
Of particular importance is the recommendation to calculate the organic matter requirement (AOR<sub>C</sub>) based on the biodegradable COD removed (Metcalf & Eddy, 2003, Henze, et al 2008), if possible, by means of respirometry.

The reason for this is that, if BOD<sub>5</sub> is used, when there is a significant percentage of the slowly biodegradable fraction of COD (sbCOD) of very low activity, it may not be able to detect this type of oxygen demand. Thus, even if estimated values of oxygen requirement per BOD<sub>5</sub> unit load are applied, in these cases it would not be representative of an overall oxygen demand of organic matter and there would be a risk of calculating an oxygen requirement lower than that actually needed by the process (see case study)

### 5.2.2. Oxygen Transfer Efficiency Under Standard Conditions: SOTE %

SOTE is the efficiency in the transfer of oxygen to the process under standard conditions (20 °C, 1 atmosphere and 0 mg/L of oxygen) at full capacity and in clean water.

The manufacturer provides a graph of the SOTE value from the average flow rate per diffuser and depth of the diffusers in the biological reactor (Figure 7). The value, thus obtained, provides a calculation basis for obtaining reference parameters.



### 5.2.3. Standard Oxygen Requirement: SOR (kg O<sub>2</sub>/d)

The SOR is related to the amount of oxygen that must be transferred to meet the AOR after adjusting the conditions of the biological reactor. It is for this reason that it is usually used in conjunction with AOR in the AOR/SOR relationship. This is one of the parameters that serves to assess the oxygen sufficiency for the process and also to compare different aeration systems.

The standard oxygen transfer rate (SOTR) must be equal to the SOR in a running process. For no reason, the SOR is calculated with the same mathematical formula as the SOTR referring to the oxygen flow (WEF, SVU Rapport-2019 23)

$$SOR = Q_{O_2} * SOTE \quad (9)$$

Where:

Q<sub>O<sub>2</sub></sub> : Average flow rate of oxygen delivered to the process (kg O<sub>2</sub>/d)

#### 5.2.4. Ratio of Actual Oxygen Requirement to Standard Oxygen Requirement reference: AOR/SOR

The AOR/SOR ratio can be used as the primary endpoint parameter. In fact, many manufacturers (Xylem, among others) propose this relationship to assess and calculate the flow of oxygen.

In reality, this relationship does nothing more than subject to the basic principle, by which the requirement of average oxygen is indirectly related to the flow of oxygen that is being supplied. For this reason, the AOR/SOR parameter can be taken as a parameter for the first assessment and the initiation of the procedure.

The AOR/SOR ratio usually has a normal range of between 0.3 and 0.5

For fine bubble aeration systems, the usual AOR/SOR reference value is 0.33 (CED Engineering, Harlan H. Bengtson – 2017, Sanitaire, University of Idaho, Environmental Engineering, CVE – 2021, others)

This value of 0.33 will be taken as the basis for the calculation of other reference parameters. The first evaluation of the aeration system can therefore be based on the AOR/SOR ratio. Therefore, for example, values below 0.3 imply deficient aeration and this would mean that an abnormally high flow rate is being supplied for the current oxygen requirement.

#### 5.2.5. Simplified calculation of the Oxygen Transfer Efficiency: $OTE_f$ (%)

The oxygen transfer efficiency of the process is one of the most important parameters in aeration systems. The higher the  $OTE_f$ , the less air must be supplied to a reactor to ensure the amount needed in the process.

The determination of the  $OTE_f$  allows plants to assess the long-term operating costs of their aeration systems and confirm that sufficient capacity is available to meet the oxygen requirement demanded by the process input load. Therefore, it is a parameter that can be considered as fundamental for the monitoring of the aeration system.

With current performance and process conditions, the simplified and dynamic way to calculate the  $OTE_f$  is by the relationship between the oxygen requirement of the inlet load and the current flow rate of oxygen supplied (Lee E. Ferrell, P.E., BCEE, CEM, LEED Green Assoc.- 2010; Viktor Larsson – 2011, among others)

$$OTE_f = 100 * \frac{AOR}{Q_{O_2}} \quad (10)$$

#### 5.2.6. Oxygen flow reference: $Q_{O_2.ref}$ (kg $O_2/d$ )

Based on the reference value of AOR/SOR = 0.33, the equation for the calculation of the reference flow rate (equation 10) can be obtained.

The reference quad ( $Q_{O_2.ref}$ ) would correspond to the estimated flow rate that would be needed, for the same AOR requirement, after effective maintenance of the diffusers (cleaning or change)

$$Q_{O_2.ref} = \frac{AOR}{(0.33 * SOTE)} \quad (11)$$

$$Q_{air.ref} = \frac{0.285}{24} * Q_{O_2.ref} \quad (12)$$

The corresponding reference air flow ( $Q_{\text{air.ref}}$ ) will be obtained by applying the conversion factor of kg O<sub>2</sub>/d to Nm<sup>3</sup>/h (Equation 12)

### 5.2.7. Fouling factor estimation : F

This is the factor that assesses the current state of the diffusers in terms of dirt or aging.

The use factor (fouling & aging) F is defined as the ratio of the diffuser's standard oxygen transfer efficiency at any time ( $\alpha\text{FSOTE}$ ) to the optimal standard oxygen transfer efficiency ( $\alpha\text{SOTE}$ )

Thus, since the ratio of the  $\alpha\text{FSOTE}/\alpha\text{SOTE}$  ratio is proportional to  $[\text{AOR}/\text{QO}_2]/[\text{AOR}/\text{QO}_{2.\text{ref}}]$ , in simplified mode, we can estimate that the F-factor is calculated by dividing the reference flow rate and the current flow rate of oxygen or air (Equation 13)

$$F = \frac{Q_{\text{aire.ref}}}{Q_{\text{aire}}} \quad (13)$$

The usual range of the F-factor is between 0.7 and 0.9.

The F-factor, in fine-pored diffusers, decreases over time due to aging, fouling, inorganic fouling, or changes as a result of wastewater quality, sludge characteristics, and operating conditions.

When the F value is very close to or below 0.7, it will indicate that there is a reduced oxygen transfer, which may be due to the fouling and/or aging of the membranes of the diffusers, so a new cleaning or a change of membranes could be considered.

Diffuser membranes and couplings typically have a service life of between 8 and 10 years. Therefore, from the age of 8, in the event of a notable aeration deficiency and with a factor of less than or close to 0.7, a change of membranes could be considered when this may represent an important energy optimisation (Equation 13)

### 5.2.8. Estimated energy optimization: OE (%)

It represents the estimated optimization that can be involved in effective maintenance in a fine bubble aeration system by cleaning or changing membranes (in the event that the diffusers are already old enough for their replacement)

To do this, the theoretical percentage of optimization is calculated from the difference between the current and the reference flow with respect to the current one.

$$\text{OE} \approx 100 * \frac{Q_{\text{O}_2} - Q_{\text{O}_{2.\text{ref}}}}{Q_{\text{O}_2}} \quad (14)$$

## 6. CONCLUSIONS

Here we have presented a procedure composed of two groups of simple equations with the clear objective of following the basic principle of relating the average oxygen requirement of the input load with the oxygen that is being supplied. This relationship is linked to a contrasted reference in order to obtain an assessment of the parameters obtained. In this way, this procedure allows the aeration system to be assessed and periodically monitored by fine bubble membrane diffusers and to make the appropriate decisions.

In all this, it is important to take into account the powerful tool that the AOR/SOR ratio can mean and that in many cases could be sufficient as an assessment parameter, without having to go any further. To do this, the correct calculation of the AOR is essential.

The procedure is not intended to be scientifically accurate, but for a WWTP it is sufficient to be perfectly clear about the adequacy of the aeration system and to obtain a parameter that indicates the convenience of cleaning or changing membranes. On the other hand, it is clear that it offers the important advantage of assessing and monitoring the status of the aeration process globally.

The set of simple equations presented are easy to accommodate to any spreadsheet, with the Surcis support.

It is important to add that the reference value of 0.33 in the AOR/SOR ratio can not only be used to assess the aeration system but also as a design tool, mainly to calculate the flow of oxygen necessary for a given oxygen requirement.

The set of parameters of the mathematical model presented in this paper can give way to the calculation of other parameters, such as the  $kLa_f$ ,  $O_{Tref}$ ,  $\alpha$  estimated factor, which can be added to the package of those already calculated to increase the evaluation and monitoring criterion if necessary.

## 7. CASE STUDY FOR THE ASSESSMENT OF THE AERATION SYSTEM OF A MUNICIPAL WWTP

As an example of the application of the procedure described, a study has been carried out of the aeration system of a municipal WWTP whose operation is carried out by the spanish DAM group to which, once again, we thank for its important collaboration both in the provision of the data of the current process and in the BM Respirometry tests carried out in its laboratory.

### 7.1. Process data

**Table 3.** Technical data sheet and conditions of the wastewater treatment process

Parameter / Type	Description	Mean Value
Process type	Extended aeration	-
Type of diffusers	Fine bubble diffusers membrane	-
h	Diffuser depth	4.235 m
System age	Diffusers age	> 8 years
Cleaning diffusers	Last cleaning	4 months ago
T	Average temperature	20 °C
Q	Influen flow	3.145 m <sup>3</sup> /d
Q <sub>aire</sub>	Air flow	5.800 Nm <sup>3</sup> /h
Q <sub>O2</sub>	Oxygen flow	39.672 kg O <sub>2</sub> /d
OD	Dissolved oxygen in the aerobic zone	0.7 mg/L
COD <sub>in</sub>	Influent COD	1.055 mg/L
COD <sub>ef</sub>	Effluent COD	35 mg/L
COD <sub>e</sub>	Eliminated COD	1020 mg/L
bCOD <sub>e</sub>	Eliminated biodegradable COD (En this specific case: bCOD <sub>e</sub> = COD <sub>e</sub> )	1020 mg/L
TKN <sub>in</sub>	Inflluent TKN	101 mg N/L
TKN <sub>ef</sub>	Effluent TKN	5 mg N/L
Nn	Eliminated TKN	96 mg N/L

## 7.2. Results summary

**Table 4. Results of the study on the assessment of the aeration system in a municipal WWTP**

Parameter	Descripción	Result
AOR	Actual Oxygen Requirement.	2525 kg O <sub>2</sub> /d
SOR	Oxygen Requirement under Standard conditions	10.910 kg O <sub>2</sub> /d
AOR/SOR	Actual Oxygen Requirement / Standard Oxygen Requirement ratio	0.23
SOTE	Oxygen Transfer Efficiency under Standard conditions	27.5 %
OTE <sub>f</sub>	Actual Oxygen Transfer Efficiency in the process	6.3 %
Q <sub>O<sub>2</sub>.ref</sub>	Reference Oxygen flow	28055 kg O <sub>2</sub> /d
Q <sub>aire.ref</sub>	Reference Air flow calculated from Q <sub>O<sub>2</sub>.ref</sub>	4101 Nm <sup>3</sup> /h
F	Fouling Factor	0.7
OE	Theoretical Energy Optimisation, for the same AOR and conditions, in the event of a membrane change.	29 %

## 7.3. Analysis of the results obtained

1. In this treatment plant, the BOD/COD ratio is 0.34. Which, in principle, seems to mean that it is a wastewater with VERY low biodegradability. However, with the respirometry test for the biodegradable COD (bCOD) with a Surcis BM analyzer, the wastewater biodegradability is of 96%. The reason for this discrepancy is that there is a significant percentage of slowly biodegradable COD (sbCOD) with a very small activity that BOD<sub>5</sub> does not seem to be able to detect. On the other hand, this high degree of biodegradability detected by respirometry justifies the high performance obtained in the COD removal.
2. The AOR/SOR ratio of 0.23, far below 0.3, gives a primary assessment of a clear deficiency of the aeration system.
3. The F-factor of 0.7, even if it is in the low normal range, when taking into account the AOR/SOR value of 0.23 which is below the reference value, must be assessed as critical. Therefore, taking into account that the diffusers have been in operation for more than 8 years, it can be deduced that they are responsible for the deficiency of oxygen transfer.
4. Although the cleaning of the diffusers was carried out approximately four months ago, the aeration performance is still relatively low and the change of the diffuser membranes can lead to a significant energy optimisation (29%) by obtaining a theoretical reduction in the air flow from 5.800 Nm<sup>3</sup>/h to 4.101 Nm<sup>3</sup>/h for the same average oxygen requirement.

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