CHEMICAL ENGINEERING RESEARCH AND DESIGN 92 (2014) 1891–1897

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

CO_2 mass transfer and conversion to biomass in a horizontal gas–liquid photobioreactor

P. Valiorgue[a,*], H. Ben Hadid[a], M. El Hajem[a], L. Rimbaud[b,1], A. Muller-Feuga[b,1], J.Y. Champagne[a]

[a] LMFA, UMR CNRS 5509, Université de Lyon, Ecole Centrale de Lyon, Université Lyon 1, INSA de Lyon, ECL, 20, Avenue Albert Einstein, 69621 Villeurbanne Cedex, France

[b] Microphyt, 713, Route de Mudaison, 34670 Baillargues, France

ABSTRACT

This study deals with CO_2 mass transfers and biomass conversion in an industrial horizontal tubular photobioreactor. An analytical approach is used to determine an expression modeling the influence of CO_2 mass transfers on the overall biomass conversion efficiency for a given culture broth, heat and light conditions. Fluid mechanics and mass transfer are predicted with a classical two-phase flow approach (Taitel and Dukler, 1976) combined with a dissolution correlation developed and tested in the laboratory (Valiorgue et al., 2011). The influence of the stripping gas, removing the excess of oxygen in the liquid, on the conversion to biomass efficiency is shown to be not negligible. The expression is used to evaluate how the photobioreactor's design and process parameters can be tuned in order to improve biomass conversion efficiency. The biomass conversion efficiency evolution with the photobioreactor's length was found to behave asymptotically and it was explained by the relative orders of magnitude of gas dissolution and gas stripping. It has been shown that the gas flow rate for stripping and therefore the oxygen removal will be limited when further increasing the industrial photobioreactor's length for a given objective of CO_2 conversion to biomass efficiency.

Keywords: Mass transfer; Gas–liquid; CO_2 biomass conversion; Photobioreactor; Microalgae; Process model; CO_2 bioremediation

1. Introduction

Microalgae cultures have been recently regarded as a means to bioremediate industrial CO_2 waste. However, the efficiency of the conversion of the CO_2 into biomass has been seldom documented, and a significant part of the gas introduced in microalgae production systems is suspected of being released in the atmosphere. Improving the modelling of such biotechnological processes will help increasing the biomass conversion efficiency of industrial waste gas containing 10–20% of CO_2 (Cheng et al., 2006; Ayhan, 2011; Zeiler et al., 2014). High-density photoautotrophic microalgal growth in enclosed photobioreactors necessitates gas, light, momentum and heat exchanges (Cheng et al., 2006; Mandalam and Palsson, 1998). Mass transfer modelling is a first step toward understanding the coupled physics–biology in the photobioreactor and improving the CO_2 conversion to biomass.

This study deals with the experimental assessment and modelling of CO_2 biomass conversion in a horizontal co-current gas–liquid photobioreactor converting CO_2 into value-added microalgae. The windy, wavy and wiped tubular photobioreactor investigated has been designed for slow growing and fragile species with the ambition of improving accessibility to the huge biodiversity of microalgae. For

* *Corresponding author*. Mobile: +33 632298274.
E-mail address: pierre.valiorgue@gmail.com (P. Valiorgue).
URL: http://www.microphyt.eu/ (A. Muller-Feuga).
Received 22 May 2013; Received in revised form 3 February 2014; Accepted 17 February 2014
Available online 25 February 2014
[1] Mobile: +33 614796892.
http://dx.doi.org/10.1016/j.cherd.2014.02.021
0263-8762/

Greek symbols

η	mass transfer efficiency (MTE)
ν	kinematic viscosity [m^2/s]
Φ	pipe diameter [m]
Φ_h	hydraulic diameter of the duct [m]
ϕ	molecular gas flux [mol/(s × m^2)]
ρ	density [kg/m^3]

Latin symbols

A	section area [m^2]
c	constant in the friction factor correlation
C	carbon dioxide molar concentration [mol/m^3]
D	diffusion constant [m^2/s]
g	gravity [m/s^2]
h	height [m]
k	mass transfer coefficient [m/s]
k_{La}	volumetric mass transfer coefficient [1/s]
L_{tubes}	total tube length of the photobioreactor [m]
M	molar mass [kg/mol]
m	carbon dioxide mass [kg]
p	pressure [Pa]
R	ideal gas constant [J/mol K]
Re	Reynolds number $Re = (U \cdot \Phi_h)/\nu$
S	perimeter [m]
Sc	Schmidt number $Sc = \nu/D$
Sh	Sherwood number $Sh = (k_L \cdot \Phi_h)/D$
T	temperature [K]
t	time [s]
U	mean velocity over the duct section area [m/s]
v	exponent in Eq. (8), see Taitel in Taitel and Dukler (1976)
w	exponent in Eq. (8), see Taitel in Taitel and Dukler (1976)
x	coordinate in the downstream direction along the duct [m]
X	Lockhart and Martinelli parameter

Subscripts and superscripts

biomassconv	CO_2 contained in the output dry microalgae
diss	CO_2 dissolved
eq	equivalent height
G	gas
i	interface
injected	CO_2 injected into the photobioreactor
L	liquid
undiss	CO_2 undissolved and directly rejected to the atmosphere
prod	production of the microalgae mass harvested
residual	CO_2 dissolved in the liquid and remaining dissolved
S	superficial, for single fluid flow
sat	saturation
stripped	CO_2 driven to the atmosphere by the stripping air
~	dimensionless variable

the purpose of reducing mechanical stress and avoiding cell wall disruption, the pump device is operated under low pressure and bubbling has been reduced by removing the direct airlift achieving mass transfer usually placed in the culture loop (Muller-Feuga et al., 2012, 2011). Carbon dioxide and oxygen mass transfers are achieved through co-current circulation of gas and liquid within the photobioreactor along with photosynthesis. Carbon is provided to the cells via punctual injections of gas that contains up to 10% of CO_2 and are monitored by a feedback loop maintaining a constant pH. Excess of oxygen inhibiting microalgae growth is removed from the culture broth by continuously injected stripping air (Muller-Feuga et al., 2011; Ogawa et al., 1980).

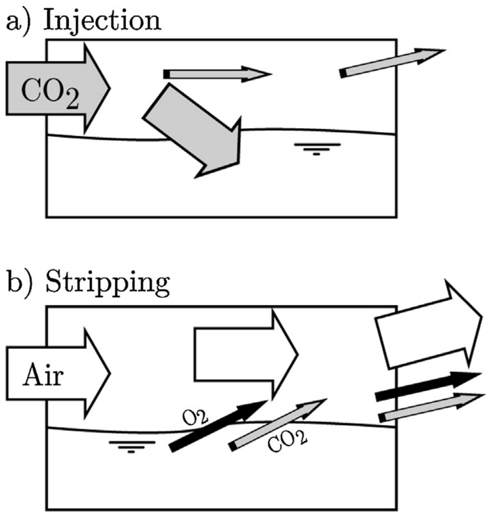

Fig. 1 – Diagram of the carbon dioxide punctual dissolution phase (a) and continuous air stripping phase (b).

A few mass transfer models and measurements applied to photobioreactors can be found in the literature of the two last decades. As highlighted in Sobczuk et al. (2000), Doucha et al. (2005), CO_2 biomass conversion efficiency depends on CO_2 concentrations both in the air–CO_2 mixture injected in the photobioreactor and in the algal suspension (Doucha et al., 2005). Therefore, mass transfer efficiencies (MTE) measurements should be reported for a given operating injected gas conditions as done in Doucha et al. (2005), for an outdoor culture of *Chlorella spirulina*. Very few data concerning the produced biomass and the injected mass of CO_2 are available in the literature as can be found in Doucha et al. (2005).

Mass transfer models of photobioreactors reported in the literature enable to determine overall mass transfer coefficients from correlations of the parameters of the process (Baquerisse, 1999; Loubiere et al., 2011; Reyna-Velarde et al., 2010; Fan et al., 2008). To our knowledge, there is no analytical study in the literature concerning CO_2 mass transfer and biomass conversion in a horizontal gas–liquid photobioreactor. Such an analytical study would determine where the CO_2 which has not been converted to biomass has been lost and how process parameters can be tuned in order to improve biomass conversion efficiency for a given culture condition.

This paper is structured in three sections. In the first section, a CO_2 mass balance over an horizontal photobioreactor will allow to express mass transfer efficiencies as a function of operating parameters. Experimental measurements will then be explained in the second section and finally, results will be presented and discussed.

2. Mass transfer modeling

2.1. *Conservation of mass*

As depicted on Fig. (1a), the carbon dioxide mass injected in the photobioreactor, $m_{injected}$, is partially dissolved into the