Contribution To Optimize Oxygen's Diffusion In The Two Stages High Rate Algal Pond

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Abstract: Morocco lags behind regarding liquid sanitation, however this problem was frowned upon, the awareness' level was raised up, and many efforts were deployed to face the problems of waste water treatment and re-use.

Several waste water-treatment plants were built these last years, using either intensive or extensive processes. The extensive processes remain the most dominant due to their best adaptation to the Moroccan context. As a matter of fact, High Rate Algal Pond (HRAP) remains one of the most adapted processes with a not yet standardized operating criterion. The studies led on this process succeeded to apprehend the treatment performances in term of hydraulic and organic load and showed the good adaptability of this kind of process for the small and average communities.

In order to increase the organic and hydraulic capacity of the High Rate Algal Pond for the same area of occupancy, we thought of designing a two stages pond that would absorb load's fluctuations.

Studies have been carried out to optimize the height of the floor, considering the sunshine of the site throughout the year and the upper pond's shadow's effect on the lower one.

The channel's functioning is governed by an algo-bacterial symbiosis in unstable equilibrium, which may be affected by the diurnal and nocturnal mode of operation; the oxygen factor remains the only key parameter for detecting any dysfunction, to this end, it is delusive to admit that the production of an amount of oxygen beyond the Biological Oxygen Demand (BOD) has no effect on the algal biomass. In order to determine the produced oxygen's quantity by the algal activity during the diurnal period, we shall consider the following quantity: the Produced Oxygen (Op) which represents a constant ratio between the oxygen released by photos

ynthesis of algae and the luminous energy during the considered residence time; and the quantity of oxygen actually used (O'p) which will be calculated by a balance of material on the oxygen. However, the modeling's complexity of the dissolved oxygen distribution lies in the flow equation, as well as in the establishment of the kinetic models of the various biological mechanisms involved in the oxygen balance. Nevertheless, in our approach, the biological phenomena's complexity has been simplified by considering algae and bacteria as

chemical species which undergo the action of hydrodynamics (transport, diffusion, turbulence ...) and which react according to a determined kinetic.

The modeling of the interaction between turbulence and the kinetics of the reaction mechanism made it possible to express the average reaction rates as a function of the known variables of the kinetics and as a function of the characteristics of the turbulence which happens to play a decisive role.

To conduct the simulations, the proper choice was the ANSYS Fluent calculation code. This has contributed to a better understanding of the implemented calculations, as far as iterative processes and spatial discretization are concerned.

We used the ANSYS Fluent 18.0 software to identify the various phenomena and mechanisms governing the Two Stages High Rate Algal Pond's function and also to validate the numerical model using the experimental and theoretical studies already carried out on the High Rate Algal Pond.

The study of the oxygen diffusion in the Two Stages High Rate Algal Pond (TS-HRAP) focused on the diurnal and nocturnal periods, for the both of layout's variants: in series and in parallel.

By increasing the organic load of the influent and reducing the residence time of the higher channel in series mode, we have observed an improvement in the purifying power of the bottom channel functioning in series mode.

In the light of these results, we revealed the possibility of an improvement of the purification's rate by choosing the in series mode either by increasing the organic charge of the influent, or by reducing the residence time of the higher channel.

Keywords : High Rate Algal Pond (HRAP) - The Two Stages High Rate Algal Pond (TS-HRAP) – Hydrodynamics – diffusion – oxygen- Algae – Bacteria- Organic matter- Biological Oxygen Demand (BOD)-residence time- simulation- optimization.

I. INTRODUCTION

The high rate algal pond is one of the most suitable treatment systems for small and medium-sized agglomerations under the climate conditions of Morocco. It is an extensive process that allows us to optimize and save the area.

In order to increase its purification performances, the idea of adding an identical stage stands as a solution that would allow:

- Make the system an intensive one , while enduring hydraulic and organic load variations.
- Adapt the system to a larger agglomeration by increasing the served population.

The following figure shows a general view of the installation of the Two Stages High Rate Algal Pond (TS-HRAP), done with ANSYS Designer Modeler:

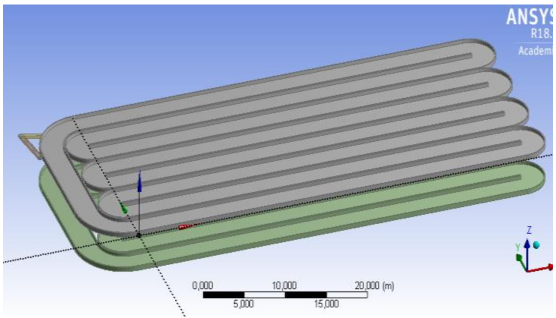

Fig.1: Perspective view of the two stages algal system

The equation of hydrodynamic and diffusion phenomena was based on data and results of previous work on the flow in the HRAP. We took advantage of these considerations to define our modeling for a turbulent monophasic flow of a homogeneous incompressible fluid. This seemed mandatory to establish the equations and to choose the numerical resolution patterns.

Indeed, in the presence of so many mathematical patterns of the turbulence, which differ in terms of theoretical approach and the empirical constants; our choice was based on a recent version of the K-Ɛ model, which adapts to the real flow within the HRAP, while offering in the same time a compromise between the accuracy of the results and the compilation time.

However, the complexity of the modeling of the dissolved oxygen distribution lies in the equation of the flow, and in the establishment of the kinetic models of the various biological mechanisms involved in the oxygen balance.

Indeed, the operatory conditions and the physical parameters (pressure, temperature and sunshine ...) involved in TS-HRAP's functioning differ greatly between the diurnal period and the nocturnal period. Therefore, the study of the oxygen distribution in these two periods is required.

The modeling of the interaction between the turbulence and the kinetics of the reaction mechanism makes it possible to express the average reaction rates as a function of the known variables of the kinetics and as a function of the characteristics of the turbulence which happens to play a decisive role.

The established resolution models for the transport equation of species' mass fractions do not consider the effects of turbulence in the calculation of the equation's original compounds. These original compounds figuring in the species' transport equations are calculated according to the chemical reactions' mechanisms, using turbulent reactions models.

The calculation code ***ANSYS Fluent*** suggests several models of interaction between turbulence and reactions, among the lot, we could use the **Finite-rate / Eddy-dissipation** model which calculates and considers the minimum of the Arrhenius rates according to the law of velocity and the mixture rate. In order to model the hydrodynamics of the algal channel in staggered mode and the oxygen's diffusion, we made three fundamental choices, distinguishing the case of the hydraulic arrangements in series and in parallel.

These choices concern:

- The geometry's representation and the computational domain's mesh;
- The turbulence model;
- The boundary conditions.

The hydraulic supply in series and in parallel of the superimposed ponds has a strong influence on the system's performances.

II. MATERIALS AND METHODS

II.1. Equation implementations

II.1.1. Oxygen in the HRAP

During the channel's functioning, the global equation of oxygen transfer is written as below:

$$\frac{dc}{dt} = [K_L.a.(c^* - c)] + \left[K_D.\frac{A}{V}.(c^* - c)\right] + P - R \quad (1)$$

In which :

- **K_L .a. (c*-c)**: the compound of artificial aeration
- **K_D. A /V. (c*-c)** : the compound of oxygen transfer in the gas-liquid interface;
- **P** : the rate of oxygen's production by photosynthesis (mg/j/l) ;
- **R** : the rate of oxygen consumption in the channel (mg/j/l).

The produced oxygen:
Assuming that there is a constant ratio between the produced oxygen by the algae's photosynthesis and the luminous energy, the oxygen production **Op** (mg/l) during the residence time T is expressed by the formula:

$$O_p = \frac{S.T.F}{e.d} \quad (2)$$

In which :

- **S** : solar radiations flow (cal/m^2.j) ;
- **F** : Photochemical efficiency (%) ;
- **T** : Residence time (j) ;
- **d** : Channel's depth (m) ;
- **e** : ratio between the produced oxygen and the luminous energy equal to 3,68 cal/mg of oxygen.

The oxygen actually used:
It's the quantity of oxygen actually used **Op'.** It's calculated from the balance of matter on the oxygen.

To calculate Op', the saturation concentration of oxygen c* at an average temperature of 25°C, under usual pressure conditions equal to **8 mg/l**..

The ratio R_0 is defined as below:

$$R_0 = \frac{O'_p}{O_p} \quad (3)$$

II.1.2. TS-HRAP modeling:

The equation of the various parameters makes our model to be as representative as possible of the reality, namely the preponderant chemical and biological reactions considered, the different species reacting together, the actual geometry of the channel, the initial and boundary conditions, as well as the physical operatory parameters such as pressure, temperature and insolation ...

Indeed, the operatory conditions and the physical parameters involved in the TS-HRAP's functioning during the daytime are considerably different from those of the night time. To this end, the study of the oxygen distribution in both periods is necessary.

II.1.3. Hydrodynamics of the TS-HRAP

The fluid within the channel is a mixture of waste water and microscopic algae, the concentration of algae is too low to influence the liquid's physical characteristics. Therefore, the fluid will now be considered **Newtonian**.

For an average flow velocity of **15 cm / s**, corresponding to the velocity recommended by OSWALD [1] for optimum and economical functioning, hydraulic flow parameters are shown in the following table:.

Table I: The hydraulic parameters of the TS-HRAP

Parameter	Value	Observation
Number of Mach	0.0001	Incompressible mixture
Number of Reynolds	56250	Turbulent flow
Number of Froude	0 .005	River flow

II.1.4.Equations of hydrodynamics:

The equations ruling over the TS-HRAP's hydrodynamics are:

1-The continuity equation or the mass conservation equation:

$$\frac{\partial \rho}{\partial t} + div\,(\rho\vec{v}\,) = S \qquad (4)$$

ρ : fluid's density (kg.m^{-3}) ;

$\vec{v}$: fluid's velocity (m.s^{-1}) ;

S: term wells / source (kg.m^{-3}.s^{-1}).

2-The equation of momentum :

$$\frac{\partial(\rho\vec{v})}{\partial t} + div(\rho\vec{v}\vec{v}) = -\overrightarrow{grad}\,p + div\,\vec{\vec{\tau}} + \vec{f} \quad (5)$$

- $\rho\vec{v}\vec{v}$: the momentum tensor;
- $div\,(\rho\vec{v}\vec{v})$: the flow balance input/output of momentum for the elementary volume;
- $\vec{\vec{\tau}}$: the stress tensor due to the viscosity of the liquid (Pa).

3-The equation of energy :

$$\frac{\partial(V_i\,(\rho E+p))}{\partial x_i} = \frac{\partial}{\partial x_i}\left[k_{eff}\frac{\partial T}{\partial x_i} - \Sigma_j h_j\vec{J_j} + V_i(\tau_{ij})_{eff}\right] + S_h \qquad (4)$$

- **K** **eff** : the effective conductivity defined by: $K_{eff} = K_{moy} + K_{tur}$ as K_{moy} : the average conductivity; K_{tur} : the turbulent conductivity.
- **Jj** : the specific diffusion flow of the species j.
- **E :** is the result of the formula: $E = h - \frac{P}{\rho} + \frac{V_i^2}{2}$
- **h**: the sensitive enthalpy, for an incompressible fluid.

3-The transport equation :

$$\frac{\partial}{\partial t}(\rho Y_j) + \frac{\partial}{\partial t}(\rho V_i\,Y_i) = \frac{\partial}{\partial x_i}\vec{J}_i + R_i \quad (7)$$

- V_i : component of the velocity along an axis;
- Y_i : mass fraction of each species;
- R_i : Reaction rate or Production rate of the species i;
- J_j : The diffusion flow of species i due to the concentration gradient.

After the equation, simplifying assumptions are required for the numerical resolution by the software, namely:

- The flow regime is permanent, so : $\partial/\partial t = 0$
- The mixture is considered to be a homogeneous and incompressible fluid, so the variation of ρ is negligible regarding time and space:
  ρ = constant;

-The mixture is considered to be a Newtonian fluid, so the fluid's viscosity:$\boldsymbol{\mu}$ = *constant;*

- The mixture is subjected to a single volume force which is its weight:

$$\vec{f} = \rho.\vec{g} \qquad (8)$$

Where:

$\vec{g}$: the acceleration of gravity (m.s^{-2})

II.2. The simulation software

In order to carry out the simulations, we chose to use **ANSYS FLUENT 18.0** (academic version), which is known to be the most powerful simulation tool of *Computational Fluid Dynamics* **(CFD)** which studies the movements of a fluid, or their effects, by the numerical resolution of the equations governing the flow.

ANSYS Fluent is a user-friendly, general-purpose tool that provides all the physical capabilities required to model fluid flows, turbulence, heat, mass and chemical reactions transfer and deliver fast and accurate results for a wide range of CFD applications.

This simulation tool requires knowledge of the structure's geometry, the study of boundary conditions and the choice of the turbulence model. It allows representing the three-dimensional flows (velocity field, current line, concentration of species, etc.)

II.2.1. Geometry (Design Modeler)

It defines the configuration of the problem to be analyzed. It involves:

- Creating the system's geometry in ANSYS Design Modeler ;
- Editing and improving the created geometry while making the necessary readjustments.
- Explicitly identifying all fluid and solid areas of the model

II.2.1. Meshing

This tool allows creating a mesh for the defined geometry, going through four basic steps, which can be summarized as follows:

1. Generating a default mesh
2. Defining mesh attributes
3. Defining named selections
4. Generating a new mesh

II.2.2. Setting and solution (FluentSolver)

The setting component helps to specify the physical and chemical phenomena to be modeled and the types of used materials (fluid or solid) and their properties.

As for the solution component, it allows to choose the iterative process, proposing in particular several numerical schemes for the spatial and temporal discretization, and for the velocity/pressure coupling as well.

II.2.3. Results (Post Processeur)

This component allows visualizing the field's geometry and mesh, displaying the required results with the post-processor tools that are integrated in "Fluent solver" such as: Graphics and Animation, Plots and Reports.

II.3. Convergence

At every iteration, Fluent helps to judge the convergence's state by calculating the residues, which corresponds to the imbalance of the equation (the general discretized equation) summed on all the cells of the field.

III. Results and discussions.

This study allowed us to go through the different mechanisms involved in the oxygen balance within the HRAP, and the set of physicochemical parameters that govern the gas transfer of oxygen through the air / water interface.

We believe that the oxygen balance in the channel's functioning is directly related to the different coefficients of the oxygen concentration, which helps to judge the appropriate functioning of the photo-bioreactor on one hand, and to improve the models of its design on the other hand.

Shaping the algal system HRAP into a staggered mode and its adaptation to Moroccan conditions by design patterns, would require mastering the principle of the system's functioning as well as its characteristics which would allow the good oxygenation for better purification efficiency.

We come to the conclusion that adapting the TS-HRAP to Moroccan standards by design's patterns would involve equating and modeling the various hydrodynamic and bio-reactive mechanisms that control the oxygen distribution within the system.

The equation of hydrodynamic and diffusion phenomena was based on data and results of previous work on the flow in the HRAP. We took advantage of these considerations to define our modeling for a turbulent monophasic flow of a homogeneous incompressible fluid. This seemed mandatory to establish the equations and to choose the numerical resolution patterns..

First of all, we presented and justified the choice of the calculation code ANSYS Fluent, used to successfully carry out our simulations. This allowed a better understanding of the calculations, especially the iterative processes and the spatial discretization.

The next step was to make the fundamental choices to model the hydrodynamics of the Two Stages Algal pond and the oxygen diffusion. For this end, we distinguished the cases of in series and in parallel hydraulic arrangements.

a- The higher channel.

In series arrangement and during diurnal period

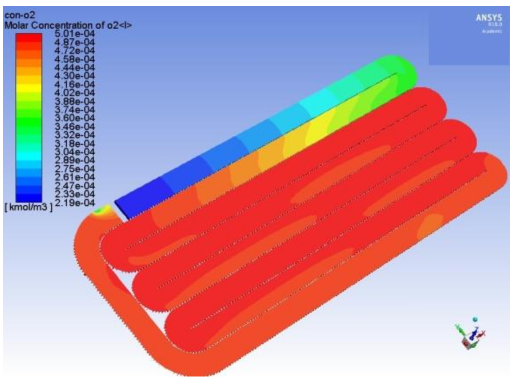

Fig.2: Oxygen distribution in the higher channel during the diurnal period

From this graph, we can notice that the concentration of dissolved oxygen increases gradually from the mixing zone until reaching homogeneity throughout the channel.

In series arrangement and during nocturnal period

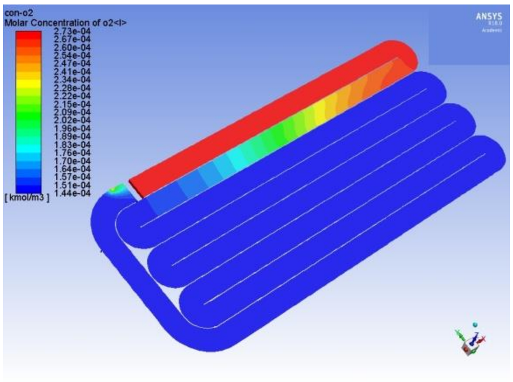

Fig.3: Oxygen distribution in the higher channel during the nocturnal period

The first ascertainments we can squeeze out of this simulation are summarized as follows:

After the exit of the mixing wheel, the effluent has an oxygen concentration close to saturation (8 mg / l), this is due to the oxygenation that the fluid has undergone the fluid during the day time.

The oxygen concentration decreases gradually throughout the first two corridors, before stabilizing at a value of 4.46 mg / l. in fact the biodegradation and the algal respiration continue to consume oxygen, and the oxygen supply through the aeration due to the mixing thus prevents reaching the critical values (1mg/l).

b- The bottom channel ;

In daytime the distribution of oxygen in the bottom channel is represented by the following figure:

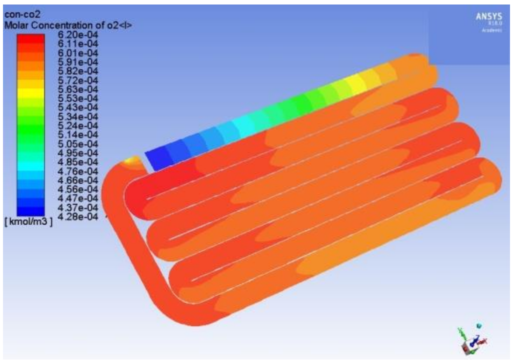

Fig.4: Oxygen distribution in the bottom channel during the diurnal period

From this graph, we may easily assert:

The variation of the oxygen concentration in the bottom channel is identical to the one described for the upper channel except that:

The maximum value reached is 19.23 mg / l (6.01.10-4 kmol / m3), which means that the effluent at the entrance from the higher channel is rich in oxygen.

The zones (orange), characterized by a slight decrease in the concentration of dissolved oxygen, are more accentuated than those of the upper channel due, on the one hand, to the mask effect already explained above and, on the other hand, to the variations of algae’s concentration.

During the nocturnal period, the oxygen distribution in the bottom channel is represented by the following figure:

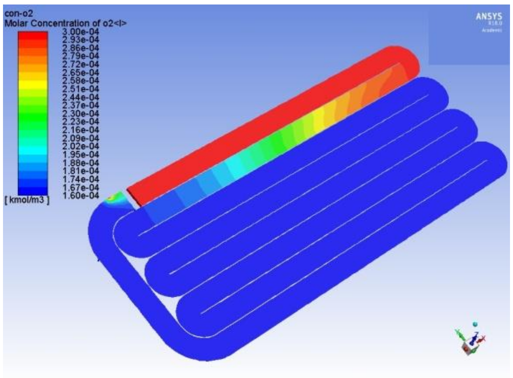

Fig.5: Oxygen distribution in the bottom channel during nocturnal period.

The variation in oxygen concentration in the bottom channel is similar to the one already described for the same period in the upper channel, except that the values obtained are slightly higher, since the bottom channel has already experienced more oxygenation during the diurnal period.

As for the oxygen diffusion in the TS-HRAP in parallel layout, the same results as in series layout remain valid for the upper channel; but for the bottom channel two cases remain to be distinguished according to the diurnal and nocturnal period.

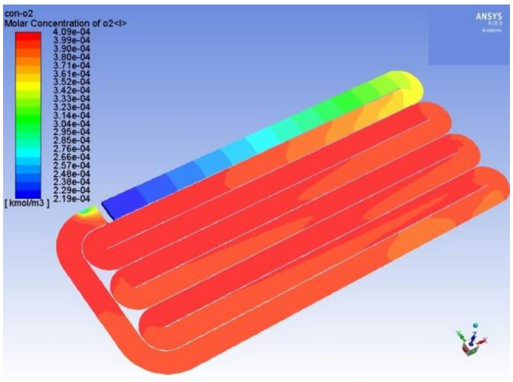

Fig.6: Oxygen distribution in the bottom channel during diurnal period.

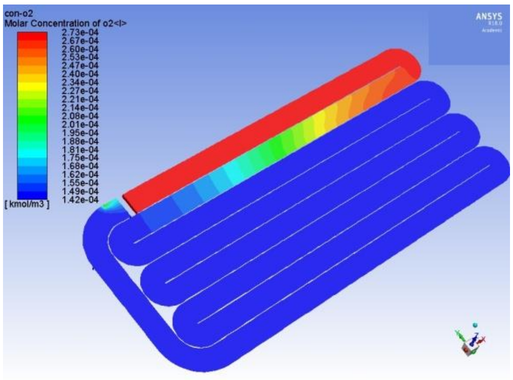

Fig.7: Oxygen distribution in the bottom channel during nocturnal period.

From the figures above, we can see that the variation of the oxygen during the two periods looks like the higher channel's one for the in parallel layout, with a small decrease in the found values this is being explained by the mask effect.

The hydraulic supply for the in series and in parallel layout of the superimposed ponds, has shown a great influence on the performance of the staggered mode, in effect:

The TS-HRAP in parallel layout allows processing double the flow rate, but by generating an effluent of a lower quality than the one of the TS-HRAP in series layout. This variant could therefore be an introduction to an all new intensive system for large agglomerations, but for wastewater with very specific characteristics.

The TS-HRAP in in series layout allows to :
- Gain in terms of served population served while increasing the organic load to be treated, with better purification performance.
-Decrease the residence time.
-Process a great volume of waste water.
- Reduce the required surface area and water losses by evaporation, which would be of significant economic interest.

IV. Conclusions

This paperwork focuses on the use of ANSYS Fluent simulation software to model the oxygen diffusion in a Two Stages High Rate Algal Pond(TS-HRAP). It is part of a large-scale study to define the TS-HRAP's appropriate mode of functioning in terms of purification efficiency in order to make this system an intensive one able to treat double the flow rate for the same area and thus adapt it to the larger agglomerations.

The ANSYS Fluent 18.0 software was used to identify the various phenomena and mechanisms governing the Two Stage High Rate Algal Pond and to validate the numerical model using the experimental and theoretical studies already carried out on the High Rate Algal Pond.

This model was then used to study the oxygen diffusion in the TS-HRAP during the diurnal and nocturnal periods for the in series and in parallel arrangements.

It was concluded that by increasing the organic load of the influent and reducing the residence time of the higher channel for the in series layout, we could see an improvement in the purifying power of the bottom channel functioning in series layout.

Going through the results unveils the possibility of an improvement in the purifying efficiency in the serial layout either by increasing the organic charge of the influent or by reducing the residence time of the upper channel.

The validation of the results depends on the experimental confirmation on prototypes or real superimposed ponds, in order to calibrate the conclusions elaborated during this study.

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