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Light transfer in bubble sparged photobioreactors for H_2 production and CO_2 mitigation

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Abstract

This paper presents a parametric study simulating light transfer in a photobioreactor containing gas bubbles and filamentous cyanobacteria *Anabaena variabilis* suspended in water. To the best of our knowledge, this paper presents for the first time a model for such system: (i) using a consistent set of radiation characteristics of the medium derived from experimental data and from Mie theory; (ii) accounting for anisotropic scattering by both the bubbles and the filamentous microorganisms; (iii) considering the spectral dependency of radiation characteristics in the spectral range from 400 to 700 nm using a box model, and (iv) evaluating light transfer in a photobioreactor containing genetically engineered microorganisms with reduced pigment content. The steady-state one-dimensional radiation transfer equation is solved using the modified method of characteristics and a quadrature with 24 directions per hemisphere adapted to forward scattering media. The parameters investigated include the bacteria concentration, the bubble radius, and the void fraction, as well as the approximate scattering phase function. It was established that the strongly forward scattering by the bubbles must be accounted for and the truncated phase function (TPF) is recommended. In the absence of bubbles, ignoring in-scattering by the bacteria leads to errors as high as 20%. On the other hand, accounting for in-scattering with isotropic phase function gives acceptable results. Moreover, genetically reducing the pigment content of the microorganisms by an order of magnitude increases the significance of forward scattering of light by the microorganisms. This in turn, increases the penetration depth and can be accounted for by either the Henyey–Greenstein or the TPF approximations. Finally, the model presented can also be applied to (i) other types of microorganisms such as unicellular green algae or photosynthetic bacteria, (ii) different photobioreactor processes such as food product or pharmaceutical production, or (iii) photochemical reactors.

Keywords: Photobiological hydrogen production; Carbon dioxide mitigation; Genetically modified bacteria; Reduced pigment; Algae; Cyanobacteria; Bubble column; Airlift; Photobioreactor; Light transfer; Modeling

1. Introduction

Increased amounts of greenhouse gas emissions as well as the exhaustion of inexpensive and accessible fossil fuel resources are calling for clean and renewable energy sources. Hydrogen, to be used in fuel cells, is considered to be an attractive alternative fuel since water vapor is the only byproduct from its reaction with oxygen. Photobiological hydrogen production by cultivation of cyanobacteria (or green algae) offers a clean and sustainable alternative to thermochemical or electrolytic production technologies.

During photobiological hydrogen production, light from the sun is absorbed by microorganisms such as algae, cyanobacteria or photosynthetic bacteria to produce hydrogen [1]. The reader is referred to Refs. [1–6] for detailed reviews of photobiological hydrogen production. In particular, the cyanobacterium *Anabaena variabilis* has been studied extensively and identified as a good candidate for hydrogen production [7]. Therefore, it is chosen as the microorganism of interest in the present study.

The cyanobacterium *A. variabilis* is a photosynthetic prokaryote which uses CO_2 as its carbon source, water as its electron source, and sunlight as its energy source. Fig. 1 (a) shows a micrograph of a filament of *A. variabilis*, approximately 5 μm in diameter and 100 μm in length, composed of vegetative cells and heterocysts. It uses the light energy in the

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Nomenclature

A_i	interfacial area concentration, m^2/m^3
a	bubble radius, m
$A_{abs,\lambda}$	spectral mass absorption cross-section of microorganisms, m^2/kg
D	dilution factor
$S_{sca,\lambda}$	spectral mass scattering cross-section of microorganisms, m^2/kg
f_1	weighing factor in TPF
f_B	void fraction
G	irradiance, W/m^2
g	asymmetry factor
h_1	weighing factor in TPF
I	light intensity, $W/m^2/sr$
k	absorption index
n	index of refraction
$Q_{sca,B}$	scattering efficiency of the bubbles
r_X	radius of microorganisms
$\vec{s}$	unit vector into a given direction
v_X	specific volume of the microorganisms, m^3/kg
w_i	weighting factors of the Gaussian quadrature
X	microorganism concentration, kg dry cell/m^3
z	distance from the illuminated surface, m

Greek symbols

β	extinction coefficient, m^{-1}
θ	polar angle, rad
θ_i	discrete polar angles corresponding to the directions of the Gaussian quadrature, rad
Θ	angle between incident and scattered directions, rad
κ	absorption coefficient, m^{-1}
λ	wavelength, nm
λ_c	box center wavelength, nm
σ	scattering coefficient, m^{-1}
ϕ	azimuthal angle, rad
Φ	scattering phase function
χ	size parameter
Ω	solid angle, sr
ω_{eff}	average single scattering albedo

Subscripts

abs	refers to absorption
in	refers to incident radiation
D	refers to the dilution factor
w	refers to water
X	refers to bacteria or bacteria concentration
λ	refers to wavelength
HG	refers to Henyey–Greenstein phase function
PAR	refers to photosynthetically active radiation ($400\,nm \leqslant \lambda \leqslant 700\,nm$)
TPF	refers to truncated phase function
sca	refers to scattering

spectral range from 400 to 700 nm, known as the photosynthetically active radiation (PAR). In turn, it produces biomass (i.e., it multiplies), as well as oxygen and hydrogen. In addition, *A. variabilis* is capable of fixing molecular nitrogen present in air using the enzyme nitrogenase [5]. As part of its nitrogen fixation metabolism, it generates hydrogen as a byproduct [5]. In the absence of molecular nitrogen, hydrogen production by the nitrogenase enzyme is promoted [5]. However, the functioning of nitrogenase, both for fixing nitrogen and producing hydrogen, is inhibited by the dissolved oxygen in the growth medium [8]. In addition, *A. variabilis* also possesses the enzyme uptake hydrogenase which consumes hydrogen to reduce molecular oxygen [5].

Dissolved oxygen accumulation, limited light penetration, and carbon dioxide availability to the microorganisms are the major factors affecting the performance of a photobioreactor for the production of hydrogen [2]. Researchers are trying to overcome these limitations by genetically engineering microorganisms and designing novel photobioreactors [7,9,10]. For example, *A. variabilis* has been genetically modified to lack the hydrogen consuming enzyme uptake hydrogenase [11–13]. The mutant forms had 3–4.3 times higher hydrogen production rates compared with the wild forms. In addition, Melis et al. [10,14] reduced the pigment content of the green algae *Dunaliella salina* from 1×10^9 Chlorophyll molecules per cell (Chl/cell) to 0.15×10^9 Chl/cell for overcoming the light penetration problem in large photobioreactors. More recently, Polle et al. [15] genetically engineered the green algae *Chlamydomonas reinhadtii* to have a truncated light harvesting chlorophyll antenna size. The authors reported that the microorganisms with less pigments had higher quantum yield, photosynthesis rate, and light saturation irradiance. In addition, Melis et al. [6,10] showed that pure hydrogen production can be achieved by *C. reinhadtii* under sulfur deprivation. The authors stated that with this method photosynthetic oxygen production is slowed down and pure hydrogen is produced by the culture, overcoming the oxygen inhibition of the hydrogen producing enzymes, as well as eliminating the dangerous mixtures of hydrogen and oxygen. As an alternative, Greenbaum et al. [16] experimentally showed that the inhibitory effect of molecular oxygen on hydrogen production can be alleviated by having a headspace volume three time that of the liquid phase which ensures low dissolved oxygen concentration in the bacteria medium. By having a large headspace volume, the molar fraction of oxygen is kept low in the gas phase which ensures more oxygen to partition into the gas phase. This approach can