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RESEARCH NOTE

EFFECT OF AIR FLOW RATE ON OXYGEN TRANSFER IN AN OXIDATION DITCH EQUIPPED WITH FINE BUBBLE DIFFUSERS AND SLOW SPEED MIXERS

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Abstract—The effect of air flow rate on oxygen transfer efficiency was examined in clean water and under process conditions in an oxidation ditch equipped with fine bubble membrane diffusers and large blade slow speed mixers. Under process conditions, an increase in the air flow rate resulted in a decrease of the oxygen transfer efficiency similar to that observed in clean water. Consequently, the value of the alpha factor was in the order of 0.58 independently of the air flow rate (between 45 and 110 $m^3 h^{-1}$ per m^2 of membrane). The combined influence of the air flow rate and of the horizontal liquid velocity on the oxygen transfer efficiency was studied. Results have evidenced that regrouping the diffuser grids and applying a horizontal flow could lead to a significant limitation in the impact of the air flow rate on the oxygen transfer efficiency. Finally, the use of the off gas method to determine the oxygen transfer efficiency of an aeration system at a given air flow rate led to the definition of a relationship, that enabled the evaluation of the system oxygenation capacities at air flow rates different from the one at which the measurements were initially performed.

Key words—activated sludge, air flow rate, alpha factor, fine bubbles, horizontal flow, oxidation ditch

NOMENCLATURE

A	constant
$Cs_{f,10}$	concentration of oxygen at saturation in process water at 10°C ($mg\ l^{-1}$)
Cs_{10}	concentration of oxygen at saturation in clean water at 10°C ($mg\ l^{-1}$)
$K_La_{f,10}$	oxygen transfer coefficient in process water at 10°C (h^{-1})
K_La_{10}, K_La_T	oxygen transfer coefficient in clean water at 10 and T°C (h^{-1})
m	constant
OTE_f	oxygen transfer efficiency under process conditions (%)
Q, Q^j, Q^k	supplied air flow rate ($m^3 h^{-1}$)
q_i	collected off gas flow rate at the measurement point i, divided by the surface of the collection hood ($m^3 h^{-1} m^{-2}$)
q_i^j, q_i^k	off gas flow rates at the measurement point i when the supplied air flow rate is Q^j and Q^k, ($m^3 h^{-1} m^{-3}$)
$SOTE_f$	overall standard oxygen transfer efficiency in process water (%)
SOTE	overall standard oxygen transfer efficiency in clean water (%)
$SOTE_{f,i}$	local standard oxygen transfer efficiency in process water at the measurement point i (%)
$SOTE_{f,i}^j$, $SOTE_{f,i}^k$	local standard oxygen transfer efficiencies determined at the measurement point i, when the supplied air flow rate is Q^j and Q^k
T	temperature (°C)
V	volume of water (m^3)
y_i	mole fraction of oxygen in the supplied air (–)
y_i', y_o'	mole fractions of oxygen in the supplied air and in the off gas, H_2O and CO_2 being previously removed
α	ratio of K_La in process water to K_La in clean water at equivalent conditions
θ	temperature correction factor, $\theta = 1.024$
ρ_i	density of oxygen at temperature and pressure at which gas flow is expressed ($kg\ m^{-3}$)

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INTRODUCTION

Over the last ten years, fine pore diffused aeration through elastic micro-perforated membrane diffusers has been largely used in France to supply oxygen in activated sludge treatment plants. These diffusers are frequently installed in oxidation ditches also equipped with large blade slow speed mixers, to dissociate the aeration and mixing functions.

In clean water, an increase in the air flow rate results in a decrease of the oxygen transfer efficiency. This decrease is caused by an *increase in the size of the air bubbles* when the air flow rate increases, due to (i) a stretching of the membrane under the effect of the gas pressure resulting in an increase in the pore size (Rice and Lakhani, 1987; Da Silva-Déronzier, 1994; Hebrard, 1995); (ii) an increase in the coalescence of the air bubbles (Calderbank *et al.*, 1964; Huibregtse *et al.*, 1983).

Furthermore, the increase of the air flow rate also affects the vertical movements of the water caused by the rise of the air bubbles (spiral flows). These vertical flows, which occur between diffusers or grids of diffusers, accelerate the upward velocity of the air bubbles and are greater when the air flow rate is risen (Da Silva-Déronzier, 1994; Roustan and Line, 1996). Any increase in the air flow rate therefore results in a *reduction of the residence time* of the air bubbles in the water, and consequently of the oxygen transfer efficiency.

Under process conditions, an increase in the air flow rate also results in a decrease of the oxygen transfer efficiency. However, it does not always match that observed in clean water, leading to a variation in the alpha factor (ratio of the oxygen transfer coefficients in process and clean water at equivalent conditions of temperature, mixing, geometry) (Hwang and Stenstrom, 1985; EPA, 1989).

Finally, the relationship between the oxygen transfer efficiency and the air flow rate can be written as follows:

$$\mathrm{SOTE}^j = \mathrm{SOTE}^k \left(\frac{Q^j}{Q^k}\right)^m \tag{1}$$

where SOTE^j, SOTE^k are the overall oxygen transfer efficiencies at standard conditions [temperature of 10°C, atmospheric pressure of 1013 hPa, dissolved oxygen concentration of 0 mg l^{-1}] (%); Q^j, Q^k are the supplied air flow rates (m^3 h^{-1}) and m is a constant.

The greater the effect of a variation in the air flow rate on the oxygen transfer efficiency, the higher the absolute value of m. The values quoted by the EPA in clean water (1989) for fine pore aeration systems are between -0.10 and -0.19 in the case of micro-perforated membranes for basins totally covered with diffusers, and between -0.24 and -0.28 for porous diffusers arranged along one wall of the aeration tank (spiral roll configuration).

The aim of the work presented was to study the influence of the air flow rate on the oxygen transfer efficiency in an oxidation ditch, in clean water and under process conditions. The influence of the diffuser layout and of the horizontal velocity of the mixed liquor was also examined.

MATERIALS AND METHOD

Milly la Forêt oxidation ditch

The measurements were performed in the oxidation ditch of Milly la Forêt wastewater treatment plant, which operates under extended aeration (F/M < 0.1 kg BOD/kg MLVSS/d). The ditch, illustrated in Fig. 1, is equipped with 720 SANITAIRE 9′ EPDM diffusers (fed with air by a ROBUSCHI/RB 80 blower) arranged in ten grids. Agitation was provided by two FLYGT mixers, type 4430, 2 m in diameter, mounted side by side. A frequency drive unit (10–50 Hz) was used to modulate the rotation speed

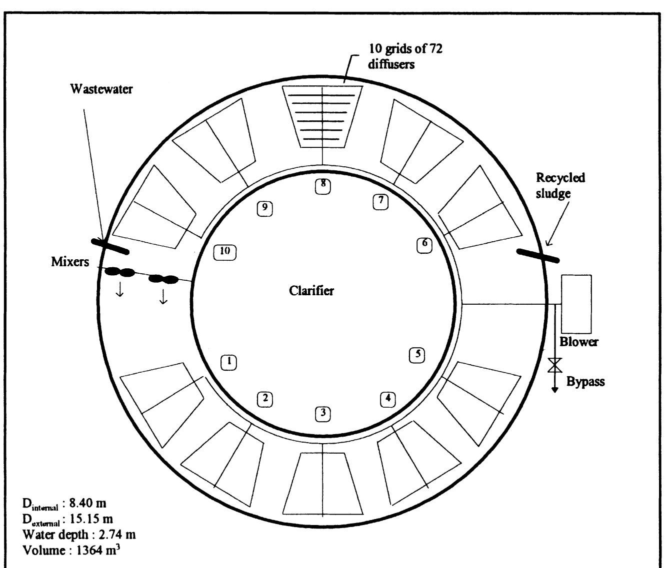

Fig. 1. Diagram of the oxidation ditch at Milly la Forêt.

of the mixers and therefore the horizontal velocity of the liquid (clean water or mixed liquor).

Determination of the standard oxygen transfer efficiency in clean water

The oxygen transfer coefficients were measured in clean water (Da Silva-Déronzier, 1994) according to the non steady state method (Héduit and Racault, 1983a, b; ASCE, 1992; Duchène *et al.*, 1995). Results are expressed at 10°C according to (2):

$$K_\mathrm{L}a_{10} = K_\mathrm{L}a_T\theta^{(10-T)} \tag{2}$$

where $K_\mathrm{L}a_{10}$, $K_\mathrm{L}a_T$ are the oxygen transfer coefficients in clean water at 10 and T°C (h^{-1}), T is the temperature (°C) and θ the temperature correction factor ($\theta = 1.024$).

The standard oxygen transfer efficiency (SOTE), defined as the ratio of the mass of oxygen transferred to the liquid to the mass of oxygen supplied per time unit, was deduced from the oxygen transfer coefficient using the following expression:

$$\mathrm{SOTE} = \frac{K_\mathrm{L}a_{10}\mathrm{Cs}_{10}V}{\rho_i Q y_i} \tag{3}$$

where Cs_{10} is the concentration of oxygen at saturation in clean water at 10°C ($\mathrm{mg\,l^{-1}}$), V is the volume of water (m^3), ρ_i is the density of oxygen at temperature and pressure at which gas flow is expressed ($\mathrm{kg\,m^{-3}}$) and y_i is the mole fraction of oxygen in the supplied air (–).

Determination of the oxygen transfer efficiency under process conditions

The in-process oxygen transfer efficiencies of the aeration system were determined by the off gas method, approximately one year after the clean water measurements. The oxygen transfer efficiency is deduced from the oxygen content in the supplied air and in the off gas as follows (Redmon *et al.*, 1983):

$$\mathrm{OTE_f} = 1 - \frac{y_i'(1-y_\mathrm{o}')}{y_\mathrm{o}'(1-y_i')} \tag{4}$$

where $\mathrm{OTE_f}$ is the oxygen transfer efficiency under process conditions [temperature of T°C, atmospheric pressure of P hPa, dissolved oxygen concentration of $C\,\mathrm{mg\,l^{-1}}$] (%), y_i', y_o' are the mole fractions of oxygen in the supplied air and in the off gas, H_2O and CO_2 being previously removed.

As the surface of the aeration tank did not enable all the off gas to be collected, the oxygen transfer efficiencies were determined from the sampling of the gases exiting the tank at various points along the ditch, using 2 m^2 collection hoods.

The oxygen transfer efficiencies measured at each hood location ($\mathrm{OTE}_{\mathrm{f},i}$) were expressed at 10°C, 1013 hPa and at a dissolved oxygen concentration of 0 $\mathrm{mg\,l^{-1}}$, to yield local standard oxygen transfer under process conditions ($\mathrm{SOTE}_{\mathrm{f},i}$). The overall standard oxygen transfer efficiency of the aeration system ($\mathrm{SOTE_f}$) was obtained by weighting the local efficiencies ($\mathrm{SOTE}_{\mathrm{f},i}$) by the gas flow rates collected (q_i) at the n sampling points (Redmon *et al.*, 1983; ASCE, 1996; ATV, 1996):

$$\mathrm{SOTE_f} = \frac{\sum_{i=1}^{i=n}\mathrm{SOTE}_{\mathrm{f},i}q_i}{\sum_{i=1}^{i=n}q_i} \tag{5}$$

The oxygen transfer coefficient under process conditions at 10°C ($K_\mathrm{L}a_{\mathrm{f},10}$) was deduced from the overall standard oxygen transfer efficiency ($\mathrm{SOTE_f}$) using Eq. (6):

$$K_\mathrm{L}a_{\mathrm{f},10} = \frac{\mathrm{SOTE_f}\rho_i Q y_i}{\mathrm{Cs}_{\mathrm{f},10}V} \tag{6}$$

where $\mathrm{Cs}_{\mathrm{f},10}$ is the concentration of oxygen at saturation in process water at 10°C ($\mathrm{mg\,l^{-1}}$).

Determination of the alpha factor

The alpha factor, which is the ratio of the oxygen transfer coefficient under process conditions ($K_\mathrm{L}a_{\mathrm{f},10}$) to the oxygen transfer coefficient in clean water ($K_\mathrm{L}a_{10}$), was calculated using Eq. (7):

$$\alpha = \frac{K_\mathrm{L}a_{\mathrm{f},10}}{K_\mathrm{L}a_{10}} \tag{7}$$

Measurement of the air flow rate

The supplied air flow rate was measured by means of a diaphragm disposed in the main pipe of the blower, in compliance with the AFNOR NF X 10-102 (1971) standard. A bypass was used to modulate the air flow rate.

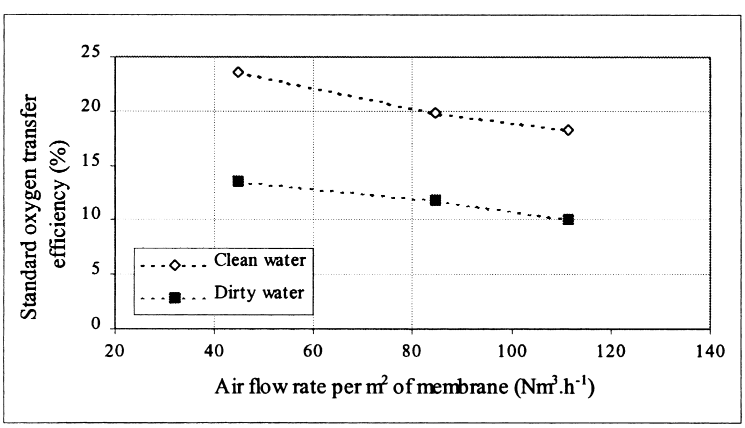

Fig. 2. Effect of air flow rate on the overall standard oxygen transfer efficiency in clean water and under process conditions. Grids 1–4 in operation; horizontal liquid velocity = 0.33 m s^{-1}.

Table 1. Overall standard oxygen transfer efficiencies in clean water and under process conditions and corresponding alpha factors for different air flow rates

Air flow rate (N m^3 h^{-1}) (per m^2 of membrane)	SOTE (%) (% per m of immersion)	$SOTE_f$ (%) (% per m of immersion)	Alpha factor
485 (45)	23.6 (9.5)	13.5 (5.4)	0.58
914 (85)	19.9 (8.0)	11.8 (4.7)	0.60
1207 (112)	18.3 (7.3)	10.1 (4.1)	0.56

RESULTS AND DISCUSSION

Influence of air flow rate on alpha factor

Fig. 2 shows the overall standard oxygen transfer efficiencies determined in clean water and in process conditions as a function of the supplied air flow rate, when four diffuser grids were in operation (grids 1, 2, 3 and 4, see Fig. 1).

Under process conditions, as in clean water, an increase in the air flow rate leads to a decrease in the oxygen transfer efficiency, practically identical in both cases. Consequently, the value of the alpha factor, as shown in Table 1, remains almost constant.

For an air flow rate per m^2 of membrane comprised between 45 and 112 m^3 h^{-1} and a horizontal velocity of 0.33 m s^{-1}, the alpha factor, when four grouped grids of diffusers were in operation, was in the order of 0.58, regardless of the air flow rate supplied.

Expression of the local oxygen transfer efficiencies ($SOTE_{f,i}$) as a function of the collected gas flow rate

Figs 3–5 show the local oxygen transfer efficiencies as a function of the collected flow rate for the various configurations of the aeration system (see Fig. 1). Each point on the graphs corresponds to one measurement of the oxygen transfer efficiency and of the off gas flow rate for one hood location. At least three measurements of the oxygen transfer efficiency and of the off gas flow rate were performed per grid of diffusers in operation (Gillot, 1997; Gillot *et al*., 1997).

The two first graphs (Figs 3 and 4) show the classic shape of the curves representing the oxygen transfer efficiency as a function of the air flow rate in clean water, with the SOTE decreasing steeply in a first part and then more gradually toward an asymptotic limit in a second part. The last graph (Fig. 5) shows a more gradual decrease of the SOTE, due to higher values of supplied air flow rates (points located in the second part of the "classical curve giving SOTE vs. flow rate"). Furthermore, these graphs point out the discrepancy of the collected flow rate and consequently of the SOTE along the ditch, due to a nonuniform distribution of the supplied air among the different diffuser grids.

Applying Eq. (1) to the local oxygen transfer efficiencies ($SOTE_{f,i}$) and to the collected flow rates (q_i), the value of m can be determined as:

$$\mathrm{SOTE}_{f,i}^{j} = \mathrm{SOTE}_{f,i}^{k}\left(\frac{q_i^j}{q_i^k}\right)^m$$

This relationship can also be written as:

$$\mathrm{SOTE}_{f,i} = A(q_i)^m \qquad (8)$$

Table 2 shows the values of m determined by

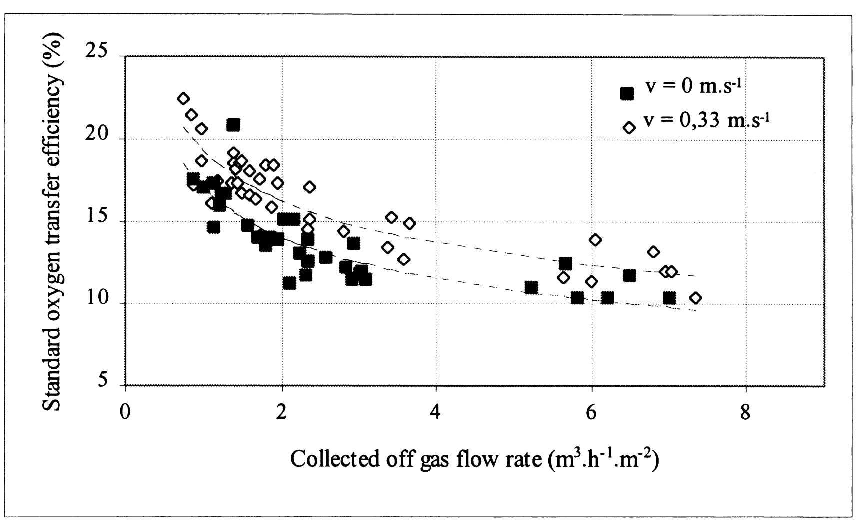

Fig. 3. Local standard oxygen transfer efficiency ($SOTE_{f,i}$) as function of the collected flow rate (q_i) at each hood location; ten grids in operation; Q = 894 N m^3 h^{-1} (33 m^3 h^{-1} per m^2 of membrane).

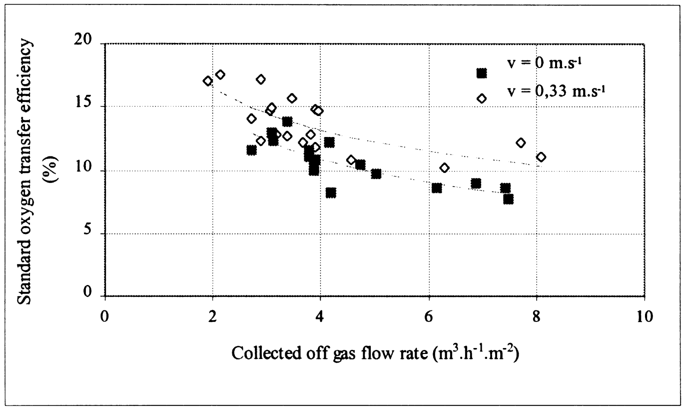

Fig. 4. Local standard oxygen transfer efficiency ($SOTE_{f,i}$) as function of the collected flow rate (q_i) at each hood location; one out of two grids in operation; (1, 3, 5, 7 and 9); $Q = 723\ N\,m^3\,h^{-1}$ (53 $m^3\,h^{-1}$ per m^2 of membrane).

Table 2. Values of m determined for different configurations of the aeration system

Configuration	Grids in operation	Air flow rate ($N\,m^3\,h^{-1}$) (per m^2 of membrane)	Horizontal velocity ($m\,s^{-1}$)	m	Number of points	R^2
1	1–10	894 (33)	0	−0.285	33	0.72
	1–10	894 (33)	0.17	−0.266	30	0.69
	1–10	894 (33)	0.33	−0.250	39	0.79
	1–10	894 (33)	0.45	−0.264	30	0.61
2	1, 3, 5, 7, 9	723 (53)	0	−0.450	19	0.58
	1, 3, 5, 7, 9	723 (53)	0.33	−0.337	17	0.65
3	1, 2, 3, 4	1207 (112)	0.33	−0.276	16	0.37

adjusting the curves obtained for each test to Eq. (8) using a least squares nonlinear regression.

The model applied (Eq. (1)) fails to explain all the variability of the measurements (R^2 from 0.37 to 0.79), which may also be induced by other factors than the air flow rate (accuracy of the SOTE measurement, location of the tested grid in relation to the others, range of collected flow rates, number of sampling points). The R^2 determined for configuration 3, which is particularly low, may be attributed to the almost constant oxygen transfer efficiency resulting from the high value of the supplied flow rates. For the other two air flow rates tested in configuration 3 (485 and 914 $N\,m^3\,h^{-1}$, cf. Fig. 2 and Table 1), the values of m obtained were not taken into account due to an insufficient number of measuring points (485 $N\,m^3\,h^{-1}$) or to a very limited range of flow rates collected (914 $N\,m^3\,h^{-1}$).

The absolute values of m obtained are slightly

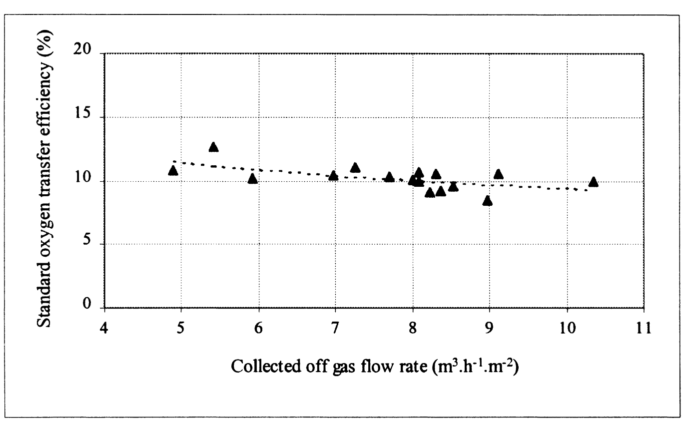

Fig. 5. Local standard oxygen transfer efficiency ($SOTE_{f,i}$) as function of the collected flow rate (q_i) at each hood location; four grouped grids in operation (1, 2, 3 and 4); $v = 0.33\ m\,s^{-1}$; $Q = 1207\ N\,m^3\,h^{-1}$ (112 $m^3\,h^{-1}$ per m^2 of membrane).

Table 3. Conditions of oxygen transfer measurements in clean water and under process conditions

	Grids in operation	Horizontal velocity (m s^{-1})	m	Air flow rate (N m^3 h^{-1})
Mixed liquor	1, 2, 3, 4	0.33	−0.276	485, 914, 1207[a]
Clean water	1, 2, 3, 4	0.33	−0.276	485, 914, 1207[a]
Clean water	1–10	0	−0.285	894[a], 1032, 1202, 1462
		0.17	−0.266	894[a], 1032, 1202, 1462
		0.33	−0,250	894[a], 1202, 1462
		0.45	−0.264	894[a], 1202, 1462
Clean water	1, 3, 5, 7, 9	0	−0.450	723[a], 1227
		0.33	−0.337	723[a], 1227

[a]Air flow rate from which the value of m was calculated.

higher than those quoted in the EPA (1989) for fine pore aeration systems using micro-perforated membranes in clean water in the case of tanks totally covered with diffusers (0.10–0.19). They are often of the same order of magnitude as those quoted for porous diffusers in a spiral roll configuration (0.24–0.28).

These values are close for configurations 1 and 3. They appear to be higher, in absolute values, when the diffuser grids are spaced out (configuration 2) and, for a given configuration, in the absence of horizontal velocity. The latter two situations are characterised by large vertical movements of the liquid created by the rising air bubbles between grids of diffusers and/or between individual diffusers. The application of a horizontal velocity is able to neutralise partially the spiral flows and thus to reduce the impact of the air flow rate on the oxygen transfer efficiency.

Expression of the standard overall oxygen transfer efficiency of the aeration system (SOTE)

The local oxygen transfer efficiencies ($\mathrm{SOTE}_{\mathrm{f},i}$) measured are linked by Eq. (1):

$$\mathrm{SOTE}_{\mathrm{f},i}^{j} = \mathrm{SOTE}_{\mathrm{f},i}^{k}\left(\frac{q_i^{\,j}}{q_i^k}\right)^m$$

Assuming that the variation in the collected off gas flow rates at each measurement point is proportional to the variation in the total supplied air flow rate ($q_i^k/q_i^{\,j} = Q^k/Q^{\,j}$), the overall oxygen transfer efficiency of the aeration device for the air flow rate Q^k may be expressed as:

$$\mathrm{SOTE}_{\mathrm{f}}^{k} = \frac{\sum_{i=1}^{n}\mathrm{SOTE}_{\mathrm{f},i}^{k} q_i^k}{\sum_{i=1}^{n} q_i^k} = \frac{\sum_{i=1}^{n}\mathrm{SOTE}_{\mathrm{f},i}^{j}(q_i^k/q_i^{\,j})^m q_i^k}{\sum_{i=1}^{n} q_i^{\,j}(Q^k/Q^{\,j})}$$

$$\mathrm{SOTE}_{\mathrm{f}}^{k} = \frac{\sum_{i=1}^{n}\mathrm{SOTE}_{\mathrm{f},i}^{j} q_i^{\,j}(Q^k/Q^{\,j})^{m+1}}{\sum_{i=1}^{n} q_i^{\,j}(Q^k/Q^{\,j})} = \mathrm{SOTE}_{\mathrm{f}}^{\,j}\left(\frac{Q^k}{Q^{\,j}}\right)^m$$

The value of m deduced from the sampling of the *local* oxygen transfer efficiencies and off gas flow rates at a given supplied air flow rate (Q^j) thus makes it possible to estimate the *overall* oxygen transfer efficiency of the aeration system for a different supplied air flow rate (Q^k).

Each value of m, determined for a configuration of the aeration system at a given air flow rate, was used to calculate the overall standard oxygen transfer efficiencies for the same configuration at the other air flow rates tested:

- under process conditions, for configuration 3 (cf. Tables 1 and 2);
- in clean water for configurations 1 and 2: the influence of the air flow rate on the oxygen transfer efficiency in activated sludge was not studied for these configurations, the values of m determined under process conditions were however applied

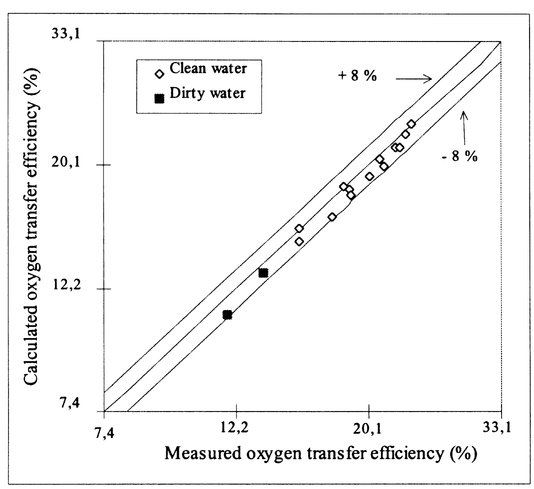

Fig. 6. Standard oxygen transfer efficiency deduced from the values of m as a function of measured standard oxygen transfer efficiency.

to overall oxygen transfer efficiencies determined in clean water at different air flow rates (Da Silva-Déronzier, 1994).

The measurement conditions are summarised in Table 3.

Fig. 6 shows the overall oxygen transfer efficiencies calculated from the values of m vs. the measured values.

For a fixed configuration of the aeration system, the oxygen transfer efficiencies can be calculated for different air flow rates from the value of m and from the oxygen transfer efficiency obtained at a given air flow rate. The relative deviations between the calculated and the measured values are less than $\pm 8\%$. Furthermore, in the experimental conditions, the values of m obtained under process conditions can be used to estimate the oxygen transfer efficiencies in clean water, according to Eq. (1).

CONCLUSION

The measurements performed in the oxidation ditch of Milly la Forêt wastewater treatment plant showed that:

- In the presence of a horizontal liquid velocity, an increase in the air flow rate leads to a decrease in the oxygen transfer efficiency similar either in clean water or under process conditions, resulting in a constant alpha factor.
- The influence of the air flow rate on the oxygen transfer efficiency appears to be higher when the diffusers grids are spaced out and in the absence of any horizontal velocity, namely when the vertical movements of liquid caused by the rise of the air bubbles are the greatest.
- The application of a horizontal velocity is able to neutralise partially the spiral flows and to reduce the impact of the air flow rate on the oxygen transfer efficiency.
- Measurement of the oxygen transfer efficiency by the off gas method at a given air flow rate makes it possible to define a constant, m, such as at each measurement point:

$$\mathrm{SOTE}_{\mathrm{f},i}^{k} = \mathrm{SOTE}_{\mathrm{f},i}^{j}\left(\frac{q_i^k}{q_i^j}\right)^m.$$

For the same configuration of the aeration system, this relationship can be applied to the overall oxygen transfer efficiency, thus enabling an assessment of the oxygen transfer capacities of the system for a supplied air flow rate (Q^k) different from the initial flowrate (Q^j):

$$\mathrm{SOTE}_{\mathrm{f}}^{k} = \mathrm{SOTE}_{\mathrm{f}}^{j}\left(\frac{Q^k}{Q^j}\right)^m$$

Under the prevailing conditions, the above equation was also applied with success to oxygen transfer efficiencies in clean water, the value of m being the one determined under process conditions.

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