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OPTIMIZATION OF OXYGEN TRANSFER IN CLEAN WATER BY FINE BUBBLE DIFFUSED AIR SYSTEM AND SEPARATE MIXING IN AERATION DITCHES

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ABSTRACT

The influence of design parameters on the transfer of oxygen was studied in different ring ditches equipped with fine bubble membrane air diffusers and separate mixing. The results produced evidence that the oxygen transfer efficiency (OTE) decreases when the air flow rate per diffuser increases. OTE increases asymptotically with the horizontal water flow (50% for velocity up to 0.5 m/sec). It increases also when the diffuser modules are brought closer together. Theoretical analysis enabled ranking of the impact of the design parameters on which the oxygen transfer is dependent, namely the interfacial area (a) and the oxygen transfer coefficient (Kl). The increase in the air flow rate per diffuser essentially reduces the interfacial area by an increase in the diameter of the initial air bubbles and by a reduction of the contact time due to an acceleration of the "spiral flows" (vertical rotation of water flow). The horizontal rotation of water increases the interfacial area most probably by decreasing the diameter of the initial air bubbles and by a lengthening of the contact time resulting from a reduction in the large spiral flows. Bringing the diffuser modules closer together makes longer the contact time by a reduction in the large spiral flows.

KEYWORDS

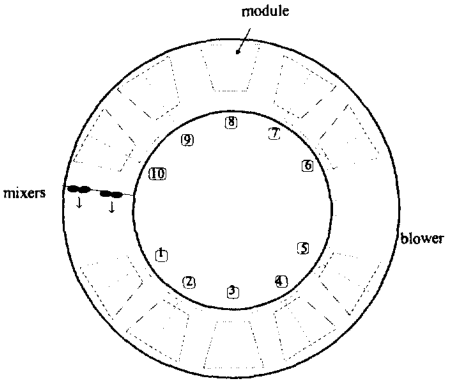
Clean water; diffused air; full scale; horizontal flow; mixing; oxygen transfer.

INTRODUCTION

There has been an increase in France, over the last few years, in the number of wastewater treatment plants which combine a fine pore aeration system and a separate stirring system with a mixer. The aeration system includes diffusers (disks, rectangles or tubes equipped with a microperforated elastomer membrane) which does not clog significantly when aeration is stopped. The dissociation of aeration and mixing offers several advantages : (i) it increases the potential elimination of nitrogen by increasing the denitrification rate, thanks to the mixing which improves the contact between the substrate, the nitrates and the denitrifying bacteria when aeration is stopped; (ii) it enables the recovery of sludge deposited in the empty spaces between the diffusers; (iii) it enables an increase in the oxygen transfer by the horizontal rotation of water (Pasveer *et al.*, 1965; Graaf, 1979; Deronzier, 1994). The purpose of this paper is to present experimental results evidencing the influence of the design parameters (air flow rate per diffuser, horizontal water velocity, layout of the diffusers) on oxygen transfer in clean water, and to propose means for optimizing the oxygen transfer by fine bubble aeration and separate mixing.

MATERIALS AND METHODS

The experimental study of the role played by each of the design parameters on oxygen transfer consisted of several series of measurements (seven are presented here) in different aeration ditches, in particular at the treatment plant of Milly La Forêt. For each measurement, the overall oxygen transfer coefficient (K_La) was measured in clean water and by varying one single parameter. The aeration tanks studied were ring ditches equipped with an aeration system by fine bubble diffused aeration consisting of diffusers arranged in modules and supplied with air by a blower (Figure 1). Mixing was provided by slow, large-blade mixers. The oxygen transfer capacity, OC, (or mass of oxygen transferred per hour) was measured using the unsteady state clean water test (Héduit *et al.*, 1983a, b). The horizontal water velocity was determined, aeration stopped, using an OTT CE hydrometric propeller. The measurements were recorded at 20 points evenly located along the radius of the aeration ditch over a section upstream of the mixers, for 30 seconds at each point. The mean horizontal water velocity is the arithmetic mean of the local measures (Deronzier *et al.*, 1997; Da Silva-Deronzier, 1994).



volume : 1400 m^3,
water depth : 2.75 m
mixing : two Flygt, type 4430 mixers with a 2 m. banana blade diameter. A frequency variator enables flow modulation.
aeration system : 720 Sanitaire 9' EDPM micro-perforated membrane diffusers spaced regularly over 10 unconnected units and a Robuschi RB 80 blower.

Figure 1. Scheme of an experimental ditch (Milly La Forêt).

The air flow rate was determined in different ways, depending on the site configuration. At certain sites, it complied with the standard NF X 10-102 (AFNOR, 1971) the measurement principle of which consists of creating a loss of head by the introduction of a diaphragm on the discharge pipe. The difference in pressure between upstream and downstream of the diaphragm is measured by a U water pressure gauge. The absolute pressure upstream of the diaphragm is measured by a Haenni pressure gauge. At other sites, the air flow rate was measured with a Pitot Zéphir 5M tube from Solomat. Finally, when it was impossible to measure the air flow rate directly, it was determined from data supplied by the constructor of the blower.

RESULTS AND DISCUSSION

Influence of the air flow rate per m^2 of membrane

All authors are agreed that the oxygen transfer efficiency, OTE, (fraction of the oxygen in the injected air which is dissolved) or OTEd (OTE/depth of submergence for the diffusers) decreases according to the air flow rate per diffuser (EPA, 1989). Nevertheless, measurements of oxygen transfer efficiency at different air flow rates per diffuser were taken to quantify this phenomenon in the various ditches studied and to analyse the influence of the air flow rate on the parameters which influence oxygen transfer. In six aeration ditches equipped with different diffusers (disks of varying diameters, and tubes), two measurements of oxygen transfer were performed with the air flow rate approximately doubling. The air flow rates were related to the area of perforated membranes. The results obtained are shown in Figure 2. They show that a decrease in the air flow rate of 10 m^3/hr per square metre of membrane results in a percentage increase in OTEd of between 1.5% and 5%. For example, at Saint Germain's ditch, the OTEd respectively measured for air flow rate per m^2 of perforated membranes of 47.1 and 80.2 were 6.07% and 5.34% and the percentage increase in the oxygen transfer efficiency is 4.13% for a decrease of air flow rate of 10 m^3/h per m^2 of perforated membrane. The different increase in oxygen transfer efficiency for an identical reduction in the air flow rate per m^2 of membrane can be explained, on the one hand, by the different membranes studied, on the other hand, by the different specific air flow rates studied (between 20 to 200 m^3/h per m^2 of perforated membrane). It is interesting to remark that the variation of the percentage increase of OTE (1.5%-5%) is low compared to the difference of specific air flow rates. Furthermore, the increase is greater in the presence of a horizontal water flow.

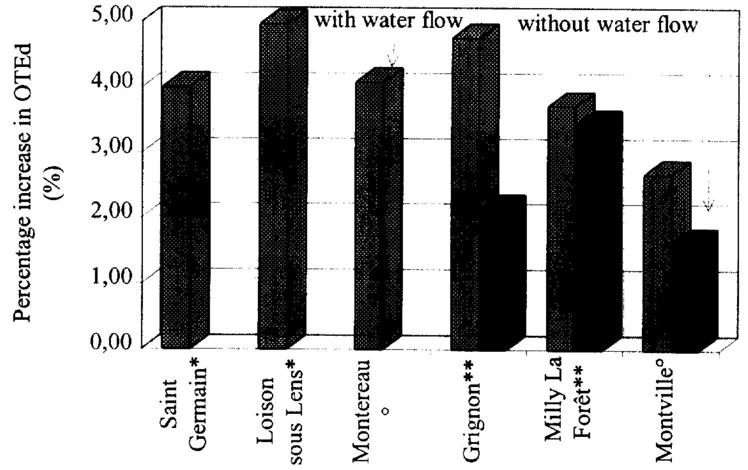


Figure 2. Percentage increase in OTEd for a decrease of air flow rate per square metre of perforated membrane of 10 (m^3/h per m^2 of perforated membrane). *: air flow rate measured with a Pitot tube; **: air flow rate measured in compliance with the standard NF X 10-102; °: air flow rate obtained from data supplied by the constructor.

Understanding the decrease in the oxygen transfer efficiency following an increase in the air flow rate per diffuser requires a preliminary study of the two parameters which rule oxygen transfer, shown by the oxygen transfer equation (1). These parameters are the interfacial area, a, (exchange surface area related to the water volume), and the oxygen transfer coefficient based on liquid film resistance, Kl. The interfacial area depends on the size and shape of the air bubbles and on the transfer time. The oxygen transfer coefficient depends on the mixing of the water.

$$\frac{dC}{dt} = Kl\ a\ (Cs - C) = K_La\ (Cs - C) \qquad \text{at t°C, temperature} \qquad (1)$$

where: C is the dissolved oxygen concentration (mg/L) at the time, t, (sec), Kl is the oxygen transfer coefficient based on liquid film resistance (m/sec), a is the interfacial area (m^{-1}), Cs is the saturated concentration of dissolved oxygen (mg/L), K_La is the overall oxygen transfer coefficient (/sec).

Evolution of the interfacial area by modification of the bubble size. The impact of an increase in the air flow rate on the interfacial area was studied. The coalescence of the air bubbles in water is negligible (Calderbank *et al.*, 1964; Otake *et al.*, 1976) and does not explain the results obtained. The next analysis shows that the interfacial area is reduced when the air flow rate increases because, on the one hand, the diameter of the initial air bubbles is enlarged and, on the other hand, the air-water contact time is reduced.

Several domains of air bubble formation must be distinguished. Hayes *et al.* (1959) and McCann *et al.* (1969, 1971) showed that for low gas flow rates the volume of the bubbles remains fairly constant, but that the frequency of bubble formation increases with the flow rate. For higher flow rates, the frequency of bubble formation remains relatively constant, but the volume increases with the flow rate. Kupferberg *et al.* (1969) proposed a domain half way between the two. For average flow rates, the size of the air bubble depends on the flow rate and to a lesser extent on the diameter of the opening. Treybal (1980) set the limits of the previous domains. Our experimental conditions were those for which the Reynolds number, Re ($R_e = d_0 V_0 \rho_G / \mu_G$), for the diffuser is less than 2 100, and the air flow rate per diffuser is low, namely $Q_0 < [20 (\sigma d_0)^5 / (g^2 (\rho_L - \rho_G)^2 \rho_L^3)]^{1/6}$.

These conditions correspond to a formation of individual bubbles of regular shape. Their diameter, D, depends solely on the size of the diffuser opening. By equalizing the Archimedes thrust exerted on the bubble with its weight, plus the surface tension stress, we obtain :

$$D = [6\sigma d_0 / g (\rho_L - \rho_G)]^{1/3} \tag{2}$$

where: D is the diameter of the bubble (m), σ is the gas-liquid surface tension (N/m), d_0 is the pore diameter (m), g is the gravity acceleration (N/kg), ρ_L is the density of water (kg/m^3), ρ_G is the density of air (kg/m^3), Q_0 is the air flow rate per opening (m^3/sec), V_0 is the speed of the gas through the opening (m/sec) and μ_G is the gas viscosity (kg/m.sec).

The diffuser fitted with a perforated membrane opens under the gas pressure. The greater the air flow rate, the larger the diffuser opening. So the diameter of the air bubbles which depends on the openings of the diffuser (equation 2) depends consequently on the air flow rate in the case of a diffuser fitted with membrane. An increase of the air flow rate per diffuser induces an increase of the diameter of the air bubble and consecutively a decrease of interfacial area.

In the case of ceramic diffusers, the opening is constant whatever the air flow rate is. The diameter of initial bubbles is therefore constant (equation 2) and does not depend on air flow rate. However, a decrease of OTE according to the air flow rate per diffuser have been observed with ceramic diffusers (Table 1).

Table 1. Impact of air flow rate per diffuser on OTE and on OTEd for ceramic diffusers (Nokia HKR 215) on a ring ditch (volume: 892 m^3, water depth: 3.92 m)

total air flow rate (m^3/hr)	air flow /diffuser (m^3/hr)	OC (kg O_2/hr)	OTE (%)	OTEd (%/m)
424.2	1.9	19.2	16.2	4.60
1004.4	4.5	42.0	15.0	4.26

So the decrease of OTE when the air flow rate per diffuser increases is explained partly by the increase of air bubble size according to the air flow rate. The other reasons making clear the results obtained are presented below.

Evolution of the interfacial area by modification of air-water contact time. The final speed of an isolated bubble, which rises freely in water, is an increasing function of the diameter of the air bubbles. It increases from 18 to 21 cm/sec for a diameter of between 1.5 and 2 mm, and from 21 to 23 cm/sec for a diameter of between 2 and 3 mm, and remains more or less constant for a diameter of between 3 and 4 mm (Haberman *et al.*, 1954).

Thus, an increase in the air flow rate per diffuser, inducing the formation of increasingly large bubbles, indirectly causes a negligible decrease in the water-air contact time if the initial diameter of the bubbles is between 1.5 and 3 mm, and no decrease if the diameter is between 3 and 4 mm. Furthermore, the contact time is related not only to the rising speed of the air bubbles but also to the vertical water flow. The spacing of the diffusers provoke a vertical rotation, or "spiral flow". A distinction can be made between the large spiral flows which occur between the diffuser modules and the small spiral flows which occur between the diffusers themselves. Fujie (1992) quantified the rising speed of the liquid, U_L, induced in a parallel-piped tank fitted with diffusers over one half of the floor, and thus demonstrated that this is an increasing function of the air flow rate.

$$U_L = K\,(HQ)^n \qquad (3)$$

where: Q is the air flow rate, H is the depth of submergence for the diffusers (m), K is a constant parameter, n = 1/3 or 1/2 according to the air flow rate.

So as a result of an increase in the air flow rate per diffuser the interfacial area reduces not only because of a bubble size increase but also because of a decrease of air-water contact time.

Evolution of the oxygen transfer coefficient by modification of the hydraulic regime. Furthermore, the oxygen transfer coefficient based on liquid film resistance, Kl, can be improved by increasing the difference between the oxygen concentrations in the air and in the water. Practically speaking, this means that, during the rise of the air bubble, the renewal speed of the liquid layer around the air bubble by a water film with a lower oxygen concentration must be increased. The energy, Pu (J/sec), released by the air bubbles, in the case of a reversible and isothermal expansion, is expressed by (Roques, 1979):

$$Pu = (\rho_G q/M)\,R\,T\,\ln(1 + H/10.33) \qquad (4)$$

where: ρ_G is the density of air (kg/m^3), q is the volume air flow rate (m^3/sec), M is the molar air mass (kg/mol), R is the perfect gas constant (J/mol. °K), T is the air temperature (°K), and H is the depth of submergence for the diffusers (m).

Table 2 shows the specific dissipated energies, as a ratio of the energy released by the expansion of the bubbles over the volume of water, P_{ds}, measured at Milly La Forêt's ditch. It shows that an increase in the total air flow rate from 335 m^3/h to 1569 m^3/h results in an increase of the specific dissipated energy of 4.9 W/m^3.

Table 2. Energy released by the expansion of the air bubbles according to the air flow rate (Milly la Forêt)

total air flow rate (m^3/hr)	335	520	751	981	1569
OTEd (%/m)	9.7	9.4	8.2	7.9	7.0
P_{ds} (W/m^3)	1.32	2.05	2.97	3.87	6.20

Furthermore, it has been shown (Da Silva-Deronzier, 1994) that an increase in the water flow up to 0.5 m/sec results in a negligible renewal of the water. If it is considered that 50% of the power consumed by the mixers is released into the water, the specific dissipated energy corresponding to a flow of 0.5 m/sec is 3.4 W/m^3. This value is of the same order of magnitude as the increase in the specific dissipated energy resulting from an increase in the number of about five in the air flow rate. It can therefore be concluded that a variation in the air flow rate has probably little influence on the renewal of the liquid layer around the air bubble and consecutively on oxygen transfer coefficient, Kl.

Influence of horizontal water velocity

Numerous measurements of the influence of horizontal water velocity on oxygen transfer were performed in several ditches. The results obtained show an improvement in oxygen transfer of between 35% and 55% resulting from the horizontal rotation of the water in the order of 0.35 m/sec for depth of submergence of diffusers between 2.7 m and 5.5 m and air flow rates per diffuser of between 1 and 5 m^3/h per diffuser. In more precise terms, the oxygen transfer capacity is an increasing asymptotic function of the water flow rate. Over a speed of 0.40 m/sec, the increase in oxygen transfer is extremely slight. It would not appear that the increase in oxygen transfer depends significantly either on the air flow rate or on the configuration of the aeration system, as suggested by the results obtained at the treatment plants : Milly La Forêt and Grignon (Tables 3 and 4).

Table 3. Increase of OC as a function of horizontal water flow for various module layouts and air flow rates (Milly La Forêt). Air flow rates were measured in compliance with the standard NF X 10-102 *: all the modules are supplied in air; **: 1 module out of 2 is supplied in air

horizontal water flow (m/sec)	Increase of OC (compared to OC without horizontal water flow) (%)			
	Air flow rate per diffuser : 1.33 (m^3/hr. diffuser *)	Air flow rate per diffuser : 2.18 (m^3/hr diffuser *)	Air flow rate per diffuser : 2.23 (m^3/hr diffuser **)	Air flow rate per diffuser : 2.48 (m^3/hr diffuser **)
0.35	-	34	39	38
0.48	45	41	48	-

Table 4: Increase of OC as a function of horizontal water flow for two air flow rates (Grignon). Air flow rate were measured in compliance with the standard NF X 10-102 (AFNOR, 1971)

horizontal water flow (m/sec)	increase of OC (compared to OC without horizontal water flow)(%)	
	Air flow rate per diffuser : 5.27 (m^3/hr. diffuser)	Air flow rate per diffuser : 3.11 (m^3/hr. diffuser)
0.33	35	48

The impact of horizontal water rotation on the interfacial area and on the oxygen transfer coefficient based on liquid film resistance were shown in a previous work (Da Silva-Deronzier, 1994). The horizontal flow acts mainly on the interfacial area by lengthening the contact time thanks to a decrease in the effects of the small spiral flows (which occur between the diffusers themselves) on oxygen transfer and probably by a reduction in the size of the air bubbles at the level of the diffusers.

Influence of diffuser modules layout

The sizing of the aeration system, the number of diffusers and the air flow rate of the blower are determined by technical factors (the necessity of providing the daily input of oxygen required to treat the carbon design loading and increasingly often the nitrogen load) and also by economic factors. The results on the influence of the air flow rate on oxygen transfer show that, for the same input of oxygen, oxygen transfer efficiency increases with the number of diffusers since the air flow rate per diffuser decreases (Table 5).

Table 5: OTEd as a function of modules number and layout (Milly La Forêt). *: results obtained for a horizontal water flow of 0.3 m/sec, **: results obtained for an air flow rate of 1317 m^3/h

	air flow rate 1569 m^3/hr water flow 0 m/sec	air flow rate 1569 m^3/hr water flow 0.35 m/sec	air flow rate 1290 m3/h water flow 0.35 m/sec
number and module layout	OTEd (%/m)	OTEd (%/m)	OTEd (%/m)
10 (1 à 10)	6.25	8.33	9.06*
5 (1, 3, 5, 7, 9)	5.23	-	7.43**
4 (1, 2, 3, 4)	-	7.03	6.77

The objective of the series of experiments performed at the site of Milly La Forêt was to define the optimal arrangement for oxygen transfer of a given number of diffuser modules. The oxygen transfer was thus measured for three different configurations of the aeration system: 5 diffuser modules were thus brought into operation: 1 to 5 first of all, then 1, 3, 5, 7 and 9, and finally 1, 4, 6, 9 and 10 (cf. figure 1). The air flow rate per diffuser was 3.15 m^3/h and the horizontal water flow was 0.35 m/sec. The results obtained (Table 6) show that the three configurations of the aeration system studied are not equivalent: the closer the modules, the better the oxygen transfer. This is explained by the spiral flow phenomenon. In fact, by making distant the diffuser modules, the number of large spiral flow goes up. As a result the interfacial area decreases because the air-water contact time is reduced. Furthermore, these results confirm the conclusion on the influence of the horizontal flow on the large spiral flows. The three configurations studied differ by the number of large spiral flows (which occur between the diffuser modules). As the oxygenation transfer efficiencies are unequal, despite an identical water flow rate for the three configurations, the hypothesis that the horizontal flow does not entirely break the spiral flows is validated.

Table 6. OC and OTEd as a function of module layout

module layouts	OC (kg O_2/hr)	OTEd (%/m)
1, 2, 3, 4, 5	73.1	7.99
1, 3, 5, 7, 9	68.0	7.43
1, 4, 6, 9, 10	65.7	7.17

CONCLUSIONS

The work presented studied the influence of design parameters (the air flow rate per diffuser, the horizontal flow and the diffuser layout) of a dissociated aeration system (diffused aeration and large-blade, slow-speed mixers) on the transfer of oxygen in clean water.

The experimental study performed on several ditches showed that a decrease in the air flow rate per diffuser increases the oxygen transfer efficiency. It also showed that the oxygen transfer capacity is an increasing asymptotic function of the horizontal water rotation velocity. Finally, it showed that different diffuser layouts, by the spacing of the diffuser modules in operation, give different results: the closer the modules, the better the oxygen transfer.

The experimental results can be explained by the influence of the design parameters on the interfacial area (a) and on the oxygen transfer coefficient based on liquid film resistance (Kl). Analysis showed that variations in the air flow rate per diffuser have a negligible effect on Kl. But an increase in the air flow rate reduces the interfacial area by increasing both the initial diameter of the air bubbles and the vertical convection movement of water, inducing a reduction in the air-water contact time. Horizontal water velocity has also a negligible effect on Kl. But it induces an increase of the interfacial area by making longer the air-water contact time (reduction of the small spiral flows) and probably by reducing the size of the air bubbles at the level of the diffusers. To bring the diffuser modules closer increases the interfacial area by increasing the contact time (partial breakage of the large spiral flows).

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