# Mass transfer, light pulsing and hydrodynamic stress effects in photobioreactor development

**Article** · January 2015

DOI: 10.3303/CET1543040

CITATION
1

READS
105

**4 authors:**

Cicci Agnese
Sapienza University of Rome
**17** PUBLICATIONS **111** CITATIONS
SEE PROFILE

Marco Stoller
Sapienza University of Rome
**91** PUBLICATIONS **1,031** CITATIONS
SEE PROFILE

Monica Moroni
Sapienza University of Rome
**88** PUBLICATIONS **905** CITATIONS
SEE PROFILE

Marco Bravi
Sapienza University of Rome
**50** PUBLICATIONS **551** CITATIONS
SEE PROFILE

CHEMICAL ENGINEERING TRANSACTIONS
VOL. 43, 2015
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Chief Editors: Sauro Pierucci, Jiří J. Klemeš

**ISBN** 978-88-95608-34-1; **ISSN** 2283-9216
DOI: 10.3303/CET1543040

# Mass Transfer, Light Pulsing and Hydrodynamic Stress Effects in Photobioreactor Development

Agnese Cicci[a*], Marco Stoller[a], Monica Moroni[b], Marco Bravi[a]

[a]Dipartimento Ingegneria Chimica Materiali Ambiente, Sapienza Università di Roma, Roma, Italy
[b]Dipartimento di Ingegneria Civile Edile ed Ambientale, Sapienza Università di Roma, Roma, Italy
agnese.cicci@uniroma1.it

Photobioreactor scalability involves multiple different interacting aspects including mass transfer, light pulsing and hydrodynamic stress. An efficient carbon dioxide supply and a frequent displacement of cells from poorly to highly illuminated zones is desired to maximise the achieveable specific growth rate. However, a strong mixing is energy consuming and may reduce the specific growth rate because of induced cell damage.
The current work examines mass transfer effects in photobioreactor development and estimates their relationship to light pulsing and hydrodynamic stress effects with a special reference to the novel inclined, thin-layer, wavy-bottomed cascading photobioreactor.

## 1. Introduction

Microalgae are a current food and source of food fractions and are also touted to be a potential feedstock for green biochemicals and biofuels. However, the cost competitiveness of producing microalgae does not warrant their deployment as an energy-bearing feedstock yet.
Several hindrances prevent the adoption of microalgae as a energy utility feedstock, among which low photosynthetic efficiency, low scalability, energivorous operation, and high materials cost, all of which are actively being scavenged to make way to the large scale deployment of microalgal biomass production technology.
Scalability is a multifaceted issue, in that it is a plurime collection of different interacting aspects including mass transfer, light pulsing and hydrodynamic stress. While uniform levels of high ($CO_2$) and (low) $O_2$ ensure a uniformly high specific growth rate throughout the photobioreactor volume, uniform and constant lighting at high levels is undesired because of photoinhibition effects which apply a severe haircut on the maximum achievable specific growth rate. Together, these issues would suggest that high-rate mixing of concentrated biomass suspensions would warrant a maximal specific growth rate. However, strong mixing is energetically costly on the one hand, and deleterious because of the entailed hydrodynamic stress effects (which, again, may reduce the specific growth rate) on the other.
Mass transfer from gas phase to liquid phase has been identified as an important rate-limiting step in many chemical process industries. The rate of mass transfer is expressed by the overall volumetric mass transfer coefficient, which is a function of interfacial area and liquid phase mass transfer coefficient. Several models have been proposed in the literature for determining the volumetric mass transfer coefficient, also known as $k_La$. Most of the models proposed are based on the concept of a rigid interface or an interface where surface renewal occurs through the displacement of liquid at the interface or combination of these concepts (Ranganathan and Sivaraman, 2011). The $k_La$ of photobioreactors is dependent on various factors such as agitation rate, the type of sparger, surfactants/anti-foam agents and temperature.
Mass transfer coefficients are often, although not routinely measured by photobioreactor developers. Merchuk et al. (1998, 2007), Doucha and Lívanský (2006) and Pirouzi et al. (2014) are among those who carried it out. However, knowing mass transfer capabilities is fundamental to understanding the potential of a photobioreactor geometry to scale or to increase its performance when other bottlenecks are removed.

Please cite this article as: Cicci A., Stoller M., Moroni M., Bravi M., 2015, Mass transfer, light pulsing and hydrodynamic stress effects in photobioreactor development, Chemical Engineering Transactions, 43, 235-240 DOI: 10.3303/CET1543040

The current work examines mass transfer effects in photobioreactor development and estimates their relationship to light pulsing and hydrodynamic stress effects. The inclined, thin-layer, wavy-bottomed cascading photobioreactor (Moroni et al., 2014) will be adopted as the case study because of its ordered local recirculation streams wich warrants a continuous renewal of the liquid surface layer and a (perceived) pulsing of light of adjustable frequency and because it is suited for microalgal cultures where the culture medium itself is not transparent (Cicci et al., 2014). Furthermore this photobioreactor requires an external circulation pump which may be chosen among different types entailing different hydrodynamic stress effects.

## 2. Materials and Methods

The core of the experimental set-up is a 120-cm long, 15-cm wide waved surface made from a commercial semifinished wavy surface, provided with 10 cm high side transparent glass rims, which was installed with the ridges lying on a (virtual) plane inclined with respect to a horizontal plane. The waved surface comprises 15 complete vanes and has an inclination of 6° and 9°, as described in Moroni et al. (2013). The mass transfer experiment consisted in feeding the wavy channel with an assigned flow rate of deoxygenated water and recording the resaturation occurring to the downflowing liquid. The wavy channel was provided with a disengagement zone occupying the two cavities located immediately upstream of the actual section of the photobioreactor used for the measurement and separated from it by a short weir designed in order to avoid splashing during overflow. The water discharged at the channel exit was collected into an output reservoir (Fig.1).

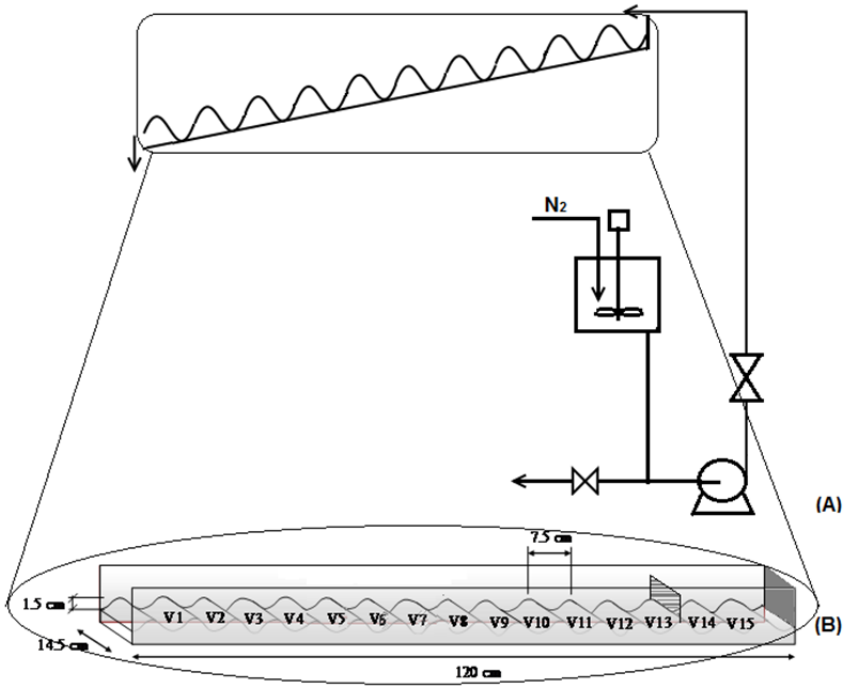


*Figure 1: Experimental set-up*

### 2.1 Gas Mass Transfer Determination

Tap water collected in stirred tank (Fig.1 A) was deoxygenated by insufflation with gaseous nitrogen until oxygen concentration in the tank was reduced to 1.5 ppm. Nitrogen was sparged in the stripping tank by a large porous stone and measurement of the prevailing dissolved oxygen concentration was carried out in a location inside the tank which was not disturbed by the raising nitrogen bubbles. Then, pumping was started and the measurements in the adopted locations of the photobioreactor were started in vanes 1, 7 and 13 of the wavy PBR (Fig.1 B). Due to the large amount of deoxygenated water required, each measurement was initiated from a separate batch of deoxygenated water; care was taken of ensuring the very same set of initial conditions for every discharge pertaining to the same replica. Oxygen measurements were carried out with a recording instrument fitted with a chemiluminescent probe (HACH model 440d).

To maintain alignment with previous investigation by Moroni et al., (2013) concerning fluid dynamics, testing was carried out at 600 and 900 L/h, and the inclination of the photobioreactor was set at 6° and 9°.

### 2.2 Axial and Transverse Dispersion and Relationship to the Gas Mass Transfer

Mixing is usually characterised tracing the decay of repeating pulses of some tracer injected in the bioreactor. This is also the way many photobioreactor geometries have been tested (e.g. Marchuk et al., 2007 and Pirouzi et al., 2014). However, the local recirculation photobioreactor is a piece of equipment that is not complete per se, as it requires a recirculation device, which may be chosen among centrifugal pump, air-lift pump and possibly others, and may be arranged in different fashions which would influence the final recirculation performance. Here, we want to characterise the fundamental functional element, that is the sloping wavy surface exposed to the incident light. Mixing was therefore locally evaluated by tracing a pulse of injected dye over a section of the photobioreactor comprising two full cavities. The tracer (a concentrated water solution of a red, water-soluble pigment) was neutrally buoyant. The injection was performed on the crest uphill of the first cavity and the detection was performed on the crest downhill of the second cavity, where the liquid layer has the minimum thickness and flows plug-wise.
The dye (2 mL) was injected, manually, as a short (on average 0.70 s) rectangular pulse. After the injection the dye spot extends both axially and laterally. The travelling spot evolution was monitored by taking a video at 30 fps with a camera located just above the target zone of the photobioreactor.
The detection area was a narrow rectangle (180 x 20 pixel) covering the flow channel width and required using image analysis tools (ImageJ; Rasband 1997-2014). The video was split into frames and each frame was processed in order to detect, for every pulse, the injection start and end and the flow of the dye over the detection frame. The cancellation of the effects of the sligtly irregular brightness in the view field was carried out by splitting each frame into the red, green and blue components. The red component showed no visible evidence of the dye spot, which was clearly evident in the green and, even more, in the blue component. Cancelling was obtained by blending the red and blue components with suitable calibration weights.
The obtained pixel data of each rectangular frame were post-processed as follows: the average brightness and the average brightness of the rectangular frame from a dye-free image was subtracted from it; the standard deviation of the brightness over the rectangular field was calculated. Both time-dependent brightness values were converted into concentration values by considering the average thickness of the liquid layer overpassing the crest determined by Moroni et al. (2013) and by using a calibration relationship. This latter was obtained applying the same image processing to a set of pictures of samples of the same dye prepared at logarithmically scaled dilutions.
The concentration tail after each pulse injection was integrated over the observed pulse duration. After removal of a few evident outliers the material balance was found to be consistent.
Mixing was characterised by the complement to 1 of the Lacey index (1957), defined as:

$$M = \frac{\sigma - \sigma_\infty^2}{\sigma_o^2 - \sigma_\infty^2} \tag{1}$$

For the segregated pulse, $\sigma_o^2$ was calculated as $\varphi_1 \cdot \varphi_2$, $\varphi$ being the (volume) concentration of the dye in the injection section.

## 3. Results and Discussion

The values of the oxygen transfer coefficient that can be calculated from the experimental data obtained during the described runs are reported in Table 1.
It can be seen that when the photobioreactor is installed with the steeper inclination, the adopted flow rate has a very limited influence over the mass transfer coefficient, while when the installation angle is lower this coefficient increases upon a liquid flow rate increase.
Moroni et al. (2013, 2014) show that the installation angle has a profound influence on the fluid dynamic pattern inside the vanes. Indeed, when the photobioreactor surface is installed at the lower angle, an effective local recirculation pattern establishes inside the vane, so that the liquid stream which is travelling in the forward direction in the vicinity of the vane bottom bifurcates and part of it flows backward on the surface, mixes with the entering stream from the upflow vane and plunges in the vane again. On the contrary, when the installation is made with the steeper inclination, no recirculation flow is observed and the whole liquid stream exhibits a downward flow.
When considering the mass transfer and the recirculation patterns together, it is clear that while the higher angle may be slightly more beneficial from the mass transfer point of view, the opportunity of an increased

photosynthetic efficiency owing to the pulsed light effect is lost. Furthermore, a slightly smaller photobioreactor surface area can be deployed with the higher angle.

*Table 1: The oxygen transfer coefficients calculated for the local recirculation photobioreactor as a function of installation angle and liquid flow rate.*

| Inclination (°) | Flowrate (L/h) | $K_La$ ($s^{-1}$) | CV |
|---|---|---|---|
| 6 | 600 | $4.2 \cdot 10^{-3}$ | 2% |
| 6 | 900 | $1.6 \cdot 10^{-2}$ | 18% |
| 9 | 600 | $1.7 \cdot 10^{-2}$ | 12% |
| 9 | 900 | $1.8 \cdot 10^{-2}$ | 3% |

When the lower installation angle is adopted, conversely, no compromise has to be made: the higher flow rate is beneficial both from the mass transfer and local recirculation frequency aspects.
The dye tracer injection experiments performed in parallel to the oxygen transfer ones aim at further elucidating the relationship between the axial experimental fluid dynamic results presented by Moroni et al. (2013) and the current observations concerning mass transfer.
During the dispersion flow of a pulse dye in an open convective flow, the concentration profile widens both in the direction parallel to flow and in the transverse direction as shown in Figure 2.
The local dye concentration exhibits a peak which dampens over the time past and the distance travelled from the injection point. The maximum of the pulse decays over time according to:

$$c(t) = \frac{(M/A)}{\sqrt{4\pi E t}} \tag{2}$$

where M is the mass of injected material, A is the area through which dispersion occurs, and E is the dispersion coefficient. For the current application, A was taken to be equal to the cross section of a rectangular-cross section prismatic duct having the same length and the same volume of the wavy volume over which the dye pulse dispersion was monitored. The time, t, in turn, was taken equal to the average residence time of the duct. Once the following was assumed and the maximum experimental value of each peak was adopted for c(t), the value of E was calculated to be equal to $3.03 \cdot 10^{-2}$ $cm^2/s$. By remembering that the meaning of E is the same as that of a diffusivity, we can see that dispersion in the channel is about three orders of magnitude more efficient than molecular diffusion, and we can expect that the same improvement should apply equally well to solutes of any kind, from gases to nutrients and substrates.

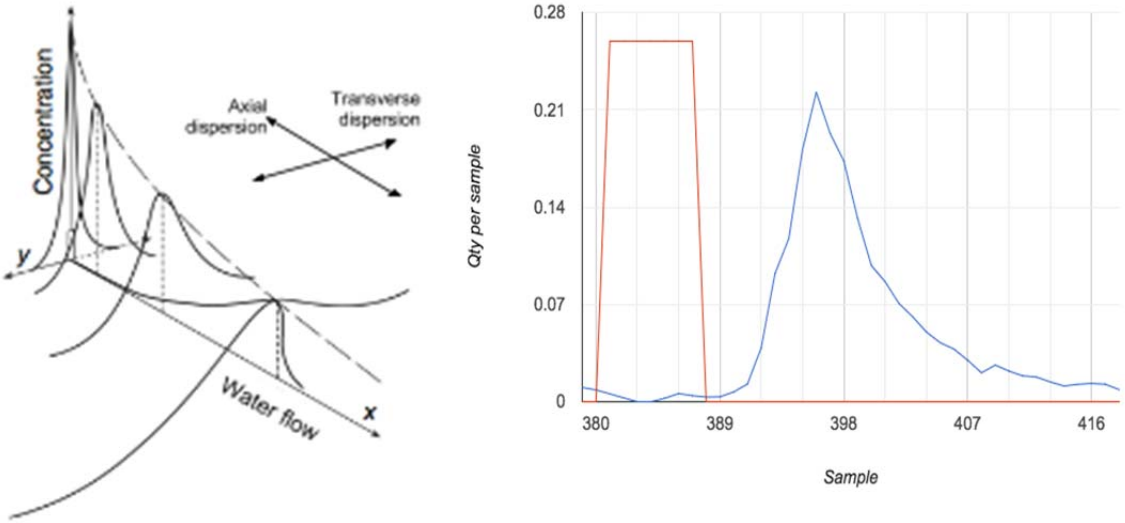


*Figure 2: Advancement of the pulse core in a convective flow with dispersion (Adapted from Cussler, 2013) (left); a pulse of injected dye and the relevant observed response(right).*

By considering the dimensional relationship

$$K = \frac{D}{z} \tag{3}$$

and by assuming z to be equal to the length travelled by the liquid during the time the dispersion tail flows over the detection zone, a mass transfer coefficient K was calculated. For the entire wavy channel, under the equivalent geometric assumption (that is, considering the surface covering all the 12 vanes participating in the mass transfer to be flat) the gas-liquid interface extends by 0.126 $m^2$, while the calculated operating holdup is 1.5 L. The value of the mass transfer coefficient which can be anticipated from dye dispersion measurements, $2.6 \cdot 10^{-3}$ $s^{-1}$, is in reasonable agreement with actual value found experimentally ($4.2 \cdot 10^{-3}$ $s^{-1}$).
Moroni et al. (2013, 2014) fluid dynamic analysis shows that the flow across the vane at 6° is composed by one straight stream and one thumbling stream. The two moving liquid masses exchange material during the whole duration of their contact near the vane bottom, and likely mostly at their meeting in the upstream zone of the vane. A suitable compartental model should feature a small volume exhibiting a well mixed flow and two more volumes exhibiting plug flow: the thumbling and the straight flowing ones. However, this is just a purely "axially sectional" view, as the dye pulse tracing experiments have shown that, while the transverse profile of the dye at the observation point is homogeneous (a mixing index <1% was measured), this is not quite so at the crest between the first and the second vane. Actually, indeed, the ratio:

$$n = \frac{\tau}{\sigma_\tau^2} \tag{4}$$

shows that an adequate compartimentalisation of the very first section of the photobioreactor after the injection section should include 6 perfectly mixed volumes in series. Therefore, a dye tracing experiment aimed at finding an optimal compartmental model for the local recirculation photobioreactor would be better performed with two separate observation slots located at some distance (> 2 vanes) downstream of the (laterally) well homogenised section of the wavy channel, providing a sufficiently conspicuous pulse in order to collect a significant signal.
The wavy-bottomed thin-layer LRPBR photobioreactor investigated has equivalent or slightly better gas transfer performances than the flat-bottomed thin-layer photobioreactor discussed by Doucha and Lívanský (2006). In particular, performance is comparable when the LRPBR is installed at 6° and operated at 600 L/h and slightly better ($k_L$ is $2 \cdot 10^{-4}$ instead of $0.5 \cdot 10^{-4}$) when it is installed at 9° slope and/or operated at 900 L/h. Pirouzi et al. (2014) and Marchuk (2007) measured mass transfer coefficients in the range $10^{-3}$ to $10^{-2}$ $s^{-1}$ (external air-lift photobioreactor) and $2 \cdot 10^{-3}$ to $8 \cdot 10^{-3}$ $s^{-1}$ (inclined tubular photobioreactor), respectively. Rubio et al. (1999) separately quantified the contribution of the various sections of a airlift horizontal tubular photobioreactor and found that the air-lift accounted for $K_La$ values as high as 0.12 $s^{-1}$. In this work only the contribution to mass transfer coming from the section of the circuit exposed to light was characterised so that variation of the mass transfer coefficient along the channel length are not expected upon scale-up. The local recirculation photobioreactor must be completed with a circulation device, which may well impact not only the mass transfer coefficient, but also hydrodynamic stress. An air-lift device would boost mass transfer, while a centrifugal pump may not only be neutral from the point of view of gas transfer, but even be deleterious as a consequence of a greater hydrodynamic stress (Scarsella et al., 2011).

## 4. Conclusions

The wavy bottom local recirculation photobioreactor is a novel type of microalgae growing bioreactor which features a hydrodynamic capable of creating light flashing and promote sustained biomass growth. This paper determined the gas transfer coefficient of this photobioreactor in some key installation and operational configurations in order to pave the way to the analysis of its biomass production potential and pinpoint required development areas for its scaleup.

**Acknowledgements**

The collaboration of Mr Augusto Piazza, Miss Giorgia Sed and Miss Martina Buldo during the experimental work is gratefully acknowledged.

## References

Cicci A., Stoller M., Bravi M., 2013, Analysis of Microalgae Growth in Residual Light: a Diagnostics Tool for Low-Cost Alternative Cultural Media, Chemical Engineering Transactions, 38, 79-84.

Cussler E. L., 2009, Diffusion: mass transfer in fluid systems. Cambridge University Press, ISBN 978-0521871211.

Doucha J., Lívanský K., 2006, Productivity, $CO_2/O_2$ exchange and hydraulics in outdoor open high density microalgal (*Chlorella* sp.) photobioreactors operated in a Middle and Southern European climate. J Appl Phyc 18, 6, 811-826.

Merchuk J. C., Rosenblat Y., Berzin I., 2007, Fluid flow and mass transfer in a counter-current gas–liquid inclined tubes photo-bioreactor. Chem Eng Sci 62, 24, 7414-7425.

Moroni M., Cicci A., Bravi M., 2013, Experimental Investigation of Fluid Dynamics in a Gravitational Local Recirculation Photobioreactor, Chemical Engineering Transactions, 32, 913-918, DOI:10.3303/CET 1332153.

Moroni M., Cicci A., Bravi M., 2014, Experimental investigation of a local recirculation photobioreactor for mass cultures of photosynthetic microorganisms. Water Res 52, 29-39.

Pirouzi A., Nosrati M., Shojaosadati S. A., Shakhesi S., 2014, Improvement of mixing time, mass transfer, and power consumption in an external loop airlift photobioreactor for microalgae cultures. Biochem Eng J 87, 25-32.

Ranganathan P., Sivaraman S., 2011, Investigations on hydrodynamic and mass transfer in gas–liquid stirred reactor using computational fluid dynamics, Chem Eng Sci 66, 3108–3124.

Rasband W.S., ImageJ, U. S. National Institutes of Health, Bethesda, Maryland, USA, http://imagej.nih.gov/ij/, 1997-2014.

Rubio F. C., Fernandez F. G., Perez J. A., Camacho F. G., Grima, E. M., 1999, Prediction of dissolved oxygen and carbon dioxide concentration profiles in tubular photobioreactors for microalgal culture. Biotechnol Bioeng 62, 71-86.

Scarsella M., Torzillo G., Cicci A., Belotti G., De Filippis P., Bravi M., 2012, Mechanical stress tolerance of two microalgae. Process Biochem 47, 11, 1603-1611.

Torzillo G, Giannelli L, Martinez-Roldan S. J., Verdone N, De Filippis P., Scarsella M, Bravi M, 2010.
Microalgae culturing in thin-layer photobioreactors. Chemical Engineering Transactions 20, 265-270.