NEW GENERATION PHOTOBIOREACTOR CHARACTERIZATION

Investigation of a case study with *in situ* light generation in 2D-cylindrical geometry

Jean-François **CORNET**[a], Jérémi **DAUCHET**[a], Victor **GATTEPAILLE**[a], Catherine **CREULY**[a], Laurent **POUGHON**[a], Caroline **GENTRIC**[b], Charlène **THOBIE**[b], Jérémy **PRUVOST**[b], Jack **LEGRAND**[b], C.-Gilles **DUSSAP**[a]

[a] Université Clermont Auvergne, CNRS, SIGMA Clermont, Institut Pascal, F-63000 Clermont-Ferrand, France

[b] Laboratoire GEPEA, UMR CNRS 6144, University of Nantes, CRTT 37 Bd de l'Université, 44602 Saint Nazaire Cedex, France

Contact: jean-francois.cornet@sigma-clermont.fr

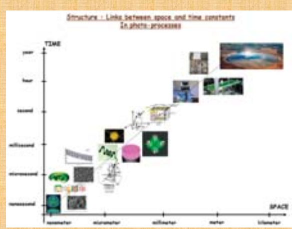
INTRODUCTION

Photobioreactors (PBR) are assumed to be of prime interest in closed ecological life support systems in order to ensure the production of edible biomass but mainly to authorize the conversion of CO_2 into O_2 with short time constants (i.e. the control of crew atmosphere). Nevertheless, the biomass volumetric growth rate $<r_X>$ must be as high as possible in order to decrease the volume (or the mass) of the PBR enabling to regenerate the atmosphere (roughly 1 kg O_2 by day for one man). Furthermore, for any geometry of PBR, this maximum volumetric growth rate is approximately given by [1] :

$$< r_X >_{\max} \cong M_X \rho_M \bar{\phi}' \frac{2\alpha}{1+\alpha}(1-f_d)\, a_{light} \frac{K}{\left(\frac{n+2}{n+1}\right)} \ln\left[1+\frac{\left(\frac{n+2}{n+1}\right) q_0}{K}\right]$$

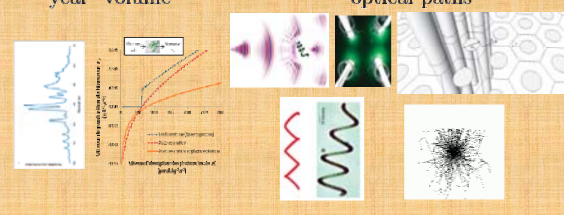
This demonstrates that high volumetric productivities (HVP) will be reached with increasing both the specific illuminated area a_{light} and the incident photon flux density q_0 (PFD) as much as possible. For artificially illuminated PBR of large size, this is only feasible using internal *in-situ* or *ex-situ* generated light guaranteeing an up-scalable process for a given crew. The conception, sizing and optimization of HVP internally illuminated 1D-cartesian or 2D-cylindrical PBR [2,3] requires then to develop multi-scale predictive and robust knowledge models for mainly radiative transfer, photon transport and thermo-kinetic coupling, then to solve them by refined numerical procedures as exposed hereafter. In the section "*Case study of an advanced concept of 2D-cylinfdrical HVP-PBR*" below, we propose and analyze the design of a 300 L PBR, available for the oxygen supply of one man.

OPTIMIZED PHOTOBIOREACTORS FROM MULTISCALE KNOWLEDGE MODEL AND INTEGRAL FORMULATION



A multi-scale knowledge model describing all the controlling steps of the whole process has been developed. Its parameters have then been reified, i.e. their value were theoretically calculated (optical and radiative properties, quantum and energetic yields…) avoiding their identification on a specific sep-up and guarantying the genericity of the model that has been validated on hundreds of configurations and boundary conditions. The corresponding complexity at every space-time scales, including radiative transfer problems, is particularly well adapted to an integral formulation.

$$\underbrace{\int dt \int d\vec{r}\, \frac{1}{V}}_{\text{year} \quad \text{volume}}\, r_X \left(\underbrace{\int_{\lambda_{min}}^{\lambda_{max}} d\lambda\, p_\Lambda(\lambda) \int d\gamma\, p_\Gamma(\gamma)\, w(\gamma)}_{\text{optical paths}} \right)$$

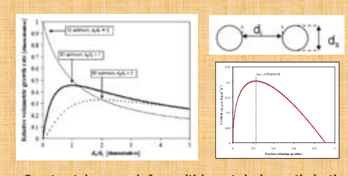


MONTE CARLO METHOD

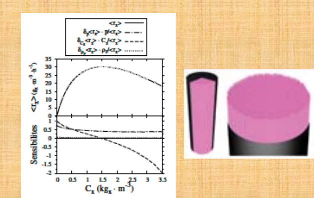
The most recent advances in Monte Carlo method are used to solve the multi-scale and integral formulation knowledge model [4,5]. This method is usually considered as a reference for solving the radiative transfer equation, with systematic estimation of the standard error. Monte Carlo is also well-suited for solving high-dimensional integral problems generated by our multi-scale model. Furthermore, systematic sensitivity estimation to all the model parameters is available, with the same calculation time.

OPTIMIZATION PROCEDURE

The predictive knowledge models developed must be associated to any optimization approach in order to design highly kinetically and thermodynamically efficient concepts of photobioreactors. To the date, the constructal approach has been used [2], enabling to minimize entropy generation at different scales of the process, associated with the corresponding optimal layout, and leading step by step to the final design. Alternatively, an important breakthrough is expected regarding new capabilities of Monte Carlo method in calculating domain (geometry) sensitivities in the future. This method could authorize a direct calculation of the reactor optimal design (aggregating all the scales in a unique calculation) with lower calculation times under the constraint of maximizing kinetic efficiency.



Constructal approach for multi-layout design optimization



Sensitivity to the model parameter calculated by Monte Carlo method for design optimization

CRITICAL ITEMS FOR ACTUAL DESIGN

If the previous approach has been proved efficient for PBR conception and design, mainly regarding light transfer, the increase of volumetric kinetic performances by internal illumination evidences numerous critical items regarding photobioreaction engineering. Five points are mainly concerned : internal light generation, mass transfer, heat transfer, mixing and hydrodynamics, and finally, possible metabolic deviations… Each of them requires to seek technical solutions, which may be strongly different for gravity, reduced gravity or microgravity situations.

☛ Internal Light Generation

	In situ light generation	Ex situ light generation
1D Cartesian geometry	Lateral illuminating panel (LED panel or LED strips)	Lateral illuminating panels (LED coupled to lighting fabrics or LED coupled to PMMA panel)
2D Cylindrical geometry	Fluorescent tubes with hot or cold cathodes. Quasi-radial LED strips or EL wires	Lateral diffusing optical fibres supplied with discharge lamps or LED

☛ Mixing and Hydrodynamics

The smallest distance between internal illuminating structures (fluorescent tubes with hot cathodes) $d_s = d_i$ has been chosen around 1 cm guaranteeing no mixing problem with gas-lift functioning. In microgravity condition, mixing should be ensured by pump and would require special attention…

☛ Mass Transfer

The volumetric mass transfer coefficient K_La characterizes the time constant for CO_2 transfer from the crew and O_2 recovery.

$$y^S_{CO2} \cong y^{crew}_{CO2} - r'_X \frac{60}{0.2}\frac{RT}{P}$$

$$K_L a \geq \frac{r'_X}{\left(\frac{y^S_{CO2} P}{H(T)} - \frac{(C_T)_{\lim}}{K(pH,T)}\right)}$$

- For a mole fraction in the crew compartment y^{crew}_{CO2} = 1.5%, the output PBR CO_2 mole fraction is 6600 ppm at pH = 9.5 and the minimum K_La is 20 h^{-1} (easy to ensure).
- For a mole fraction in the crew compartment y^{crew}_{CO2} = 1.0%, the output PBR CO_2 mole fraction is 1600 ppm at pH = 9.5 and the minimum K_La is 170 h^{-1} (extremely difficult to ensure).

These high values, related to high r'_x (HVP), are impossible to reach in microgravity conditions with membrane modules for mass transfer.

☛ Heat Transfer

The HVP-PBR are concepts with obligatory high electrical and light energy consumption. The proposed advanced concept hereafter generates roughly 15 kW of heat which must be removed through a surface exchange of 1.57 m^2.
- With U = 500 $W.m^{-2}.K^{-1}$, the ΔT obtained with a cold fluid in an external double jacket is equal to 20°C (easy);
- With U = 200 $W.m^{-2}.K^{-1}$, the ΔT obtained with a cold fluid in an external double jacket is equal to 50°C (difficult).

☛ Metabolism Deviations

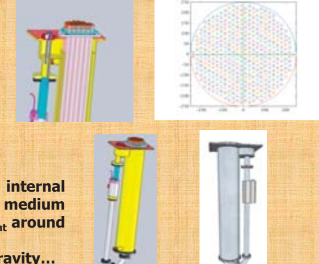
No metabolic deviations expected for distances d_i between internal illuminating structures higher than 1 cm. Important problems can arise (fouling, clogging,…) for distances of some millimeters when increasing the confinement to increase the specific illuminated area. Effects of reduced or micro-gravity would require specific dedicated experiments to analyze properly this critical item.

PROPOSAL FOR A CASE STUDY OF ADVANCED CONCEPT WITH *IN SITU* LIGHT GENERATION IN 2D-CYLINDRICAL GEOMETRY

The proposed design is built on two criteria: i) keep a distance d_i between illuminating structures around 1 cm to avoid metabolic deviations linked to confinement and ii) ensure a production of 1 kg O_2 by day for one man.

The proposed gas-lift PBR has a diameter of 0.5 m and a height of 1.5 m (total volume of 300 L and liquid volume of 230 L). The diameter of the fluorescent tubes for culture illumination is d_s = 1.1 cm, equaled to the distance inter tubes on a line d_i = 1.1 cm. The number of U-bent tubes is then n = 212 and the incident light flux is q_0 = 150 W/m^2. The total illuminating surface is 22 m^2 for a specific illuminated area a_{light} = 100 m^{-1}.

Such PBR ensures a volumetric growth rate r_x = 0.1 $g.L^{-1}.h^{-1}$ with *Arthrospira* or an oxygen volumetric rate r_{O2} = 6.10^{-3} $mol.L^{-1}.h^{-1}$, i.e. a production of around 1 kg O_2 by day (one man).



CONCLUSIONS

Theoretical tools and basic engineering knowledge are available to conceive, design and size large 1D or 2D photobioreactors with internal illumination and high volumetric biomass growth and oxygen rates. The objective to reach a total volume of 100 L with only 75 L of culture medium to regenerate the atmosphere for one man is feasible, but requires distances between adjacent illuminating structures of roughly 2 mm (a_{light} around 3-400 m^{-1}). At this level of confinement, important and unexplained metabolic deviations are observed, even on earth.
Additionally, the proposed current designs are mainly gas-lift concepts available on earth or in reduced gravity, but not functional in micro-gravity…

[1] Cornet J.-F., Dussap C.-G. 2009. *Biotechnol. Prog.*, **25**: 424-435.
[2] Cornet J.-F. 2010. *Chem. Eng. Science*, **65**: 985-998.
[3] Pruvost J., Cornet J.-F. 2012. *Microalgal Biotechnology vol.1 "Potential and Production"*, Chap. 10, Posten & Walter ed., pp. 181-224.
[4] Dauchet J., Blanco S., Cornet J.-F., El Hafi M., Eymet B., Fournier R. 2013. *J. Quant. Spectrosc. & Radiat.Transfer*, **128**: 52-59.
[5] Dauchet J., Cornet J.-F., Gros F., Roudet M., Dussap C.-G. 2016. *Adv. Chem. Eng. "Photobioreaction Engineering"* , Chap. 1, **48**: 1-106.