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Progress in modeling of high-rate algal ponds

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ABSTRACT

The objective of this paper is to present experimental methodologies developed in the field of process engineering facilitating the quantification of the main processes involved in high rate algal ponds (HRAPs). The model presented is based on the River Waters Quality Model No. 1. The hydrodynamic system is particularly simple and the reactor is modeled with a series of perfectly mixed recirculation reactors. For the calibration of the model, one must go through the study of the main axes of this model. The hydrodynamics of the reactor fitting Voncken's model: circulation time (T_c), recirculation flow rate, water velocity (V_c), Peclet's number, etc.), the gas–liquid transfer processes for oxygen but also for NH_3, CO_2 and the photosynthesis-related biochemical processes were monitored. The simulation is conducted in a HRAPs pilot plant using the WEST program. The oxygenation factor was optimized and set by a series of experimental data obtained on the pilot station located in Marrakech. The obtained result show a strong link between concentration of algae and dissolved oxygen concentrations with maximum levels reached after 500 h. The maximum concentration of algae and oxygen are in the order of 500 and 16 g m^{-3}, respectively. This is one more element to judge the consistency of our model. Additionally, the simulation of heterotrophic biomass, algae biomass, nitrogen concentration, chemical oxygen demand removal efficiency and oxygen concentrations vs. time in the HRAPs with the classical cycles due to day/night conditions show that the influence of light is clearly marked on the oxygen and algae concentrations. The methodology adopted to characterize the gas transfer coefficient is suitable for piston reactors with recirculation.

Keywords: High rate algal ponds; Hydrodynamic; Gas–liquid transfer; WEST® program

1. Introduction

The high rate algal ponds (HRAP) process of wastewater treatment constitutes an economical and efficient alternative in semi-arid countries such as Morocco. This technique is based on a symbiosis between the bacteria and algae which aims to accelerate the treatment process by promoting algal production. The successful operation of algal treatment systems depends upon establishing a dynamic equilibrium between algal oxygen production and bacterial oxygen consumption [1].

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HRAPs are considered to be effective reactors to reclaim water, nutrients and energy from organic wastewaters [2–5]. This system has several advantages such as elimination of pathogenic microorganisms for better utilization in irrigation, removal of nutrients by assimilation and stripping, and great production of algal biomass for use as a fertilizer, protein-rich animal feed or for conversion into biofuel such as: biogas via anaerobic digestion; bioethanol via carbohydrate fermentation; bio-crude oil via high-temperature liquefaction; or biodiesel via lipid trans-esterification [6,7].

The performances of a wastewater treatment plant (WWTP) have so far been evaluated by calculating average efficiencies of mean parameters such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), N and P removal efficiencies. However, HRAPs performance depends on climatic (light, temperature), operational (pH, CO_2 concentration), water depth, dissolved oxygen, nutrients, hydraulic retention time and biological variables (parasites, fungi, zooplankton grazers) [8–11]. The management of river catchment is changing fast, especially in Europe, where the quality of the aquatic (receiving) ecosystem has now also to be taken into account. This means that new tools have to be developed with a view to characterizing into detail the interactions between WWTP and water bodies.

Therefore, the HRAPs is a complex system. In this context modeling is an essential tool for effective management of the system. A first model including processes described in the River Water Quality Model No. 1 was presented in Auckland [12]. This first model adopted a methodology similar to that used for River Waters Quality Model No. 1 (RWQM1) [13] as well as other types of models such as the IWA models ASM1, ASM2 and ASM3 [14].

The previous model was therefore accomplished by: (i) adding a second type of algae, in order to be able to take into account the changes of dominant species; (ii) including gas/liquid mass transfer for oxygen, CO_2 and NH_3; (iii) adding an aerobic contribution of sediments in the process (oxygen and substrate consumption); (iv) and taking into consideration disinfection kinetics (for one specie) [15–20]. However, the models described in previous works didn't take into account the luminous intensity.

The HRAPs reactor is open to the atmosphere and has some serious drawbacks that may limit their performance. These include the high risk of culture contamination, high final biomass concentrations incurring high harvesting costs, the lack of temperature control, and the poor gas/liquid mass transfer [21–23].

Various gaseous compounds, especially oxygen, CO_2, NH_3, H_2S or even VOCs can be exchanged between the liquid phase and the atmosphere depending on operating conditions but also on the period of day (light or dark) periods for example. A realistic mathematical model of HRAPs has hence to take those exchanges into account, which means that the corresponding gas transfer coefficients have to be quantified. There are some well-known methodologies for measuring oxygen transfer coefficients [24] but these have usually been developed for perfectly mixed reactors.

New methodologies are therefore necessary to characterize the main gas transfer coefficients for O_2, CO_2 and NH_3 at least in the case of plug flow reactors with recirculation.

Like any other mathematical model, the proposed model is useful for simulation purposes, but it can also be used to help in the quantification of the main processes involved in those rather complex ecosystems. Moreover, it has been developed to facilitate the connection with river models (such as RWQM1) as most of the state variables are identical [25]. This should enable a better description of the effects of outlets of HRAPs and stabilization ponds in rivers. An evaluation of fluxes of substrates and biomasses to the river should hence be possible. The model presented here was developed as part of the WEST® system.

This study intends to simulate key parameters such as light intensity, efficiencies of mean parameters (BOD, COD, N and P removal), algal biomass and oxygen concentration within the high rate algal ponds by implementing an airlift for water velocity. The previous simulation studies did not use the light intensity, for this purpose a model coupling technique was used to implement the effects of this parameter. On the other hand, this study proposes a methodology to investigate the gas transfer coefficient (Kl.a) adapted in the systems where the hydrodynamics do not correspond to a perfectly mixed reactor but to a plug flow reactor with recirculation.

2. Material and methods

2.1. HRAPs pilot plant

A small pilot plant was built in order to facilitate the methodology development for the modeling of HRAPs prior to developing full-scale facilities (Fig. 1).

The records that were subject of mathematical simulations were harvested on the channel installed on the site, located in Marrakech (Morocco) between the 31° North Latitude and Longitude 8° West, at an altitude of 468 m above the sea's level.

The HRAPs pilot plant in the current study is using an airlift mixing system, it is made by Plexiglas materiel with the following characteristics: surface of 2.4 m^2, 8 channels, water depth over 15 m, volume of 0.28 m^3, air flow rates from 7 to 10 ($Nm^3\ m^{-2}\ h^{-1}$), airlift section of 144 cm^2 (Table 1).

2.2. HRAPs experimental setup

2.2.1. Hydrodynamics studies

A hydrodynamic test was conducted referring to the study [17]. NaCl was used as a tracer in clear water because it is inexpensive and therefore it is possible to use high quantities of salt if the study were to be reproduced a large scale. For this experiment, 80 g of NaCl was added in the inlet of the pilot plant and conductivity was monitored at the outlet using a multi-probe type YSI 6920.

Three different airflow rates (26, 37 and 59 $Nm^3\ h^{-1}$) were tested for the airlift system, and four different rotation speeds (2, 3 and 4 rnd min^{-1}) 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 was 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

Fig. 1. Pilot plant used for the development of methodologies.

Table 1
Characteristics of the pilot plant

HRAPs-pilot	Characteristics
Mixing system	Airlift
Surface (m^2)	2.4
Number of channels	8
Water depth (m)	>15
Volume (m^3)	0.28
Air flow rates ($Nm^3\ m^{-2}\ h^{-1}$)	7 to 70
Airlift section	144 cm^2

time corresponds to the time interval elapsing between two successive peaks. The water velocity U_c (when $U_c = L/T_c$, with L is the linear length of the channel). This velocity will be also related to the mixing properties of the system.

2.2.2. Gas transfer

A quantity of nitrogen is injected into the pilot by the airlift system, the objective being to deoxygenate the pilot's water by "stripping" the oxygen. Once the pilot's water has been deoxygenated (OD = 0), thanks to a 3-way valve we switch "instantly" from nitrogen to air at the same previously set flow rate, while maintaining a flow which we will consider then as established (stationary) in the pilot. The evolution of the dissolved oxygen concentration is recorded every second at the three different locations as defined above [26].

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, and 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).

2.3. WEST® program

The HRAPs pilot plant data is modelled by using Worldwide Engine for Simulation and Training WEST® [27,28]. This program offers a user-friendly modeling and simulation platform for different processes: wastewater modeling and simulation, river and catchment modeling and simulation, fermentation modeling and simulation, ecological modeling and simulation. This system greatly facilitates process optimization, cost reduction bottleneck identification, controller design, automation and even training of operators. WEST® includes a model base, a graphic interface and finally a simulation environment adapted to wastewater treatment models.

The parameters used for the calibration of this model are oxygen concentration, light intensity, COD, nitrogen, pH and biomass.

3. Results and discussion

3.1. Hydrodynamic study

It is widely mentioned in literature that the hydrodynamics of HRAPs correspond to a dispersive plug flow with recirculation that fits Voncken's model [29]. Pulse tracer experiments can be realized in various operating conditions (mainly airflow rates) to characterize the interactions between homogenizing and hydrodynamics of the reactor. Tracer studies can be performed using NaCl or other tracers such as LiCl or Rhodamine WT.

In Fig. 2 an example of hydrodynamic study using NaCl is demonstrated. It is also shown that Voncken's

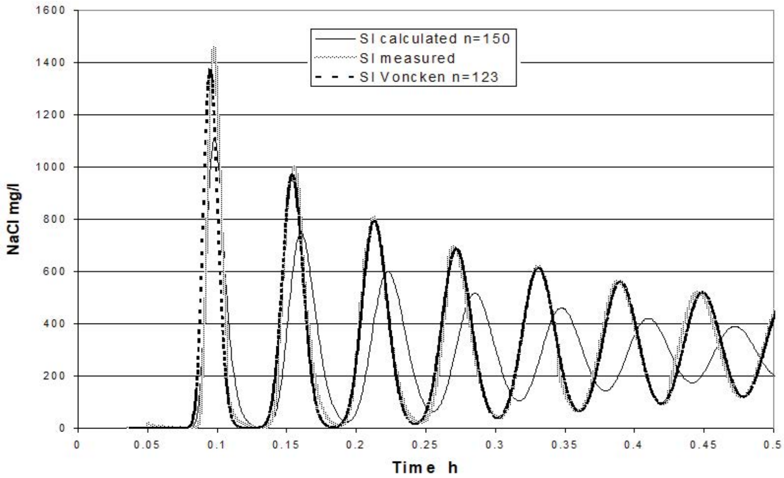

Fig. 2. Example fitting Voncken's model.

model not only fits the experimental data but it also gives another good approximation with 123 (One hundred and twenty-three) reactors in series.

The correlation between T_c and the dispersion number in the reactor is observed in Fig. 3. T_c is the average elapsed time between 2 maxima. V_c is deducted as L/T_c and the total Q (1 + r) flowrate as $V_c \times A$, where A is the cross section of the channel.

Similar properties can be obtained by facilities equipped with paddle wheels. Fitting Voncken's model provides T_c and Peclet's number (or the number of reactors in series) as showed in Figs. 4 and 5.

3.2. Gas transfer study

The gas transfer experiment was conducted in clear water (no biomass was present) where nitrogen gas was used in the beginning of the experiment at a given flow rate to deoxygenate the reactor and also to get a steady state value of the flow pattern in the reactor at the same time. The gas phase was then quickly switched to air (at the same flow rate) at the same time as the hydrodynamic tracer was injected (pulse signal), as described in the Hydrodynamic section.

Dissolved oxygen was monitored continuously at various points in the reactor, rising step by step until saturation was reached. Fig. 6 shows the result of gas transfer study in which conditions corresponds to the same hydrodynamics conditions as illustrated in Fig. 2. Again, the model fits very well with experimental data. The Kl.a parameter in the airlift part of the system is fitted at 149 h^{-1}. Similar experiments are in progress with a view to measuring CO_2 (at pH 2), NH_3 (at pH 12) and propane transfer coefficients in clean water. Those transfer coefficients were also being checked when biomass will be present in the reactor.

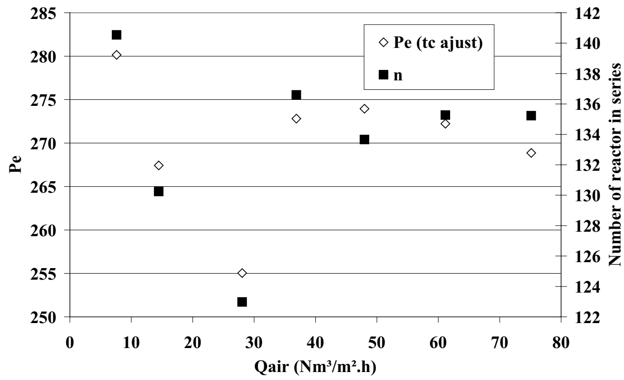

Fig. 3. Relationship between Peclet's number (Pe or n) and airflow rate (Q_{air}) in the airlift.

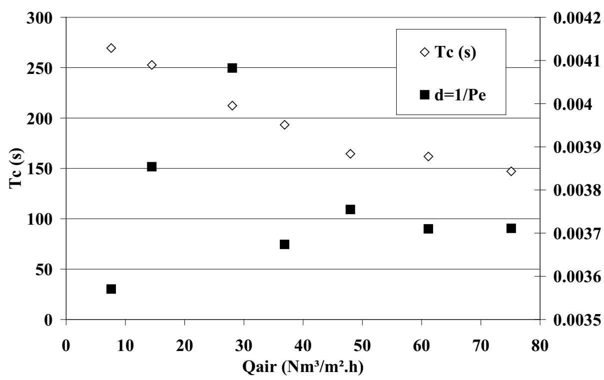

Fig. 4. Relationship between circulation time (T_c) and dispersion number (Pe) and airflow rate.

3.3. WEST simulation

3.3.1. Light intensity

The model was developed using WEST version 3.71, using the ODE solver CVODE provided in this package to resolve the differential equations. The following figures show a simulation of heterotrophic biomass (all degraders), algae biomass, Nitrogen concentration, the COD removal efficiency [25] and the oxygen concentrations vs. time in the HRAPs with the classical cycles due to day/night conditions.

As it is shown in Fig. 7, the light influence is clearly marked on the oxygen and algae concentrations. Future paper will give more information on parameters sensitivity analysis.

3.3.2. Nitrogen

Fig. 8 shows that day and night variations are well marked and of the order of magnitude to those observed in the field. The graph's study shows a net decrease of ammonia concentration at the outlet, this may be reflected in the denitrification phenomenon. There is also a disappearance of the cyclic probably nitrates in part to a denitrification.

3.3.3. Organic load

Fig. 9 shows that the initial substrates (soluble and particulate) are largely degraded. Unfortunately, the lack of data has not made it possible to compare the purifying yields calculated with those simulated.

Figs. 8 and 9 show that the HRAPs model is able to simulate other parameters continuously, and this is very interesting when one must meet discharge standards for example, what is more, when new safety standards and environment in the field of water and in particular in the treatment, monitoring as well as require a more extensive control of the processes employed for treatment.

3.3.4. Oxygen and biomass

Fig. 10 shows the evolution of the dissolved oxygen and the concentration of algae as a function of time. This curve simulated by the WEST program is very logical: it shows a strong link between the concentrations of algae and dissolved oxygen concentrations. This is one more element to judge the consistency of our model.

Fig. 11 depicts the autotrophic and heterotrophic biomass concentrations evolutions vs. time.

4. Conclusion

The high rate algal pond is a system suitable for the efficient treatment of wastewater in developing countries. However, and giving the high number of parameters (e.g., Kl.a, Pe, algal biomass) which condition the proper functioning of such a system, modeling is a good management tool to guarantee a good purification performance.

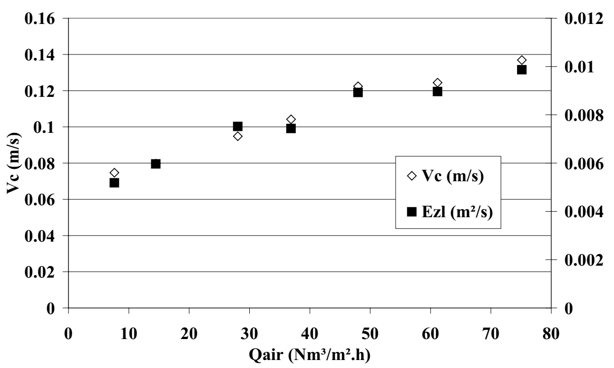

Fig. 5. Relationship between water velocity (V_c), dispersion coefficient (E_z) and airflow rates.

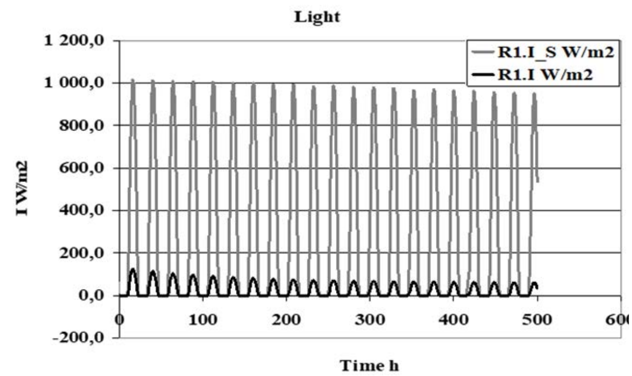

Fig. 7. Light intensity W m^{-2} vs. time; I_S: surface intensity and I light intensity in water (integration on water depth with self-shading of the algae and biomass).

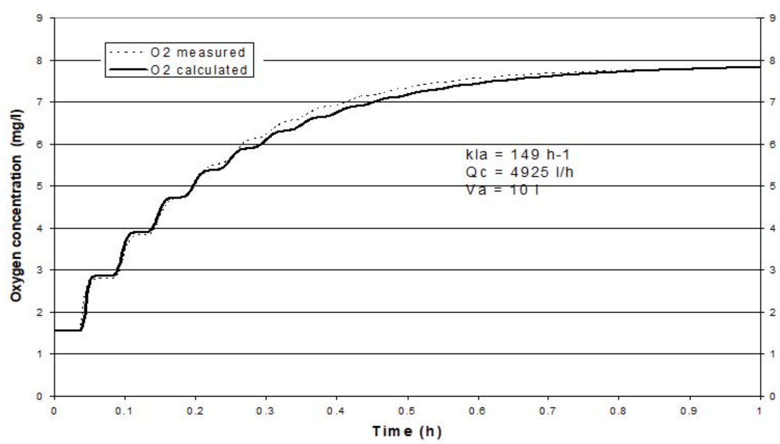

Fig. 6. Kl.a measurement.

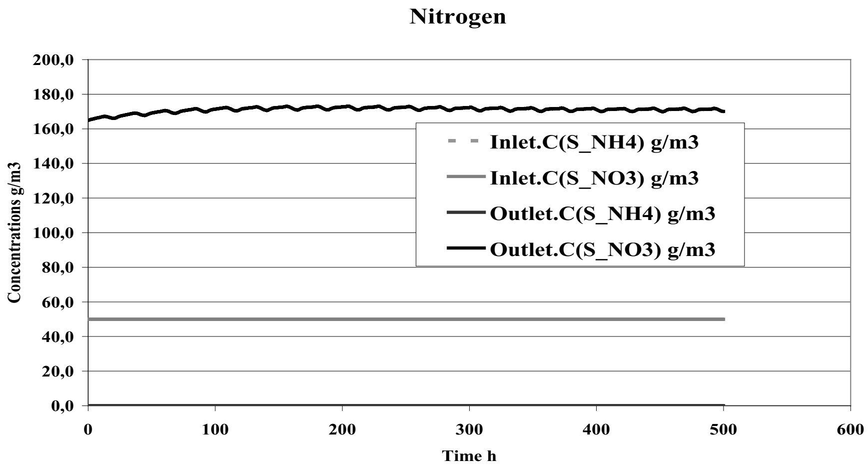

Fig. 8. Nitrogen concentration (inlet and outlet) vs. time.

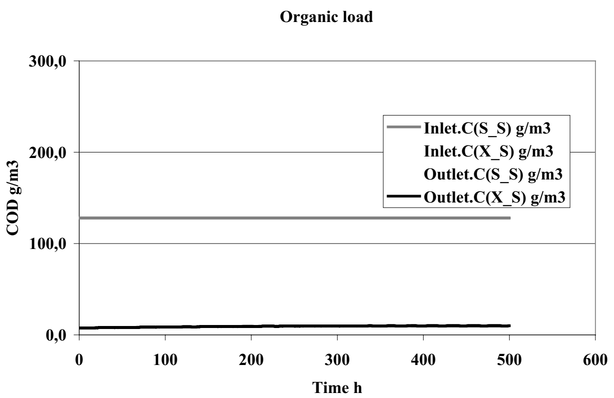

Fig. 9. COD soluble and particulate (inlet and outlet) vs. time.

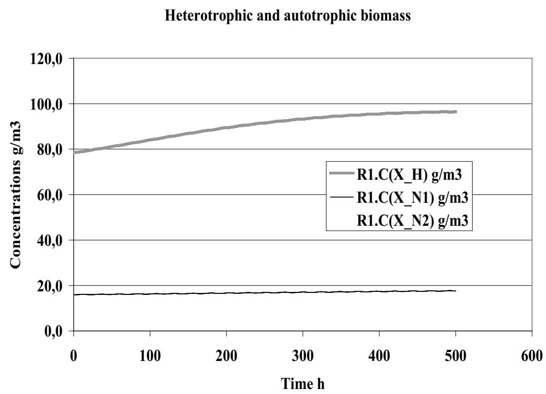

Fig. 11. Heterotrophic and autotrophic biomass concentrations vs. time.

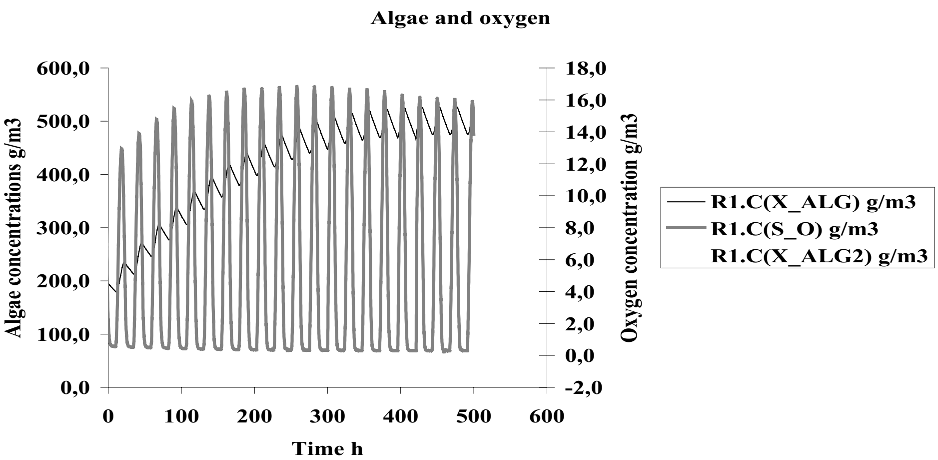

Fig. 10. Algae and oxygen concentrations vs. time.

In this work, several key parameters were determined (e.g., Kl.a, Pe, T_c, V_c). Simulation using WEST software have been applied and first results are very encouraging. HRAPs is now included in the process database. This ensures the model development benefits from all the features of the WEST® system, especially the parameters estimation module which has been used to fit parameters such as Kl.a. The next step will be the application of this model to data collected on a full-scale algal channel using this time a parametric sensitivity study, which may be beneficial for better calibration of our model.

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Symbols

C	—	Tracer concentration, mg L^{-1}
C_0	—	Normalized initial tracer concentration, mg L^{-1}
d	—	Dispersion number, inverse of Peclet's number, adim
E_z	—	Dispersion coefficient, m^2 s^{-1}
Kl.a	—	Oxygen transfer coefficient, h^{-1}
L	—	Length of reactor, m
n	—	Number of reactors
Pe	—	Peclet's number = $V_c \times L/E_z$, adim
Q	—	Water inlet flow rate, m^3 h^{-1}
Q_{air}	—	Airflow rate in the air-lift reactor, Nm^{3}m^{-2} h^{-1}
r	—	Recirculation ratio, adim
T_c	—	Time of circulation, s
V_c	—	Water velocity, m s^{-1}

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