

Comparison of oxygen and carbon dioxide balances in HRAP (high-rate algal ponds)

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Abstract We previously suggested a method to characterize the oxygen balance in High-Rate Algal Ponds (HRAPs). The method was based on a hydrodynamic study of the reactor combined with a tracer gas method to measure the oxygen transfer coefficient. From such a method diurnal variations of photosynthesis and respiration can be quantified and the net oxygen production rate determined. In this paper we propose a similar approach to obtain carbon dioxide balances in HRAPs. Then oxygen and carbon dioxide balances can be compared.

Keywords Algae; gas transfer; high rate algal ponds HRAP; inorganic carbon; productivity; respiration rate

Introduction

The mathematical modeling of wastewater systems such as activated sludge and fixed biomass reactors has been very successful in the past years. For WSPs and HRAPs mathematical modeling is still in its infancy, probably due to the fact that the systems do not appear to be sophisticated at first sight but have in fact a very complex biological behavior. For example, the real contribution of algae in the system is difficult to evaluate. As the photosynthetic process is directly related to the carbon dioxide balance and thus to the pH changes in the system, it is important to quantify the carbon dioxide balance and to examine, for example, whether the carbon dioxide could be the limiting factor for algal growth. Various authors, such as Goldman *et al.* (1972), Schindler and Fee (1973), and Azov *et al.* (1982), have suggested that carbon dioxide could be the limiting factor for algal growth.

As for other bioreactors, a mathematical model of an HRAP has to describe the hydrodynamic behavior of the tank. In the case of an HRAP the flow pattern can be approximated by a plugflow model with recirculation

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

$E(\theta)$: distribution of adimensional residence time

Pe : Peclet number (dimensionless)

θ : adimensional time = $t/(Q/V)$

t_c : travel time of the dye tracer for a complete loop in the reactor(s)

From tracer experiments the Peclet number and the recirculation flowrate can be calculated using Eq. (1). If this is combined with the hydrodynamic study, the oxygen transfer coefficient can be determined, assuming that in a plugflow reactor the state variables are constant in a cross section.

The oxygen balance between two sections of the reactor may be written as

$$\frac{dC}{dt} = Kl'a(C'_s - C) + P - R \quad (2)$$

Kla'	reaeration coefficient for oxygen (h^{-1})
C_s'	dissolved oxygen concentration at saturation in wastewater ($mg.l^{-1}$)
C	dissolved oxygen concentration in wastewater ($mg.l^{-1}$)
R	dissolved oxygen consumption rate in HRAP ($mg.l^{-1}.h^{-1}$)
P	dissolved oxygen production rate by photosynthesis in HRAP ($mg.l^{-1}.h^{-1}$)

Kla' can be obtained from the tracer gas experiment (El Ouarghi *et al.*, 2000). Dissolved oxygen concentrations are measured continuously between two sections. At night $P = 0$ and equation 2 may be solved to estimate R values.

If R can be assumed to be constant at night, when $P = 0$, the reaeration coefficient Kla' can be calculated by Eq. (3), which is the integration of Eq. (2). If R may be assumed as constant, the oxygen mass balance during the light period yields P values.

$$C_t = C_s - \left(\frac{R}{Kla} \right) - \left[C_s - C_0 - \left(\frac{R}{Kla} \right) \right] \cdot e^{-Klat} \quad (3)$$

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 2).

The feasibility of the method has been demonstrated. Similarly we may also write an equation for total inorganic carbon

$$\frac{dC_{in}}{dt} = F(C_{in}) - P(C_{in}) + R(C_{in}) \quad (4)$$

where C_{in} = Total inorganic carbon ($mg.l^{-1}$)
 $P(C_{in})$ = Total inorganic carbon consumption by photosynthesis ($mg.l^{-1}.h^{-1}$)
 $R(C_{in})$ = Total inorganic carbon production by respiration ($mg.l^{-1}.h^{-1}$)
 $F(C_{in})$ = Total inorganic carbon flux across the air-water interface ($mg.l^{-1}.h^{-1}$)

In this equation $P(C_{in})$ – the consumption of C_{in} due to photosynthesis – is equal to 0 at night. There is still a discussion as to whether the real substrate for algae is C_{in} (Goldman *et al.*, 1974 a and b) and thus total inorganic carbon or H_2CO_3 or dissolved CO_2 (King, 1970; King and Novak, 1974).

Material and methods

The experiments were performed on a full-scale facility located at Rabat (Morocco) already described by El Ouarghi *et al.* (2000). During the study we measured various parameters, namely, dissolved oxygen concentrations, conductivity, pH, salinity, temperature, turbidity, etc. These parameters were monitored continuously at several locations in the pond by means of two probes (3800 WQLS). Productivity and respiration rates were measured by the classic light-and-dark bottles method. Samples were also collected during a 24 h period for titrimetric alkalinity measurements by an automatic titrator (TitraLab™80).

Software that was developed previously (Vasel, 1988) in the laboratory is utilized to calculate the various species of inorganic carbon as function of temperature, pH, conductivity and alkalinity. A similar procedure to the one developed for oxygen can be used for carbon dioxide, thus yielding $R(C_{in})$ and $P(C_{in})$ values for the 24-hour period. Cycles are observed as for oxygen and a comparison can be made for $R(O_2)/R(C_{in})$ as well as for $P(O_2)/P(C_{in})$.

An example of daily variations in oxygen, carbon dioxide and pH is given in Figure 1.

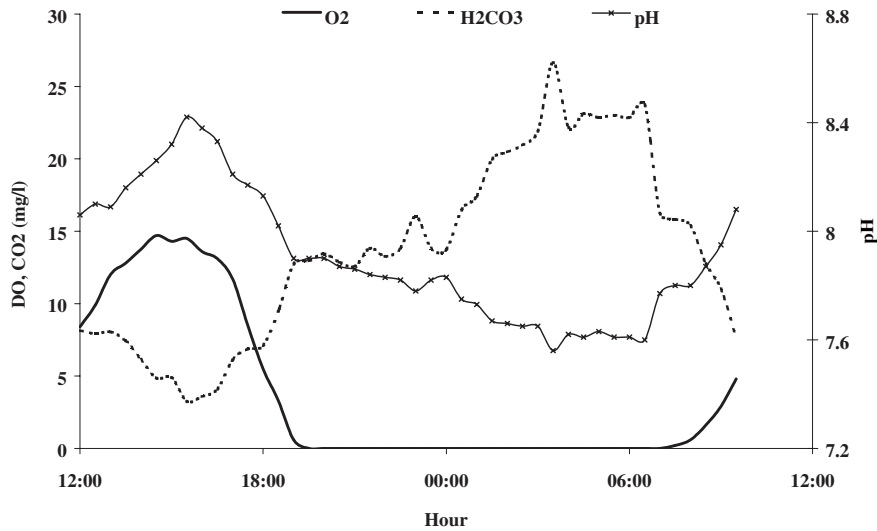


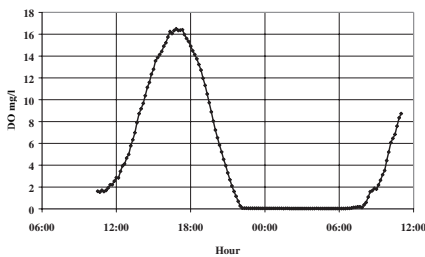
Figure 1 Example of daily variations of oxygen, carbon dioxide and pH in the HRAP

Notice that the amplitudes of the variations are usually higher in HRAPs than in WSPs, with oversaturation for oxygen at some periods but also anoxic conditions at night.

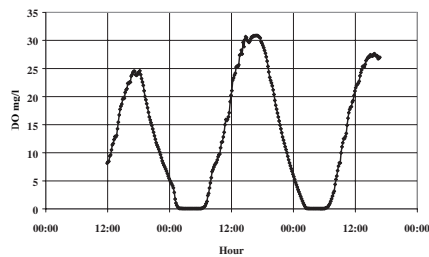
The method described previously by El Ouarghi *et al.* (2000) for oxygen can be applied for a given period of time. Such measurements are presented in Figure 2 and Table 1. As it can be seen, Kla obtained appears quite different, this fact is due to the various process operating conditions during the experiments. Several plant parameters didn't remain constant: paddle wheel velocity, organic load, inlet flowrate, and this may affect the Kla dramatically.

In Figure 3 daily variations of the CO_2 are given. The following parameters were measured on each sample collected: temperature, pH, conductivity and alkalinity.

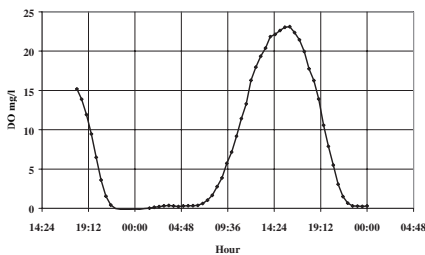
At night, when photosynthesis stops, the term $P(C_{in})$ is equal to zero and Eq. (4) may be



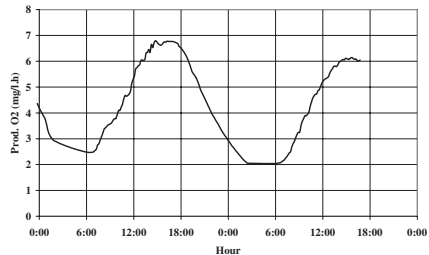
(a) oxygen cycle 1



(b) oxygen cycle 2



(c) oxygen cycle 3

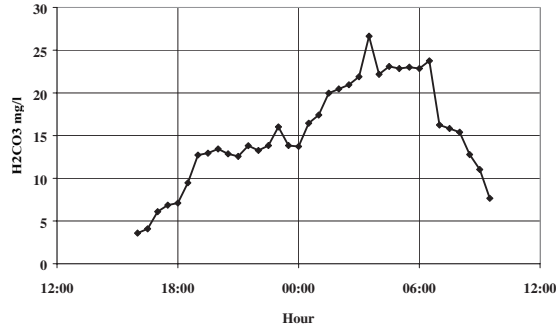
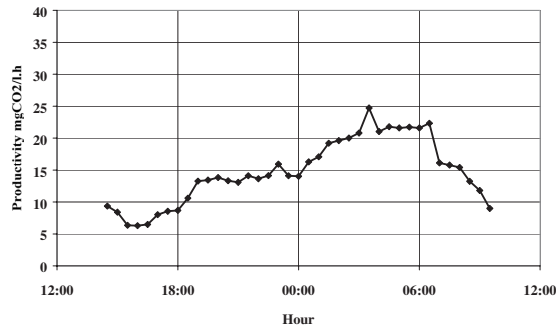


(d) example of calculated productivity $P(O_2)$

Figure 2 (a) Oxygen cycle 1, (b) Oxygen cycle 2, (c) Oxygen cycle 3, (d) Example of calculated productivity $P(O_2)$

Table 1 results obtained on the 3 oxygen cycles

Cycle number :	C_S (mg/l)	Kla (h^{-1})	R (mg/l.h)
1	8.21	0.71	6.50
2	8.36	0.97	4.82
3	8.00	0.58	7.30

**Figure 3** H_2CO_3 concentration during the night**Figure 4** Productivity $P(C_{in})$ during the night

integrated, yielding a solution formally similar to Equation 3. This means that the same solving methods can be used.

If we assume that $R(C_{in})$ remains constant, the mass balance for C_{in} can be calculated from Eq. (4) as dC_{in}/dt is measured, $R(C_{in})$ and $F(C_{in})$ are known from the previous step and $P(C_{in})$ is thus calculated from point to point. Finally the daily variations for $P(C_{in})$ are obtained as presented in Figure 4. The results obtained are:

$$Kla(C_{in}): 0.828 (h^{-1})$$

$$C_S(C_{in}): 7.35 (mg/l)$$

$$R(C_{in}): 8.75 (mg/l.h)$$

Conclusion

The methods developed in this paper are able to calculate the respiration rate R and transfer coefficient Kla when the productivity term P is null, by a simple non linear regression. From the coefficients determined, a net productivity can be then calculated in real time. The same methods are applicable either for inorganic carbon or oxygen.

The comparison of the productivity in term of inorganic carbon and oxygen can be made as well as a comparison of the respiration rate in the same way. The only limitation of the method is that the measurements of oxygen and inorganic carbon must be realised at the same time. The calculation examples in this paper clearly show that measures taken at different times are not comparable, since the Kla coefficient can be affected by the operating parameters, but our main goal was to finalize the method.

Following papers will present complete cycles on O_2 and CO_2 , that will permit full comparison of productivity and respiration ratios for oxygen and CO_2 for $R(O_2)/R(C_{in})$ as well as for $P(O_2)/P(C_{in})$.

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References

- Azov, Y., Shelef, G. and Moraine, R. (1982). Carbon limitation of biomass production in high rate oxidation Ponds. *Biotech. Bioeng.*, **24**, 579–594.
- Chabir, D., El Ouarghi, H., Brostaux, Y. and Vasel, J.L. (2000). Some influences of sediments in aerated lagoons and waste stabilization ponds. *Wat. Sci. Tech.*, **42**(10–11), 237–246.
- El Ouarghi, H., Boumansour, B.E. and Dufayt, O. et al. (2000). Hydrodynamics and oxygen balance in high-rate algal pond. *Wat. Sci. Tech.*, **42**(10), 349–356.
- Frankignoulle, M., Bourge, I., Canon, Ch. and Dauby, P. (1996). Distribution of surface seawater partial CO_2 pressure in the English Channel and in the Southern Bight of the North Sea. *Continental Shelf Research*, **16**(3), 381–395.
- Goldman, J.C., Porcella, D.B., Middlebrooke, E.J. and Toerien, D.F. (1972). Review Paper : The Effect of Carbon on Algal Growth : Its Relationship to Eutrophication. *Wat. Res.*, **6**, 637–679.
- Goldman, J.C., Jenkins, D. and Oswald, W.J., (1974a). Discussion: The kinetics of inorganic carbon-limited algal growth. *JWPCF*, **46**, 2785–2787.
- Goldman, J.C., Oswald, W.J. and Jenkins, D. (1974b). The kinetics of inorganic carbon-limited algal growth. *JWPCF*, **46**, 554–574.
- King, D.L. (1970). The role of carbon in eutrophication. *JWPCF*, **42**, 2035–2051.
- King, D.L. and Novak, J.T. (1974). Discussion: The kinetics of inorganic carbon limited algal growth. *JWPCF*, **46**, 1812–1816.
- Schindler, D.W. and Fee, E.J. (1973). Diurnal variation of dissolved inorganic carbon and its use in estimating primary production and CO_2 invasion in lake 277. *J. Fish. Res. Bd Can.*, **30**, 1501–1510.
- Vasel, J.-L. (1988). Contribution à l'étude des transferts d'oxygène en gestion des eaux, thesis, FUL, Arlon (Belgium).