Design of a Stacked-layer Tubular Photobioreactor for Microalgae Cultivation

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Abstract
A tubular photobioreactor is one of the most effective methods of microalgae cultivation because of the high solar receiver area and better biomass productivity. However, the pressure drop along the tubular solar receiver induces a relatively high dead zone. An optimal design is necessary to maximize biomass productivity. In this article, the proposed model can reduce the dead zone by up to 15% under a pressure drop of 106 Pa. To optimize the area requirement, three configurations with different stacking angles of 30, 45, and 60°, are simulated. The optimal 60° stacked-layer model is then connected to an airlift device to demonstrate the complete system. This model can circulate seawater inside the reactor at an average velocity of 0.188 m/s with 0.07 m/s of air inlet velocity. The radial flow can force the microalgae from the inner part of the tube to the outer part and back again throughout the entire stacked section. This turbulence will enhance biomass productivity because the microalgae are moved from the darker interior of the tube to the periphery where they are exposed to solar radiation. The optimal stacked-layer tubular photobioreactor has a slope of 60° with four stacked layers. This modification promotes the circulation of microalgae in both axial and radial directions.

Keywords: Computational fluid dynamics (CFD), Microalgae cultivation, Stacked tubular photobioreactor

1 Introduction

Algae are used by humans in many ways: as a food source, for water treatment, and as an indicator to study environmental change. Microalgae are also used commercially in pharmaceuticals and cosmetics, and for aquaculture purposes [1]. In addition, microalgae have been demonstrated to be a source of biodiesel, a fuel which can potentially replace the less environmentally friendly petroleum diesel. Moreover, microalgae consume carbon dioxide (CO_2) as a carbon source. Thus, biodiesel production from microalgae will not contribute to global warming by excessive release of CO_2 [2]–[4]. Therefore, designing efficient

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microalgae cultivation systems is an area of ongoing research. There are two types of algae cultivation systems: open and closed. The common open system includes large ponds, tanks, circular ponds and raceway ponds. However, their limitations include a large area requirement, high evaporative losses, greater risk of contamination, and inefficient light utilization by algal cells [2], [5], [6]. A tubular photobioreactor, as a closed system, can promote better control of the culture environment, including carbon dioxide supply, evaporation loss, microbial contamination, and land use. The ideal tubular photobioreactor design should be able to efficiently collect solar radiation in a compact land area, while minimizing the pressure drop and the dead zone [7]–[12]. This study focuses on the design of a tubular photobioreactor to reduce pressure drop, dead zone and area demand, while preserving the turbulent flow. The flow behavior inside the tubular photobioreactor is simulated by a computational fluid dynamics (CFD) method, which serves as an efficient tool to fulfill the objectives of the experiment [13], [14].

2 Methodology

The conventional model of a tubular photobioreactor is assessed in order to determine the velocity profile of microalgae and water, the dead zone formation, the pressure drop along the solar receiver, and the area requirement. The length of the tubular photobioreactor is limited by the oxygen concentration. At the lowest flow velocity of 0.17 m/s, the tubular photobioreactor should not exceed 80 m because at this length the dissolved oxygen concentration peaks at 300% of air saturation [9]. Therefore, the length of the basic model of a tubular photobioreactor in this study is appoximately 40 m, which is sufficient for the purposed performance and the acceptable oxygen concentration. This basic model consists of a single-layer solar receiver loop with a diameter of 0.1 m and length of 10 m, with a radius of curvature of the U-bend of 0.35 m and horizontal spacing of 0.1 m. Figure 1 depicts the three U-bends and four straight tubes.

A two-phases model of seawater and microalgae cells is simulated in this study. The cell density of microalgae is approximately 100 × 10^6 cells/ml, with cell diameter of 10 µm [15]. Hence, the volume fraction of microalgae would be 0.05 and the density

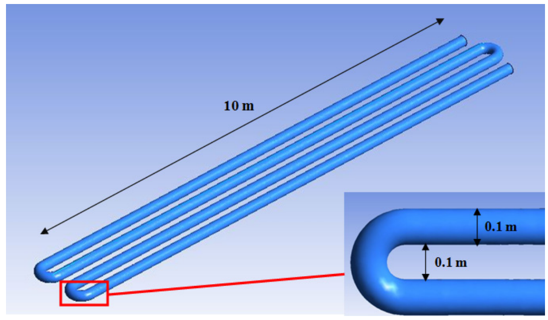

Figure 1: Basic model tubular photobioreactor with 3 U-bends.

of seawater is 1,020 kg/m^3 [16]. The density of microalgae is approximately 1,300 kg/m^3. A Eulerian multiphase model is selected to treat the microalgae cells as continuous phase. The viscosity of seawater and microalgae can then be assumed as 1.003 × 10^{-3} kg/(ms). Two boundary conditions are used in the simulation: inlet and outlet boundaries. At the inlet boundary, the flow velocity of water and microalgae phase is 0.17 m/s. The volume fraction of microalgae at the inlet is 0.05, which is assumed to be the inside concentration. At the outlet boundary, the pressure is set at atmospheric pressure.

The bend configuration of each is modified by increasing the curvature radius, the angle of curvature and the spacing between adjacent tubes to 0.35 m, 210°, and 0.4 m ; respectively. This modification aims to reduce the dead zone formation and the pressure drop along the tubular photobioreactor.

Next, the modified model is stacked up to four layers. Three models are simulated, with various slopes relative to the horizontal plane: 30, 45 and 60°, as shown in Figure 2. The length of each straight tube can be decreased in order to reduce the area requirement.

Finally, the simulation results of 30, 45 and 60° tubular photobioreactors are compared in order to determine the minimum pressure drop and area requirement. Then the optimal model is attached to an airlift device to establish a complete system. As shown in Figure 3, the airlift system consists of three parts: the riser, the gas separator and the downcomer. The riser is a vertical tube with a diameter of 0.1 m (the same as the solar receiver), and the height is 2 m. The width and length of the gas separator are 0.1 m and 0.9 m, respectively [17], [18].

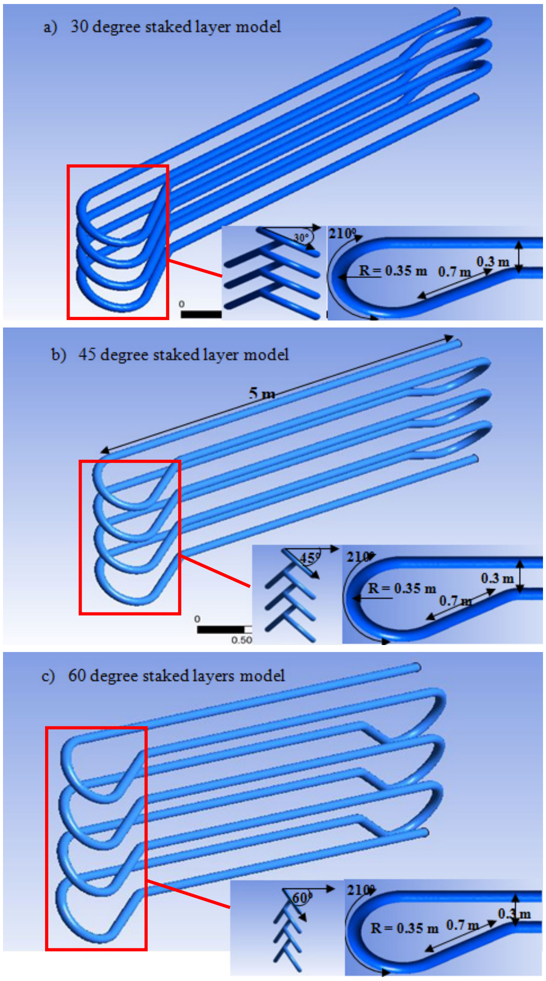

Figure 2: Stacked-layer tubular photobioreactors.

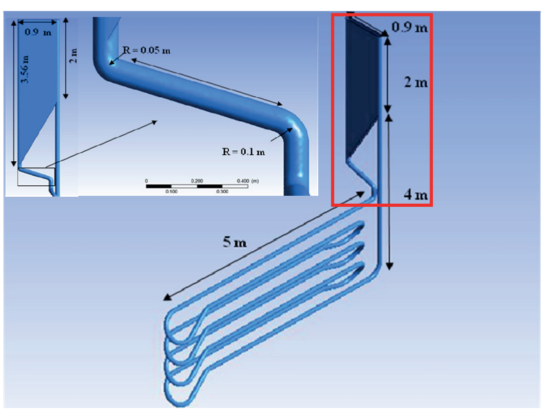

Figure 3: 60° stacked-layer tubular photobioreactor with airlift system.

The heights of the two sides of the gas separator are different: one side is 2 m and the other is 3.56 m. Hence, the bottom of the gas separator is sloped at 60° in relation to the horizontal plane in order to prevent the microalgae accumulation [9], [19]. The downcomer consists of a 0.78 m sloped tube connected to the gas separator with a 0.05 m elbow, and connected to the solar receiver with two 0.1 m elbows. Technically, there is a hole at the bottom of the riser feeding the air to circulate the system. The model is simulated by two-phase assumption: air and seawater. At the inlet boundary, air velocity is set to 0.07 m/s and the pressure is atmospheric pressure [17]. All simulations are performed by a cluster computer with 64 modes and CFD software (Fluent; ANSYS, Canonsburg PA, USA).

3 Results and Discussion

A dead zone developed in the basic model, especially at the U-bend. Modification was proposed by utilizing a total tube length of 43.27 m and an area requirement of 17.28 m^2. The dead zone can be reduced by modifying the bend of the solar receiver loop. However, some dead zone still occurs at the joint of the bend and the straight tube. The dead zone can be reduced to 15.09%.

The modified model of a tubular photobioreactor not only decreases the dead zone but also decreases the pressure drop along the solar receiver to 105.6 Pa. This is in terms of energy consumption. According to the modified model tubular photobioreactor, the modification of bends can reduce the dead zone and the pressure drop. Therefore, the tubular photobioreactor can be stacked up to four layers in order to reduce the area requirement. The area requirement of 30, 45 and 60° model tubular photobioreactors is approximately 5.8, 4.7, and 3.3 m^2 ; respectively All three models are used to study the effect of the angle on the dead zone and pressure drop. Figure 4 shows the microalgae fluid velocity profile for the 30, 45 and 60° stacked-layer models of a tubular photobioreactor.

The dead zone and pressure drop of 30, 45 and 60° models are similarly developed. The dead zone can be calculated as shown in Figure 5. The dead zone of the 30, 45 and 60° models are 15.76, 15.69, and 15.71%, respectively. Therefore, the slopes of the stacked layers of the tubular photobioreactor have no significant effect on the dead zone. In addition, the

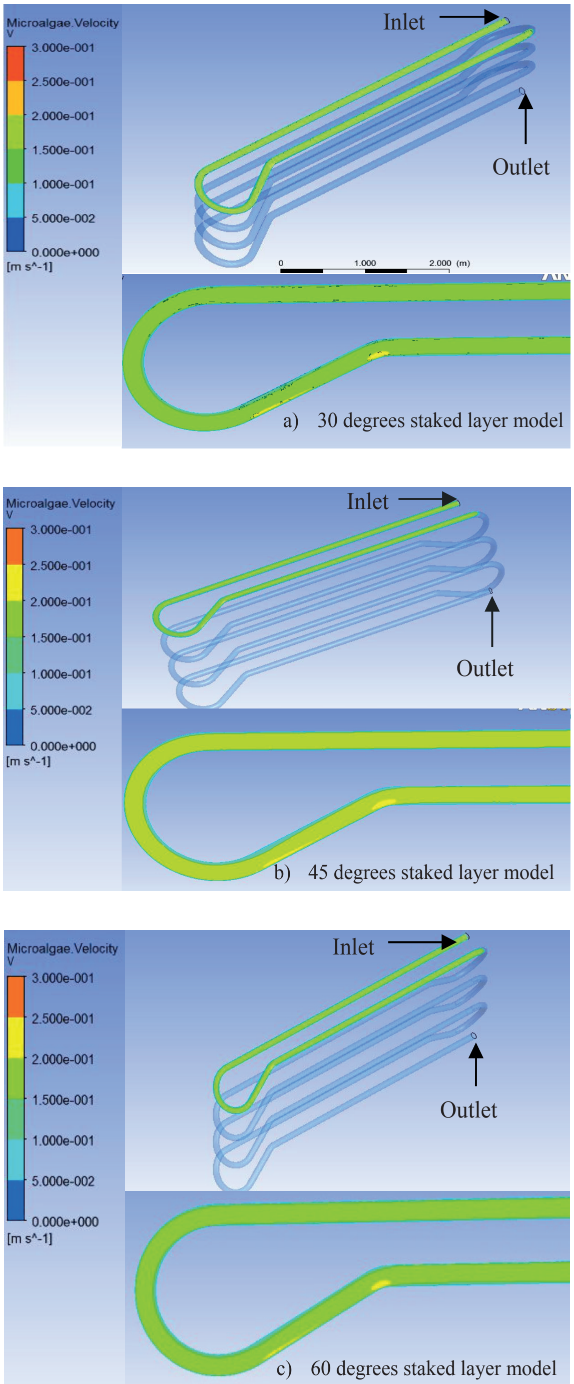

Figure 4: Microalgae fluid velocity profiles for the upper layer 30, 45 and 60° stacked-layer tubular photobioreactors.

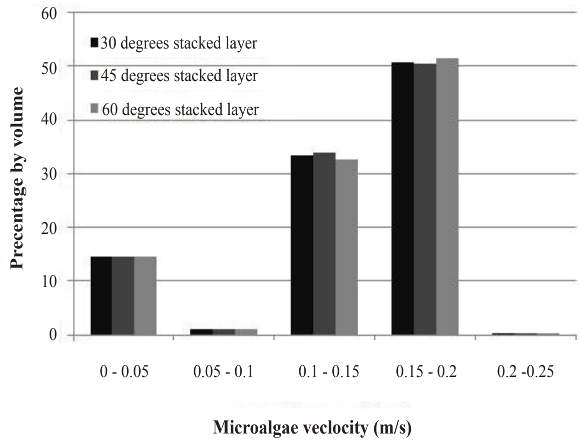

Figure 5: Percentage of microalgae in region of different volume fraction within stacked-layer model tubular photobioreactors.

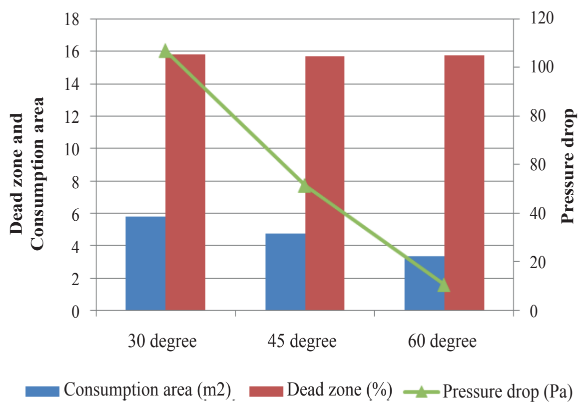

Figure 6: Comparison of Consumption area (m^2) Percentage of Dead zone and Pressure drop (Pa) within stacked-layer model tubular photobioreactors.

pressure drop along the solar receiver loop is 106.79, 51.36 and 10.59 Pa, respectively as shown in Figure 6. Therefore, the incremental slopes of each layer result dramatically the lower pressure drop. The greater turbulence can enhance the possibility of driving microalgae to the periphery of the transparent tube to be exposed to the maximum sunlight. A comparison of the three proposed models shows that the 60° stacked-layer model can give the best performance, since it provides the lowest pressure drop and requires the lowest area. Consequently, this model is chosen

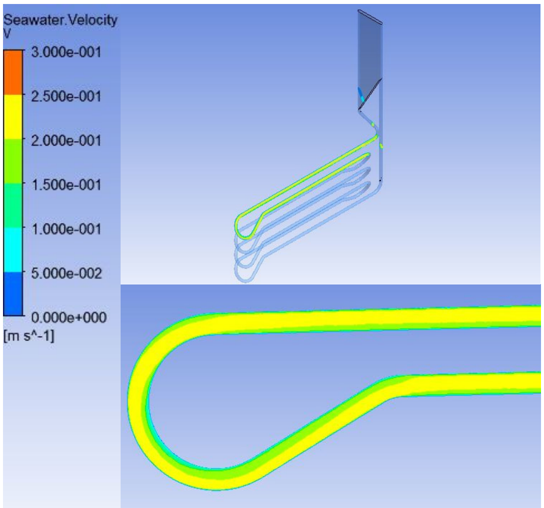

Figure 7: Seawater velocity profile of the 60° stacked-layer model of a tubular photobioreactor at air velocity = 0.07 m/s.

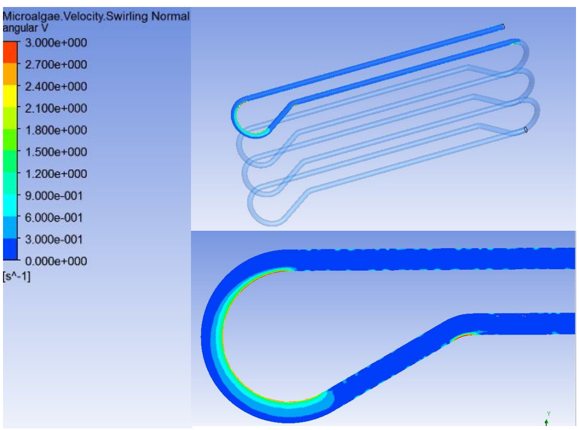

Figure 8: The microalgae angular velocity for 60° stacked layers model of tubular photobioreactor (First layer).

for assembly with an airlift system in order to study the flow behavior inside the tubular photobioreactor. Figure 7 shows the seawater velocity profile of the upper layer of the 60° stacked-layer model assembled with an airlift system. At an air inlet velocity of 0.07 m/s, the average seawater velocity is 0.19 m/s, with a Reynolds number of 19,686. The flow inside the tubular photobioreactor creates turbulence behavior. A swirling flow is also developed that can move the algae in and out in a radial direction as shown in Figure 8.

4 Conclusions

The objective of this study is to improve the basic tubular photobiorector in order to minimize the dead zone, reduce area demand and reduce pressure loss. The tubular photobioreactor geometry is prepared using CAD software and imported to Fluent software to simulate the flow behavior. The results show a dead zone around the U-bend of 25.86% (7.21 m^2), while the pressure drop along the solar receiver is 120 Pa. The U-bend is then modified by increasing the radius of curvature to 0.35 m and the angle of curvature from 180° to 210°.

The dead zone is thereby reduced to 15.06% and the pressure drop is reduced to 105.6 Pa. However, the area requirement actually increases to 17.28 m^2. Therefore, the solar receiver loop must be reconfigured to achieve the optimal configuration. The model is stacked up to four layers to reduce the area requirement. Three models of stacked-layer tubular photobioreactors are proposed. The 60° stacked-layer model can exhibit the best performance by minimizing the pressure drop to 10.59 Pa and the area requirement to 3.34 m^2. Moreover, the dead zone (15.71%) is not significantly increased. The 60° stacked-layer model consists of one 5 m tube and seven 4.17 m tubes which are stacked in up to four layers. The bend of each layer is modified by increasing the radius and the angle of curvature to 0.35 m and 210°, respectively. In addition, each layer is sloped at 60° to the horizontal plane.

Finally, the 60° stacked-layer model is assembled with an airlift system in order to study the flow behavior and demonstrate the full-scaled system. According to the simulation result, the average seawater velocity is equal to 0.19 m/s which ensures the turbulent flow at an air inlet velocity of 0.07 m/s. Therefore, it can be concluded that the 60° stacked-layer model with an airlift system is practically the optimal prototype of tubular photobioreactor.

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