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Microscopic flows of suspensions of the green non-motile *Chlorella* micro-alga at various volume fractions: Applications to intensified photobioreactors

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ABSTRACT

An experimental study of flows of the green non-motile *Chlorella* micro-alga in a plane micro-channel is presented. Depending on the value of the cell volume fraction, three distinct flow regimes are observed. For low values of the cell volume fraction a Newtonian flow regime characterised by a Poiseuille like flow field, absence of wall slip and hydrodynamic reversibility of the flow states is observed. For intermediate values of the cell volume fraction, the flow profiles are consistent with a Poiseuille flow of a shear thinning fluid in the presence of slip at the channel's wall. For even larger cell volume fractions, a yield stress like behaviour manifested through the presence of a central solid plug is observed. Except for the Newtonian flow regime, a strong hydrodynamic irreversibility of the flow and wall slip are found. The calculation of the wall shear rate and wall stress based on the measured flow fields allows one to identify the mechanisms of wall slip observed in the shear thinning and yield stress regimes.

1. Introduction

Micro-algae are a large and biologically diverse group of aquatic microorganisms with a relatively simple unicellular structure that can be found in various environments ranging from freshwater for some species to sea water for others. Most micro-algae species are photoautotrophic which means they convert solar energy into chemical forms through photosynthesis.

During the past several decades the micro-algae have received a considerable amount of interest due to their potential use in several key industries related to food, cosmetics and *"green"* energy. From an economical perspective their most appealing application is undoubtedly that as a potential feedstock for the biofuel production. This is because micro-algae may generally produce polysaccharides (sugars) and triacylglycerides (fats) which are the raw materials for producing bioethanol and biodiesel fuels. Whether the micro-algae can make it as a viable *"green"* energy alternative in the near future is an intricate matter of both economic and energetic efficiency [1].

Among a variety of species of micro-algae, *Chlorella vulgaris (CCAP 211–19)* is a good candidate for the large scale production of biofuels and, for this reason, it has been intensively studied [2–5]. It is a non-motile alga (it has no flagellum) with an average diameter of roughly 4 μm. Its membrane is quite rigid due to the presence of chitin-like glycan in the cell wall, [6]. Thus, the *Chlorella* micro-alga can sustain relatively high hydrodynamic stresses without any cellular damage [7].

There currently exist two main technologies for the cultivation of the micro-algae: *raceway pond* systems and *photobioreactors* (PBRs). A typical raceway pond is a closed and shallow (with depth varying from 0.2 m to 0.5 m) loop, open to the air. The large open surface allows an optimal exposure to light but it may also favour the formation of superficial films. In PBRs the culture medium is enclosed in a container with optically transparent walls and the micro-algal suspension is circulated from a central reservoir. Thus, the PBR systems allow for a better control culture environment but, in turn, are getting more expensive than the traditional raceway pond systems. In addition to that, the energy consumption may also be higher than in the case of the raceway ponds ([1,8–10].

However, due to a high degree of control of the culture conditions, the intensified PBR technology allows a higher productivity. With an appropriate engineering and operating protocol, a high

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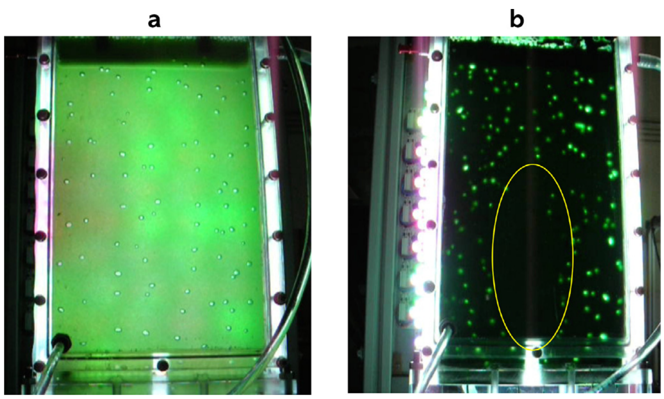

Fig. 1. Images of gas bubbles raising within a flat panel PBR filled with a suspension of *Chlorella* microalaga at two different concentrations: **(a)** $C_x \approx 0.5$ g/l **(b)** $C_x \approx 5$ g/l. The closed curve in panel (b) highlights a dead flow zone. The animated versions of the pictures are available online as a supplemental material.

cell density culture (biomass concentration) can be obtained. Hydrodynamics is one of the key aspects when working in high cell density culture. High cell density cultures are indeed obtained in systems having a very high ratio between the illuminated surface and the culture volume, which translates into a shallow depth, typically smaller than 0.01 m [11,12,13]. The high degree of geometric confinement combined with a high biomass concentration typically leads to a decrease of the mixing performances which can have several negative impacts on the process: a decrease of the efficiency of the mass transfer (mixing), an increase in the risk of biofilm formation and an overall less efficient light conversion in the systems due to smaller displacement of flowing cells along the light gradient in the culture volume. In this context, optimising the hydrodynamic conditions is of paramount practical importance.

A comprehensive review of the progress in the theoretical/numerical work dealing with the optimisation of the hydrodynamic conditions in intensified PBRs has been recently presented in [14]. As most flows in intensified PBRs are characterised by a large Reynolds numbers (*Re*), a first difficulty encountered in the CFD studies of flows in PBRs is related to the proper choice of a turbulence model. Many authors chose the $k-\epsilon$ model which is implemented in commercially available CFD software packages such as FLUENT or Comsol Multiphysics [15,16].

The numerical studies of flows of micro-algae suspensions in PBRs may be challenging even at low *Re* (i.e. no inertial nonlinearity in the momentum equation), however. Whereas a dilute micro-algae suspension may be well approximated by a Newtonian fluid characterised by a linear stress-rate of strain relationship, semi-dilute and concentrated suspensions which are relevant to many industrial processes [17] are characterised by a strongly nonlinear constitutive relationship.

To better understand the impact of the rheological properties of the micro-algae suspensions on their flow behaviour we illustrate in Fig. 1 two photographs of a flat panel PBR containing a dilute (left panel) and a concentrated (right panel) suspension of the *Chlorella* micro-alga being stirred by injection of gas bubbles from the bottom.

The dimensions (height, width, depth) of the PBR illustrated in Fig. 1 are 25 cm × 15 cm × 7 mm. The PBRs are illuminated from behind by a LED panel. The animated version of each snapshot is available online as a supplemental material. The stirring flow is generated by controlled injection of gas bubbles through orifices machined within the bottom plate of the container at equidistant locations. Due to their large buoyancy, the evenly injected gas bubbles raise and create local mixing which allows an optimal exposure of the micro-algae to the illuminated regions of the PBR located in the proximity of the optically transparent walls. In the case of the dilute suspension ($C_x \approx 0.5$ g/l), the gas bubbles raise at locations which are more or less evenly distributed along the horizontal direction although their trajectories are not perfectly linear but show some oscillatory (swirling) behaviour (see the Supplemental material).

A fundamentally different motion of the gas bubbles is observed in the case of the concentrated solution ($C_x \approx 5$ g/l) in the form of a dead flow zone located around the central part of the PBR. As the gas bubbles are uniformly injected through the bottom plate of the PBR through equidistant orifices, the sole interpretation of this observation is that the rheological behaviour of the suspension is spatially non-uniform (along the horizontal direction) and strongly non Newtonian (with a larger apparent viscosity) around the central part of the PBR. This very simple experimental observation performed in conditions which are relevant to the intensified PBR technology indicates that in a range of large micro-algae concentrations (which is the range of practical interest) both the rheology and the hydrodynamics significantly depart from the Newtonian behaviour.

To our best knowledge, there exist only few previous studies of the rheological properties of suspensions of *Chlorella* micro-alga. The rheological study by Wu and his coworker indicates that as the volume fraction is increased the rheological behaviour of suspensions of *Chlorella pyrenoidosa* micro-alga changes from Newtonian like to non-Newtonian [18]. A more recent study of the rheological behaviour of suspensions of *Chlorella vulgaris* with volume fractions spanning a wide range was reported in [19].

In the context of the intensified PBRs, however, the relevance of rheometric flows is somewhat hard to define. The present study concerns with a systematic characterisation of flows of suspensions of *Chlorella vulgaris* in a plane micro-channel. As the actual tendency is to decrease the characteristic size of intensified PBRs down to a millimetre scale, we believe that a microscopic flow investigation would bring valuable insights that could contribute to an optimised designed of the PBRs. The central aim of this study is to provide a systematic description of the microscopic flow behaviour in a wide range of cell volume fractions and correlate the results with the rheological properties of the suspensions. The paper is organised as follows:

The experimental setup, the experimental methods and the preparation of the micro-algae suspensions are detailed in Section 2. The experimental results are presented in Section 3. A brief reminder of the rheological properties of *Chlorella* suspensions at various volume fractions is presented in Section 3.1. A systematic description of the microscopic flows is presented in Section 3.2. The paper closes with a brief discussion of the main findings and their possible impact on the design of hydrodynamic optimisation of the intensified PBRs, Section 4.

2. Experimental setup and methods

2.1. Microscopic flow control and investigation

The experimental setup is schematically illustrated in Fig. 2(a). Our experiments have been conducted in a borosilicate glass made micro-channel (from Micronit, Holland) with a rectangular cross section. The width of the micro channel is $W = 150\,\mu$m its depth is $H = 50\,\mu$m and its length is $L = 4$ cm. The corresponding hydraulic diameter is $D_h = 2WH(W+H)^{-1} = 75\,\mu$m. Based on the hydraulic diameter one can estimate the Reynolds number as $Re = \rho U D_h/\eta$ where U denotes the velocity scale and η the viscosity scale. All the experiments discussed herein have been conducted at very low Reynolds numbers, $Re < 2.2 \times 10^{-2}$. The suspensions feeding the micro-channel and collected at the outlet were held in plastic containers rigidly mounted on vertical rails. Each experimental