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Han's model parameters for microalgae grown under intermittent illumination: Determined using particle swarm optimization

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ABSTRACT

This work provides a model and the associated set of parameters allowing for microalgae population growth computation under intermittent lightning. Han's model is coupled with a simple microalgae growth model to yield a relationship between illumination and population growth. The model parameters were obtained by fitting a dataset available in literature using Particle Swarm Optimization method. In their work, authors grew microalgae in excess of nutrients under flashing conditions. Light/dark cycles used for these experimentations are quite close to those found in photobioreactor, i.e. ranging from several seconds to one minute. In this work, in addition to producing the set of parameters, Particle Swarm Optimization robustness was assessed. To do so, two different swarm initialization techniques were used, i.e. uniform and random distribution throughout the search-space. Both yielded the same results. In addition, swarm distribution analysis reveals that the swarm converges to a unique minimum. Thus, the produced set of parameters can be trustfully used to link light intensity to population growth rate. Furthermore, the set is capable to describe photodamages effects on population growth. Hence, accounting for light overexposure effect on algal growth.

1. Introduction

Microalgae growth is receiving increasing attention in the scope of producing biofuels or fixing atmospheric CO_2 (Chen et al., 2011; Packer et al., 2011; Quinn et al., 2011; Yang et al., 2011). Two different experimental approaches coexists: open ponds and photobioreactors. The first ones deliver a cost effective high scale solution, at the price of low control over the growth conditions and a very high risk of contamination (Davis et al., 2014). The second allows for a very tight control of operating conditions, while being expensive and scalable only with difficulty.

Because of their very controlled nature, photobioreactors are reasonable assumed to be perfectly stirred reactors regarding nutrients and dissolved gases concentrations (Bitog et al., 2011; Rampure et al., 2007). Regarding illumination inside of the reactor, it is well known that such an assumption cannot be drawn because of light attenuation (Bernard, 2011; Bernardi et al., 2016; Grima et al., 1994). Yet, light is key to microalgae growth. It is therefore a critical parameter when designing a photobioreactor.

In 2013, Béchet et al. (2013) reviewed the currently available models for determining the amount of light received by a culture and its impact on algal growth. The existing models can be sorted out into three different categories:

- black boxes: they predict the total photosynthetic yield of a culture as a function of the total or averaged light intensity reaching the culture (MacIntyre et al., 2002). These models are very easy to handle. In addition, they allow for a simple 0D modeling approach. Nevertheless, their shortcomings are numerous, the most dramatic one is that they critically depend on the experimental data that have been used to calibrate them. Obviously, they can not account for light attenuation in the reactor.
- local light intensity models: they describe the attenuation of light throughout the reactor. Thus they allow for spatial integration of light and related growth rate distribution over the reactor volume. Usually, they can account for light attenuation based on cell density and cell pigment content (Undurraga et al., 2016). They yield significantly better results than black boxes models. Nevertheless, they assume that microalgae response to light is always in steady state. Thus, they are not able to take into account dynamic temporal effects (light/dark cycle) inside of the reactor which is today known to have an important impact on microalgae behavior (Abu-Ghosh et al., 2016).

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Nomenclature

Latin symbols

A	A state (open) of a photosynthetic unit, –
B	B state (processing) of a photosynthetic unit, –
C	C state (damaged) of a photosynthetic unit, –
D	diameter, m
F	cost function, –
I	light intensity, μmolQuanta/m^2/s
K	light to growth rate dimensionless constant, –
k_d	photosynthetic unit photodamage rate, μmolQuanta/m^2/s
k_r	photosynthetic unit repair rate, 1/s
l	length, m
Me	maintenance rate, 1/h
P	linear pumping power, W/m
Re	Reynolds number, $Re = \frac{DV}{\nu}$
t	time, s
t_i	illumination time, s
V	velocity, m/s

Greek symbols

α	absorption coefficient, 1/m
μ	population growth rate, 1/h
ν	kinematic viscosity, m^2/s
rho	density, kg/m^3
σ	photosystem cross section, m^2/μmolQuanta
τ	turnover rate, 1/s

Subscripts

exp	experimental observation
i	dummy index
PSII	PhotoSystem II
num	numerical prediction
sun	sun
vortex	turbulent vortex

- mechanistic models: they describe the microalgae response to light in term of activation of the key proteins at stake in the photosynthetic process. Among them, Han's model (HAN, 2002) is nowadays widely used in the community (Baklouti et al., 2006; Esposito et al., 2009; Hartmann et al., 2013; 2014; Nikolaou et al., 2016). It is an improvement of the firstly proposed model (HAN, 2001) which take into account photodamages due to light overexposure.

The model used to describe culture response to illumination has strong implications on the choice of the model describing algae motion inside of the reactor. While black boxes models work perfectly well with perfectly stirred reactor assumption. Mechanistic models would require to know the position of the microalgae inside of the reactor, and the corresponding illumination, to yield the full-extend of their power.

Han's model particularly well suited for photobioreactor numerical design. Indeed, using CFD capabilities, it is nowadays possible to access light pattern seen by tracers reproducing microalgae (Hartmann et al., 2014; Sato et al., 2010). Yet, assuming that light is the limiting growth factor, finding a tight set of Han's model parameters linking directly intermittent light exposure to growth rate is a difficult task. Most of the time, in literature, light supply is coupled with other nutrient limitations and population light adaptation strategy (Baklouti et al., 2006; Esposito et al., 2009; Geider et al., 1998). Hence, it is quite challenging to implement such models. Furthermore, such a complexity is not mandatory when solely light effects are to be investigated.

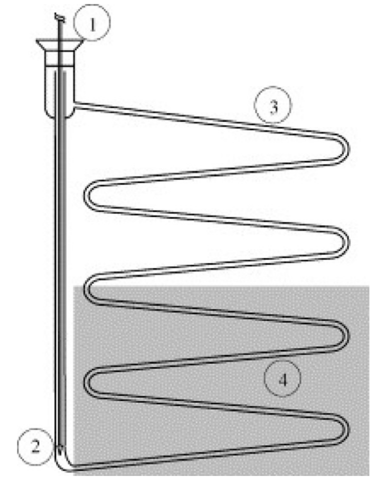

Fig. 1. Scheme of the tubular loop reactor with air lift pump. (1) Gas inlet; (2) gas sparger (air+CO_2); (3) illuminated part of the tubular reactor; (4) dark part of the tubular reactor (Wu and Merchuk, 2001).

The aim of this work is to provided a set of parameter allowing for population growth computation, under nutrient excess assumption, as a time dynamic function of illumination. To do so, a dataset available in literature will be used (Wu and Merchuk, 2001). In their work, authors grew microalgae in excess of nutrients under flashing conditions. Light/dark cycles used for these experimentations are quite close to those found in photobioreactor, i.e. ranging from several seconds to one minute (Barbosa et al., 2003; Janssen et al., 1999; Sato et al., 2010). In a second part of their work, the authors used an heavy mathematical treatment and assumption to use ordinary least square method to calibrate a model (Eilers and Peeters, 1988). Even though their model is resembling to the widely popular Han's model, the parameters cannot be transposed. Thus in this work, Han's model parameter will be produced using Particle Swarm Optimization method.

2. Experimental dataset

In their original work, the authors grew Red Marine algae, *Porphyridium* sp. (UTEX637) in a photobioreactor (Fig. 1). Extensive description of the experimental procedure is available in Wu and Merchuk (2001). In this work only the main features will be summarized. The reactor is mainly composed of two parts:

- A gas column with a sparger (elements 1 and 2 and Fig. 1), ensuring fluid motion through the reactor and CO_2 supply to the culture medium thanks to 3% CO_2 air bubbling.
- A small diameter tube, where algae are exposed to light on the upper part of the tube (element 3 and Fig. 1), then travel thought a darkness in the lower of the tube (element 4 and Fig. 1).

The average cycle time of algae around the reactor is 45 s. Illuminations time (t_i) can be adjusted by varying the length of the dark zone of the reactor. In this case, illumination time range between 45 s, i.e. constant illumination, down to 28.3 s. Hence an illumination proportion ranging from 63 to 100% over a constant period of 45 s.

Light intensity was set to three different values: 110, 220 and 550 μmolQuanta/m^2/s, referred as low, medium and high intensity lighting. The purpose the high intensity lighting was to trigger photodamage. In addition to using a small diameter tube, the authors took care to verify that no biofilm was developing on the tube surface. Hence, the lighting is uniform throughout the photobioreactor.