26th International Conference
ENGINEERING MECHANICS 2020
Brno, Czech Republic, November 24 – 25, 2020

EVALUATION OF DIFFERENT DRAG MODELS FOR SIMULATIONS OF A BUBBLY FLOW IN A FLAT-PANEL PHOTOBIOREACTOR

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Abstract: *The presented paper provides an introduction into the research of the fluid dynamics of a flat-panel photobioreactor. The scope of the paper deals with the setup of the baseline two-phase hydrodynamic model. The photobioreactor is modelled using the computational fluid dynamics software with the eulerian multiphase model. The assessment of the photobioreactor includes a comparison of three drag models: Grace, Tomiyama, and Ishii-Zuber. All three models are expected to be suitable for bubbles of various sizes and shapes. However, the results show that there are some differences in predictions of the gas hold-up and velocities.*

Keywords: Photobioreactor, Multiphase, Fluid flow, Drag.

1. Introduction

The utilization of flue gases from waste incineration plants in algal biotechnology is an attractive plan for the reduction of CO_2 emissions. However, for an effective application of such technology, all aspects of microalgae cultivation must be understood. Therefore, small-scale photobioreactors for the cultivation of various species of microalgae are beneficial for characterization of the growth parameters. Subsequently, such characterization can later serve in more effective design and scale-up of photobioreactors where biomass is produced in commercially feasible amounts.

For comprehensive modelling of biomass production, it is necessary to approach all sub-models. This includes a multiphase flow model, a mass transfer model, a radiation model, and an algae growth model (Gao et al., 2018). In addition to that, all sub-models need to be coupled with respect to the information they provide about physical, chemical and biological phenomena.

This paper deals with the hydrodynamic sub-model that is based on discretized Navier-Stokes equations solved in the ANSYS Fluent, a computational fluid dynamics (CFD) software. The hydrodynamic sub-model also forms a base for implementation of subsequent models. Therefore, in order to have a reliable and numerically stable complete model for biomass production, it is necessary to properly set-up this multiphase flow model.

The paper presents different drag models that are important in the modelling of phase interaction and discusses their suitability for the application of interest. The hydrodynamic model used in this work is, therefore, a baseline multiphase model that will be further elaborated with the inclusion of other relevant phenomena, e.g. turbulence, lift force or wall lubrication.

2. Mathematical model

The flow inside a photobioreactor is always composed of a mixture of phases. The vessel is primarily filled with a liquid, water, that serves as an environment for living cells, usually modelled as solids. In addition

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doi: 10.21495/5896-3-432

to that, a gaseous phase, air or CO_2, flows through that mixture.

The studied photobioreactor is a flat-panel stirred vessel with volume of approx. 400 ml. The gas is delivered via 4 gas-inlet ports at the bottom of the aerator tube with a diameter of 0.7 mm. Agitation of the mixture is done with the stirrer in the lower corner of the vessel. The rotational speed of the motor that powers the stirrer can be controlled up to 600 RPM. However, for the purposes of this paper, the stirrer is stationary. The illustration of the photobioreactor is shown in Fig. 1. Other technical details about the vessel can be found in (Nedbal et al., 2008).

Fig. 1: Photobioreactor of the interest (Photon Systems Instruments 2020).

Fluid dynamics simulations of the gas-liquid system are performed within the full Eulerian-Eulerian multiphase modelling framework. All phases combined form interpenetrating continua where the amount of each phase is determined by the volume fraction α. The framework uses a single pressure field that is shared among all phases. Momentum equations are calculated for the continuous and each of dispersed phases separately. The presented model of the photobioreactor uses water as the primary phase and CO_2 as the secondary phase. The continuity and momentum equations for a fluid phase q are as follows:

$$\frac{1}{\rho_{rq}}\left(\frac{\partial}{\partial t}\left(\alpha_q\rho_q\right) + \nabla\cdot\left(\alpha_q\rho_q\vec{v}_q\right)\right) = 0 \quad (1)$$

$$\frac{\partial}{\partial t}\left(\alpha_q\rho_q\vec{v}_q\right) + \nabla\cdot\left(\alpha_q\rho_q\vec{v}_q\vec{v}_q\right) = -\alpha_q\nabla p + \nabla\cdot\bar{\bar{\tau}}_q + \alpha_q\rho_q\vec{g} + \sum_{p=1}^{n}\left(K_{pq}\left(\vec{v}_p - \vec{v}_q\right)\right) + \sum\vec{F} \quad (2)$$

Where the right-hand side of the (2) covers the pressure gradient, viscous stress, gravity, interphase momentum exchange, and the sum of interfacial forces between the gaseous and liquid phase. The sum of interfacial forces may include a lift force, a virtual mass force, or a wall lubrication force. For the purpose of this paper, these external forces are neglected.

Bubbles are modelled as spheres with an algebraic relationship connecting a bubble diameter, d_p, and the interfacial area density A_i. The interfacial area density and the exchange coefficient, K_{pq}, for bubbly flows is defined as:

$$A_i = \frac{6\alpha_p}{d_p} \quad (3)$$

$$K_{pq} = \frac{\rho_p}{6\tau_p} d_p A_i \frac{C_D Re}{24} \quad (4)$$

Where bubble size, d_p, is set to 3.5 mm, and the drag coefficient, C_D, depends on a selected drag model. The bubble size was chosen based on the observation of bubbly flow in a real photobioreactor. Drag models considered in this paper were selected regarding their suitability for bubbly flows where bubbles can have various shapes and sizes. They are Grace (Grace et al., 1976), Tomiyama (Tomiyama, 1998), and Ishii-Zuber (Ishii and Zuber, 1979).

3. Numerical model

The geometry was meshed with polyhedral cells with an edge size of 1 mm, resulting in approx. 1M cells. The transient, double-precision, pressure-based solver was used for simulation of bubbly flow in the photobioreactor. As for the initialization of tasks, the reactor was filled with water with zero-velocity fields. The moment simulations started was the moment the gaseous phase started to be injected into the vessel. The numerical model uses the eulerian multiphase model with 2 phases. Since no agitation was employed, there was no turbulence model considered.

The boundary condition at the inlet was set to the mass flow rate of CO_2 to 5.9593e-6 kg/s, i.e. 200 ml/min. The degassing boundary condition was set at the top of the reactor. As for other walls, the no-slip condition was applied for the primary phase and the free-slip condition was applied for the secondary, gaseous, phase.

To capture the phase interface, the Modified HRIC spatial discretization scheme for volume fraction was employed. Pressure discretization is performed with the PRESTO! scheme. The solution convergence was evaluated based on the levels of residuals and the amount of CO_2 inside the photobioreactor. A converged solution at a time step was considered when levels of absolute, locally scaled, residuals were below 1e-4.

4. Results and conclusion

Numerical simulations were performed for the three aforementioned drag models. All analyses have a time span of 5 s with the time step size of 1e-4 s. The progress of analysis was monitored with reporting of velocity magnitudes, pressure, and volume fractions from points distributed across the vessel, reporting of mass flow rate through the degassing boundary, and reporting of the total mass of CO_2 in the vessel.

Following plots show the velocity magnitudes of water at selected points (Figs. 2 and 3), and total amount of CO_2 retained inside the photobioreactor (Fig. 4).

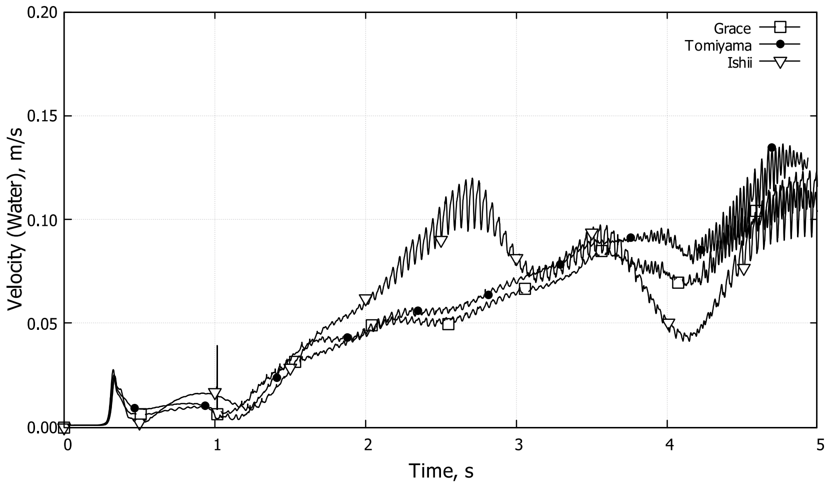

Fig. 2: Velocity magnitudes of water at half the height of the vessel.

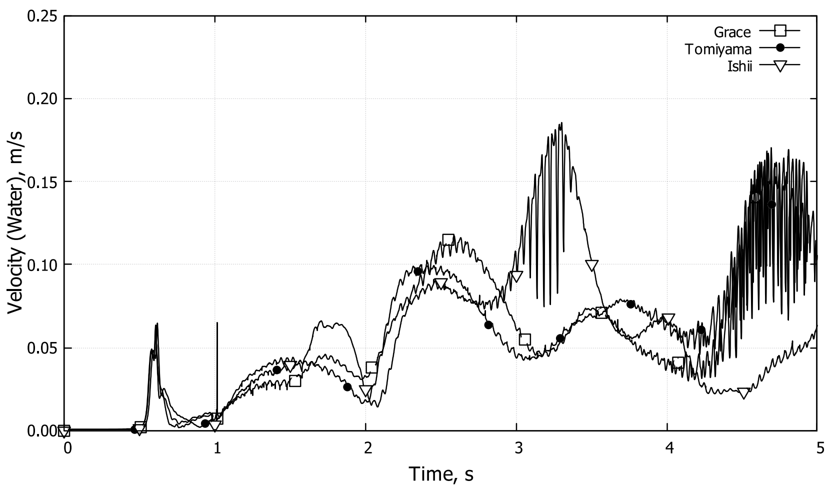

Fig. 3: Velocity magnitudes of water at 2/3 of the vessel's height.

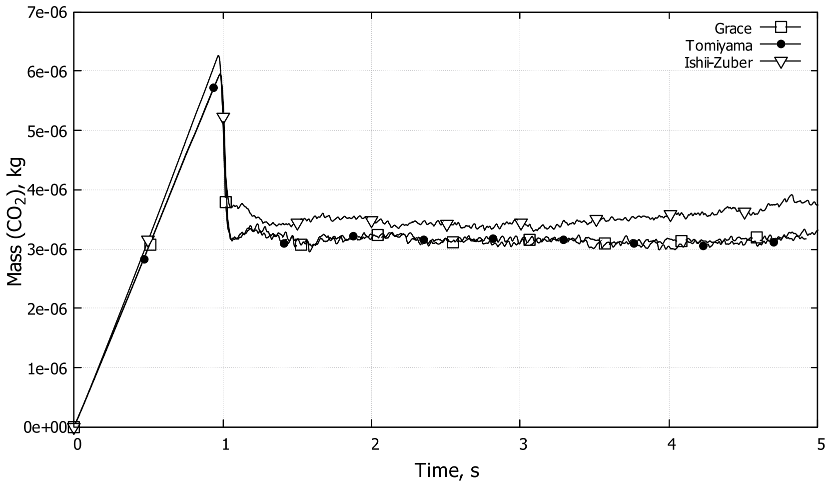

Fig. 4: Gas hold-up.

The Grace and the Tomiyama models show similar velocity profiles for water. The Ishii-Zuber model, however, shows at some places a different trend. Also, its reported values oscillate. Similarly, the Grace and the Tomiyama models show similar results for the gas hold-up. Stabilizing at the approx. 3.2e-6 kg of CO_2. While the Ishii-Zuber model predicts a higher value, close to 4e-6 kg of CO_2. All drag models, however, predict that it takes 1 s to reach the stabilized state.

Acknowledgement

This research was supported by the EU project Strategic Partnership for Environmental Technologies and Energy Production, funded as project No. CZ.02.1.01/0.0/0.0/16_026/0008413 by Czech Republic Operational Programme Research, Development and Education, Priority Axis 1: Strengthening capacity for high-quality research.

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