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Numerical analysis of the effects of air on light distribution in a bubble column photobioreactor

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ABSTRACT

Light distribution inside photobioreactors (PBR) is a crucial parameter for the determination of growth of phototropic microorganisms and reactor productivity. In order to compute the light propagation inside PBR, scattering due to the presence of microorganisms is often neglected, since it is difficult to measure experimentally and it is not trivial to handle numerically. Moreover, absorption is usually assumed constant, but it is affected by the concentration of microorganisms and the presence of gas bubbles. In the present contribution we study how the flow hydrodynamics and local gas fractions inside a bubble column PBR affect the light distribution. First, we perform numerical simulations of a bubble column flow at different gas superficial velocities. Afterwards, we use instantaneous air volume fractions to calculate the effective scattering and absorption coefficient of the mixture, as well as the effective scattering phase function. Finally, we compute the polychromatic light distribution inside the PBR by means of a Lattice-Boltzmann solver. On the one hand, we find that gas bubbles affect both spatial distribution and magnitude of the light intensity field and their impact increases at higher gas superficial velocity. On the other hand, we also observe that the biomass counteracts these effects already at concentrations less than 1 kg/m^3 so that the role of the gas phase on light fields seems to be of minor importance in PBR.

1. Introduction

Bubble column photobioreactors are common installations for the cultivation of microalgae. Their application covers a wide range of different scales, spanning from laboratory to large scale cultivation [1–5]. Thereby, illumination may occur either by sunlight or artificially, either from external or internal sources. The frequent usage of bubble columns is due to their beneficial characteristics, including simple design and low investment costs [5], easy mode of operation, possibility to cultivate under low shear conditions [6–8], as well as excellent mass transfer characteristics particularly with regard to carbon dioxide supply and oxygen removal [9,10]. Moreover, due to several applications of bubble column reactors in different industries, existing scaling laws [11,12] provide indicators regarding important and still unsolved upscaling issues, which arise for instance from the sensitivity of hydrodynamic mixing and gas-liquid mass transfer efficiency with respect to the geometric aspect ratio or pneumatic power input. Mastering these issues is a necessity for an economic feasible large scale production of microalgae biomass and intracellular metabolites.

Recently, multiphysics simulations of phototrophic cell cultivation in PBR have become more popular [13–21], since they represent a valid alternative to time consuming and costly experimental investigations. Simulations can also be coupled to mathematical optimization algorithms [22], in order to find optimal geometrical designs or process conditions (e.g. the intensity or spectrum of the light source, air mass flow) to achieve a desired process outcome such as a maximum biomass concentration. Therefore, the simulation of phototrophic cultivation processes requires a proper modeling of the physical environment inside the reactor, and/or kinetic modeling of the cells metabolic response to environmental stimuli. An example of this is the modeling of the cellular energy metabolism to predict the specific growth rate with respect to light intensity. Important physical fields that have to be determined in this context are the fluid flow field as well as the spatial distribution of light. While the latter determines the overall supply of energy for phototrophic growth, the former affects gas liquid mass

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transfer, mixing of cells and therefore, growth conditions of individual microorganisms.

However, modeling of physical phenomena in PBR is not trivial, and an adequate modeling of gas-liquid multiphase flows requires the correct determination of momentum transfer between both phases. Thereby, two-dimensional numerical simulations of bubble column flow require a significantly lower computational time compared to three-dimensional ones. Therefore, they have been extensively used to test different flow models, like for instance, the classic Euler-Euler approach [23], the Algebraic Slip Mixture Model (ASMM) [24], a modified Euler-Euler model for the liquid phase [25], according to the formulation of Zhang and Prosperetti [26,27], and the Eulerian-Lagrangian approach [28], among others. Although it is reported that they compare favorably with experiments in terms of time average gas-holdup [23], liquid velocity and turbulent kinetic energy [24], two-dimensional simulations ignore the three-dimensional nature of turbulence [29]. They are also seen to predict a frozen plume that does not oscillate, due a too high turbulent viscosity [29,30]. In addition to, they are found to be highly grid dependent [29]. Therefore, three-dimensional simulations are necessary to obtain a correct determination of the flow field, although they are computationally much more expensive. Three-dimensional simulations have been carried out for different reactor geometries, like for instance, an empty cylindrical bubble column [31], a cylinder with internal solid plates to increase the gas holdup and mixing time [32], and a square bubble column [33], among others. Comparing numerical results with the experiments of Deen and Solberg [34], Masood *et al.* [35] performed a comprehensive analysis and comparison of different turbulence closure models for the liquid phase, as well as for different drag force correlations. Additionally, they examined the influence of interphase forces such as lift, virtual mass, wall lubrication and turbulent dispersion forces on the flow field. Other researchers focus on the heterogeneous regime, considering also bubble coalescence and break-up effects. Chen *et al.* [36] carried out two-dimensional axis symmetric simulations implementing a bubble population balance equation (BPBE) together with bubble break-up and coalescence models. They reported that the BPBE improves the predictions compared to a single bubble group model in the churn-turbulent flow regime. Diaz *et al.* [37] validated their numerical results with experiments, comparing both single and multiple size group model. They concluded that at sufficiently high values of gas superficial velocity, computations with the multiple size group result in better agreement with experiments.

Concerning the modeling of light propagation, most commonly researchers choose analytic expressions, such as Beer's law [19,20,38–40], Cornet's model [41,42] or regression models to fit experimental or numerical data [15]. All of these models are one-dimensional, but they differentiate in their degree of accuracy. While Beer's law considers only the light absorbed by the cell culture, Cornet's model is based on a two-flux approximation and distinguishes between anisotropic forward and backward scattering in its advanced formulation [42]. A more detailed approach is to take the three-dimensional nature of scattering into account by solving the governing equation of light transport, which is the Radiation Transfer Equation (RTE). This approach is increasingly chosen by researchers, using different numerical methods [13,14,43–47]. However, major difficulties in the computation of light distribution are the determination of absorption and scattering characteristics of cell suspensions, emission characteristics of light sources and internal reflectivity [48]. These difficulties lie on challenging experimental measurements [49,50] and model uncertainties [50,51]. Moreover, non-uniform spectral distribution of radiation characteristics, and their temporal variation due to cell growth and photoacclimation add further complications. The situation is even more complex in cultivation systems where the radiation characteristics of suspensions are affected by the presence of a gas phase. In contrast to the extensive numbers of investigations dealing with the effects of the gas phase on liquid flow, little work was done concerning the effects of gas bubbles on light fields. Lee and Palson [52] state without experimental evidence that gas sparging increases the light penetration depth. Miron *et al.* [1] experimentally investigated light fields in a bubble column PBR and found a higher light dispersion inside the column due to reflections on gas bubble surfaces. However, the study fully neglects the presence of microalgae cells, which clearly affect the light field by absorption and scattering. More recently, Berberoglu *et al.* [45] included the effect of gas bubbles in a 1D light propagation model for a plane-parallel PBR. In their model, they considered different air volume fractions (up to approx. $0.075\,\mathrm{m}^3/\mathrm{m}^3$, not clearly specified) and relatively low biomass concentrations (up to $0.35\,\mathrm{kg}$ dry matter/m^3). They found significant backscattering of light under these conditions. Therefore, the overall amount of energy in the system increased, thus leading to higher local light intensities. However, they assume the void fraction to be randomly distributed in space so that a potential error source arises. For example, in case of dip tube spargers, the gas is expected to be concentrated in the center of the reactor. Therefore, its effect on the light distribution should be weak, since light energy is mostly absorbed near the reactor walls. In contrast to the findings of [1,45], the results of Wheaton and Krishnamoorthy [43] indicate that the presence of air bubbles has little effects on the light distribution. The authors combined a fluid-dynamical model for bubbly flows with computations of radiation transport in order to investigate the effects of micro-bubbles, air mass flow rate and algae concentration. They conclude that at higher biomass concentrations the effect of air on light distribution is weaker. However, results regarding the computed flow fields are not reported and scattering by algae is not considered although is it well established that true light intensity profiles in PBR deviate from predictions which assume a purely absorbing suspension [14,53].

With regard to the contradictory results concerning the impact of the gas phase on light distribution in air-sparged PBR, the aim of this work is to contribute with clarifying information into this debate. We hypothesize that the presence of a gas phase lowers light attenuation and therefore increases the local light intensity; however we expect the effect to become less important if the culture density increases. Although this presumption seems to be *a priori* obvious, it is not clear to what extent the increase of light availability due to the presence of a gas phase affects the specific rate of cell growth. Thus, to put it simply, the key question to be answered is whether the presence of a gas phase has to be considered for accurate predictions of cell growth or not.

To answer this question, we perform full 3D simulations of the flow field in a benchtop scale bubble column PBR, determining the local gas distributions under different operating conditions. Extending the work of McHardy *et al.* [47], we consider local scattering of light caused by gas bubbles and algae cells and investigate their effects on the polychromatic light distribution in the bubble column at different gas superficial velocities. Thereby, instead of treating the air as homogeneously distributed in the PBR [45], the spatial characteristics of bubble localization are considered. The effect of the gas phase on cell growth is examined by coupling the computed light fields to the Aiba growth model and compared to simulations which take only the presence of microalgae cells into account.

The paper is organized as follows: first, the underlying modeling approach is presented in Section 2. The calculated flow field and the corresponding spatial distribution of radiation characteristics are presented in Section 3. In addition, in this section we quantify the effects of gas superficial velocity and biomass concentration on the light fields and specific cell growth rates in the PBR. Finally, we discuss our findings with regard to prior experimental and numerical results in Section 4.