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OPTIMIZATION OF NITROGEN REMOVAL IN SMALL ACTIVATED SLUDGE PLANTS

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ABSTRACT

In France, many small sewage treatment plants are of the activated sludge/extended aeration type and, generally, only receive a part of their nominal organic load. They are mostly equipped with surface aerators whose Standard Wire Aeration Efficiency is in the range 1.3 - 1.9 kg O_2 kWh^{-1}. Consequently the sludge age and the supply of oxygen are sufficient to obtain a large elimination of nitrogen from domestic waste water even when the sludge temperature is low.

However the concern is with the optimizing of the nitrogen treatment by the nitrification of ammonia in the aeration basin whilst avoiding any parasitic denitrification in the clarifier.

Amongst other investigations, 4 small domestic wastewater treatment plants were studied over several months. A number of adjustment modifications were imposed on them in order to optimize the elimination of nitrogen : The final concentrations to be reached were : $N\text{-}NH_4^+$ lower than 5 $mg.l^{-1}$ and $N\text{-}NO_3^-$ lower than 3 $mg.l^{-1}$.

The daily operating time of the aerators depends on the received load, the sludge concentration and the oxygenation capacity. When the works are under-loaded, the non-operational periods of the aerators should be as long as 1 1/2 and 2 hours in order to achieve the nitrates reduction. When the load is higher, the time required to attain anoxia after the shutdown of the aerators is shorter and the length of the non-operational periods can be reduced. These field experiments have allowed an evaluation of the tolerances around an optimum adjustment of the aeration operation : a reduction of 5 to 10 % of the daily aeration time may bring about an increase in the residual concentration of Kjeldahl nitrogen which reaches 10 $mg.l^{-1}$. Conversely, sludge losses may take place in the clarifiers if the daily aeration time is increased by 5 to 10 % in the case of completely mixed basins equipped with slow vertical shaft aerators, and more than 15 % in the case of oxidation ditches (better denitrification probably due to the continuation of the current after stopping the rotors). The sludge concentration should be kept within fairly tight limits (± 0.5 $g.l^{-1}$). It is however essential to rectify the aeration adjustments during the seasons : a rise in the sludge temperature of 10°C generates an increase in the total oxygen demand by 3 to 5 %.

The particular case of plants with anoxic zone ahead is finally discussed.

KEYWORDS

Nitrification; denitrification; activated sludge; aeration adjustment; full scale experiments.

INTRODUCTION

The majority of sewage works were designed for the treatment of particle and organic pollution of waste water. Over the last ten years or so, the need for nitrogen treatment has progressively become apparent: ammonia is toxic to aquatic life; the demands on oxygen as a result of its oxidation in rivers are high; ammonia makes preparation of drinking water difficult and the substances resulting from its oxidation represent a public health risk.

French regulations have been modified to take account of the new requirement to remove nitrogen (circular of 4 November 1980 defining levels of treatment pertaining to Kjeldahl nitrogen and overall nitrogen concentrations) while Kjeldahl nitrogen is taken into account in charges collected and subsidies granted by the Water Authorities.

Today we need to design water treatment plant able to eliminate nitrogen, and often, also to manage existing installations with the same aim in mind. Large numbers of small treatment plants are of the activated sludge/extended aeration type and receive a part only of their nominal organic load. They are mostly equipped with surface aerators whose Standard Wire Aeration Efficiency is in the range of 1.3 - 1.9 kg $O_2.kWh^{-1}$ (HEDUIT and RACAULT 1983). Under these conditions, sludge age and oxygenation capacity are sufficient to ensure elimination of the major part of the nitrogen in domestic waste water, even at low temperatures (HALL and MURPHY, 1985; INOMAE et al, 1987; CHARPENTIER 1989).

The experiments we describe have had the aim, on the one hand, of testing the capacity of such plants to eliminate nitrogen when operating at close to nominal organic load, and on the other hand, to define the aeration adjustments which under various conditions of load and temperature will make it possible to obtain a high degree of elimination of nitrogen.

THEORETICAL APPROACH

Bacterial oxygen consumption is a function of three factors:

- oxidation of organic matter
- sludge endogenous metabolism
- nitrification-denitrification.

Oxygen requirements of activated sludge over a period of a few hours can be evaluated using a simplified expression taking account of the various factors (cf. Annex 1). This expression as applied to plant treating 100 kg $BOD.d^{-1}$ (2000 eqP) reveals a daily oxygen requirement of around 180 kg, 35% is required by oxidation of organic matter, 40% for sludge endogenous metabolism and 25% for the treatment of nitrogen. This estimate allows a priori determination of timescales available for nitrification and denitrification. For this type of plant, a slow speed 11 kW surface aerator (Nominal Volumetric Power Input 36.7 $W.m^{-3}$) whose Standard Wire Aeration Efficiency would be in the order of 1.6 kg $O_2.kWh^{-1}$, would have an hourly oxygen input under process conditions of around 13 kg $O_2.h^{-1}$ (cf.Annex 2). Under such conditions, daily oxygen requirements of 180 kg could be achieved in 14 hours, thus leaving some ten hours for denitrification.

Clearly this theoretical evaluation needed to be tested in reality so as to establish whether these timescales were compatible with processing times for relevant reactions.

EQUIPMENT AND METHODS

The effect of seasonal variations of temperature on treatment, at given aeration adjustments, was studied at nominal extended aeration load in Hautot/Mer plant. The aeration adjustment reliably providing a high degree of nitrogen elimination at low temperatures and at nominal organic load was researched in Fontenay-Tresigny plant. Tolerances around the optimum adjustment level were tested. Work of a similar type was carried out in two under-loaded plants (Larchant and Changis/Marne).

These four waste water treatment plants were studied over a period of several months, and their major characteristics are shown in Table 1.

Geographical location (departement)	Design load kg BOD.j-1	Average load (% of the design load)	BOD/TKN ratio rN	Nitrogen to be nitrified per day (estimation) N kg.j-1	Average daily flow (Qm) m3.j-1	Volume of the aeration tank (V) m3	MLVSS average conc. g.l-1	N/MLVSS ratio g.kg-1.d	Tank shape	Type of slow speed surface aerator (Nbr)	Aerator size kW	Volumetric power input W.m-3
HAUTOT/MER (Seine-Maritime)	100	95 %	4.3	17	250	310	4.7	11.7	cylind	vertical shaft (1)	11	35.5
FONTENAY-TRESIGNY (Seine et Marne)	300	117 %	8.3	23	1200	1040	5	4.4	ring	rotor (2)	2 x 15	29
LARCHANT (Oise)	50	30 %	3.75	3.2	55	150	3.2	6.7	cylind conical	vertical shaft (1)	5.5	37
CHANGIS/MARNE (Seine et Marne)	100	30 %	5	4.3	150	377	4.3	2.6	ring	rotor (1)	11	30

$N = BOD/[rN] - 0.8 \times BOD \times 0.07$
where BOD : daily BOD load (kg.j-1)

Table 1: Major characteristics of the waste water treatment plants studied

The flows were measured using an ISCO bubble flow-meter (with record and printer), coupled to the plant weirs. The inlet and outlet water samples were collected by APAE 241 F and ISCO automatic samplers respectively.

Samples taken on an hourly basis were proportionally adjusted to flows in order to establish 24 h composite samples for the purposes of analysis.

Analysis of COD, BOD, MLSS, MLVSS, TKN, NH_4^+, NO_2^- and NO_3^-, were carried out in conformity with AFNOR standards.

Dissolved oxygen concentrations in the aeration basins were monitored using Ponselle oxymetric sensors (O_2P oxymeters with a Goerz Servogor 460 graphic recorder).

RESULTS AND DISCUSSION

HAUTOT SUR MER treatment plant (cf. figure 1)

This plant operates at close to nominal loads in carbon and nitrogen. It is equipped with a surface aerator operating for fifteen minutes in half hour cycles (48 cycles per day).

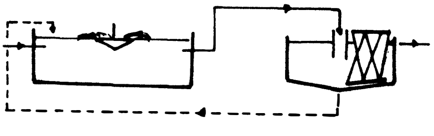

Fig. 1 - Schematic diagram of HAUTOT-sur-MER plant

Results of the three measurements carried out are reported in Table 2.

The plant having become operational in the winter, the absence of nitrification in the first experimental period can be explained by the difficulty of establishing nitrifying flora at low temperatures (7° C). During the second period, sludge temperature rose to 11° C. Nitrification was complete. (Residual ammonia nitrogen levels [2 to 3 $mg.l^{-1}$] are due to short circuiting of water at entry and exit points). Suspended solid concentration in composite exit samples of around 15 $mg.l^{-1}$ gives clear indication of absence of parasitic denitrification in the clarifier. During the third period, at the same adjustment level, denitrification was better (with a slight increase of Oxygen Uptake Rate and therefore of the daily time under conditions of anoxia).

A high degree of nitrification-denitrification in a classical extended aeration plant at its nominal organic load is therefore achievable at low temperature.

Date	Temperature °C	[MLVSS] g.1-1	effluent concentration mg N.1-1			Daily aerobic time (aert) (hours) *	Daily anoxic time (anoxt) (hours) *	Estimated nitrification rate g N.kgMLVSS-1 h-1 (1)	Estimated denitrification rate g N.kgMLVSS-1 h-1 (2)
			NH4-N	NO2-N	NO3-N				
january 9 january 31	7	5.35	60	12	3	-	-	-	-
april 23 april 24	11	4.8	2	-	6.4	17	7	> 0.65	1.5
july 3 july 5	16.2	4.6	3	0.2	0.6	16	8	> 0.75	> 1.5

* estimated from dissolved oxygen monitoring
(1) N nitrified/V x [MLVSS] x aert
(2) N denitrified/V x [MLVSS] x anoxt

Table 2 - HAUTOT SUR MER treatment plant : Results of measurements

The following remarks may be made :

Given the high number of cycles (48), and low temperature (11°C), time available for nitrification is considerably higher than the turbine operating time (nitrification continues after each close-down of the aerator during the phases of decreasing of dissolved oxygen). Inversely, periods of anoxia are considerably shorter than the periods of shut-down of the aerator.

. At 11°C, the estimated denitrification rate (1.5 g $N\text{-}NO_3$.kg MLVSS^{-1}.h^{-1}) is clearly higher than rates obtained by GRANGE and ROLLIN (1984) under extended aeration conditions ($v = 0.95\ e^{0.0875\ (T-20)}\ .\ 10^3$ or 0.45 g $N\text{-}NO_3$.kg MLVSS^{-1}.h^{-1} at 11°C). This could be a consequence of a high N/MLVSS ratio (cf table 1) and of a good mixing of raw water and sludge (high number of cycles). The installation of a 24 hour timer (clock-sequensor) adjustable over 15 minute periods would allow adaptation of cycles to loads and control of denitrification during the period of nighttime under-loading. This should be accompanied either by the introduction of raw water into the bottom of the aeration basin, or by the installation of a mixer to promote good contact between nitrates and the source of carbon, hence rapid processing.

FONTENAY-TRESIGNY treatment plant (cf. figure 2)

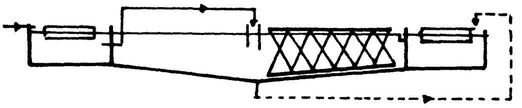

Fig. 2 - Schematic diagram of FONTENAY-TRESIGNY plant

As was the case above, the organic load received by this plant is close to nominal. Nitrogen levels in raw water are lower than normal (link with a dairy) and sludge levels are extremely high (evacuation problem). Each of the two rotors is 24 h timer controlled.

In the winter period we researched the aeration adjustment providing reliable and virtually complete elimination of nitrogen and tested possible variations around this adjustment.

Results of the measurements carried out are given in the table 3.

Optimum daily aeration time chosen of 9 hours and 45 minutes (setting 2) is higher than need be. The figure takes account of difficulties in controlling sludge levels and allows complete nitrification to be achieved even if sludge concentration rises. Nevertheless, in relation to this "optimum" an increase of 15% in the daily rotors operating time has no noticeable effect on the quality of treated water (settings 5 and 6) which indicates a certain ditch adjustment flexibility.

. It is essential that the rotors operate simultaneously in order to achieve sufficient daily anoxia time so as to avoid sludge losses (setting 3 and 4).

Setting	Experimental period	Temperat. ° C	Daily aeration time (hours)	Number of cycles per day (Rotors running)	[MLVSS] g.1-1	Effluent concentration mg N.1-1			Daily aerobic time (aert) (hours) *	Daily anoxic time (anoxt) (hours) *	Estimated nitrification rate g N.kgMLVSS-1 h-1 (1)	Estimated denitrification rate g N.kgMLVSS-1 h-1 (2)	Comment
						NH4-N	NO2-N	NO3-N					
1	january 16 january 30	9	7.45	11 [simultaneously]	6.2	13	0.05	0.03	11	13	Σ	-	
2	january 30 february 11	8.5	9.45	11 [simultaneously]	5.5	3.5	0.01	0.02	14	10	> 0.3	> 0.4	
3	february 11 february 25	8.5	9.45 9.45	23 [separately]	4.5	2.4	0.45	0.5	19	5	> 0.25	> 1	sludge losses
4	february 25 march 10	9.1	10.45 11	23 [separately]	5	1	0.55	0.7	21	3	> 0.2	> 1.5	sludge losses
5	march 10 march 23	9	10.45	11 [simultaneously]	4.55	1	0.2	0.5	15	9	> 0.3	> 0.5	
6	march 23 april 11	10	11.10	11 [simultaneously]	5	1.5	0.06	1.46	15	9	> 0.3	> 0.5	

* (1) (2) cf. table 2

Table 3: FONTENAY-TRESIGNY treatment plant : Results of measurements.

. Resulting denitrification rates for settings 3 and 4 (out of phase operation of the rotors) have been over-estimated, given the intensity of denitrification in the clarifier.

LARCHANT treatment plant (cf.figure 3)

This plant receives approximately 30% of its nominal organic load. The turbine is under 24 hour timer control. In the winter period were searched and tested fine adjustments capable of ensuring ammonia nitrogen concentration less than 5mg.l^{-1} without sludge losses through denitrification (sludge levels being kept here under tighter control). The effect of temperature on the effectiveness of treatment was then assessed. Results obtained are shown in the table below :

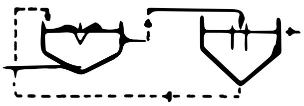

Fig.3 - Schematic diagram of LARCHANT plant

Setting	Experimental period	Temperature ° C	Daily aeration time hours)	Number of cycles per day	[MLVSS] g.1-1	Effluent concentration mg N.1-1			Daily aerobic time (aert) (hours) *	Daily anoxic time (anoxt) (hours) *	Estimated nitrification rate g N.kgMLVSS-1 h-1 (1)	Estimated denitrification rate g N.kgMLVSS-1 h-1 (2)
						NH4-N	NO2-N	NO3-N				
1	december 24 february 19	5	5 h 45	13	3.1	8.5	0.5	2.5	17	7	0.35	> 0.8
2	february 19 march 9	6	6 h 45	13	3.3	3.3	0.35	12	18	6	> 0.35	0.8
3	march 9 march 23	6,5	6 h 45	10	3.1	2	0.4	8	15.5	8.5	> 0.4	0.7
4	march 23 april 9	10,5	7 h 30	10	3.2	0.7	0.55	5	15.5	8.5	> 0.45	0.7
5	april 9 april 27	13	6 h 45	9	3.2	3.7	-	0.85	14	10	0.45	> 0.7
6	june 23 july 9	21	6 h 45	9	3.5	14	-	0.27	13	11	0.35	> 0.4

* (1) (2) cf table 2

Table 4: LARCHANT treatment plant - Results of measurements

. At around 6°C, nitrification is complete. The chosen aeration adjustment for an MLVSS concentration of 3.3 ± 0.2 g.l^{-1} is of 6 hours 45 minutes of aeration per day in 10 cycles (setting 3) : reduction by 1 hour of aeration time raises concentrations of N-NH_4 to 8.5 mg.l^{-1} (setting 1). Concentration of nitrates on exit being high, this timing cannot be increased overmuch. Tolerances around the adjustment for this temperature are probably in the region of ± half an hour (or ± 8% of daily aeration time). Raising of temperature to 13°C linked to a reduction of number of cycles improves denitrification (setting 5) while at 21°C aeration time is insufficient to ensure complete nitrification (setting 6) : the rise observed in ammonia levels is above all a consequence of the increase of sludge endogenous metabolism (3 to 5 % of the total oxygen demand). This increased demand could be satisfied by an increase of the daily aeration time in the order of half an hour.

CHANGIS/MARNE plant (cf. figure 4)

This plant receives 30% of its nominal organic load, raw water being more dilute than in the above cases. The rotor is 24 hour timer controlled. Optimum adjustment was researched and tested under winter conditions. Results of measurements are shown in Table 5.

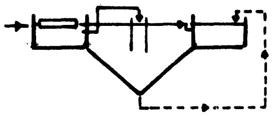

Fig. 4 - Schematic diagram of CHANGIS-sur-MARNE plant

Setting	Experimental period	Temperature °C	Daily aeration time (hours)	Number of cycles per day	[MLVSS] g.l-1	Effluent concentration mg N.l-1			Daily aerobic time (aert) (hours) *	Daily anoxic time (anoxt) (hours) *	Estimated nitrification rate g N.kgMLVSS-1 h-1 (1)	Estimated denitrification rate g N.kgMLVSS-1 h-1 (2)
						NH4-N	NO2-N	NO3-N				
1	december 19 january 11	9	6 h	8	4.2	2.02	0.09	0.8	10 h	14 h	› 0.25	› 0.2
2	january 11 january 18	9	5 h 30	8	4.5	3.5	0.17	0.14	9 h 30	14 h 30	› 0.25	› 0.15
3	january 18 january 30	6.5	5 h	8	4.45	8.4	0.56	1	9 h	15 h	0.2	› 0.10
4	february 1 february 12	6.5	7 h 30	8	4	1.3	0.12	0.8	11 h	13 h	› 0.25	› 0.2
5	february 12 february 25	5.5	7 h 30	15	4.35	0.5	0.15	6.1	17 h 30	6 h 30	› 0.15	0.3

* (1),(2) cf table 2

Table 5: CHANGIS/MARNE treatment plant - Results of measurements

. The optimum adjustment for temperatures between 5.5° and 9°C at an MLVSS concentration of 4.3 ± 0.2 $g.l^{-1}$ is of 5 hours 30 minutes per day in 8 aeration cycles (setting 2). Reduction by half an hour of this time raises nitrogen concentration to 8.4 $mg.l^{-1}$ (setting 3). Inversely the increase of aeration time by 2 hours while retaining the same number of cycles (setting 4) has no negative effect on the quality of treatment which tends to confirm the flexibility of ditch aeration adjustment in relation to that in a classic aeration basin.

The increase in the number of cycles (setting 5)gives rise to increased concentration of nitrates : as with LARCHANT, periods of shut-down of between 1 1/2 and 2 hours per cycle are required.

RECAPITULATION AND CONCLUSIONS

The study of four monitored plants has thrown light on the following points:

. At nominal load of extended aeration, a high degree of nitrification-denitrification of domestic waste water is likely achievable, at more than 5°C, in a single tank, when the plant is equipped with an efficient surface aerator (Standard Wire Aeration Efficiency : 1.6 - 1.7 kg $O_2.kWh^{-1}$) with specific Volumetric Power Input of between 35 and 40 $W.m^{-3}$. At less than full load, a high degree of elimination of nitrogen requires a lesser aeration capacity.

The daily clock-determined operating time of the aerators is a function of received load, of sludge concentration and aerator performance. Optimum adjustment of aeration aims at obtaining in 24 h composite exit samples an ammonia nitrogen concentration lower than 5 $mg.l^{-1}$ and nitric nitrogen level lower than 3 $mg.l^{-1}$ (so as to avoid the risk of sludge losses in all seasons).

. When a small plant is equipped with more than one aerator, they must operate simultaneously. This may not be the case for plug flow tanks with a number of aerators.

. Maintenance of minimum aeration times and a high degree of nitrogen elimination involves rigorous control of sludge concentration : the theoretical approach (cf. Annexes 1 and 2) permitted observation of an increase of mixed liquor volatile suspended solid concentration of 0.5 $g.l^{-1}$ induced in this case by increased oxygen requirements corresponding to more than half an hour's operating time of the aerator, a requirement liable to raise the concentration of ammonia nitrogen by over 10 $mg.l^{-1}$ if it is not satisfied (case of low dilution effluent).

. In a completely mixed basin, tolerances around optimum adjustment of operating aerators may be extremely reduced (5 to 10 % of daily aeration time).

. In oxidation ditches, the effects of excess aeration seem to be minimised and an increase of 15% of the daily aeration time in relation to optimum adjustment can have no effect on treatment quality (better denitrification is probably due to current remaining after the shut-down of the rotors).

. At times of significant underloading, the shut-down periods of the aerators must be as long as 1 1/2 and 2 hours in order to achieve a correct denitrification. At higher loads, the time necessary to attain anoxia after shut-down of the aerators is shorter, the duration of periods of shut-down may be reduced and the number of daily aeration cycles increased.

. A good mixing of sludge and raw water accelerates denitrification.

. Aeration adjustments must take account of seasonal factors: an increase of 10° in sludge temperature results in an increase of 3 - 5% in total oxygen requirements.

The low tolerances around optimum adjustment levels for classic aeration basins may justify the setting up of an anoxia zone ahead carrying out part of the denitrification, so rendering the system less sensitive to excess oxygen. In such a set-up, sludge loading factor would be calculated on the total mass of sludge used in the aeration and anoxia tanks. At nominal load the hydraulic retention time should be around 7 hours in the anoxia zone, the circulation rate of aerated liquor limited to around 400% of average flow and the rate of re-circulation of settled sludge in the order of 150% of average flow. In conditions of underloading, recycling must be maintained at a high level in order to limit the sludge residence time in the anoxia tank to 2 hours (risk of filamentous microorganisms) : intensive recycling inhibits the denitrification process, and therefore requires, as under full load conditions, partial denitrification in the aeration basin (CEMAGREF, 1989). The question then arises of the design of a variable configuration anoxia zone.

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ANNEX I

Oxygen utilization relationship

$$O_2 = a'Le + \frac{t}{24}\ b'Sv + 4,3\ N - 2,85\ c'N$$

where :

O_2 : amount of oxygen to be supplied during the period taken into consideration

a' : mass of oxygen required per unit mass of BOD removal (kg O2.kg BOD^{-1}) (a' = 0,65 for low loaded plants)

Le : mass of BOD to be removed during the period (kg)

t : length of the period (h)

b' : endogenous oxygen uptake rate (kg O_2.kg $MLVSS^{-1}.d^{-1}$) (b' = 0,07 for low loaded plants)

Sv : mass of mixed liquor volatile suspended solids in the aeration tank (kg)

4,3 : mass of oxygen required per unit mass of nitrogen to be oxidized (kg O_2.kg N^{-1})

N : mass of nitrogen to be oxidized during the period (kg)

2,85 : equivalence between oxygen and nitrate as electron acceptor under anoxic conditions

c' : fraction of nitrate nitrogen to be denitrified.

Example :

Design load : 2000 population equiv. (100 kg BOD.d-1, 24 kg TKN d^{-1}) extended aeration.

- Sludge loading factor (Cm) : 0.1 kg BOD.kg $MLVSS^{-1}.d^{-1}$)
- Volume of the aeration tank (V): 300 m^3
- t : 24 h
- Sv : 1000 kg
- N : 24 -(0.8.Le) 0.07 = 18.4 kg
- c' : 0.7

O_2 = 180 kg O_2 per day

ANNEX II

Estimation of the hourly oxygen input of an aeration device under process conditions

$$(HOI)^* = SWAE \times P \times \alpha \times 1.02^{T-10} \times \frac{[\beta(Cs)_T - C]}{(Cs)_{10}}$$

(HOI)* : Hourly oxygen input under process conditions (kg $O_2.h^{-1}$)

SWAE : Standard Wire Aeration Efficiency (kg $O_2.kWh^{-1}$)

P : Delivered power (kW)

α : Alpha factor = ratio of the overall oxygen transfer coefficient in activated sludge to this coefficient in clean water at equivalent conditions of temperature, geometry mixing, ... (dimensionless).

T : Field temperature (° C)

β : beta factor = ratio of oxygen saturation in effluent water to oxygen saturation in clean water at equivalent conditions of temperature and partial pressure (dimensionless).

$(C_s)_T$: Dissolved oxygen saturation concentration in clean water at T°C ($mg.l^{-1}$)

$(C_s)_{10}$: Dissolved oxygen saturation concentration in clean water at 10°C ($mg.l^{-1}$)

C : Operating dissolved oxygen concentration ($mg.l^{-1}$)

Example :

Design load : 2000 population equiv.

- Surface aerator
- SWAE : 1.6 kg $O_2.kWh^{-1}$
- P : 11 kW
- α : 0.9
- T : 10°C
- β : 0.97
- $(C_s)_{10}$: 11.26 $mg.l^{-1}$
- C : 1.5 $mg.l^{-1}$

(HOI)* ≃ 13 kg O_2 per hour