Hydrodynamics and oxygen balance in a high-rate algal pond

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Abstract As for any other system used in wastewater treatment, it is important to know the mixing characteristics and net oxygen balance in high-rate algal ponds (HRAPs). The design of HRAPs obviously is conducive to plug flow, but with a large recirculation flow rate. The pond's treatment capacity will also depend on the net oxygen balance resulting from photosynthesis and respiration. In order to define an appropriate model describing the oxygen balance in the system, two techniques are respectively used for determining the hydrodynamic parameters and oxygen transfer coefficients of HRAPs.

Keywords HRAP; RDT; mass transfer coefficient; oxygen balance; tracer gas; primary production

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Introduction

High-rate Algal Ponds (HRAPs) for domestic sewage treatment are a new technology that is attracting more and more interest in various countries, especially in hot climates (Bontoux and Picot, 1994). The basic principle of this technique is to promote the growth of the algal biomass that provides the major source of oxygen for the bacteria degrading the organic matter. As for any other bioreactor, it is important to know the flow pattern in the tank. Obviously the HRAP design is conducive to plug flow, but with a large recirculation flowrate. Moreover, the treatment capacity of the pond for organic compounds will depend on the net oxygen balance and thus on photosynthesis and respiration.

Various models have been suggested to describe the HRAP. Indeed, Mesple (1993) distinguishes between deterministic and stochastic models, the latter based mainly on multivariate analysis. It seems that the first deterministic model was that of Buhr and Miller (1983), who described an already very sophisticated model that took the system's hydrodynamic behaviour into account. Buhr and Miller (1983) simulated variations in the process parameters (pH, DO and substrate concentration) according to channel length and time of day, but did not describe the changes in bacterial and algal biomass. Moreover, examination of their equations shows that the model accounted for the algae's contribution to the oxygen balance through photosynthesis but neglected to factor in algal respiration. Despite this omission, their approach to modelling the system was good. Grobbelaar *et al.* (1988, 1990) modelled algal productivity in relation to temperature and incident light intensity as well. This model has been used by Martin and Fallowfield (1989) to evaluate optimum pond area in Australia. More recently Portielje *et al.* (1996) employed a model, likewise based on the dissolved oxygen balance, in which the respiration rate was temperature dependent and photosynthetic activity was a P-I function.

In this study we focused on the hydrodynamic characterisation of, and oxygen balance in, a real HRAP located at Rabat in Morocco. The oxygen balance technique consists in measuring the various sources and sinks for dissolved oxygen in the bioreactor, namely, photosynthesis, the reaeration coefficient, and oxygen uptake. As it is difficult to quantify the oxygen transfer due to physical exchanges when the bacteria and algal biomass are simultaneously active, we adopted and compared two methods

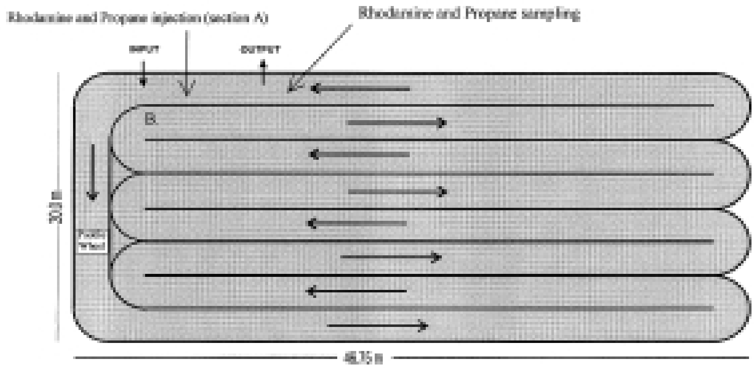

Figure 1 Diagram of the HRAP located in Rabat

for evaluating the oxygen transfer coefficient, namely, the tracer gas and oxygen balance methods.

Materials and method

The experiments were carried out on two full-scale HRAPs installed at the Hassan II Agronomic Institute of Rabat and in Ouarzazate City, Morocco. The Rabat plant has a capacity of 2000 population equivalents, is 400 m long, has a uniform width of 2.5 m, and is 0.5 m deep. For the hydrodynamic study we also took measurements on the Ouarzazate HRAP.

Dye and tracer gas

The tracer dye used in the tracer pulse-injection technique was fluorescent rhodamine WT(20%). The tracer dye was diluted in approximately 10 litres of wastewater before injection. This solution was injected rapidly (pulse injection) in section A of the algal channel reactor (Figure 1). Dye tracer concentrations were monitored by collecting samples every 5 minutes for 8 hours. The samples were analysed in the laboratory using a precalibrated spectrophotometer. The method to calculate RTD (Residence Time Distribution) has been described elsewhere (Naméche and Vasel, 1996).

Propane was used as a tracer gas for measuring the reaeration process. This method was developed to determine the atmospheric reaeration coefficient in rivers (Rathbun and Schultz, 1975) but has been extended to other bioreactors, namely, trickling filter, Rotating Biological Contactor systems (RBCs) and activated sludge reactors (Boumansour *et al.*, 1995; Boumansour and Vasel, 1996). To our knowledge propane had never been used before for reaeration studies in algal systems. Airtight vials were used for sampling. Propane was analysed by gas chromatography coupled to a “Head Space” system. The method has been described by Boumansour (1994) and allows assays of samples containing suspended solids.

During the study we also measured various other parameters, namely, dissolved oxygen concentrations, conductivity, pH, salinity, temperature, turbidity, etc. These parameters were monitored continuously in several locations in the pond by means of two probes (WQLS 3800). Productivity and respiration rates were measured by the classic light-and-dark bottles method.

Results and comments

Hydrodynamic study

Figure 2 shows how the fluorescent dye concentration at the sampling point varies over time after the pulse injection. As expected, the C-diagram has multiple peaks. This phenomenon is due to flow recirculation.

Table 1 Hydraulic parameters in two HRAP reactors

	HRAP Ouarzazate	HRAP Rabat
	Experimental curve	Experimental curve
Mean residence time (hours)	70	126
Standard deviation (hours)	85	88
% short circuiting	38	37
Peclet number	70	117
N, series of perfectly mixed reactors	2	2
Recirculating time (min)	252	79
Dye recovery (%)	92	91

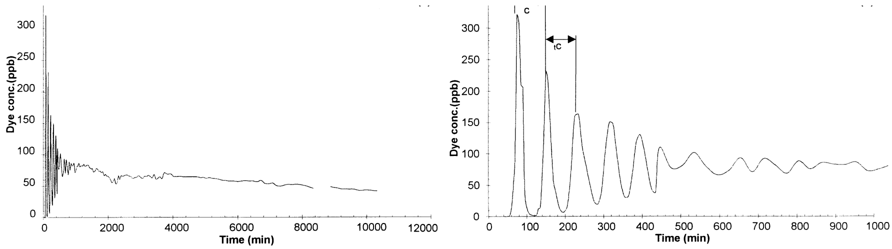

Figure 2 Tracer response curve after pulse injection (Rabat)

From Figure 2a we see that the peak dye concentration decreases due to loss of tracer in the outflow. In Figure 2-b, tc represents the length of time taken by the dye to make a complete loop in the reactor. The value of tc is around 75 minutes.

The response of the tracer has been interpreted and the best flow pattern found for this reactor is the dispersed plug-flow model with recirculation (Eq. 1).

$$E(\theta) = \mathrm{e}^{-\theta \frac{t_c}{t_{th}}} \cdot \sqrt{\mathrm{Pe} / 4\pi\theta} \cdot \sum_{i=1}^{\infty} \mathrm{e}^{-\left[\frac{\mathrm{Pe}}{4\theta} \cdot (i-\theta)^2\right]} \qquad (1)$$

E(θ) : distribution of adimensional residence time

Pe : Peclet number (dimensionless)

θ : adimensional time = t.(Q/V)

t_c : length of time taken by the dye to make a complete loop in the reactor(s)

Fitting Eq.1 to the experimental curve of Figure 2 led to the parameters summarised in Table (1). It should be noted that the best fit parameters obtained with Eq. 1 yield a number of recirculations and a Peclet number of 96 and 119, respectively. If the HRAP is considered a "semi-open" reactor, the recirculation time and Peclet number are equal to 79 min and 117, respectively.

A similar experiment was performed in the HRAP of Ouarzazate. The results are also given in Table 1.

Figure 2 shows that in the HRAP reactor the dye tracer is completely mixed 17 hours (96 recirculations) after a pulse injection. Table 1 shows the existence of significant short-circuits in both Ouarzazate and Rabat's HRAPs. This percentage is calculated as $100 \cdot (1 - t_{sm}/t_{th})$ and confirms the observation of Buhr and Miller (1983), who consider the system to be a plug-flow type with a small amount of dispersion that can be represented by a large number of CSTRs in series (40–120). Macroscopically and over a longer time the reactor continues to respond like a perfectly mixed model due to the large number of recirculations of an element of fluid before it leaves the system. Between two sections of the reactor we may consider that we have a plug flow pattern, as for a river.

After the tracer experiment, the inlet was modified and placed at point B in Figure 1. The water flow in the channel was also reversed. These modifications made it possible to reduce the short-circuiting.

Determination of reaeration transfer coefficient

Tracer gas method. The dissolved oxygen balance equation (Eq. 5) contains the reaeration transfer coefficient (*Kla*). As in a river, this term provides a measure of the physical absorption of oxygen from the atmosphere. It is difficult to quantify the reaeration coefficient in the presence of pollution and photosynthesis (Bennett and Rathbun, 1972; Vollenweider, 1974). For HRAP we applied a methodology based on tracer gas methods, a tracer gas being a gas that is neither produced nor consumed in the reactor and undergoes physical exchange (desorption) only. So far, we have used propane as a tracer gas to determine true oxygen transfer coefficients (Boumansour and Vasel, 1996, 1998) in various bioreactors. This technique is based on the fact that there exists a constant ratio between the oxygen transfer coefficient and the tracer gas transfer coefficient. We first checked that under our experimental conditions this ratio was not affected by parameters such as temperature, surfactant, inert and biological suspended solids, etc.

This tracer gas method is an interesting way to measure *Kla* values. The advantages and possibilities of this method are described elsewhere (Kilpatrick *et al.*, 1989; Boumansour *et al.*, 1995).

The technique uses simultaneous injection of two tracers in section A:

- Pulse injection of a fluorescent dye that indicates the sampling time for tracer gas.
- Propane, used as a tracer gas, is injected into the channel across its entire width through a triple perforated membrane diffuser system. The gas injection was stopped after 40 minutes.

The changes in the propane concentration in the algal-bacterial reactor were monitored by collecting samples in the middle of Section A every 5 minutes for 4 hours. Figure 3 shows the dissolved propane concentration versus sampling time.

It will be noted that our experiment was run in batch mode. As for the tracer dye, we found that when the travel time (t_c) from the point of the dye injection to the sampling stations increased, the plateau concentration of dissolved propane decreased, due to the amount of propane desorbed.

$$Klap = \frac{1}{T_c} \ln \frac{(\overline{C}_P Q)}{(\overline{C}_P Q)_2} \qquad (2)$$

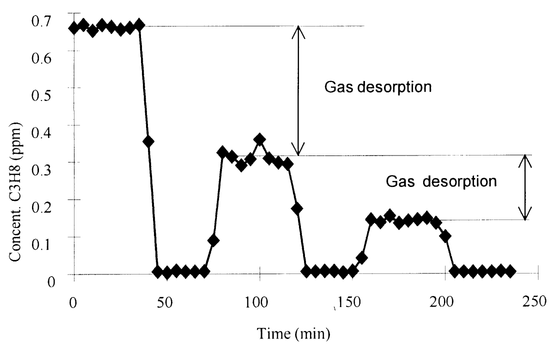

Figure 3 Dissolved gas concentration behaviour in HRAP (Rabat)

Klap : propane gas desorption coefficient (h^{-1})

$\bar{C}_p$: dissolved propane concentration ($mg \cdot l^{-1}$)

Q : water flow in section A ($l \cdot h^{-1}$)

T_c : travel time measured between two centroids of successive dye tracer response curve (h)

The subscripts 1 and 2 refer to two successive plateaux of tracer gas concentrations.

From a hydrodynamic point of view we know that the equations corresponding to plug flow are applicable to the HRAP system. The *Klap* measured in HRAP can be converted to *Kla* for oxygen using the following expression previously established by Boumansour *et al.* (1995).

$$Kla = 1.378\, Klap \quad (3)$$

The experiment was conducted twice to check the method's reproducibility.

The reaeration coefficient is usually expressed as being at 20ºC. Boumansour (1994) showed that when propane is the tracer gas the reaeration coefficient at 20ºC can be expressed as

$$Kla\,(20) = 1.378\, Klap\, (1.024)^{(20-T)} \quad (4)$$

Dissolved oxygen balance method. The dissolved oxygen balance equation developed by Odum (1956) includes all the sources and sinks of oxygen in a flowing stream. We applied this equation to a HRAP system. This process is described by the following equation:

$$\frac{dC}{dt} = Kla'\left(C_s' - C\right) + P - R \quad (5)$$

Kla' reaeration coefficient for oxygen (h^{-1})

Cs' dissolved oxygen concentration at saturation in wastewater ($mg \cdot l^{-1}$)

C dissolved oxygen concentration in wastewater ($mg \cdot l^{-1}$)

R dissolved oxygen consumption rate in HRAP ($mg \cdot l^{-1} \cdot h^{-1}$)

P dissolved oxygen production rate by photosynthesis in HRAP ($mg \cdot l^{-1} \cdot h^{-1}$)

Oxygen concentrations were monitored continuously at several locations in the studied high rate algal pond. Various methods have been suggested to estimate *Kla*' (Bennett and Rathbun, 1972) in rivers from Eq. 5, but some of them are not very accurate. Simonsen and Harremoës (1978) developed a twin curve method for rivers, whereby *Kla* can be calculated from the dissolved oxygen curve at night (when P=0) when R can be considered to be constant.

The mean respiration rate was measured using several samples from the experimental basin and was estimated to be approximately 8 mg $O_2 \cdot l^{-1} \cdot h^{-1}$. For our calculations we needed to monitor the dissolved oxygen concentration over 24 hours. An example of the results obtained for a 24-h run is given in Figure 4.

Table 2 Determination of oxygen transfer coefficient by tracer gas and oxygen balance methods (HRAP, Rabat)

	Tracer gas method	Oxygen balance method
Kla 20 (h^{-1})	0.68 0.761	0.71

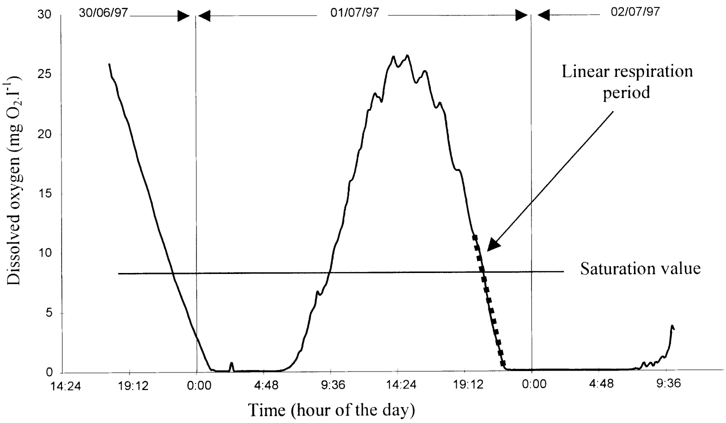

Figure 4 Dissolved oxygen concentration measured in the HRAP

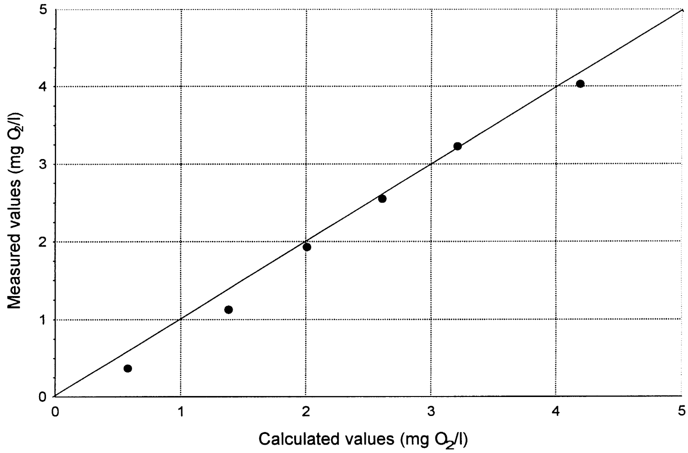

Figure 5 Comparison between observed and calculated C_t

Very large variations in the dissolved oxygen values can be observed in HRAPs, which drop from supersaturation during the day to nearly zero (anoxic) at night. From the wastewater treatment point of view the system should be regulated to ensure enough oxygen for the degradation of organic matter.

If R can be assumed to be constant, at night (when P=0) the reaeration coefficient Kla' can be calculated by Eq. 6, which is the integration of Eq. 5.

$$C_t = C_s' - \left(\frac{R}{Kla}\right) - \left[C_s' - C_0 - \left(\frac{R}{Kla}\right)\right] \cdot e^{-Klat} \qquad (6)$$

This equation is adjusted using a successive iteration procedure in "Statistica®". The data used for this calculation correspond to the linear part of the respiration curve obtained during night recordings of the dissolved oxygen content of the basin when C is below the saturation level (see Figure 4).

Figure 5 gives an example of the comparison between measured values of C_t and those observed and calculated using this estimation method.

The results obtained after nine adjustments give an estimated mean Kla of 0.761 h^{-1}±0.12 at 20°C. It should be noted that the standard deviation value (0.12) indicates the good Kla estimation obtained with this oxygen balance method.

Table 2 gives the oxygen transfer coefficients obtained by the transfer gas and oxygen balance methods. It can be seen that the standard deviation between oxygen transfer coefficient (tracer gas method) is around 4%.

In this example, the *Kla* values obtained by the two methods are close. From this *Kla* value the maximal reaeration rate of the system can be calculated as 5.74 mg $O_2 \cdot l^{-1} \cdot h^{-1}$(for this value we have adopted $C_s = 8.26$ mg $O_2 \cdot l^{-1}$, $C_0 = 0$ mg $O_2 \cdot l^{-1}$ and *Kla* 20 = 0.7 h^{-1}).

Daytime respiration rates were estimated using the light and dark bottles technique. At night and when the pond was fully anaerobic the respiration rates were assumed to be equal to the reaeration rates, since all the oxygen transferred was instantaneously consumed.

When we plug into Eq. 6 the *Kla* value determined by the tracer gas and oxygen balance methods, we obtain a respiration rate of around 8 mg $O_2 \cdot l^{-1} \cdot h^{-1}$ at 24ºC.

Photosynthetic oxygen production

When oxygen uptake (*R*) is constant and *Kla* is known, then Eq. 5 can be used to evaluate oxygen production. The *R* adopted in our case is equal to 8 mg $O_2 \cdot l^{-1} \cdot h^{-1}$ obtained at 24ºC.

The primary production rates calculated by solving for *P* clearly show a cyclic diurnal variation (Figure 6), with a maximum value of 25 mg $O_2 \cdot l^{-1} \cdot h^{-1}$ around 14:30. Figure 6 shows the photosynthetic oxygen production and respiration rates calculated using the value of *Kla* determined by the tracer gas and oxygen balance methods.

Integrating the values displayed on this graph over a 24-hour period gave us a total 24-hr oxygen consumption of 186 mg $O_2 \cdot l^{-1} \cdot d^{-1}$, while the primary production reached 217 mg $O_2 \cdot l^{-1} \cdot d^{-1}$. These results prove that algal photosynthesis is a sufficient source of oxygen since it exceeds total uptake by more than 15%. On the other hand, the main problem associated with the huge algal biomass observed in HRAPs is the length of the anoxic period. Reducing algal density could therefore represent one way to reduce the oxygen demand of the system and maintain higher removal rates even during the dark period.

Conclusions

The high-rate algal pond is a new treatment technology still in development but showing extremely encouraging results. At the present time, no specific design and management strategies have been proposed in the literature. The aim of our work was to characterise the oxygen balance of a high-rate algal pond located in Rabat. A method based on the continuous monitoring of dissolved oxygen concentrations was used in order to estimate the respiration, reaeration and primary production terms involved in this balance. By combining hydrodynamic studies of

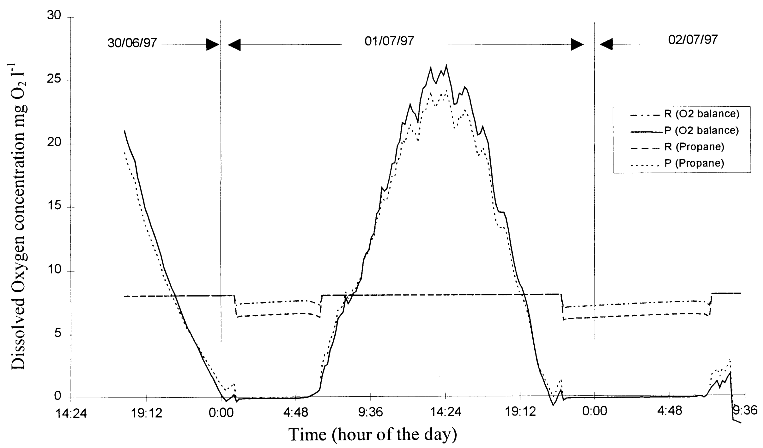

Figure 6 Calculated primary production and respiration rates

the reactor and tracer gas experiments we succeeded in measuring reaeration coefficient values in a full-scale facility's HRAP. This confirms the validity of our procedure.

A systematic anoxic period was observed at night, the possible consequences of which were the release of foul odours and decreasing effluent quality. During the daytime, algal photosynthesis proved to supply enough oxygen to maintain the system's hetero- and autotrophic biomass as well as organic biodegradation. Most of the time the oxygen supply was so important that oversaturation was observed nearly from sunrise to sunset. These observations clearly show that one management option could be periodic harvesting of the algal biomass in order to reduce the overall respiration rate, especially at night, without altering the system's treatment capabilities. Moreover, such microalgae removal, if conducted on a large scale, could present some interesting by-product development opportunities (protein, compost and fertilisers production, pigment extraction, aquaculture, etc.).

The next stage of our study will be to gain a better understanding of the relations between primary production and climatic conditions in order to optimise the quantity of algal biomass that may be harvested.

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