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Reduction of energy consumption by replacing surface aerators with fine bubble aeration in Slobozia Wastewater Treatment Plant, Romania

Reducerea consumului de energie prin înlocuirea aeratoarelor de suprafață cu aerare cu bule fine în Stația de Epurare a Apelor Uzate Slobozia, România

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Abstract. The biological process in a conventional wastewater treatment plant is one of the largest consumers of energy in wastewater treatment technology. The biological process can use from about 50% to 90% of the electricity used by a treatment plant (depending on its size and technological solutions used), while the cost of energy used can be up to 15–49% of the total costs of an installation. In Slobozia Wastewater Treatment plant, the energy consumption and operational costs were very high, due to the use of surface aerators in the biological tanks. In order to optimize the biological treatment and energy consumption, the present paper analyses the replacement of surface aeration with a fixed grid aeration system with membrane diffusers. By using a fine bubble aeration – lobe blower system, optimized regarding number of diffusers, aeration grids sizing, membrane material, membrane perforations size, blower motor power, the energy consumption in a wastewater treatment plant was considerably reduced and the oxygen transfer efficiency (SAE kgO2/kWh) was increased.

Keywords: wastewater treatment plant, optimization

1. Introduction

While evaluating an aeration system with regard to performance, one must take into account the total energy cost for system operation over its life span. The challenge in calculating these costs is to reliably include efficiency data that reflects the performance we would expect to measure on site.

The performance of any aeration equipment depends on the specific site conditions inherent in the installation. Liquid depth, aeration grid configuration, tank geometry, air flow, air piping placement, and other parameters have a direct impact on oxygen transfer efficiency.

The calculation equation for the economic coefficient is as follows[1]:

$$E = \left(\frac{V}{P_C}\right)\left(\frac{dC}{dt}\right) = aK_L(C_S - C)\frac{V}{P_C}, in\ \frac{kgO_2}{kWh} \quad (1)$$

- Pc = power required for gas compression

The evaluation of aeration systems performance is based on the criteria developed by the American Society of Civil Engineers[3], together with other groups.

Fine bubble aeration systems, with flexible membranes, are the most energy efficient equipment. Membranes made using high-tech technologies can ensure an oxygen transfer efficiency of up to 10-12% oxygen transfer per meter of depth, which translates into approximately 5.50 kgO_2/kWh[2].

Mechanical surface aerators are generally limited to liquid depths of up to 3.5 m to optimize oxygenation and mixing. The area of influence of this type of aerator is significantly reduced for lower depths, due to decreased air circulation capacity and oxygen transfer efficiency. This type of oxygenation requires an increased energy consumption, exceeding 0.7 kWh/m^3 of wastewater.

The energy efficiency of the mechanical oxygenation systems is found in the range of 1.5 - 2.1 kgO_2/kWh.

Table 1

Aeration systems – Energy efficiency comparison[2]

Mechanical aeration	
Surface aerator	1.82 – 2.13 kgO_2/kWh
Diffused air aeration	
Fine bubble aerator	
Membrane diffuser (disc, tube, panel)	3.04 – 4.26 kgO_2/kWh

Fine bubble aeration systems offer energy consumption saving regardless of the depth and geometry of the tank or type of application.

The optimal sizing of the aeration system influences the rate of oxygen transfer and energy consumption. Figure 2 shows 6 different aeration system designs, for a tank with fixed dimensions and the same submersion depth. Oxygen transfer efficiency increases as the number of diffusers increases and the total air flow per tank decreases, thus decreasing the air flow per diffuser membrane.

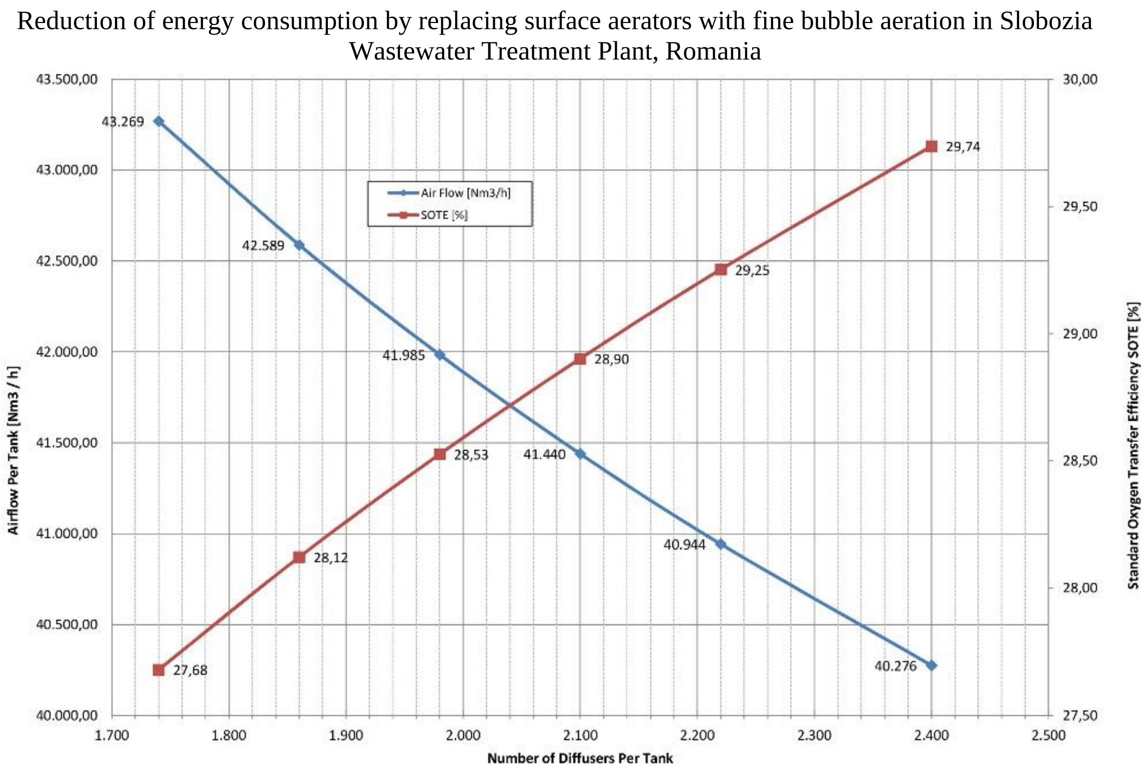


Figure 1 – Optimization of fine bubble aeration system – Oxygen Transfer (own graph)

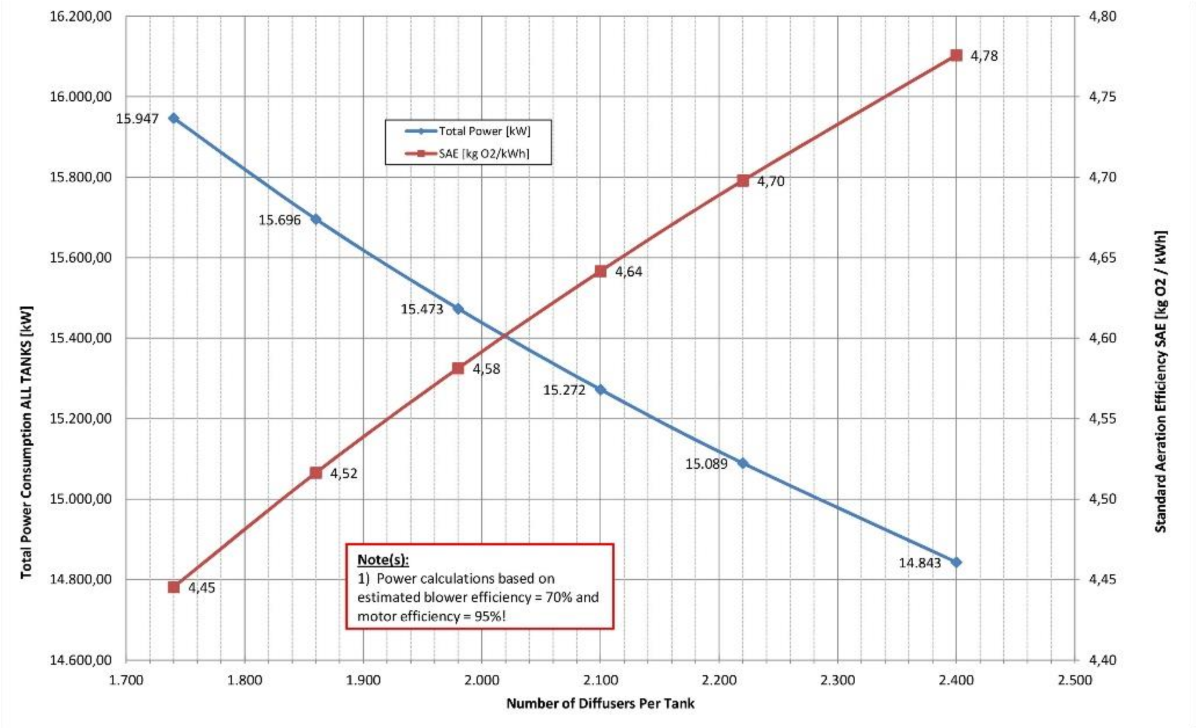


Figure 2 – Optimization of fine bubble aeration system – Energy Consumption (own graph)

2. Current situation – Slobozia WWTP

The Wastewater Treatment Plant serving Slobozia County in Romania was designed for a population equivalent of 60.000 people and a maximum daily water flow of 11.520 m^3/day.

The process is conventional wastewater treatment with activated sludge.

Figure 3 – Slobozia WWTP (Google Earth)

Inlet data and results (Appendix 1) to be taken into account in the development of this article have been corrected according to the requirements mentioned in the Government Order GD 188/2002 (technical norms NPTA-011/2002, NPTA-002/2002 and NPTA-001/2002), with reference to the water temperature in the General Project Requirements ($T_{water} = 20^0$C).

The biological treatment consists of 2 aeration tanks, with the following characteristics:

- Active units 2
- Tank aerated area surface 687,50 m^2
- Total aerated surface area 1.375,00 m^2
- Liquid depth 5,00 m
- Liquid volume 3.437,50 m^3
- Total liquid volume 6.875,00 m^3

Figure 4 – Biological tank layout (own layout)

For aeration, the plant uses surface aerators type FB 80 (Appendix 2). There are 5 aerators operating per tank.

The FB surface aerator is an open-type impeller, suitable for working with solids of various sizes. It is basically composed of a tubular shaft, an inverted cone and a certain number of driving blades, which are tangential to the central tubular shaft. The impeller is made of electro-welded steel. The impeller of the aerator, when rotating, evacuates with its blades the existing fluid around it. The evacuated fluid is continuously replaced by the fluid that occupies the base of the aerator, generating a suction from the bottom of the tank and combining a toroidal and circular movement of the entire liquid mass. In this way, a renewal of the tank surface is achieved, and speed gradients keep the activated sludge in suspension. (http://www.filtramas.com/en/catalog/biological-treatment/fb-surface-aerators/)

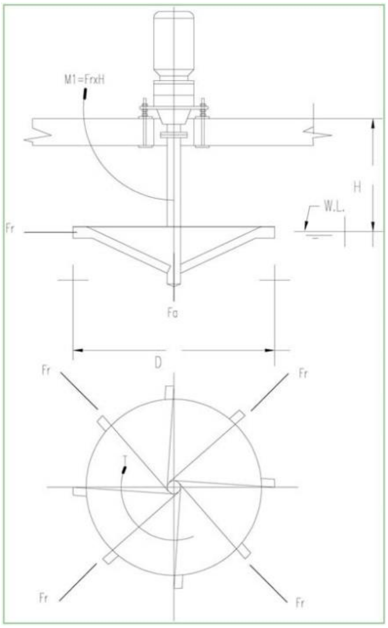


Figure 5 – Surface aerator

3. Theoretical considerations

For the dimensioning of the aeration system with pneumatic equipment, the following aspects must be taken into account:

a. Biologic tank sizing

For the analyzed application, we have 2 biological tanks, with the following dimensions per tank:

- Tank aerated area surface 687.50 m^2
- Liquid depth 5.00 m
- Liquid volume 3,437.5 m^3

b. Oxygen demand

SOR (standard oxygen transfer rate) is defined as the mass of oxygen per time unit, dissolved in a volume of liquid, produced by an oxygen transfer system operating under standard conditions of temperature, pressure, power, gas rate and DO concentration. The defined value is expressed in kgO_2/h - under normal/standard conditions, in clean water. The standard conditions for measuring oxygen transfer are defined as 1 bar ambient pressure, 20^0C water temperature, 0 mg/l dissolved oxygen and clean water.[3]

It is extremely difficult to calculate the rate of oxygen transfer in wastewater, in real conditions, due to the variety of factors impossible to control: actual temperature of the wastewater, wastewater loading, concentration of suspended solids, etc.

The efficiency of aeration systems under standard conditions is hereinafter referred to as SOTE (standard oxygen transfer efficiency).

In order to convert the measured efficiencies in standard conditions to real conditions, the SOTE value must be reduced by means of a correction factor. This factor is generally defined as the ratio of[4]:

$$AOR/SOR \tag{2}$$

- AOR = real oxygen transfer rate
- SOR = standard oxygen transfer rate

Typical AOR/SOR adjustments range from 0.3 to 0.6. Analyzing this range, it results that the actual oxygen transfer is only 30% - 60% of the measured efficiency under standard conditions.

c. Oxygen transfer efficiency from the air bubble to the liquid volume

The efficiency of an aeration system can be discussed from two perspectives:

i. Percentage of oxygen in a flow of injected gas, dissolved under given conditions for temperature, pressure, gas rate and DO concentration. The oxygen transfer efficiency per time unit is known as:
   - SOTE [%], representing the total percentage of oxygen transferred from the bubble to the water.
   - SSOTE [%/m], representing the percentage of oxygen transferred from the bubble to the water, per 1 m immersion depth
   - SSOTR [$gO_2/m^3/m$], representing the amount of oxygen transferred from the bubble to the water, per 1 m3 liquid volume and 1 m immersion depth

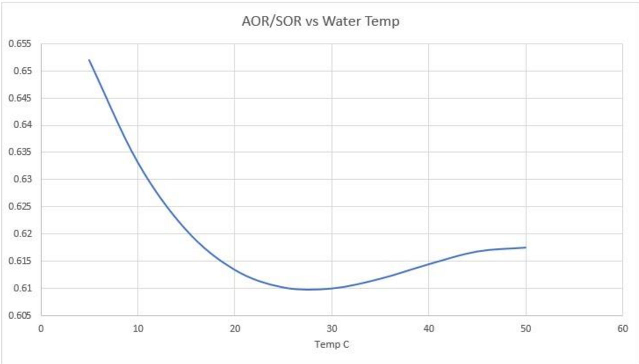
In the next chapter we will conduct various calculation to show the aeration efficiency of a floor mounted, fine bubble aeration system for the given tank dimensions and required oxygen demand.

ii. Amount of oxygen transferred to the water per 1 kWh, known as OTR [kgO_2/kWh]: This particular type of energy efficiency is the purpose of the present article.

After sizing the floor mounted, fine bubble aeration system, and the blowers required to supply the air flow for aeration, we will compare the energy consumption between the two types of aeration systems, that is surface aerators versus fine bubble aeration system.

d. Available air flow, supplied by blowers, in [Nm^3/h] – under normal conditions
e. Wastewater temperature, in [^0C]

The AOR/SOR ratio is also dependent on wastewater temperature, as shown in the below estimates.



	INPUTS	
alpha	0.8	
beta	0.98	
depth	2.70	m
elevation	0	m
depth correction	0.4	
DO	2	mg/l

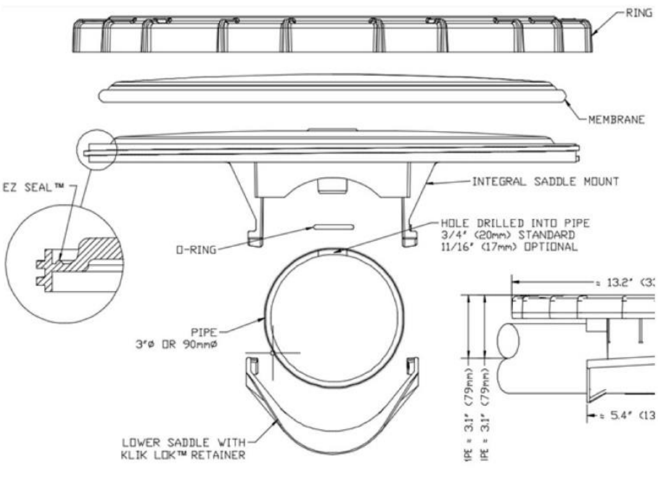
Figure 6 – AOR/SOR ratio dependent on wastewater temperature

For the present application, the fine bubble aeration system will be designed at a maximum wastewater temperature of 20^0C.

f. Organic load in the tank, as presented in the "Inlet data" table above.
g. Aeration system geometry in the biologic tank
h. Type of pneumatic aeration equipment:

The type of oxygenation equipment is chosen depending on the application, process, aeration efficiency. Fine bubble aeration equipment is applicable for high aeration efficiencies. In the case of this equipment, the air bubbles have small diameters, thus increasing the total oxygen transfer area and the oxygen transfer efficiency.

For the replacement of surface aerators in this application, fine bubble disc diffusers were chosen (Appendix 3).



Diffuser type: EDI FlexAir™ Disc 12"
Design air flow: 0-16.0 Nm^3/h
Diameter: 336 mm
Active surface: 0.059 m^2
Weight: 1.2 kg
Membrane material: EPDM
Membrane perforation: 1.0-3.0 mm

Figure 7 – Disc diffuser 12" build

4. Design of the fine bubble aeration system:

The performance capabilities of aeration systems including mechanical and diffused air systems are commonly quantified using standard methodologies under clean water conditions. In order to quantify the field performance characteristics of these systems, process water conditions must be incorporated. We employed the following methodology to determine field performance.

a. Oxygen Demand:

Oxygen demand is ultimately determined based on the mass loading of the system, originating from BOD, COD, and NH_3 coming into the influent of the plant. Part of this demand may or may not be treated upstream of the reactor by solids separation or pre-treatment (such as primary clarifiers or trickling filters). Once the remaining influent characteristics are defined, an actual oxygen demand or oxygen transfer rate (AOR) for the aeration system is determined.

b. Standardized conditions:

Once an AOR is determined, conditions must be normalized to a standard value. Standardization for oxygen transfer is defined by the following parameters:

- Clean (potable) water
- New Diffusers
- 0 mg/L operating DO
- Standard water temperature, 20^0C
- Standard pressure, 1atm

To correct for these conditions, the following equation is used based on calculations followed in the WEF Design of Municipal Wastewater Treatment Plants[4]:

$$\frac{AOR}{SOR} = \alpha * \theta^{T-20} * \frac{\tau * \beta * \Omega * C_{20}^{*} - C}{C_{20}^{*}} \tag{3}$$

- α = Alpha. Ratio of process water oxygen transfer rate to clean water oxygen transfer rate
- Ө = Theta. temperature correction factor
- for oxygen transfer rate
- T = Wastewater temperature in ^{0}C, calculated both for winter and summer conditions
- τ = Tao. Temperature correction factor for DO saturation ($\frac{C_{st}^{*}}{C_{S20}^{*}}$)
- C_{st}^{*} = tabular value of dissolved oxygen surface saturation at field temperature, 1atm and 100% RH
- C_{st20}^{*} = tabular value of dissolved oxygen surface saturation at 20^0C, 1atm, and 100% RH
- β = Beta. ratio of dissolved oxygen saturation in process water to clean water
- Ω = Pressure correction factor for DO saturation, (P_b/P_s)
- P_b = Barometric pressure under field conditions
- P_s = Barometric pressure under standard conditions, 1atm
- C_{20}^{*} = average steady state DO saturation at 20^0C and 1atm
- C = process water operating DO concentration

C_{20}^{*} can either be measured by field tests or calculated using a depth correction factor. The equation to calculate C_{20}^{*} is as follows[4]:

$$C_{20}^{*} = C_{S20}^{*} \frac{P_b + d_e}{P_b} \quad (4)$$

- d_e = effective saturation depth, d_e = 0.4 * air release depth for fine bubble

c. Diffuser sizing

Required efficiency of the selected diffuser system is determined from the following equation[4]:

$$SOTE = \left(\frac{SOR}{Q_S}\right)\left(\frac{1}{\rho}\right)\left(\frac{1}{23.17\%}\right) \quad (5)$$

- SOTE = Standard oxygen transfer efficiency
- Q_s = Standard flow rate at 20^0C, 1atm, and 35% RH
- ρ = density of air at 20^0C, 1atm, and 35% RH
- 23.17% = percentage of oxygen in air at 20^0C, 1atm, and 35% RH

The selected diffuser system should match these performance conditions in order to supply the correct amount of oxygen, using the available amount of air supplied. The performance of the system is dependent on multiple variables.

- Diffuser Submergence – the available depth of water above the centreline of the diffuser.
- Diffuser Density – commonly expressed as AT/AD (Area of Tank per Area of Diffuser).
- Airflow Rate per Diffuser
- System Configuration

Using the site-specific conditions previously listed, the value for SOR was calculated at 118.01 kgO_2/h per each tank.

For the design, we used an in-house developed Excel calculation sheet.

As input data, we took into account the given design information (Appendix 4):

The design sheet calculated a number of 568 pieces 12” disc diffusers per tank, which we now have to place in the tank layout, having in mind operational requirements, piping material and economical aspects.

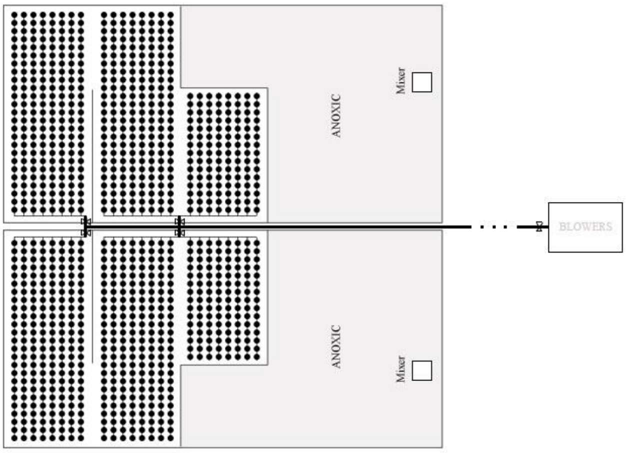


Figure 8 – Aeration system layout in biologic tanks (own design)

The figure above shows the diffused aeration system in the two biological tanks.

Aeration system is fixed on the tank bottom, being sized as two aeration grids per tank. Each aeration grid has a stainless-steel drop pipe, DN160mm, supplying air to the aeration diffusers. Each drop pipe has a valve, adjusting the air flow according to changes in loadings, wastewater temperature, etc.

The aeration system layout shows two types of grids. Grid type 1 has a main sub header pipe, DN160mm, connected to the air drop pipe. There are 8 diffuser support pipes, DN90mm, on which the disc fine bubble diffusers are installed. Grid type 2 also has a DN160mm sub header pipe, the difference being the diffuser support pipes, DN90mm. There are 16 such pipes, with different lengths.

d. Blower sizing

Based on the air requirements for diffusers system, 1087 Nm^3/h at 500 mbar(g), per aeration tank, 2 tanks in total, Atlas Copco proposed following equipment:

- Total 2+1 blowers
- Lobe blower
- With soundproof case 75 dB
- Q/blower = 1220 Nm^3/h at 500mbar(g) operating pressure
- Motor power = 22kW
- With integrated Inverter within the canopy
- With integrated controller onto the canopy, full monitoring and possibilities for remote control, Smart link available also
- Compact design 1m x 1.15m footprint

As standard Scope of supply for ZL (VCA type) lobe blowers, the following are included:

Inlet pulsation damper
Oil free 3-lobe element
Safety valve for ZL1-ZL2(DN80)
Combined start-up and safety valve for ZL2-DN100 -ZL3-ZL4
Check valve
Discharge pulsation damper
Outlet compensator (stainless steel)
Outlet air flange DIN or DIN+ANSI
Supplied with oil for 1st fill
IE3 Induction motor
TEFC IP 55
Pulley & Belt
Automatic belt tensioning system
Sound attenuating canopy
Package vibration isolators
Cubicle including:
Elektronikon® controller
VSD Inverter
Sensors discharge pressure and temperature
Flow control via 4-20 mA (external source)

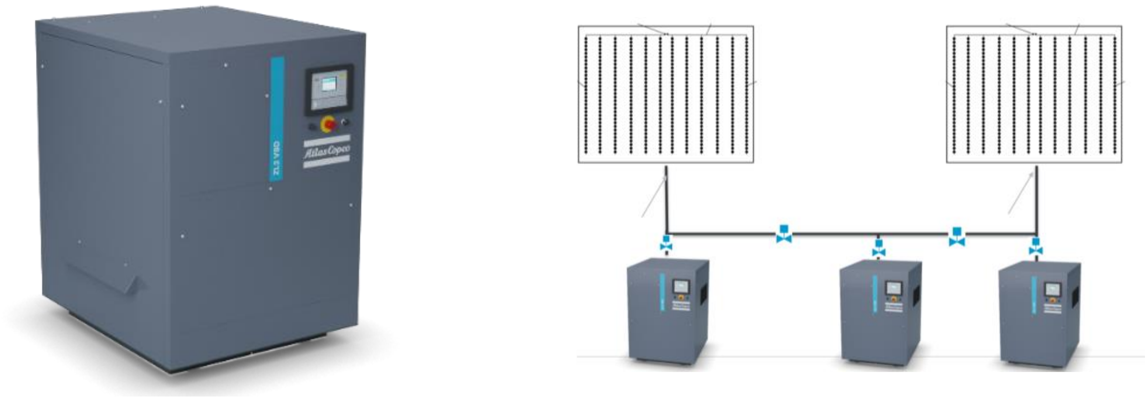


Figure 9 – Installation proposal ZL (VCA type) lobe blower

The yearly energy savings of this system versus original surface aerators system are presented in the following table, considering that cost of kWh is 0.10€.

Table 2

Yearly savings (own calculations)

Surface aerators		
Manufacturer		Filtramas S.A.
Model		FB80
Quantity	pcs	10
Package power kW	kW	25
Running hours/year	h/year	8,760
Total kWh/year	kWh (package)	219,000
Electricity cost/kWh	€/kWh	0.1
Total cost electricity €	€ (package)	219,000
Blower		
Manufacturer		Atlas Copco
Model		ZL2VSD 22K 500 lobe
Quantity	pcs	3
Inlet flow	Nm³/hr	1,078
Outlet pressure	bar	0.5
Shaft power	kW	19.9
Package power	kW	21.9
Running hours/year	h/year	5,840
Total kWh/year	kWh (shaft)	116,216
	kWh (package)	127,896
Electricity cost/kWh	€/kWh	0.1
Total cost electricity €	€ (package)	38,369
Savings/ year:	**€**	**180,631**

As shown, the calculated yearly energy savings are 180,631.00 €.

5. Conclusion

By using a fine bubble aeration – lobe blower system, optimized regarding number of diffusers, aeration grids sizing, membrane material, membrane perforations size, blower motor power, the energy consumption in a wastewater treatment plant was reduced with 85%, the oxygen transfer efficiency (SAE kgO2/kWh) was increased 2.8 times and energy costs were reduced with 180,631.00 €.

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Appendix 1 – Inlet data Slobozia WWTP

Table 1

Inlet data

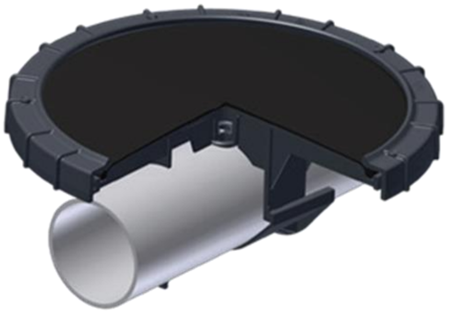
Inlet data		
Temperatures:		
Average water temperature	^0C	20
Air temperature	^0C	5
Flows		
Daily	m^3/day	11,520.00
Hourly	m^3/day	480.00
Loads		
Average BOD_5	mg/l	312.50
Maximum BOD_5	mg/l	468.75
Average COD	mg/l	625.00
Maximum COD	mg/l	937,50
BOD_5/COD ratio	%	50
Average TDS	mg/l	468.75
Maximum TDS	mg/l	703.75
TDS/ BOD_5 ratio	%	150
Average TKN	mg/l	62.50
Maximum TKN	mg/l	93.75
Total N	mg/l	62.50
Total P average	mg/l	15.63
Total P maximum	mg/l	23.44
Outlet data		
Maximum BOD_5	mg/l	25.00
Maximum COD	mg/l	125.00
Maximum TDS	mg/l	35.00
Maximum TKN	mg/l	15.00
Maximum Total P	mg/l	2.00

Appendix 2 – Technical Data Sheet surface aerator FB 80

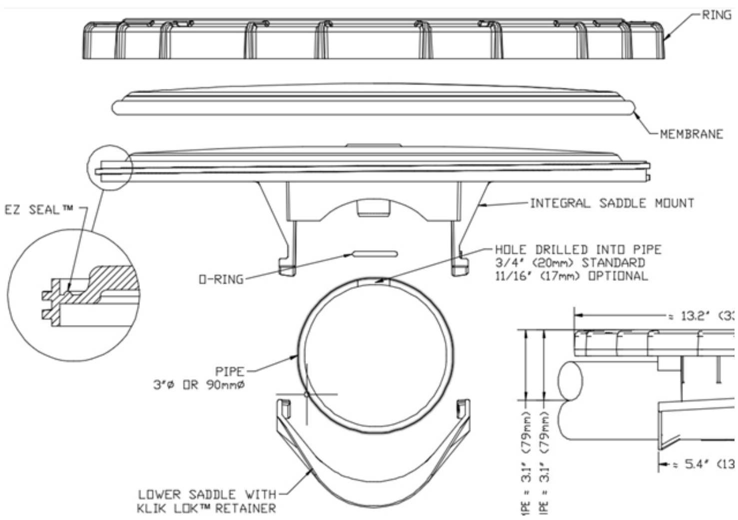
Figure 1 – Surface aerators type FB 80

Producer		Filtramas S.A.
Type		FB80
No. aerator	pcs	10
No. impeller	pcs	8
Pallet height	mm	115
Rotation speed	rpm	60.5
Container dimensions	m	12.52 x 11.62 x 4.3
Specific oxygen transfer	kgO_2/kWh	1.94
Nominal oxygen transfer	$kg\ O_2/h$	23.60
Total oxygen transfer per tank	$kg\ O_2/h$	118.01
Installed power	kW	29.44
Total installed power per tank	kW	147.20
Absorbed power	kW	25
Motor speed	rpm	1470
Outlet speed	rpm	60

Appendix 3 – Technical Data Sheet EDI FlexAir Disc Diffuser



- Glass-fiber-reinforced polypropylene body for maximum chemical, temperature, and UV resistance
- Premium quality membrane materials available: EPDM, silicone, urethane, PTFE MATRIX™, specialty polymers
- High-capacity membrane option available for maximum airflow and low operating pressure
- Triple-check valve design minimizes entry of liquid/solids into piping. Ideal for on / off applications
- Integral Saddle Mount provides ease of installation and maintenance with maximum mechanical strength
- Mounts on any pipe material (PVC, ABS, CPVC, SS, etc.)
- 12” disc available to fit 3” and 90 mm pipe sizes; 9” disc available to fit 3”, 4”, 90 mm, and 110 mm pipe sizes
- Patented EZ-Seal™ for quick membrane installation



Metric					English				
Diffuser Type	Design Airflow m^3_N/h	Overall Diam. mm	Active Surface m^2	Dry Weight kg	Diffuser Type	Design Airflow scfm	Overall Diam. in	Active Surface ft^2	Dry Weight lb
9” Nano	0-4	273	0.038	0.85	9” Nano	0-3.0	10.7	0.41	1.9
9” Micro	0-9.5	273	0.038	0.85	9” Micro	0-6.0	10.7	0.41	1.9
9” High-Cap	0-16.0	273	0.038	0.85	9” High-Cap	0-10.0	10.7	0.41	1.9
12” Nano	0-6.0	336	0.059	1.2	12” Nano	0-4.0	13.2	0.64	2.6
12” Micro	0-16.0	336	0.059	1.2	12” Micro	0-10.0	13.2	0.64	2.6
12” Macro	0-29.0	336	0.059	1.2	12” Macro	0-18.0	13.2	0.64	2.6

Appendix 4 – Technical Data Sheet EDI FlexAir Disc Diffuser

Table 3

Input data

Basin Information			
Tank / Zone	M.U.	Bio. Tank	Total (2 tanks)
Water Depth	m	5.00	
Aeration Depth	m	4.75	
Aerated Tank Floor Area (AT)	m^2	687.5	1,375
Aerated Tank Volume (VT)	m^3	3,438	6,875
Mixing			
Tank / Zone	Unit	Bio. Tank	Total (2 tanks)
Specific Airflow Rate for Mixing	$m^3_N/h/m^2$	1.50	
Volumetric Airflow Rate for Mixing	$m^3_N/h/m^3$	0.30	
Diffuser Information			
Tank / Zone	Unit	Bio.	Total (2 tanks)
Diffuser Assembly Type			
Perforated Membrane Area per Diffuser Membrane	m^2	0.059	
Oxygenation			
Tank / Zone	Unit	Bio. Tank	Total (2 tanks)
Standard Oxygen Requirement (SOR)	kgO_2/h	118.01	236.02
Specific Standard Oxygen Transfer Rate (SSOTR)	$gO_2/m^3_N/m$	22.87	

Based on the input data above, we ran the Excel design calculation sheet and obtained the results below:

Table 4

Fine bubble aeration system design calculations

Basin Information			
Tank / Zone	Unit	Bio.	Total (2 tanks)
Water Depth	m	5.00	
Aeration Depth	m	4.75	
Aerated Tank Floor Area (AT)	m^2	687.5	1,375.0
Aerated Tank Volume (VT)	m^3	3,438	6,875
Mixing			
Tank / Zone	Unit	Bio.	Total (2 tanks)
Specific Airflow Rate for Mixing	$m^3_N/h/m^2$	1.50	
Volumetric Airflow Rate for Mixing	$m^3_N/h/m^2$	0.30	
Airflow Requirement for Mixing (Q_{mix})	m^3_N/h	1,031	2,063
Diffuser Information			
Tank / Zone	Unit	Bio.	Total (2 tanks)
Diffuser Type		12in Disc	
Number of Diffuser Membranes Required	1	568	1,136
Number of Diffuser Assemblies Required	1	568	1,136
Perforated Membrane Area per Diffuser Membrane	m^2	0.059	
Perforated Membrane Area per Diffuser Assembly	m^2	0.059	
Total Perforated Membrane Area Requirement (AD)	m^2	33.8	67.5

Design Density - Floor Coverage (AD / AT)	1	4.9%	
Design Density (AT / AD)	1	20.36	
Diffuser Density, Number of Diffuser Units per AT	$1/m^2$	0.83	
Diffuser Density, AT per Diffuser Unit	m^2	1.21	
Layout Information			
Tank / Zone	Unit	Bio.	Total (2 tanks)
Number Diffuser Assemblies per Tank / Zone	1	568	1,136
Number of Grids per Tank / Zone	1	2	
Airflow for System Pipe Sizing	m^3_N/h	1,087	2,173
Number of Grids per Tank / Zone	1	2	
Average Airflow per Grid = per Drop Pipe	m^3_N/h	543	
Recommended Drop Pipe Diameter	mm	160	
Average Airflow per Sub-header	m^3_N/h	543	
Recommended Sub-header Diameter	mm	160	
Airflow per Lateral	m^3_N/h	-	
Recommended Lateral Diameter	mm	90	
Oxygenation			
Tank / Zone	Unit	Bio.	Total (2 tanks)
Standard Oxygen Requirement (SOR)	kgO2/h	118.01	236.02
Airflow Requirement for Process (Q_{oxy})	m^3_N/h	1,087	2,173
System Determining Airflow (Q_{mix} or Q_{oxy})	m^3_N/h	1,087	2,173
Specific Airflow per Aerated Tank Floor Area	$m^3_N/h/m^2$	1.58	
Airflow per Diffuser Membrane	m^3_N/h	1.91	
Diffuser Membrane Flux Rate	$m^3_N/h/m^2$	32.17	
Standard Oxygen Transfer Efficiency (SOTE)	%	36.35	
Specific Standard Oxygen Transfer Efficiency (SSOTE)	%/m	7.65	
Specific Standard Oxygen Transfer Rate (SSOTR)	$gO_2/m^3_N/m$	22.87	
SOTR per Diffuser Membrane	kgO_2/h	0.21	