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Determination of oxygen transfer coefficients in HRAP for the two aeration systems: airlift and paddle wheel

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ABSTRACT

The airlift and the paddle wheel systems are the two most widely used aeration/mixing systems for high rate algal pond facilities. Both located in the full-scale Saada (Marrakech, Morocco) plant. The gas transfer coefficient of oxygen (Kla) and the oxygenation capacity (OC) has been measured, and the energy consumption has been compared in both systems. These parameters have been determined, considering the hydrodynamic of high rate algal pond system. The tests were done in the water velocity range usually found in these types of wastewater treatment systems, in order to determine which one is the most efficient. Our results showed, for the first time, that the airlift system is more efficient in terms of energy consumption and aeration efficiency.

Keywords: Airlift; Paddle wheel; Hydrodynamic; High rate algal pond; Oxygen transfer

1. Introduction

Developed by Oswald [1] and his collaborators since 1950s, the high rate algal pond (HRAP) is a technique operates as a loop channel. The main differences between HRAP and usual wastewater stabilisation ponds (WSPs) are, shorter hydraulic residence time, smaller depth, and a continuous mechanical mixing. Indeed, HRAP is composed of channels in which the water circulates through a water jet, paddle wheel or airlift systems [2]. The agitation enables homogenization of the water column and therefore should prevent settling and accumulation of sediments.

Hydrodynamic characterization is a critical issue to better understand the coupling between the mixing equipment and the performances of the system. It also affects the modelling process and thus the potential for optimization of this type of systems. Tests carried out by El Ouarghi et al. [3] on full-scale HRAP facilities in Morocco in two cities, Rabat and Ouarzazate, showed that the hydrodynamics of the experimental HRAP can be fitted by a dispersed plug-flow model with recirculation. In the mathematical model of the HRAP previously developed by Jupsin et al. [4], the hydrodynamics was described by a series of perfectly mixed tanks with recirculation. Sharing the same advantages of conventional ponds, simplicity and economy, HRAP overcome many of their drawbacks including, poor and highly variable effluent quality, limited nutrient and pathogen removal. In addition, HRAP have the benefit of recovering wastewater nutrients as harvestable algal/bacterial biomass for beneficial use as fertiliser, feed of biofuel [5]. However, the most serious limitation in this system is the gas/liquid mass transfer [6,–8]. In this context, airlift system has been used to enhance gas-to-liquid mass transfer and create liquid circulation in the

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reactor. The oxygen transfer coefficient (Kla) is a standardized measure often used to compare and evaluate various reactor designs for use in gas–liquid mass transfer applications. The Kla term reflects the resistance of liquid film to the oxygen transfer and describes the oxygen transfer at the interface between gas and liquid phases.

In addition, the use of tracer's gaseous hydrocarbons such as propane or ethylene for determining the oxygen transfer coefficient is suitable for aquatic ecosystem without affecting biomass activity. The principle of the method is based on constant ratio between oxygen and propane (tracer gas) coefficients.

Several studies [9–12] have shown that the transfer coefficient Kla at the gas/liquid interface could be affected by various factors (cellulose, NaCl, $HgCl_2$, metabolites formed during the treatment). These factors have the same influence on the oxygen and Kla term also propane transfer coefficient Kla_p.

The aim of this study is to measure oxygen transfer coefficients (Kla) in systems where the hydrodynamics do not correspond to a perfectly mixed reactor.

- Determinate the oxygen transfer capacity (OC) of the HRAP for the two systems (airlift and paddle wheel) at various speeds.
- Compare the energy consumption in each system (airlift and paddle wheel) in the usual range of water velocities to get the same aeration capacity.

2. Materials and methods

2.1. HRAPs treatment plant and agitation systems

This study was conducted at the HRAPs treatment plant of Saada (Marrakech, Morocco) equipped with two aeration systems: the airlift and paddle wheel. According to the agitation system used, the channel's characteristics change slightly (Table 1).

The system has been described previously in more details by Zouhir [13]. The airlift is made of a 16 m^3 tank separated in two parts. The air injection is ensured in one part only (4 m^2) by a Hibon type SF+H00 air blower through 12 Bioflex III 750 perforated membrane air diffusers located 23 cm above the bottom of the tank.

The circulation and homogenization of the effluent in the Saada channel can also be ensured by a paddle wheel equipped with eight paddles (dimensions 180/45 cm) operated by a 4 kW Orbital AS 25 hydraulic engine, equipped with a Plunger type 1-CEX SD5 manual distributor to allow for the setting the wheel's rotation speed.

Table 1
Characteristics of Saada HRAP according to the agitation system used

HRAP characteristics	Mixing system: paddle wheel	Mixing system: airlift
Length (m)	30	32
Width (m)	17	17
Width of the channel (m)	2	2
Length of linear channels(m)	236	242
Surface (m^2)	510	544
Number of channels	8	8
Water depth (m)	0.5	0.5
Volume (m^3)	255	288

2.2. Determination of energy consumption by agitation systems

The power absorbed by both systems was determined as follows:

- For the airlift, the characteristic curves from the SF+H00 air blower were provided by the maker. Those curves are calculated for a set of signal frequencies, discharge temperature, the head losses previously observed, the inlet airflow and the absorbed power. This power consumption was validated for some points by direct measurements and was calculated for the other points after validation of the method.
- For the paddle wheel, we have measured the pressure and the flow rate in closed circuit between the hydraulic engine and the paddle wheel. Pressure was measured by a pressure gauge (type glycerine bath), whereas a parametric portable ultrasonic flowmeter (PT878 model) measured the airflow rate. Pressure and flow rate in the hydraulic circuit yielded the power consumption.

2.3. Oxygen transfer coefficient (Kla) and OC determination

The gas tracer method was used to quantify the gas/liquid mass transfer coefficients (Kla and OC). Propane gas is injected into the water channel by a flexible insufflation ramp, which consists of three circular perforated membrane diffusers. This type of diffuser products have fine enough bubbles, provide greater transfer surface and thus improve the transfer of propane. The propane flow rate is maintained as constant as possible throughout the injection by a pressure regulator set to a pressure of 1.3 bars. The propane tracer gas is then stripped from the ventilation system since there is no propane gas in the environment and in the atmosphere.

The Kla propane (Kla_p) transfer coefficient is determined from the variation of propane concentration as a function of time. The Kla is calculated according to Eq. (1) proposed by Boumansour and Vasel [14].

$$R=\frac{\text{Kla}}{\text{Kla}_\text{p}}=\left(\frac{D(\text{O}_2)}{D(\text{C}_3\text{H}_8)}\right)^n=1.43 \tag{1}$$

with $D(O_2)$ and $D(C_3H_8)$ the diffusion coefficients of oxygen and propane.

Yotsukura et al. [15] suggested an estimate of Kla propane by Eq. (2):

$$\text{Kla}_\text{p}=\frac{1}{T_c}\times\ln\frac{(C_\text{p}\times Q)_u}{(C_\text{p}\times Q)_d} \tag{2}$$

Kla_p is the transfer coefficient propane (h^{-1}), C_p is the concentration of propane dissolved in water (mg/L), T_c is the circulation time (h), Q is the gas flow (Nm^3/m^2 h), u and d, respectively, characterize the first and second sampling point in the pond. A hydrodynamic study was necessary to choose the points of time keeping to be tested and also to determine

Table 2
Summary of the tests

Aeration system	Test	Time of circulation T_c (min)	Water velocity U_C (cm/s)	Duration of propane injection (min)	Sampling frequency (min)
Paddle wheel	2 rmd/min	45.18	8.69	46	2.5
Paddle wheel	3 rmd/min	38.10	10.32	39	2
Paddle wheel	4 rmd/min	31.2	12.59	32	1.5
Airlift	26 Nm^3/h	45.6	8.85	46	2.5
Airlift	37 Nm^3/h	35.52	11.35	36	1.5
Airlift	59 Nm^3/h	29.88	13.47	30	1.5

the circulation time (T_c) which is necessary to interpret the propane curves for the study of gas transfer.

2.4. Tracer test

In order to compare the hydrodynamic generated by both agitation systems, we carried out four tracer tests with NaCl in clear water for each of the systems. The NaCl tracer was used because it is inexpensive since the experiments required the use of high salt concentrations. Hence, we compared NaCl and rhodamine, the results obtained were similar and both of these tracers could be used.

Three different airflow rates (26, 37 and 59 Nm^3/h) were tested for airlift system, and three different rotation speeds (2, 3 and 4 rmd/min) were tested for the paddle wheel one. The flow velocity of liquid has been selected in order to get the flow range rates as recommended for the HRAP system.

Several information were deduced from hydrodynamic study:

- The circulation time T_c is the time needed for an element of liquid to complete a loop in the channel. This circulation time corresponds to the time interval elapsing between two successive peaks.
- The water velocity U_c ($U_c = L/T_c$, L is the linear length of the channel). This velocity will be also related to the mixing properties of the system.

2.5. Gas transfer study

Six propane tests have been implemented: three for the paddle wheel and three for the airlift. For the both airlift and paddle wheel tests, the points injection of propane were chosen while ensuring the time of circulation T_c corresponding to (45.18, 38.10, 31.2 min). These values are usually met in the HRAPs. Samples are taken from the HRAP and the concentration of propane in the liquid phase was determined using gas chromatography (Shimadzu). The propane tests done in this facility are presented in Table 2.

3. Results and discussion

3.1. Kla$_p$

As presented in Fig. 1, propane desorbs gradually as the water runs into the channel, this desorption is mainly due to the turbulence prevailing in the medium (airflow rate 3,689 Nm^3/m^2 h).

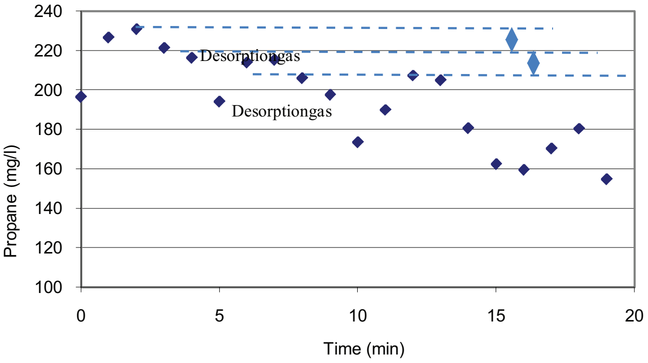

Fig. 1. Example of propane injection with the airlift system.

The desorption can be determined by several methods [16], using a simultaneous injection of the tracer gas and a tracer salt to follow the flow in the middle of the channel. Equations from these methods to determine the tracer gas desorption coefficient have been developed on the assumption plug flow to streams.

In order to interpret experimental results, we opted for a dual approach (peaks method and areas method). Significant results were only observed using the peaks method (plate method) which is quite natural as illustrated in Fig. 1, we tend to reach zero point between two successive waves then we faced a lot of uncertain peak areas calculations.

3.2. Kla

As we can clearly see in Fig. 2, Kla moves substantially with the rate of water circulation, which is linked to the speed of rotation of the impeller or to the airflow injected into the pit of the airlift [13]. The ratio between Kla for oxygen and for propane is constant and well known [12,17]. In this case, the Kla for propane is multiplied by 1.43 to get the Kla for oxygen.

The increase of the oxygen transfer coefficients correlate positively with the increase of water velocities (Fig. 2). Moreover, at the same water velocities, the Kla coefficients of the airlift system are higher than the paddle wheel.

3.3. Comparison of the two stirring systems of HRAP (airlift and paddle wheel)

Kla values obtained allow us to calculate the standard sizes used for comparing the performance of two ventilation systems, such as oxygenation capacity (OC), and hourly intake (AH). As can be seen in Table 3, at the same water velocities in the pond, the airlift system can significantly provide a higher OC than the paddle wheel.

The same observation is made for the contribution schedule, there is a report AH airlift/AH paddle wheel equal to 7, with 5 times less energy consumption in the case of the airlift (Fig. 3). The oxygen transfer results are presented in Table 3. For the same water velocities, the airlift system presents higher global oxygen transfer coefficients. This result indicates that at night, the level of dissolved oxygen (DO) in the reactor can be maintained higher with the airlift as in some HRAP the photosynthesis cycle is active enough to yield an oxygen deficit at night or at least, conditions where the DO concentration may become the limiting factor. The corresponding energy consumptions are presented in Fig. 4. These results were presented previously by Zouhir [13] and illustrate clearly that a well-designed airlift can be five times more efficient than a paddle wheel [2], to reach the same water velocity. As can be seen, the energy consumption to get the same water velocities is lower, about five times [13], with the airlift system than with the paddle wheel [18]. In the other hand, the Kla coefficients are 2 to 3 times higher, resulting in a much more efficient OC, especially at the higher speeds.

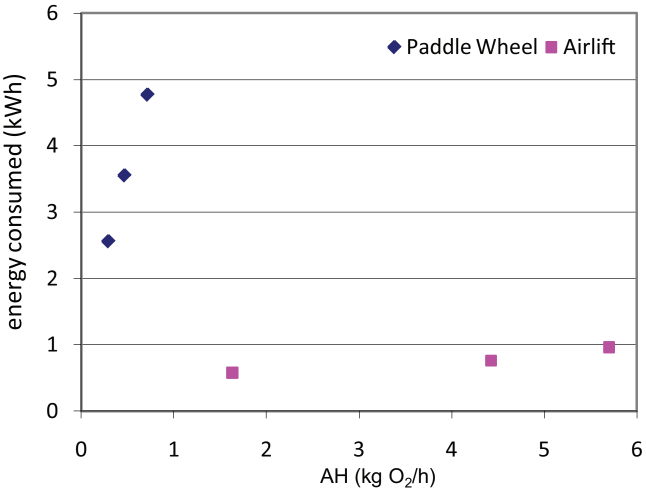

Fig. 3. Hourly intake of oxygen (AH) for two stirring systems depending on the energy consumed.

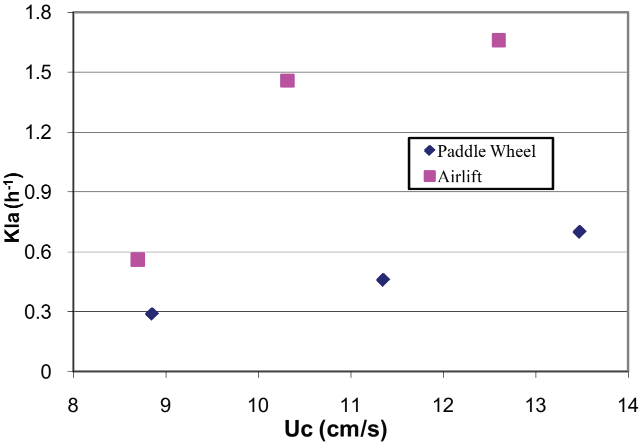

Fig. 2. Oxygen transfer coefficient (Kla) vs. water velocities in airlift and paddle wheel systems.

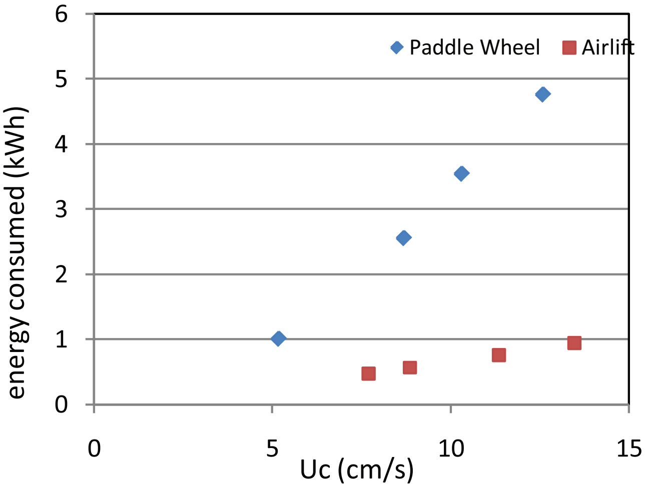

Fig. 4. Comparison of the energy consumed by the airlift and the paddle wheel vs. water velocity measured in the Saada HRAP.

Table 3
Results of aeration tests in the HRAP of Saada

Aeration system	Test	Energy consumption (kWh)	U_C (cm/s)	Kla (h^{-1})	OC (kg O_2/m³ h)	AH (kg O_2/h)	ASB (kg O_2/Kwb)
Paddle wheel	2 rmd/min	2.56	8.69	0.29	1.16×10^{-3}	0.2958	0.116
Paddle wheel	3 rmd/min	3.55	10.32	0.46	1.84×10^{-3}	0.4692	0.132
Paddle wheel	4 rmd/min	4.77	12.59	0.70	2.8×10^{-3}	0.714	0.15
Airlift	26 Nm³/h	0.57	8.85	0.56	5.68×10^{-3}	1.638	2.86
Airlift	37 Nm³/h	0.76	11.35	1.46	15.35×10^{-3}	4.423	5.80
Airlift	59 Nm³/h	0.95	13.47	1.66	19.77×10^{-3}	5.696	5.97

AH, hourly intake of oxygen (kg O_2/h); ASB, gross-specific contribution (kg O_2/Kwb).

4. Conclusion

To our knowledge, this is the first time a comparison is made on airlift and paddle wheel mixing systems on the same HRAP plant to study their aeration efficiency. In the present study, we quantified the power consumption according to the water velocity in the channel. We also quantified the various parameters (Kla) characterizing the oxygen transfer in combination with the hydrodynamic of those systems needed for the mathematical model [19]. Adoption of the usual perfectly mixed model was not possible to quantify the gas transfer coefficients. We, therefore, defined a more appropriate procedure. In terms of power consumption, and in the light of our results, the airlift is definitely the most efficient. The Kla is also up to five times higher in the case of the airlift system which will greatly help to maintain enough DO in the system at night.

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