# COMPARISON OF PADDLE WHEEL AND AIRLIFT FOR AERATION AND GAS TRANSFER IN HIGH RATE ALGAL PONDS

F. Zouhir[1], H. Jupsin[1]; Ouazzani L[2],J- L. Vasel[1]

**1** University of Liege, Unité Assainissement et Environnement, 185 Avenue de Longwy, B6700 Arlon, Belgium.
Corresponding author : Tel.: +3263230849, Fax: +3263230800, Email address: jlvasel@ulg.ac.be.
**2** Laboratoire d'Algologie, Département de Biologie, Faculty of Science Semlalia, Boulevard Moulay Abdallah – Marrakech, Maroc

## Abstract:
A comparison is done between the two most widely used aeration/mixing systems for High Rate Algal Pond facilities: the airlift and the paddle wheel. The gas transfer coefficients ($O_2$, $CO_2$, $NH_3$) have been measured in both systems and the Oxygenation Capacity as well. New methods had to be developed taking into account the hydrodynamic of such systems. The tests were done in the water velocity range usually found in these types of wastewater treatment systems, in order to determine which one in the most efficient. Regarding energy consumption and aeration efficiency the airlift system is more efficient.
Moreover the transfer coefficient for other gas and volatiles compounds such as $CO_2$, and $NH_3$ can be deducted from the results.

**Key words:** Air lift, paddle wheel, hydrodynamic, high rate algal pond, oxygen transfer

## INTRODUCTION:
The High Rate Algal Pond (HRAP), technique developed by Oswald (Oswald, 1963) and his collaborators since the fifties, operates as a loop channel. Main differences with usual WSP are: shorter HRT (Hydraulic Residence Time), smaller depth, and a continuous mechanical mixing.
This type of pond is made of channels in which the water circulates thanks to water jet, paddle wheel or airlift systems (Richmond & Beckers, 1986). The agitation enables also homogenization of the water column and therefore should prevent any 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 (El Ouarghi *et al.*, 2000) carried out on full scale HRAP facilities (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 (Jupsin *et al.*, 2003), the hydrodynamic is described by series of perfectly mixed tanks with recirculation.
Moreover agitation systems, as well as their influence on the hydrodynamics of this reactor have been compared (Zouhir *et al*, 2006) in a same full scale facility.
It appears that to get the same water velocity in the system, a well designed airlift system is much more efficient than a paddle wheel.
In this paper we have set up a comparison on the same specially built full scale facility located in Saada (Marrakech –Morocco) equipped with two agitation systems: the airlift and the paddle wheel to compare their aeration efficiency and gas/liquid transfer capacity in general

Our study aims at:

- The development of oxygen transfer coefficients (Kla) measurement in systems where the hydrodynamic doesn’t correspond to a perfectly mixed reactor.
- The characterisation of the oxygen and other gas transfer capacity of the HRAP for the two systems (air lift/ paddle wheel) at various speeds.
- The comparison of the energy consumption by each system in the usual range of water velocities to get the same aeration capacity..

**Materials and Methods:**

- A small pilot plant; the measurement methods for Kla coefficients were first developed in a small plexiglass HRAP pilot plant (280L). That has been described in details previously (Zouhir *et al*, 2006)
- Description of the full scale Saada-Marrakech plant :

As a result of cooperation between Belgium and Morocco, a HRAP plant was built in Saada Marrakech equipped with two aeration systems (airlift and paddle wheel) in order to carry out comparative research (see fig. 1).

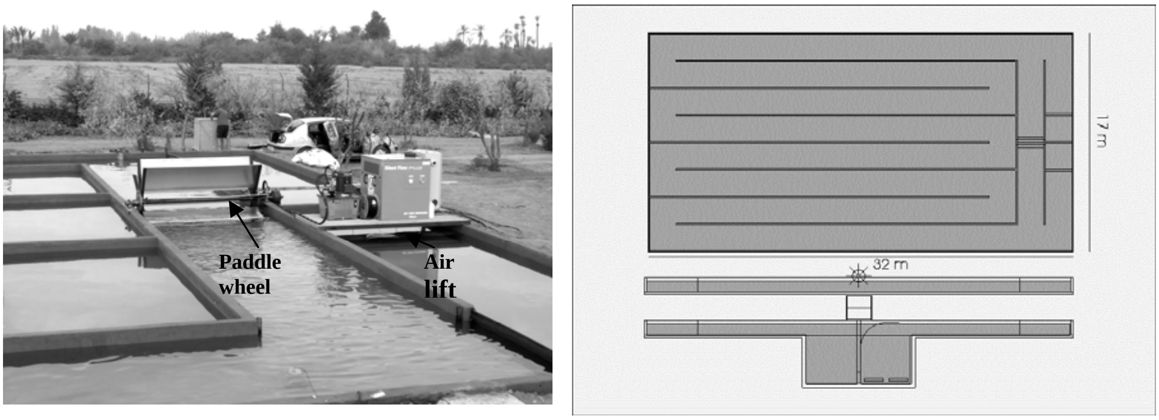


*Figure 1: Saada Marrakech treatment plant (Morocco): paddle wheel and airlift*

According to the system used, the channel’s characteristics change slightly (cf. table 1)

*Table1: Characteristics of Saada HRAP according to the agitation system used*

| The HRAP characteristics | Mixing system : paddle wheel | Mixing system : Air lift |
|---|---|---|
| length (m) | 30 | 32 |
| width (m) | 17 | 17 |
| Width of the channel (m) | 2 | 2 |
| Length of linear channels(m) | 236 | 242 |
| Surface (m²) | 510 | 544 |
| Number of channels | 8 | 8 |
| Water depth (m) | 0.5 | 0.5 |
| Volume (m³) | 255 | 288 |

The system has been described in more details in a previous paper (Zouhir *et al*, 2006).The airlift is made of a 16 m³ tank separated in two parts. The air injection is ensured in one part only (4m²) 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 (see fig. 2). A *Lenze* model *smd* frequency controller controls the air blower’s engine so that the frequency varies and consequently the air flow rate.

The paddle wheel: the circulation and homogenization of the effluent in the Saada channel can also be ensured by a paddle wheel equipped with 8 paddles (dimensions 180cm/ 45cm) operated by a 4kW ORBITAl AS 25 hydraulic engine, equipped witch a PUNGER type 1-CEX SD5 manual distributor to allow for the setting the wheel’s rotation speed (see fig. 3).

*Figure 2 : One part of the air lift with its 12 diffusers*

*Figure 3 : The paddle wheel in operation*

The power absorbed by both systems were 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 air flow and the absorbed power. This power consumption was validated for some points by direct measurements and after validation were calculated for the other points.
- ♦ For the paddle wheel, we have measured the pressure and the flow rate in the closed circuit between the hydraulic engine and the paddle wheel. Pressure was measured by a pressure gauge (type glycerine bath), whereas the air flow rate was measured by a PT878 model Panametrics portable ultrasonic flow meter. Pressure and flow rates in the hydraulic circuit yielded the power consumption.

- **Other gas transfer coefficients**

Measurements were also performed in the Plexiglas pilot plant for other gas than oxygen and propane, namely $CO_2$ and $NH_3$. For $CO_2$ a $NaHCO_3$ solution was mixed in the reactor. The pH was maintained at 4.5 (20°C) and the $CO_2$ concentration was followed in the reactor by a YSI CO2 probe. The gaz phase injected in the airlift was $N_2$ to avoid an interference due to the $CO_2$ in air.

Tests were also done with $NH_3$ (pH 12.2 and T° 16.9°C) with an $NH_3$ initial concentration of 450 ppm.

**Results and discussions:**

Methodology for Kla measurement in the small pilot plant. As it has been demonstrated previously (El Ouarghi *et al* (2000), Zouhir *et al*, 2006) the hydrodynamic of the HRAP is close to a plug flow system with recirculation. Consequently the usual method for Kla measurement (ASCE 1990) developed for completely mixed reactors cannot be used and the Kla coefficients will have to be measured in combination with an appropriate hydrodynamic model. We tested various methods such as sulphite addition (as in the ASCE procedure) prior to the test or added during the time corresponding to one loop. We also injected nitrogen gas directly in the aeration system instead of air. In the case of such small reactors the nitrogen method provided the best results and we could fit the model to get not only the Kla measurement in the airlift part of the reactor but we could also estimated the K2 (which is also a transfer coefficient) in the HRAP part that is not the airlift itself.

As expected those transfer coefficients increase when the airflow rate increases as illustrated on results in figures 4 and 5.

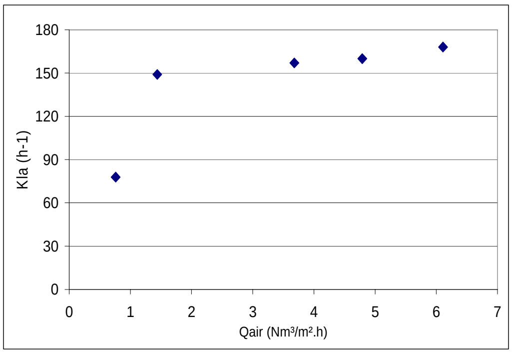


*Figure 4. Oxygen transfer coefficient* ***Kla*** *Vs air flow rate in the plexiglas pilot plant*

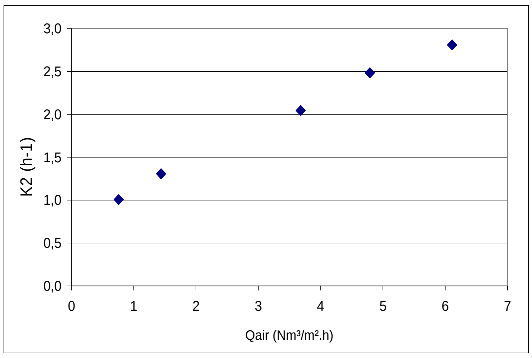


*Figure 5. . Oxygen transfer coefficient* $\boldsymbol{K_2}$ *Vs air flow rate in the plexiglas pilot plant.*

The global “apparent” transfer coefficient can be calculated as

$$Kla - global = \left(Kla * Volume_{airlift} + K_2 * Volume_{HRAP}\right) / Volume_{total}$$

The results are given on figure 6 for the Plexiglas pilot plant.

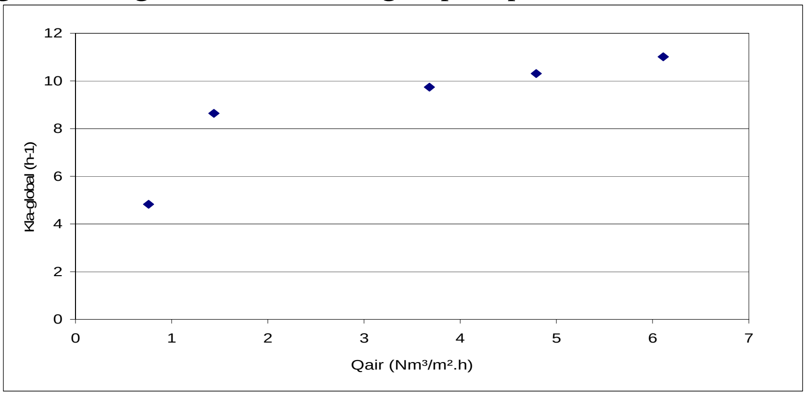


*Figure 6. Global Oxygen transfer coefficient* ***(apparent Kla)*** *Vs air flow rate in the plexiglas pilot plant.*

Measurement in Saada. The nitrogen method would be very difficult to use in full scale facilities : high quantity of nitrogen would be needed to get a oxygen concentration drop close to 1 mg$O_2$/l. We decided to use a tracer gas method based on propane that we had used already before in our lab (Boumansour *et al*, 1998). Commercial propane can be found easily and is analyzed by GC (Headspace method) on samples collected in vials closed with septums. The propane is injected through perforated membranes as shown in figures 7 and 8.

*Fig. 7 : experimental set up for propane at Saada (Marrakech)*

*Fig.8 : Propane injection in the paddle wheel system*

The propane tests done in this facility are presented on table 2.

*Table 2. Sumary of the tests in Saada.*

| Aeration system | Test | Time of circulation Tc (min) | Water velocity $U_C$ (cm/s) | Duration of propane injection (min) | Sampling frequency (min) |
|---|---|---|---|---|---|
| Paddle wheel | 2 r/min | 45.18 | 8.69 | 46 | 2.5 |
| Paddle wheel | 3 r/min | 38.10 | 10.32 | 39 | 2 |
| Paddle wheel | 4 r/min | 31.2 | 12.59 | 32 | 1.5 |
| Air lift | 30 Hz | 45.6 | 8.85 | 46 | 2.5 |
| Air lift | 40 Hz | 35.52 | 11.35 | 36 | 1.5 |
| Air lift | 50 Hz | 29.88 | 13.47 | 30 | 1.5 |

Thus the propane was injected directly after the aeration system during a time corresponding to a complete loop of the water in the reactor.
An example of such an experiment is given on figure 9. The ratio between Kla for oxygen and for propane is constant and well known (Boumansour *et al*, (1995). In this case the Kla for propane is multiplied by 1.43 to get the Kla for oxygen.
The results are illustrated on figures 10 and 11.
As can be seen the oxygen transfer coefficients increase when the airflow (airlift) or the rotation speed (paddle wheel) increase. Moreover the Kla coefficients of the airlift system are higher, at the same water velocities, than those of the paddle wheel.

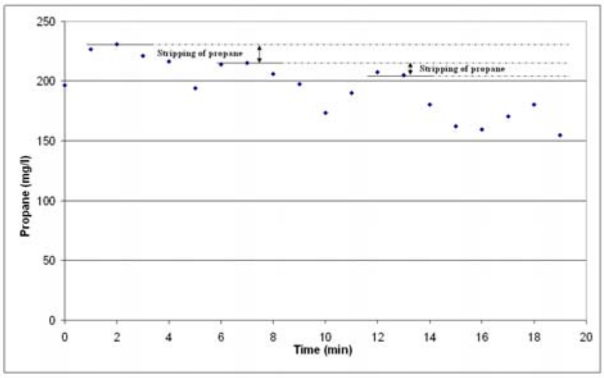


*Figure 9. Example of propane injection with the airlift system (airflow rate 3.689 Nm³/m².h).*

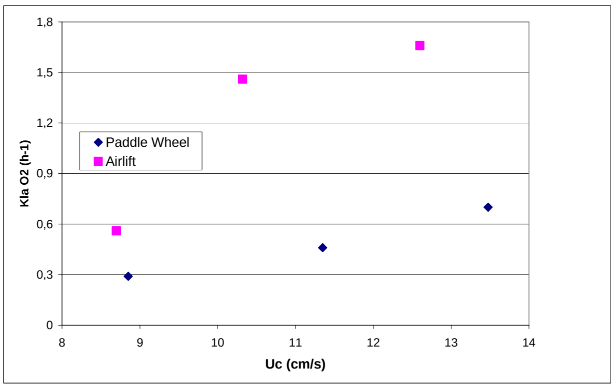


*Figure 10. Global Oxygen transfer coefficients Kla Vs water velocities in airlift and paddle wheel systems.*

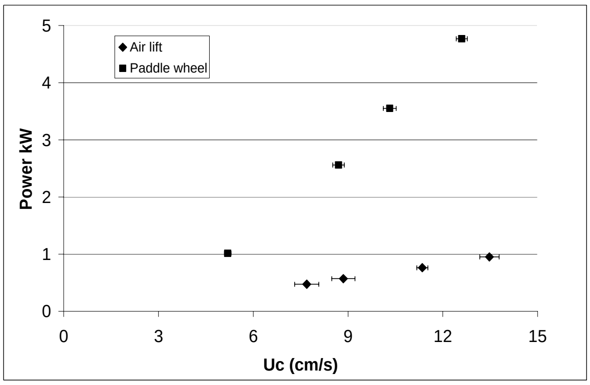


*Figure 11: comparison of the power consumption by the air lift and the paddle wheel vs water velocity measured in the Saada HRAP*

For the same water velocities the airlift system has higher global oxygen transfer coefficients. This means that at night the level of 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 dissolved oxygen concentration may become the limiting factor. The corresponding energy consumptions are presented on figure 11. These results were presented previously (Zouhir *et al*, 2006) and illustrate clearly that to reach the same water velocity the efficiency of a well designed airlift can be 5 times greater than a paddle wheel.
The oxygen transfer results are presented in table 3.

*Table 3. Results of aeration tests in the HRAP of saada*

| Aeration system | test | Energy consumption (kWh) | $U_C$ (cm/s) | Kla O2 ($h^{-1}$) | OC (kg O2/m³.h) |
|---|---|---|---|---|---|
| Air lift | 30 Hz | 0.571 | 8.699 | 0.29 | $5.68 *10^{-3}$ |
| Air lift | 40 Hz | 0.762 | 10.320 | 0.46 | $15.35 *10^{-3}$ |
| Air lift | 50 Hz | 0.953 | 12.598 | 0.70 | $19.77 *10^{-3}$ |
| Paddle wheel | 2 rpm | 2.56 | 8.851 | 0.56 | $1.16 *10^{-3}$ |
| Paddle wheel | 3 rpm | 3.55 | 11.350 | 1.46 | $1.84 *10^{-3}$ |
| Paddle wheel | 4 rpm | 4.77 | 13.475 | 1.66 | $2.8 *10^{-3}$ |

As can be seen the energy consumption to get the same water velocities are lower, about 5 times (Zouhir *et al*, 2006) with the airlift system than with the paddle wheel. In the same time the Kla coefficients are much higher (2 to 3 times) which results in a much more efficient oxygenation capacity, especially at the higher speeds.

**Other gas transfer coefficients**

The global $CO_2$ transfer coefficient obtained in the Plexiglas pilot plant is illustrated on figure 12.

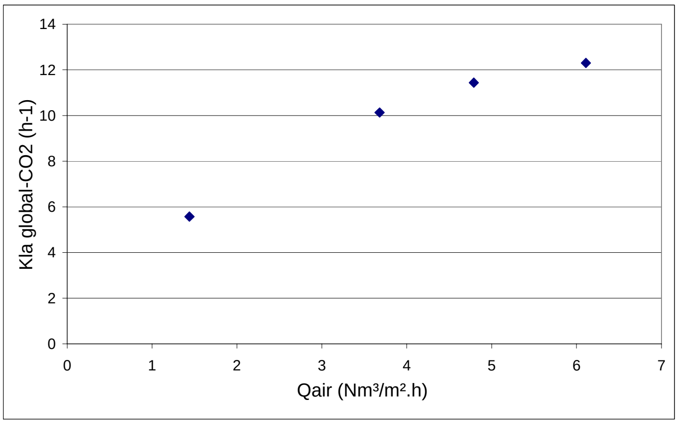


*Figure 12. Global $CO_2$ transfer coefficients Vs N2 flowrates*

Comparing the experimental $CO_2$ transfer coefficients to the global Kla values for oxygen we obtained a $KlaCO_2/KlaO_2$ ratio of 1.0439 ($r^2$ = 0.778). This ratio is close to the theoretical ratio 1.05. This means that if we know the oxygen transfer coefficient (or the propane coefficient) we can easily estimate the $CO_2$ transfer coefficient. This is important as some

authors (Glodman *et al* (1972), Schindler &Fee (1973) Azov *et al* (1982)) considered that $CO_2$ could become the limiting factor for the growth of algae in HRAP systems. This transfer coefficient is needed to establish a $CO_2$ mass balance on the system. Fot NH3 the measurement of transfer coefficient is difficult. We obtained, with a test lasting more than 100 hours, a $NH_3$ transfer coefficient of 0,017 $h^{-1}$ (pH 12.2 , t° 16.9°C) whereas the global $O_2$ transfer coefficient was 9.74 $h^{-1}$.
This means that the $NH_3$ volatilization process in the HRAP is not very active and could hardly contribute to an important nitrogen removal in the system. This confirm also consideration made by Andrianarison *et al* and Zimmon *et al* (2003) on global nitrogen mass balances

## CONCLUSION

To our knowledge, no comparison was made so far on air lift and paddle wheel mixing systems on the same High Rate Algal Pond plant for their aeration efficiency..
In this study we quantified the power consumption according to the water velocity in the channel but we also quantified the various parameters (Kla) characterizing the oxygen transfer in combination with the hydrodynamic of those systems and that are needed for the mathematical model (Vasel *et al* 2004). For this we had to define appropriate procedure to quantify the gas transfer coefficients as we cannot adopt the usual perfectly mixed model.
In terms of power consumption, the air lift is definitely the most efficient. The transfet coefficient for oxygen (Kla) is also up to 5 times higher in the case of the airlift system wich will greatly help to maintain enough DO in the system at night. For other gas we can deduct from our results at lab scale that a KlaO2/Kla CO2 ratio close to 1.03 can be adopted which can be used to establish mass balances for CO2 on the system. For $NH_3$ even at a pH >12 the transfer coefficient is very low ( in this case less than 1/500 of the one for $O_2$), confirming that the volatilisation process of NH3 could hardly contribute significantly to the nitrogen removal in those systems.

## ACKNOWLEDGMENT

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**Notations :**

Uc : water velocity (cm/s)
Tc : time of circulation (h)
L : Length of the linear channels (m)
Qair : air flow rate in the airlift ($Nm^3 m^{-2} h^{-1}$)
Kla : transfer coefficient ($h^{-1}$)
OC : Oxygenation Capacity (kg O2/m³.h)

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