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EULERIAN TRACKING OF CUMULATIVE LIGHT DOSE IN MICROALGAL PHOTOBIOREACTOR

Juřena T.*, Vondál J., Rebej M.**, Jegla Z.****

Abstract: *The present work contributes to the development of a CFD model of a laboratory stirred photobioreactor used for microalgae cultivation. A method is proposed to analyze and keep track of the amount of light incident on microalgae in the Eulerian framework. An additional scalar transport equation is defined and solved for the cumulative light dose experienced by the cells at each point of the domain. The method is capable to indicate, where the living cells are concentrated, that have been exposed to equivalent light conditions on average. However, local values deviate to a large extent from the cumulative light dose predicted by Lagrangian tracking of massless particles (tracers), so the method needs to be further improved.*

Keywords: Photobioreactor, Light, History, Microalgae, Simulation, Fluid Flow.

1. Introduction

Microalgae cultivation has earned much attention by researchers worldwide due to the capacity to turn fixed carbon dioxide and nutrients into valuable compounds. Therefore, research studies focus not only on essential principles of photosynthesis, but also on microalgae utilization in biotechnologies for biofuel production on short timescale, pollutant removal and carbon dioxide capture as in (Hossain et al., 2019) and nutrient uptake from wastewaters as in (Li et al., 2019).

Growth rate of a given microalgae specie depends on several factors including temperature and pH of the medium, availability and mass transfer of carbon dioxide, oxygen and nutrients, hydrodynamic conditions (e.g. mixing and shear stress) and light supply (e.g. wavelength range and intensity). In general, high production rates of microalgal cultures can be achieved using a closed bioreactor system due to good control over the set of the factors (Pires et al., 2017).

The present work contributes to the development of a CFD model of a closed stirred photobioreactor (PBR) – a laboratory cuvette used for microalgae cultivation. The focus is on the modelling and analysis of light intensity within the medium. As the growing microalgae cells in the PBR are carried in the flow, induced by a rotating stir bar, they move from light-rich zones near the light source to dark ones, experiencing a temporal change of light intensities. In fact, photosynthesis is found to be more efficient under dynamic light conditions due to high-frequency alternating light-dark periods, also called light-dark cycles or the flashing-light effect (Hu and Sato, 2017). Both instant and total amounts of light incident on the cells are important, as the growth ceases with intensities below a certain level. Hence, it is important to keep history of the microalgae cells exposed to the light.

The most intuitive way to represent dispersed microalgae is by a set of discrete particles, which are tracked in the Lagrangian framework. ANSYS Fluent, which is used also in this work (version 2019 R3), provides an implementation known as Discrete Phase Model (DPM), that is advantageous mainly due to its capability to track a single particle and record any quantity of interest associated with it. It is also capable to interact with a radiation model. However, an enormous number of microalgae cells do not allow tracking each individual one due to high computational demands. Such CFD works are rather rare and limited to just a

* Tomáš Juřena, PhD.: Institute of Process Enginering, Brno University of Technology, Technická 2896/2; 616 69, Brno; CZ, jurena@fme.vutbr.cz

** Jiří Vondál, PhD.: Institute of Process Enginering, Brno University of Technology, Technická 2896/2; 616 69, Brno; CZ

** Ing. Miroslav Rebej: Institute of Process Enginering, Brno University of Technology, Technická 2896/2; 616 69, Brno; CZ

** Assoc. Prof. Zdeněk Jegla, PhD.: Institute of Process Enginering, Brno University of Technology, Technická 2896/2; 616 69, Brno; CZ

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small sample of particles. For instance, (Sato et al., 2010) tracked the only algae cell as a passive tracer in a pipe-type PBR. The history of the distance of the cell from an illuminated surface was used to calculate a light intensity according to Beer-Lambert's law.

In majority of works on CFD modelling of PBR's, the Lagrangian approach is not employed for the representation of microalgae. Instead, microalgae cells are treated in the Eulerian framework and assumed to be homogeneously dispersed in the water continuum. The effect of growing medium on the light attenuation is taken into account by virtually increasing radiation properties of water (i.e. the absorption and scattering coefficients). However, such an approach does not offer a natural way to keep the history of the cells exposed to the light.

In this work, a method is proposed to analyze the light intensity experienced by living cells in the Eulerian framework. In order to keep track of the amount of light incident on microalgae, an additional scalar transport equation is defined and solved for the cumulative light dose to the cells at each point of the domain. This alternative to the DPM has the potential to decrease computational costs. While it does not provide for a complete history as in the Lagrangian framework, it is capable to indicate, where the living cells are concentrated, that have been exposed to equivalent light conditions on average. Results of the method are compared to those obtained with the DPM for a sample of particle tracers.

2. Computational model

2.1. Geometry

The geometry analysed by CFD modelling consists of a cuvette with accessories (for an insight into the modelled fluid domain, see Fig. 1). The inner dimensions of the cuvette volume, filled by algae growing medium, are 166 × 102 × 24 mm (height × width × depth). Suspended from the top there is an aerator U-tube, CO_2 probe and a thermometer. Their sizes are significant with respect to the domain. On the front wall of the cuvette, there is a magnetic stirrer in the form of a cylinder with hemispherical ends (50 mm long and 8 mm thick). Rotation speed of the stir bar is a control variable that belongs among the most important operating conditions. In the present case, the rotation speed is set at 360 rpm. As a source of light, Light-Emitting Diodes (LED) are used and placed on the bottom half of the back wall of the cuvette. The whole domain is discretized into approximately 220000 native polyhedral cells (minimum orthogonality of 0.55).

Fig. 1: Model of the cuvette.

2.2. Modelling techniques

For the purpose of the present work, it is not necessary to include models for all physical processes of microalgae cultivation. First, no interphase mass transfer is considered, which otherwise is indispensable for microalgae growth rate predictions. Second, modelling of air bubble flow in the cuvette is not considered either. Although air bubbles cause the incoming light to scatter, the effect diminishes, when the culture concentration exceeds 0.5 g/L, so that absorption by microalgae becomes dominant (Wheaton and Krishnamoorthy, 2012). The medium is water with homogenously dispersed microalgae. Their effect on light attenuation is taken into account by an increased absorption coefficient, which is set to the value of 10 m^{-1}. Radiation energy transfer is modelled using the non-grey Discrete Ordinates model with angular discretization of 4 × 4. Two wavelength bands are defined, one of which represents the monochromatic

light emitted by diodes (635 nm) and the other the rest of the longer wave spectra. The light source has the intensity of 36.7 W/m^2 (an equivalent to the intensity of 200 mole/(m^{2}s) of the LED).

The rotating stir bar is modelled by the Sliding Mesh technique with the rotation speed set at 360 rpm and the transient flow is solved with a time step of 0.001 s. Turbulence is modelled using *k*-ω SST model.

The method of tracking the incident light (i.e. the light dose experienced by the microalgae cells) in the Eulerian frame is based on solving a general scalar transport equation

$$\frac{\partial(\rho\phi)}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\phi - \Gamma\nabla\phi) = S_\phi. \quad (1)$$

As microalgae cells are carried by the flow throughout the domain, they are exposed to radiation from the light source. The light dose can be thought as of a quantity associated with the microalgae and transported by the flow. The light dose transport equation is generally written for the scalar

$$\phi = I_\mathrm{d}\frac{A_c}{\rho}, \quad (2)$$

which takes into account the growth of microalgae. In (2), I_d (expressed in J/m^2) is the light dose, A_c (m^2/m^3) is volumetric area of microalgae surface exposed to light and ρ (kg/m^3) is the medium density. On a short time scale (on the order of minutes at most), both A_c and ρ can safely be considered constant (so that the algae do not grow) and the whole transport equation can further be simplified to yield

$$\frac{\partial(\rho I_\mathrm{d})}{\partial t} + \nabla \cdot (\rho \boldsymbol{v} I_\mathrm{d}) = \rho \int_0^{4\pi} I_{635}\, d\Omega, \quad (3)$$

where I_{635} (W/m^2) is the incident radiation of the 635 nm light, which is obtained from the solution of radiation transfer equations (discrete ordinates). Note, that the general diffusion coefficient Γ (kg·m^{-1}s^{-1}) in Eq. (1) is set to zero as there is no mechanism to transport the light dose by diffusion. Higher-order discretization schemes are also necessary to reduce false diffusion. The equation is implemented in ANSYS Fluent by means of the so called User Defined Scalar (UDS). The light dose is initialized to zero in the whole domain and the tracking is started after the flow is developed. All equations are solved with the second order upwind scheme.

3. Results and discussion

The method is demonstrated on a couple of snapshots in Fig. 2 showing distributions of cumulative light dose (J/m^2) in time instants 25.5 s (i.e. 0,5 s after the tracking has been started) and 30 s. Note that also DPM tracers within a distance of 0.5 mm from the contour plane are visualized (the total of 1269 DPM tracers with uniform initial distribution are tracked in the cuvette volume). In the beginning, microalgae cells in the bottom half of the cuvette only are illuminated, while those in the upper half remain in the dark zone. As the fluid is stirred, a portion of illuminated algae cells is transported to the upper half, while at the same time some cells are moved from the dark zone to the light-rich zone. The cumulative light dose tends to homogenize. However, local maxima can still be seen around the stir bar indicating, that microalgae in these parts of the domain have more intensively been exposed to the light on average than in the rest of the domain.

The trend corresponds to that of the light history of microalgae tracers as simulated by DPM. However, local values deviate to a large extent from the light dose values associated with the tracers. While DPM tracers hold the true cumulative values of the light dose as these are given by the local radiation intensity only, local values of the transported scalar (i.e. the cumulative light dose) are obtained from a (numerical) solution of Eq. (3) as a balance of both the source and convection terms at each time step. The convection term, however, seems to dominate Eq. (3) at least in a part of the domain.

This is the main drawback of the method, which can clearly be demonstrated on a case with illuminated algae, after the LED's are switched off. With the absence of the source term, the gradients of the light dose are gradually smoothed out as the fluid volume gets mixed. Therefore, the light dose becomes homogeneous in the cuvette volume and the light history of microalgae gets lost. The level of homogeneity of a scalar quantity in a volume is a case-specific. For the present one, simulations suggest that the entire volume becomes well mixed in approximately 7 s after a tracer is introduced to the domain as a localized source. Therefore, further improvement of the method is necessary in order to correctly capture the light history to the microalgae cells.

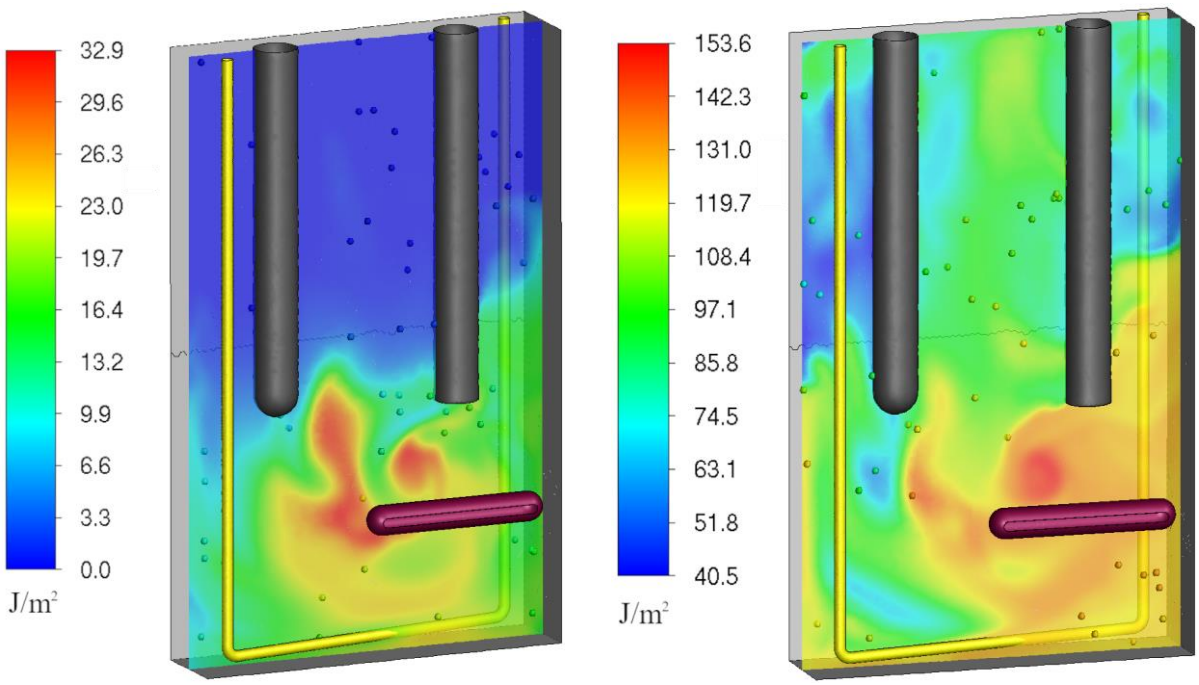

Fig. 2: Cumulative light dose distribution at time instants 25.5 s (left) and 30 s (right).

4. Conclusions

The proposed method of tracking the cumulative light dose experienced by the microalgae cells assumes, that the light dose can be thought as of a scalar quantity associated with the microalgae and transported by the flow. Results show the temporal evolution of the distribution of cumulative light dose. Local maxima can be seen around the stir bar indicating that microalgae in these parts of the domain have more intensively been exposed to the light on average than in the rest of the domain. The predicted values are also compared to the cumulative light dose obtained from the Lagrangian tracking of microalgae, which are treated as tracers. However, local values deviate to a large extent from the light dose associated with the tracers, which is attributed to the dominating effect of the convection term over the source term. Further improvement of the method is necessary in order to correctly capture the light history to the microalgae cells.

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