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Temporal scaling of the growth dependent optical properties of microalgae

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ABSTRACT

The optical properties of microalgae are basic parameters for analyzing light field distribution in photobioreactors (PBRs). With the growth of microalgae cell, their optical properties will vary with growth time due to accumulation of pigment and lipid, cell division and metabolism. In this work, we report a temporal scaling behavior of the growth dependent optical properties of microalgae cell suspensions with both experimental and theoretical evidence presented. A new concept, the temporal scaling function (TSF), defined as the ratio of absorption or scattering cross-sections at growth phase to that at stationary phase, is introduced to characterize the temporal scaling behavior. The temporal evolution and temporal scaling characteristics of the absorption and scattering cross-sections of three example microalgae species, *Chlorella vulgaris, Chlorella pyrenoidosa*, and *Chlorella protothecoides,* were experimentally studied at spectral range 380–850 nm. It is shown that the TSFs of the absorption and scattering cross-sections for different microalgae species are approximately constant at different wavelength, which confirms theoretical predictions very well. With the aid of the temporal scaling relation, the optical properties at any growth time can be calculated based on those measured at stationary phase, hence opens a new way to determine the time-dependent optical properties of microalgae. The findings of this work will help the understanding of time dependent optical properties of microalgae and facilitate their applications in light field analysis in PBRs design.

1. Introduction

The world is facing an unprecedented combination of economic and environmental challenges to meet the huge energy demand [1]. The extensive use of fossil fuels leads to growing greenhouse gases emissions which then influence the global climate [2]. The primary energy consumption of the world was predicted to increase by 37% between 2013 and 2035 [3]. Hence, it is crucial to find renewable and clean fuels to replace the traditional fossil fuels. Microalgae is a kind of fast growing microorganisms on the earth, which can produce oil of per unit area 7–31 times greater than terrestrial plants [4], and hence is considered to be the most promising alternative resources for biofuel production. Ullah et al. [4] reported that biofuels have the potential to meet 50% of the world energy consumption, meanwhile it will not produce net emissions of carbon dioxide. Moreover, the cultivation of microalgae can produce other value-added by-products which make the process more economical [5–7].

Microalgae can produce carbohydrates, proteins, lipids and oxygen within the cells, some species can also produce H_2 through the photosynthesis process as illustrated in Fig. 1. The photosynthesis process consists of two reactions, namely, light and dark reactions. During light reactions, photons are absorbed in chloroplasts to produce ATP and NADPH. These products are used in the dark reactions to produce carbohydrates, proteins and lipids [8]. Microalgae typically have efficiencies about 10 times of the terrestrial higher plants at converting light energy into bioenergy per unit area [9,10], due to microalgae cells growing in aqueous media. Many species of microalgae can also utilize waste water for microalgae cultivation [11]. Moreover, the microalgae can be cultivated in open or closed PBRs without occupying the agriculture production lands [7,11].

Although the cultivation of microalgae for biofuel production presents many advantages, its cultivation cost is still high in PBRs. It is still facing numerous challenges, such as, light utilization efficiency, a large amount of nutrients and auxiliary energy requirement during the cultivation of microalgae [12–14]. Light utilization

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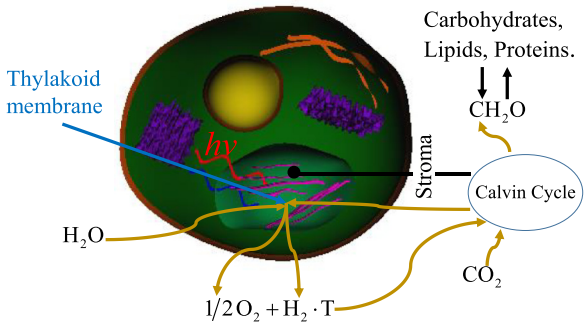

Fig. 1. Schematic of photosynthetic process in chloroplasts, light absorption and water splitting is on thylakoid membrane *via* photochemical electron transport and the stroma for dark reactions. "T" represents the chemically binds hydrogen [8].

efficiency of the PBRs significantly affects the microalgae biomass productivity [15,16]. Indeed, photosynthesis process of microalgae requires an optimum irradiance to achieve their maximum biomass production. The microalgae will suffer light inhibition for excessive irradiance [17], meanwhile, limited light irradiance will cause the decrease of biomass productivity [18,19]. Hence careful light transfer analysis must be conducted to design and optimize the light field distribution in PBRs to make them more efficient.

The optical properties of microalgae are basic parameters for obtaining light field in PBRs. Optical properties of many microalgae species at the VIS-NIR spectral range has already been experimentally determined [20–24]. Until recently, most reported optical properties of microalgae were measured at the stationary growth phase, partly due to the difficulty in on-line measurement. However, with the growth of microalgae cell, their optical properties will vary with time due to accumulation of pigment and lipid, cell division and metabolism. The effect of cell growth on the optical properties of microalgae has been rarely studied. Most recently, Heng and Pilon [25] reported their experimental study of the temporal evolution optical properties of absorption and scattering cross-sections of *Nannochloropsis oculata* in full growth phase during batch cultivation. The *Nannochloropsis oculata* was grown in a flat-plate PBR under constant irradiance by red LEDs emitting at 630 nm. The optical properties between 400 and 750 nm and pigment concentrations were measured every 24 h for up to 18 days. They found that the absorption and scattering cross-sections of the microalgae varied significantly with growth time in response to change in light fields and nutrients availability.

In this study, we report both experimental and theoretical evidence of the temporal scaling behavior of the growth dependent optical properties of microalgae cell suspensions. The concept of temporal scaling function defined as the ratio of absorption or scattering cross-sections at growth phase to that at stationary phase is introduced to characterize the temporal scaling, which is proved to be wavelength independent. The temporal scaling characteristics of the scattering and absorption cross-sections of three example microalgae, *Chlorella vulgaris, Chlorella pyrenoidosa*, and *Chlorella protothecoides*, were experimentally studied at spectral range 380–850 nm.

2. The optical properties of microalgae

The microalgae suspensions in PBRs is a typical kind of participating media of radiative transfer. When a light beam transports in the microalgae suspensions, it encounters scattering and absorption by the microalgae cells as well as by the bubbles and culture medium. The governing equation for light transport within the microalgae suspensions is the radiative transfer equation, which can be written as [1,26]

$$\mathbf{s}\cdot\nabla I_\lambda(\mathbf{r},\mathbf{s})+\beta_\lambda I_\lambda(\mathbf{r},\mathbf{s})=\frac{\kappa_{s,\lambda}}{4\pi}\int_{4\pi} I_\lambda(\mathbf{r},\mathbf{s}')\Phi_\lambda(\mathbf{s}',\mathbf{s})\mathrm{d}\Omega' \tag{1}$$

where I_λ is the spectral radiative intensity (W/m^2 · nm · sr) in direction $\mathbf{s}$ and at location $\mathbf{r}$, $\kappa_{s,\lambda}$ is the scattering coefficient (m^{-1}), $\beta_\lambda=\kappa_{a,\lambda}+\kappa_{s,\lambda}$ is the extinction coefficient (m^{-1}), $\kappa_{a,\lambda}$ is the absorption coefficient (m^{-1}), $\Phi_\lambda(\mathbf{s}',\mathbf{s})$ is the scattering phase function and Ω' is the solid angle. The scattering phase function $\Phi_\lambda(\mathbf{s}',\mathbf{s})$ stands for the probability that the radiation transfer in the solid angle dΩ' around the direction $\mathbf{s}'$ scattered into the solid angle dΩ around the direction $\mathbf{s}$ and is normalized with the following equation [26]

$$\frac{1}{4\pi}\int_{4\pi}\Phi_\lambda(\mathbf{s}',\mathbf{s})\mathrm{d}\Omega=1 \tag{2}$$

The basic characteristics of the scattering phase function is given by the asymmetry factor g_λ, which describes isotropic, backward or forward scattering features, is defined as [26]

$$g_\lambda=\frac{1}{4\pi}\int_{4\pi}\Phi_\lambda(\mathbf{s}',\mathbf{s})\cos\theta\,\mathrm{d}\Omega \tag{3}$$

where θ is the angle between the incident direction s′ and scattering direction $\mathbf{s}$. Previous studies showed that the microalgae cells featured strongly forward scattering with g_λ values around 0.97 [27]. Generally, the absorption and scattering coefficients of microalgae suspensions are time-dependent due to the growth of microalgae cells. When neglecting the contributions of bubbles and culture medium, they can be expressed in terms of the average absorption cross-section $C_{\mathrm{abs},\lambda}$ and average scattering cross-section $C_{\mathrm{sca},\lambda}$ (m^2) as [26]

$$\kappa_{a,\lambda}(t)=C_{\mathrm{abs},\lambda}(t)N(t) \tag{4}$$

$$\kappa_{s,\lambda}(t)=C_{\mathrm{sca},\lambda}(t)N(t) \tag{5}$$

respectively, where $N(t)$ is the cell number density (m^{-3}) as a function of growth time t. The number density is difficult to be measured for multicellular microalgae. Alternatively, the optical properties can also be expressed in terms of the average mass absorption cross-section $C^{\mathrm{M}}_{\mathrm{abs},\lambda}$, average mass scattering cross-section $C^{\mathrm{M}}_{sca,\lambda}$ (m^2/kg) and mass concentration X (kg/m^3) [27] as

$$\kappa_{a,\lambda}(t)=C^{\mathrm{M}}_{\mathrm{abs},\lambda}(t)X(t) \tag{6}$$

$$\kappa_{s,\lambda}(t)=C^{\mathrm{M}}_{sca,\lambda}(t)X(t) \tag{7}$$

During microalgae cell growing, it will experience the accumulation of pigment and lipid, cell division and metabolism. The time dependent cell concentration of microalgae can be modeled based on the general exponential growth law as [1,28]

$$\frac{\mathrm{d}X(t)}{\mathrm{d}t}=\mu(t)X(t) \tag{8}$$

where the μ is the specific growth rate (h^{-1}) characterizing the growth kinetics, which is generally a function of growth time. Analytical solution of Eq. (8) can be obtained as

$$X=X_0\exp\left[\tau_X(t)\right]=X_0\exp\left[\int_0^t\mu(t)dt\right] \tag{9}$$

where X_0 stands for the initial cell concentration (at $t=0$) and $\tau_X(t)=\int_0^t\mu(t)dt$.