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Hydrodynamic sloshing of microalgae in membrane type photobioreactor

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Abstract. The tropical climate, wide diversity of microalgae species, long coastline, abundant sources of agriculture effluent, and active phycology research are key factors that drives Malaysia to be highly competitive in the global microalgae market. Microalgae are vital in a variety of applications such as: biofuel, health foods, agricultural feeds and chemical extractions. However, mass cultivation of microalgae is still not cost effective in Malaysia due to huge energy consumption Therefore, cultivation of microalgae that utilizes wide ocean space and wave energy for mixing has gained interest since it has considerably lower production cost. Nonetheless, the effects of ocean wave-induced sloshing in terms of its efficiency of mixing have not been fully researched. Thus, this study has been conducted to investigate the effects of sloshing hydrodynamics in microalgae cultivation by studying the interactions of sloshing hydrodynamics and mixing efficiency inside a floating photobioreactor. A membrane type photobioreactor has been used to slosh microalgae culture on its free surface. The result of mixing efficiency for suspended solid particles in liquid is the main concern. Experiments in unidirectional excitation proven that mixing rate of solid-liquid medium is dependent on the excitation amplitude, excitation frequency and filling ratio, where mixing rate is highest at 30% filling ratio with increasing excitation amplitude and excitation frequency. With deeper comprehension on the interaction effects of sloshing hydrodynamics and mixing efficiency, upscaling of novel microalgae cultivation method in industrial size can be expected.

Keywords: Microalgae cultivation, sloshing, mixing, hydrodynamics

1. Introduction

Microalgae are known for their wide application in various industries, such as biofuels, aquaculture feeds, health foods and high-value bioactive compounds for the pharmaceutical industry [1]. Open ponds provide a cheap cultivation system to compensate for the low productivity of microalgae. The goal to improve productivity of microalgae and cultivation of wider variety of microalgae species has led to the design of closed controlled system for the cultivation of algae, which are known as photobioreactors. Nonetheless, high cultivation costs of photobioreactors have been the major barrier for its commercialization. Biofuel production facilities in Texas and Hawaii require an annual lease of $6.50/ac-year and $15/ac-year, respectively [2]. Cultivation cost contributes 30% to 40% of the total production cost [3].

By utilizing ocean waves to induce mixing in the floating photobioreactor, lower cost is expected to be achieved. However, effects of ocean-wave induced sloshing on the efficiency of mixing have not been fully researched. Thus, this experimental study has been conducted to investigate the interaction effects of regular excited sloshing hydrodynamics and mixing efficiency. The investigation covered determines the relationship between sloshing parameters, such as oscillating frequency, oscillating amplitude, and filling ratio on mixing efficiency.

2. Mixing of microalgae in cultivation

Mixing is a key parameter in the cultivation of microalgae [4]. Mixing distributes the nutrients, pH, temperature and dissolved carbon dioxide in more uniform flows [5], which also prevents appearance of dead zones, cell accumulation and attachment to the walls of photobioreactors [6]. Mixing also promotes redistribution of light intensity, by improving light/dark cycles [7]. However, in excess, mixing may lead to cell damage due to high shear stress. Studies to improve mixing focuses on land-based photobioreactors through bubble columns, airlifts, and installation of static mixers or baffles. Installation of static mixer in the tubular PBR, can yield 37.26% higher biomass productivity with induced swirling flow in the tubes with increase of inlet velocity [8]. Improving productivity through installation of baffles or mixers and optimization of flow could not significantly reduce the energy consumption of mixing devices.

2.1 Hydrodynamic sloshing

Hydrodynamic sloshing has been identified to be capable of enhancing mixing and mass transfer, by influencing the kinematic of free-surface and flow instabilities [9]. The back and forth movement in the form of splashing surface waves under periodic excitations in rotational and translational directions is crucial in fluid-structure interaction phenomenon [10]. Studies on the impacts of sloshing on mixing had been conducted for determining the thermodynamic response of methane liquid tanks, as mixing through the motion of sloshing can be utilized to achieve a faster thermal equilibrium [11]. Effects of mixing due to sloshing have also been investigated extensively in tanks containing cryogenic fuel, where the fluctuations of external forces (irregular forces) led to severe impacts due to the accumulated sloshing kinetic energy, resulting in obvious fluid mixings and fluctuations [12].

2.2 Floating Photobioreactor

Despite various studies on the effects of sloshing on mixing in terms of thermodynamics and impact forces, studies related to the effects of sloshing on mixing in photobioreactors are limited. A project by NASA focused on employing semi-permeable membranes containing microalgae that can utilize the ocean surroundings for infrastructural support, temperature regulation, nutrient supply and dewatering actions [13]. Other floating photobioreactor designs are tubular systems placed on the water surface with gas exchange and harvesting columns to control gas exchange [14], plastic bag PBR [15], and horizontal floating photobioreactor that combines raceway pond and airlift PBR [16]. Only a few studies investigated the relationship between sloshing and mixing effects, such as utilizing rocking cycle to study mixing and mass transfer [15] and development of vortices due to horizontal in sloshing tanks [17]. In conclusion, the relationship between sloshing parameters on the effects of mixing efficiency are still unknown.

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3. Experimental setup for sloshed wave-induced mixing in photobioreactor

An experiment was conducted to investigate the effects of sloshing on mixing efficiency by simulation of a photobioreactor model. The experimental setup is illustrated in Figure 1. The dimension of the PBR model was 30.5cm × 22.5cm × 16cm, with a capacity of 10 litres made from polytetrafluoroethylene (PTFE) acrylic sheets. Two analogue water turbidity sensors were installed on the PBR: one at the side and one in the middle part of the PBR, as shown in Figure 1. The measurement range was from 0% to 3.5% of total suspended solid (TSS) in the water with analogue output from 0 to 4.5V.

DC linear actuator was utilized to generate unidirectional excitation to the PBR and to simulate the conditions when a floating PBR is subjected to the excitation of ocean wave. The DC linear actuator consisted of four main components: a belt driven linear actuator (model: EGC-70-1000-TB-KF-OH-GK), a DC motor (mode: 8DCG24-40-30) powered by a 12V power supply, a rotary encoder (model: 1202B15115.20) to measure the displacement, and an Arduino UNO board with proportional integral (PI) controller to control the motion of the linear actuator. A camera was used to capture the sloshing motion inside the model tank at a frame rate of 25 frames per second (fps) and with pixel resolution of 1280 x 720.

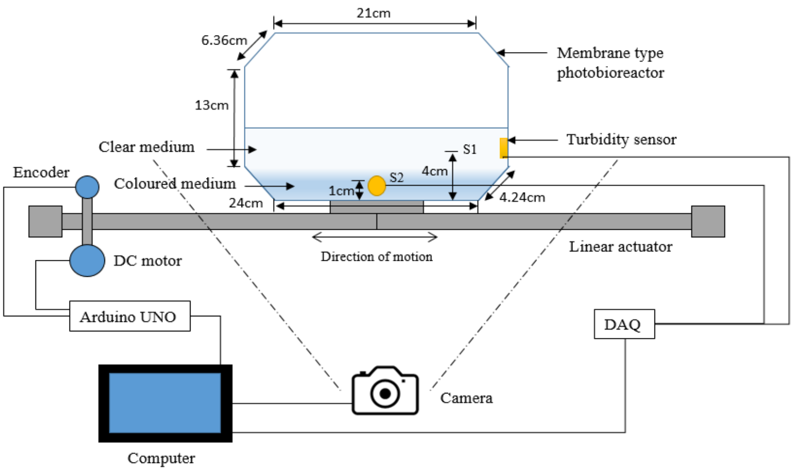

Figure 1. Experimental setup of membrane type photobioreactor

3.1 Turbidity sensor calibration

Turbidity sensors are commonly used for the measurement of microalgae, as algae are organic substances that suspend in the water due to the water flow. The turbidity sensors are calibrated by manipulating the ratio between the mass of solid and volume of water in the mixture. The relationship between turbidity and TSS is a linear relationship [18]. For this experiment, standard solutions of known TSS were produced by dissolving known quantities of solid particulates into the solvent, where tap water at room temperature was assumed to be with 0% TSS for the calibration process. Light intensity was kept constant at 150 lux, while the amount of colour dye used was made the same at 0.25ml (5 drops) throughout the experiment.

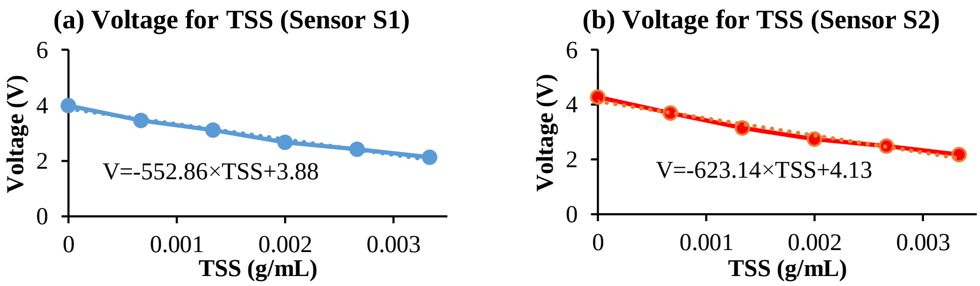

Figure 2. (a) voltage for TSS of sensor S1; (b) voltage for TSS of sensor S2

The calibration curves of the turbidity sensors (labelled as S1 and S2, respectively), for the relationship between TSS and voltage output, are illustrated in Figure 2. Within the range observed in the experiment conducted in this paper, it followed 0 to 3×10^{-3} TSS, whereby the voltage output decreased linearly with respect to TSS, as shown in Figures 2(a) and (b) for turbidity sensor S1 and S2, respectively.

4. Sloshing effects to mixing efficiency in photobioreactor

4.1 Sloshing amplitude

The results of sloshing effects on the mixing efficiency under filling ratio γ=30% of membrane type photobioreactor are shown in Figure 3 and Figure 4. The mixing efficiency was found to increase as the amplitude of the sinusoidal excitation was increased. The estimated mixing time for excitation amplitude, A=1cm could not be determined, as the mixture was not well mixed compared to the mixing time of 45s for A=2cm and 22s for A=3cm. As shown in Figure 3(a), the voltage measured for A=1cm for the time concerned remained almost stationary without much changes in the turbidity, indicating a low mixing efficiency. As shown in Figure 3(b) and Figure 3(c), there was an obvious decrease in the voltage measured, implying that the mixing of the solid powder and clear water formed a uniform suspension (constant measurement of TSS). As the amplitude of the regular excitation force was increased, the mixing efficiency increased as the mixing time to reach a new equilibrium of multiphase medium decreased.

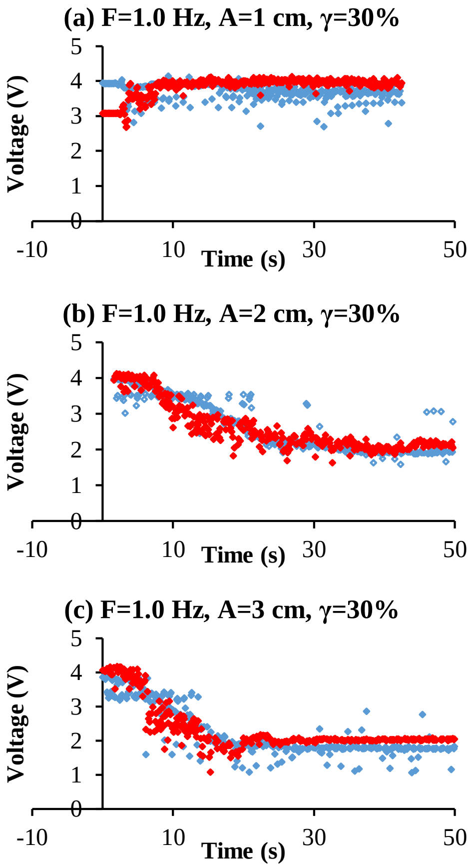

Figure 3. Sensitivity of excitation amplitude, A to mixing time of multiphase mediums with filling ratio γ=30%, (a) A=1cm; (b) A=2cm; (c) A=3cm (blue dots indicate sensor S1, red dots indicate sensor S2)

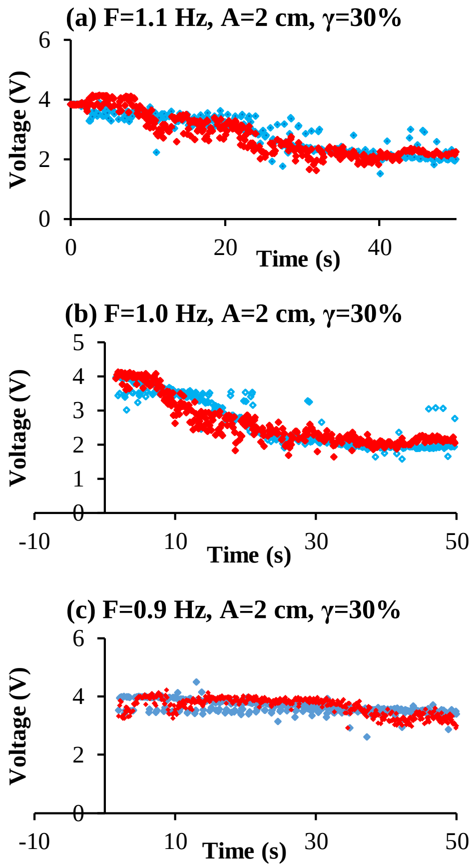

Figure 4. Sensitivity of excitation frequency, F to mixing time of multiphase mediums with filling ratio γ=30%, (a) F=1.1Hz; (b) F=1.0Hz; (c) F=0.9Hz. (blue dots indicate sensor S1, red dots indicate sensor S2)

4.2 Sloshing frequency

The mixing efficiency increased as the excitation frequency was increased albeit with the same excitation amplitude, as the displacement of the PBR model became faster. From the comparison of Figure 4(a) and Figure 4(c), it was evident that as the sloshing frequency was reduced, the mixing of the solid particles and water became less pronounced (high voltage value). At lower frequency F=0.9Hz, the same distance of A=2cm was moved at a lower speed, for comparison with higher frequency (F=1.0Hz and F=1.1Hz). Movement of water particles inside the PBR model at low excitation frequency also tended to move slower, resulting in reduction of mixing efficiency. For the excitation amplitude A= 2 cm, the mixing rates at 0.9Hz, 1.0Hz and 1.1Hz took $0.03s^{-1}$, $0.04s^{-1}$, and $0.01s^{-1}$, respectively. Although the frequency was increased, the mixing efficiency decreased. The mixing rate was found to be best at 1.0Hz, which is close to the natural frequency for the filling ratio γ=30%.

4.3 Filling ratio

Figure 5 shows that the mixing effects became less intense with the increase of filling ratio γ. In the case of filling ratio γ=30%, the voltage decreased as a heterogenous suspension of solid particles and liquid medium was formed with the increased of distribution of total suspended solids in the liquid medium. For filling ratio γ=50%, only slight mixing was observed, whereas mixing effects were not significant for filling ratio γ=70%.

The mixing effects of the substitute of microalgae culture in the PBR model were found to be influenced by the severity of its sloshing motion and the accompanying dynamic, which depended on the excitation amplitude A, excitation frequency F, and filling ratio γ [19]. Nonlinearity of sloshing flows was observed dominant at lower filling ratios, γ=30% for instance, resulting in hydraulic jump and hydro-spray formation. At higher filling ratios, sloshing was characterized by the formation of large amplitude standing waves, which did not result in much mixing effects. Although better efficiency was seen for larger amplitudes and higher frequency, other parameters should be considered, such as the light/dark cycles and shear stress tolerance of different microalgae species. Despite the limitation of the linear regular excitation motion, this study has provided insightful results of the mixing efficiency in membrane PBR under sloshing motion.

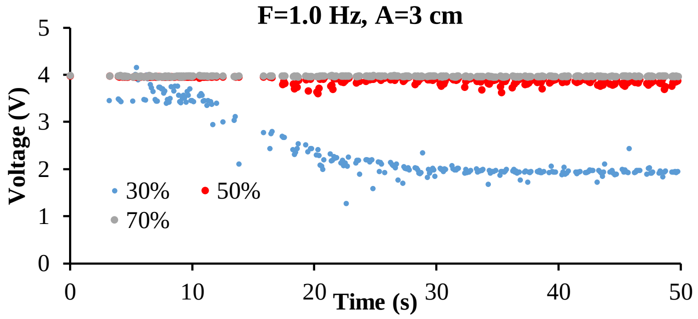

Figure 5. Filling ratio and mixing efficiency for sensor S1 at excitation frequency F=1.0Hz and excitation amplitude A=3cm

5. Conclusion

This experimental study has shown that the mixing efficiency of floating photobioreactor, by utilization of wave-energy for sloshing, is dependent on excitation amplitude, excitation frequency and filling ratio of PBR. Mixing rate is highest at 30% filling ratio with maximum excitation amplitude and excitation frequency which is close to the natural frequency of the PBR. Further studies should be conducted to study the mixing efficiency and hydrodynamic characteristics of wave-induced sloshing before implementation to floating photobioreactors.

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