Scientific achievement #1
High efficiency photobioreactor with solar light-flux dilution

Photobioreactors with high thermodynamic efficiency and volumetric biomass growth-rates are required in order to tackle the challenge of developing industrial processes producing solar fuels from only water and CO_2. The conception, sizing, optimization and control of such complex reactors can only be achieved if predictive knowledge models are built and validated. This work is led in the lab since the 90's and has recently produced important results and original concepts like photobioreactors with dilution of the incident solar flux. A patented prototype of 25 L working volume is currently under theoretical and experimental investigation.

Microalgae cultivation in solar photobioreactors is identified as a promising way to produce a wide range of interesting renewable molecules for chemistry and energy. Nevertheless the industrial-scale implementation of photobioreactors first requires the development of new technologies, or the optimisation of existing concepts, in order to reach thermodynamic efficiencies of at least 10%. This goal, imposed by the competitiveness with other solar processes, can only be achieved if predictive and robust models of the process are available for their design, sizing, optimization, control and operation. Combining these models with recent thermodynamic-based optimization techniques (Constructal theory, domain sensitivity Monte Carlo analysis, etc.) leads to the DiCoFluV concept of high-efficiency photobioreactor (see Cornet, 2010 and list of patents hereafter). On this basis, a cylindrical reactor prototype in which the incident light flux density is diluted in the culture volume thanks to a thousand of light-diffusing optical fibres has been developed in the lab (see Figure 1). Before testing the thermodynamic efficiencies in actual solar conditions, the photobioreactor is currently studied with perfectly controlled artificial light (discharge white lamps) and its experimental performances are compared with the results of our model.

This multi-scale and reified model is based, at the smallest scale, on the calculation of optical and radiative properties of microalgae with complex shapes, using a state-of-the-art predictive theoretical chain that is unique in the world (see Figure 2 and Dauchet et al., 2015). Then the radiative transfer problem (Boltzmann photon-transport equation) is solved in any complex geometry of photobioreactors using the most recent advances in the field of radiative transfer Monte Carlo (Dauchet et al., 2013), including integral formulation, sensitivity analyses and zero-variance approaches.

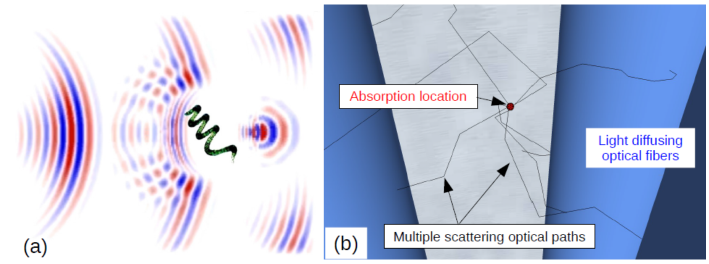

Fig. 2: Photobioreactor modelling at two different scales. (a): Resolution of Maxwell's equations for micro-algae particles with complex shape in order to retrieve the absorption and scattering properties of photosynthetic suspensions (Dauchet et al., 2015). (b): Resolution of radiative transfer equation within the complex geometry of the DiCoFluV reactor in order to retrieve the rate of photon absorption by micro-algae at any location within the anisotropically scattering and non- gray absorbing photosynthetic media characterized in (b) (Dauchet et al., 2013).

It rigorously estimates the amount of photons absorbed locally per unit time per microalgae at any location **x** within the culture volume. The algorithm consists in the backward sampling of multiple-scattering and reflection optical-paths from **x** (the absorption location) to the emitting surfaces (see Figure 2). This algorithm is implemented in the EDStar development environment, that makes available to radiation physicists a set of computation tools issued from the computer graphics research community during the last 20 years, in particular in the framework of the Physically Based Rendering Techniques (PBRT) project. The thermo-kinetic coupling with photosynthesis rates and efficiencies is then formulated using the thermodynamics of irreversible processes to determine the energetic and quantum yields. This led also to recent and new developments in the field of nonlinear Monte Carlo integral formulation.

As a perspective, the prototype must be used and operated in actual solar conditions in order to confirm that it can deliver efficiencies of roughly 15% in the visible light domain with a full-sunlight incident flux. Linked to a wavelength splitting system and converting infrared radiation into work, a future demonstrator could reach 15-20% on the entire solar spectrum, which is highly competitive with the photovoltaic technology, including additional possibility of chemical fuel storage.

CONTACTS
Jean-François CORNET
j-françois.cornet@univ-bpclermont.fr

FURTHER READING

Calculation of the radiative properties of photosynthetic microorganisms
J. Dauchet et al., Journal of Quantitative Spectroscopy and Radiative Transfer 161, 60 (2015)

The practice of recent radiative transfer Monte Carlo advances and its contribution to the field of micro-organisms cultivation in photobioreactors
J. Dauchet et al., Journal of Quantitative Spectroscopy and Radiative Transfer 128, 52 (2013)

Calculation of optimal design and ideal productivities of volumetrically-lightened photobioreactors using the constructal approach
J.F. Cornet, Chemical Engineering Journal 65, 985 (2010)

CONTRACTS

ANR Biosolis (2008-2011)
ANR PRIAM (2013-15)
PIE CNRS Photorad (2010-2011)
PEPS CNRS ITRPHPV (2012-13)
European ESA project NGPC (2015-2017)
Industrial contract : Study and simulation for a R&D microalgae platform development, with GEPEA St-Nazaire, TOTAL and AIRBUS (2010)
LabEx IMobS3 : action µ-APHIPE (2012-2017)
Idex Toulouse/Albi : action ALGUE (2015-2017)
1 French (2010) and US (2014) patents; 1 international patent (2012), 1 Soleau enveloppe (2014) and 1 patent currently under examination (CNRS)

PhD

J. Charon, J. Dauchet, V. Rochatte

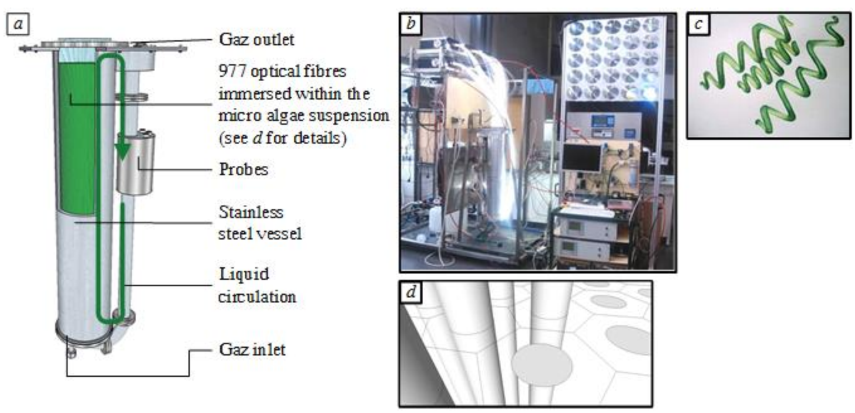

Fig. 1: DiCoFluV photobioreactor in which incident light provided by discharge lamps (as a preliminary stage before actual solar functioning) is diluted within a 22 L Arthrospira platensis culture (see micrograph c) via 977 lateral diffusing optical fibres. (a) Computer Aided Design. (b) The complete pilot plant. (d) Close up on the hexagonal fibres lattice.