Applying fine bubble aeration to small aeration tanks

Ph. Duchène, E. Cotteux and S. Capela

Cemagref, Unité de recherche qualité et fonctionnement hydrologique des systèmes aquatiques, Parc de Tourvoie, B.P. 44, 92163 Antony Cedex, France.

Abstract Because the aeration system in an activated sludge plant typically represents a large part of the total energy requirements, designers and operators need accurate oxygen transfer information to make the aeration system as energy efficient as possible. This paper presents clean water tests performed at 38 wastewater treatment plants. The Specific Aeration Efficiency results (SAE, kgO_2/kWh) are reported for: (1) large open channels (volume higher than 1000 m^3), (2) small open channels, (3) total floor coverage cylindrical tanks, and (4) cylindrical tanks with a grid arrangement. Some practical guidelines can be drawn, some of them being: (1) high SAE can be achieved at small aeration tanks (<1000m^3), applying cylindrical tanks with a total floor coverage arrangement of diffusers, volumetric blowers, and moderate air flow rates per diffuser area; (2) the high investment cost of this configuration can be justified with respect to a grid layout characterized by spiral liquid circulation which affects the oxygen transfer; (3) small open channels can meet sufficient SAE values but fail to meet in this range of tank volumes those of total floor coverage cylindrical tanks.

Keywords Fine bubble; aeration; small wastewater treatment plants; spiral flows; SAE; general layout

Introduction

The activated sludge process is likely to remain the main method of wastewater treatment; even if its intensive operation tasks may result in the choice of other biological processes in certain situations, such as in small towns and lesser developed areas.

In France, operating costs are a particularly important factor for the owners of wastewater treatment plants (WWTP), especially given public subsidies for investment. Energy requirements often account for one third of the total operating costs and aeration can represent often 60% to 65% of these power costs.

Optimization of gas-liquid oxygen transfer is therefore recognized as one of the major economic factors. Reliable methods for measuring oxygen transfer under process conditions have only been available over the last few years (Redmon *et al.*, 1983; ASCE, 1996; Capela *et al.*, 1999). Their implementation is still delicate and the results are impacted not only by the configuration of the aeration system and the tank but also by the local wastewater characteristics and the loading rate. Whilst research into diffused aeration has brought some interesting initial results (Gillot *et al.*, 1997; Wagner and Pöpel, 1998; Capela, 1999; Gillot *et al.*, 2000), it has so far failed to provide a global, modeled understanding of the oxygen transfer efficiency.

Comparisons between aeration devices in identical or similar arrangements, and certain comparisons in different diffusers layouts are currently more accessible through classic oxygen transfer clean water tests (Héduit and Racault, 1983a; ASCE, 1992; ATV, 1996).

For nearly 30 years, through its measurements performed at WWTP, Cemagref has been contributing to the selection of optimal aeration devices and energy efficient configurations (Héduit and Racault, 1983b).

Whilst ceramic fine bubble diffusers offered the best performance (Héduit and Racault, 1983b), they have since been replaced in new plants and, except for a few very large WWTP, by surface aeration systems. In the 1980s, the launch of elastomer membrane diffusers that could be shut down without causing any major damage, resulted in a renewal

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of the use of fine bubble aeration concomitant in practically all cases with the objectives of nitrification and denitrification.

In the 1990s the large recently built WWTPs (> 5,000 p.e.) were almost exclusively equipped with this type of diffusers. The advantages brought in terms of noise reduction, expected performance and, more commercially speaking, the reduction of aerosol, resulted in a massive increase in the use of fine bubble diffusers with flexible membranes, even in very small aeration tanks and in non optimized configurations.

Frequently in the case of small tanks and for economic and technical reasons, the design differed from the predominant model found in the large WWTPs in France, namely in the open channel with a dissociation of the aeration and mixing functions, where large blade mixers create a controlled horizontal velocity over the diffusers (Deronzier *et al.*, 1998).

The various adaptations to small aeration tanks cover the following major types:

- the miniature open channels
- the cylindrical tanks with a total floor coverage arrangement
- the cylindrical tanks with diffusers located in one or several separate grids.

The purpose of this article is to analyze the aeration performance results obtained at 25 WWTPs (taking as a point of reference a set of results obtained at large WWTPs) and to draw practical conclusions in the form of guidelines for the design of small tanks with fine bubble diffusers.

Material and methods

Oxygen transfer measurement

The oxygen transfer measurements were carried out in clean water according to the non-steady state method and the protocol described by Héduit and Racault (1983a), defined as a variation for experienced operators in the European standard CEN (1999).

The wire power was measured at the terminals of each motor using an energy analyzer Prowatt 3 Chauvin-Arnoux. The air flow rates were determined using a Pitot tube coupled to a flow meter Zephyr Solomat, or in a few cases calculated from data supplied by the constructor.

The horizontal water velocities in the tanks were measured at 20 points over 30 seconds using an OTT C_2 hydrometric propeller (Deronzier and Duchène, 1997). The mean horizontal velocity of the liquid was calculated as follows: (i) if the velocity field is transversally homogenous then the horizontal velocity is the arithmetic mean of the velocities measured locally; (ii) otherwise, the horizontal velocity corresponds to the mean of the local velocities weighted by the number of diffusers concerned.

The parameters acquired from the oxygenation measurements in clean water are presented in Table 1.

The saturation concentration (C_s) used in the calculation of SOTR is measured *in situ* by the Winkler chemical titration. It is a specific particularity of the method employed. The Cs value corresponds to a mean hydrostatic pressure of 36% of the diffuser submergence

Table 1 Used performance parameters

	Notation	Unit	Expression
Standard Oxygen Transfer Rate	SOTR	$kgO_2.h^{-1}$	$SOTR = K_La_{20}C_{s,20}.V.10^{-3}$
Standard Oxygen Transfer Efficiency	SOTE	%/m	$SOTE = \frac{OC_{20}}{W_0.h}$
Standard Aeration Efficiency	SAE	$kgO_2.h^{-1}.kWh^{-1}$	$SAE = \frac{OC_{20}}{P_W}$

K_La_{20}: oxygen transfer coefficient at 20°C in clean water (h^{-1}); $C_{s,20}$: DO saturation concentration ($mg.L^{-1}$); V: aeration tank water volume (m^3); W_{O2}: mass flow of oxygen in air stream ($kgO_2.h^{-1}$); h: diffuser depth (m); P_W: wire power (mixer + blower) (kW) (mean of 90% of the data). This value is significantly different from the saturation at mid-depth used in certain European countries, and results in SOTR and SAE values are anything from 3% lower for a depth of 2.5m to 8% lower for a depth of 7.5m, in relation to those measured elsewhere (i.e. in Germany).

Measurement sites

The measurement sites are presented in Table 2. They consist of large open channels (LOC) (volumes over 1000 m^3 and classic geometry), of small open channels (SOC), of cylindrical tanks with a total floor coverage arrangement (FC), and of cylindrical tanks with diffusers located in separate grids not covering the entire surface of the tank (GC).

Such a set of full-scale data merits the most complete statistical analysis possible, which is done elsewhere (Capela, 1999). We shall focus here on those aspects leading to the most evident practical conclusions concerning the diffuser layout and the aeration tank in relation to the specific aeration efficiency (SAE). Furthermore, several measurements were performed at each site: with and without the simultaneous operation of mixers, at different water depths or with different air flow rates.

Results and discussion

The results (Table 3) correspond to the best SAE value obtained at each site. The SAE values result from measurements made with the simultaneous operation of the mixers in the open channels and from measurements made with only aeration in operation in the case of the cylindrical tanks. U_L is the mean horizontal water velocity (clean water,without aeration).

The SAE value integrates a large number of parameters:

- the diffuser layout and the configuration of the aeration tank
- the efficiency of the blower
- the air flow rate per perforated surface area or per diffuser pores
- the efficiency of the diffusers
- the efficiency of the mixer.

The mean SAE values therefore only provide an initial evaluation criterion. They evidence a highly significant difference between the large open channels (LOC) and the

Table 2 Site characteristics

Type	Site number	Volume (m^3)	Diffuser depth (m)	Air flow rate$^{(1)}$ ($Nm^3.h^{-1}.m^{-3}$)	Air flow rate$^{(2)}$ ($Nm^3.h^{-1}.m^{-2}$)
LOC	13	1034–15830	3.8–7.6	0.4–1.6	43.0–148.0
SOC	7	117–820	2.5–5.4	0.5–2.7	28.7–95.2
FC	7	78–1434	3.1–6.1	0.9–2.7	67.5–113.0
GC	11	62–1320	3.8–5.2	0.8–2.5	63.3–152.0

(1) *air flow rate per m^3 of aeration tank volume*
(2) *air flow rate per m^2* of perforated area of diffusers

Table 3 Oxygen transfer efficiencies as a function of the aeration tank type

	Average SAE ($kgO_2.kWh^{-1}$)	Range of SAE ($kgO_2.kWh^{-1}$)	Increase in SOTR by mixing (%)	Change in SAE by mixing (%)	$\frac{P(mixer)}{P(blower)}$ (%)	U_L (cm/s)
LOC	3.41	2.5–4.3	+ 43	+ 27	12.6	36.2
SOC	1.95	1.3–2.6	+ 36	+ 10	23.6	35.3
FC	3.11	2.3–3.9	+ 10	–12	24.8	16.0
GC	2.12	1.1–3.1				

cylindrical tanks with a total floor coverage arrangement (FC), on the one hand, and the miniaturized open channels (SOC) and cylindrical tanks with grids arrangement (GC) on the other hand.

In the case of the large open channels, that are taken here as a point of reference, the rotation of the liquid, above a mean velocity of 30 cm/s, allows us to minimize the spiral flow effect and particularly the spiral flows which occur between the grids of diffusers or outside the grids (Deronzier *et al.*, 1998). It should be noted that the mean SAE value of these aeration tanks is quite clearly penalized by two results obtained with a type of diffusers probably less efficient (mean SAE = 3.55 kg O_2/kWh for the best 11 results).

Cylindrical aeration tanks

From comparable data in terms of volume, water depth and specific air flow rate, the mean SAE measured in tanks with a total floor coverage arrangement is 47% higher than that measured in the case of grids arrangement. This result must, however, be tempered by the results obtained in tanks with a grid arrangement where the air is supplied by centrifugal blowers, the yield of which is 20% to 30% less than that of volumetric blowers. Setting these measurements aside, the difference in SAE between the two arrangements is close to 40%, which matches previous results (Deronzier *et al.,* 1998). The grid arrangement in fact induces vertical liquid circulation movements, which accelerate the rise of the air bubbles, reduces their contact time and the oxygen transfer efficiency (Fujie *et al.,* 1997).

Interesting conclusions can be drawn from the comparison of the measurements performed with a horizontal water velocity induced by the mixers.

- In all cases, despite the relatively high stirring powers (+25% on average), the mean horizontal velocities is low (16 cm/s on average). This can be explained: i) by the use of small blade mixers (just a few dozen centimetres in diameter) with high speed (a few hundred revolutions per minute) and not, as in the large open channels, large blade mixers (diameter from 1.8 to 3 m) with slow speed (a few dozen revolutions per minute) which are more energy efficient for the direct thrust and the total induced flow rate and, ii) by the fact that in these tanks the air bubbles reduce the efficiency of the thrust of the horizontal axis mixers.
- The mean increase in the SAE due to the mixing is slightly higher in the tanks with a total floor coverage arrangement (15% on average)[1] than in the tanks with a grid arrangement (on average 8%)[1]. We can suppose that in the case of the grid arrangement, when the aeration is in operation, the bubble clouds constitute a headloss and the horizontal water velocity tends to flow around the grids of diffusers, resulting in a lower effective horizontal velocity on the diffusers than that calculated on the basis of the velocities measured without aeration.

The influence of the horizontal velocity therefore clearly corresponds to that obtained in large open channels for the tanks with a total floor coverage arrangement and would appear to be only halved in the tanks with grids (Deronzier *et al*., 1998).

As a result of these slight increases in SAE, the simultaneous operation of mixers lowers significantly SAE values, in the cylindrical aeration tanks. It can be concluded from this that in these tanks the alternate operation of aeration and mixing must be ensured (which improves the denitrification rate) and sufficient mixing by aeration alone ("self cleaning" of the floor).

All these findings lead us to recommend, for small aeration tanks, a configuration in cylindrical tanks with a total floor coverage arrangement. The periods of operation of aera-

[1] Means established on reduced numbers in comparison with Table 3.

tion must be dissociated from those of mixing. Furthermore, in the tanks with a total floor coverage arrangement, it must be possible to come back up the diffusers sector by sector, given the frequency of problems and the relatively short life time of the elastomer diffusers (a few years). The additional cost in comparison with the grid arrangement can be offset extremely rapidly by owners, especially in the French context.

The other parameters for optimization of the aeration system in clean water are common, and concern the number of diffusers, their density at the bottom of the tank, the air flow rate per perforated area of the diffusers, the water depth, and the type of blower. The first four factors are all related : at a fixed air flow rate, the greater the number of diffusers, the higher the SOTE. The water depth has practically no effect on the SAE. Various tanks studied with two water depths failed to evidence any significant difference in the SAE values (Table 4). This corroborates the results of Wagner and Pöpel (1998).

In practice, it is only under a depth of 3 m that the water depth has a negative effect on the SAE. On the contrary, very high water depths do not improve the SAE in clean water, but are likely to impact the alpha factor due to the progressive adsorption of the surfactants at the interface of the bubbles

The variability in the results of the grid arrangement can be explained to a large extent by the surface percentage of the tank occupied by the grids of diffusers. The best results, exceeding 2.5 kgO_2/kwh in SAE, were obtained in tanks where grids were added, often after initially disappointing clean water tests and where the diffuser layout comes close to a total floor coverage arrangement. In such circumstances, they no longer offer any economic advantages from the investment view sufficient to justify this non total floor coverage arrangement.

Naturally, the case of the cylindrical tanks can be extrapolated to that of the parallelepipedic tanks. Nevertheless, interesting performance results have been recorded in a tank with the diffusers located in separate grids and equipped with a vertical axis large blade mixer in a central position with a thrust from the surface towards the bottom ($OCN_{Benfeld}$=3.54 kgO_2/kWh), with the mixer operating simultaneously. This result remains to be confirmed, as the preliminary studies did not enable any modeling to be made.

Miniaturization of the open channels

Economic constraints have a particular impact on the design of these small open channels. In the case of small tanks, it is not easy to place the aeration tank, which is always ring-shaped, around a central focal zone such as an anaerobic tank, an anoxic tank or even occasionally a selector.

Two major types can be distinguished (Table 5): Type I, with simple miniaturization of large open channels with an outside radius/inside radius ratio less than 1.5 (i.e. with large central focal zone) ; and Type II, the inside radius of curvature of which is very small, with the outside radius/inside radius ratio between 2 and 5 (i.e. with small central focal zone).

The example of the aeration tank no 3 allows us to illustrate the SAE range in the case of Type I tanks. The aeration tank is equipped with two, diametrically opposite grids and a

Table 4 Influence of water depth on the oxygen transfer efficiency at the aeration tank of Graye/Mer (FC)

Water depth (m)	Volume (m^3)	Air flow rate ($Nm^3.h^{-1}.m^{-2}$)	SOTE (%/m)	Ps ($W.m^{-3}$)	SOTR ($kgO_2.h^{-1}$)	SAE (kgO_2/kWh)
6.1	475	99.5	5.2	34.7	53.9	3.2
3.1	243	112.6	5.5	40.5	31.5	3.2

P_S: specific wire power(kW), $P_s = P_w/V$

Table 5 Characteristics of miniaturized aeration open channels
(SB: small blades; LB: large blades)

Site no	Type	V (m^3)	H (m)	DD (%)	Mixer type	P_{mixer} (kW)	P_{blower} (kW)	Ps ($W.m^{-3}$)	SOTE (%/m)	SAE ($kgO_2.kWh^{-1}$)	Handicaps
1	I	216	3.1	6.7	SB	2.64	9.49	56	7.2	1.30	(1), (3), (5)
2	I	135	3.3	7.0	SB	2.33	5.02	47	4.2	1.48	(1), (3)
3	I	117	2.5	2.5	SB	1.58	6.52	69	4.8	1.27	(1), (2), (3), (4), (5), (6)
4	I	320	3.0	4.8	LB	1.06	7.32	26	5.6	2.81	(3)
5	II	823	5.4	7.5	LB	2.31	20.59	28	3.8	1.90	(2), (8)
6	II	820	5.4	5.0	LB	2.43	10.13	16	5.5	2.49	(2), (7), (8)
7	II	865	5.5	4.2	LB	4.41	17.60	26	5.2	2.26	(7), (8)

small blade mixer located immediately downstream of one of the grids. The air supply is provided by a centrifugal blower and the diffuser depth is 2.25 m. The negative impacts on oxygen transfer can be approached as follows.

1. The use of a small blade mixer (consuming an additional 1 to 1.2 kW, and lowering the SAE by approximately 16%).
2. The mixer positioned in the bubbles clouds. In this case, aeration slows down the mean velocity by 15 cm/s, instead of 1 to 2cm/s when the mixers are not directly affected by aeration, which lowers the oxygen transfer by something in the order of 25% (Deronzier and Duchène, 1997).
3. The small size of the tank implies a low volume/wetted surface ratio in relation to large open channels, which overall doubles the mixing power required, with a subsequent impact on the SAE of approximately 7%.
4. The mean horizontal velocity without aeration is only 21.5 cm/s, suggesting an oxygen transfer reduced by something of the order of 10% in relation to the optimum obtained above velocities of 30 cm/s.
5. The air supply from a centrifugal blower: loss of yield of at least 25% in comparison to a volumetric blower (i.e. ROOTS type).
6. The low diffuser depth (<3 m): presumed effect on the SAE of 5 to 10%.

In the case of the site no 3, if the SAE values measured are corrected by the various coefficients above, the result would come close to 3 kgO_2/kWh. The fact that this value is still way below the performance measured on the large open channels comes from the fact that: (i) the various coefficients 1. to 6. have been relatively reduced above, so as not to exaggerate the importance of each factor analyzed separately, and that (ii) in this particular case, the longitudinal arrangement of tubular diffusers with very low horizontal velocities is probably an additional negative factor for the oxygen transfer efficiency.

In the case of the Type II tanks, with wide tanks in relation to their overall length and with a small inside radius of curvature, the specific phenomena impacting oxygen transfer are of two kinds.

7. The absence of homogeneity across the width of the field of horizontal velocities under the combined effect of the relatively low power required, of the considerable width of the tank and of the short distance between the mixer and the first downstream grid, which all help to create counter currents.
8. The lesser efficiency of the large blade mixers due to the fact that the surface area concerned by the mixers is relatively small in relation to the cross section of the tank and to the fact that interior counter currents are created more easily as a result of the small inside radius of the tank.

The various problems affecting the aeration performance of each tank are listed in the last column of Table 5, with the codes used (n) in the comments above. The tank no 4 presents more or less the best example of what can be achieved in small tanks, evidencing furthermore performance levels below those of the majority of cylindrical tanks with a total floor coverage arrangement.

Conclusions

Fine bubble aeration by elastomer membrane for small aeration tanks, defined here as having volumes of less than 1,000 m^3 and especially for aeration tanks of less than 500–600 m^3, is often employed at the expense of the energy efficiency of oxygen transfer. However, within this size range, the use of cylindrical tanks with a total floor coverage makes it possible to reach easily SAE values that are worthwhile for local authorities, above 3 kgO_2/kWh in clean water, provided that volumetric blowers are employed and moderate specific air flow rates implemented.

The extra investment cost of this type of arrangement, maintaining diffusers that can be raised sector by sector, does not warrant the continuing use of diffuser grids which induce spiral flows uncontrollable by a simultaneous mechanical mixing.

The majority of tests performed in miniaturized open channels have so far resulted in relative failures as far as SAE is concerned. Subject to certain precautions – efficiency of the mixer and air supply equipment, minimum distance both upstream and downstream between the mixer and a single array of diffusers, avoiding excessively small inside radii – it is perfectly possible to obtain sufficient SAE values, even though they do not, within this size range, exceed those of cylindrical or parallelepiped tanks with a total floor coverage.

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