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The Development of Tubular Photobioreactor for Microalgae Cultivation

Varit Kunopagarnwong
Thongchai Rohitatisha Srinophakun*
Department of Chemical Engineering, Kasetsart University, Bangkok, Thailand
**e-mail:* fengtcs@hotmail.com

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Abstract. In a tubular photobioreactor, microalgae cells obscure one another (Self-shading), leading to the microalgae at the bottom of the tube getting less light. The objective of this research was to design and develop Tubular Photobioreactor with 93.5 liters for microalgae cultivation. The experiments had two steps. The first step was designing the solar receiver by inserting the fin into each tube wall as follows: 12-34, 1-2-3-4, 1234, and 13-24. Then, FLUENT software was used to simulate flow behavior inside the tube by Computational Fluid Dynamics by observing the pressure drop, the amount of energy consumption, and the swirling velocity to select the best fin-type. The best fin-type with the growth rate equation is introduced in the next step to simulate the microalgae's growth and movement using the user-defined function technique. The comparison of a tubular photobioreactor is investigated between fin and without fin by observing biomass production. The results showed that algae's optimum inlet velocity is 0.15 meters per second with the tubes containing fin-type 13-24. When simulating the growth behavior of microalgae, results show that the tubes without fins had lower biomass content than the 13-24 fin-type, which were 0.675 and 0.806 grams per liter, respectively, because the 13-24 fin-type will make well microalgae distribution leading to increase the light distribution too. Tubular photobioreactor fins type 13-24 had more biomass production, up to 19.4 percent.

Keywords: Computational Fluid Dynamics, Microalgae, Tubular Photobioreactor

INTRODUCTION

Algae is a bulky group of microorganisms in the Cyanobacteria type (Vieira et al., 2011). Algae has high protein content and other compounds, *i.e.,* carbohydrates and lipids. Polysaccharide Phycocyanin compound is produced from Spirulina (Gimbun et al. 2009). Hydrophilic collide compound is obtained from Rhodophyta and brown algae. Two cultivation systems of algae consist of an open and closed system. Open cultivation systems can be grouped into natural ponds (lake, lagoon) and artificial ponds. The most common use in algal culture is raceway ponds (Sompech et al., 2012). This pond looks like a racetrack and paddlewheels. Microalgae, water, and nutrient are circulated around the racetrack. The advantages of raceway ponds are that they are constructed and operated easily. However, this system has a limitation of large area requirement, high contamination, and low light utilization of algae cells. Therefore, in a closed system,

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photobioreactors are selected for algae cultivation (Molina et al. 2001). They are often placed outdoors or in greenhouses to save on the cost of lighting (Kynft et al., 2012). Photobioreactors are designed to eliminate the limitation of the open cultivation system. For instance, photobioreactors have higher productivity, consume less land area, and handle contamination (Ugwn et al. 2008).

Various configurations of photobio-reactors are proposed, such as flat plate, bubble column, and tubular photobioreactor. The flat plate photobioreactor limitation is the scaling-up requirement, which needs many compartments and support materials (Zhang et al. 2002 and Tamburic et al. 2011). Moreover, this photobioreactor type is challenging to control the temperature, leading to microalgae cell clustering on the reactor wall. The advantages of bubble column photobioreactor are high mass transfer and well-mixing with low shear stress, ease of sterilization, low energy consumption, and efficient removal of oxygen. However, the bubble column needs complex building material and has a low illumination area, which is decreased upon scale-up (Carvalho et al. 2006). A tubular photobioreactor is one of the most suitable for algae cultivation because a pump or an airlift device circulates microalgae culture in the tubular photobioreactor. The airlift device is more effective due to several reasons. The circulation is performed without moving part, which reduces the potential for contamination, microalgae cells are not damaged by mechanical part, and the airlift device combines the function of a pump and a gas exchanger that removes the oxygen produced by photosynthesis (Merchuk et al. 2000). The tubular photobioreactor benefits are large illumination area, good biomass productivity, and reasonably cheap.

Microalgae has the potential to be used as an energy source by converting them into other products like hydrogen, methane production, and ethanol. Microalgae have the genetic, metabolic, and enzymatic characteristics for the photoproduction of hydrogen (Brennan et al. 2010). Under anaerobic conditions, the eukaryotic microalgae produce hydrogen as the electron donor to fix carbon dioxide. During photosynthesis, they convert water to hydrogen ions and oxygen; then, hydrogen ions are formed the hydrogen gas via the enzyme hydrogenase (Spolaore et al. 2006).

The configurations of tubular photobioreactors are more critical because of the light distribution effect of microalgae growth. For that reason, this study will focus on designing a tubular photobioreactor to increase the efficiency of light exposure and biomass production, whereas the turbulent phenomena should be preserved. Practically, the flow behavior of the tubular photobioreactor in this study was performed by the computational fluid dynamic tool (CFD). Hence, at minimal cost, this is an efficient tool to fulfill the limitation of the experiment under a reasonable time intake.

METHODS

Overall Methodology

Firstly, the configuration of a 60-degree one-stacked layer tubular photobioreactor of (Tamburic et al. 2011), as shown in Figure 1, is specified in a simulator.

The modified 60-degree one-stacked layer was by attaching the fins along the tube and separating into 4 cases, as seen in Figure 2a to 2d with fin-dimension in Figure 3. The proposed mathematical model and boundary conditions were developed to study the hydrodynamics of microalgae and

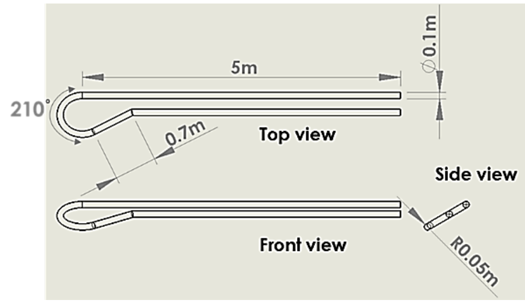

Fig. 1: The configuration of a 60-degree one-stacked layer tubular photobioreactor

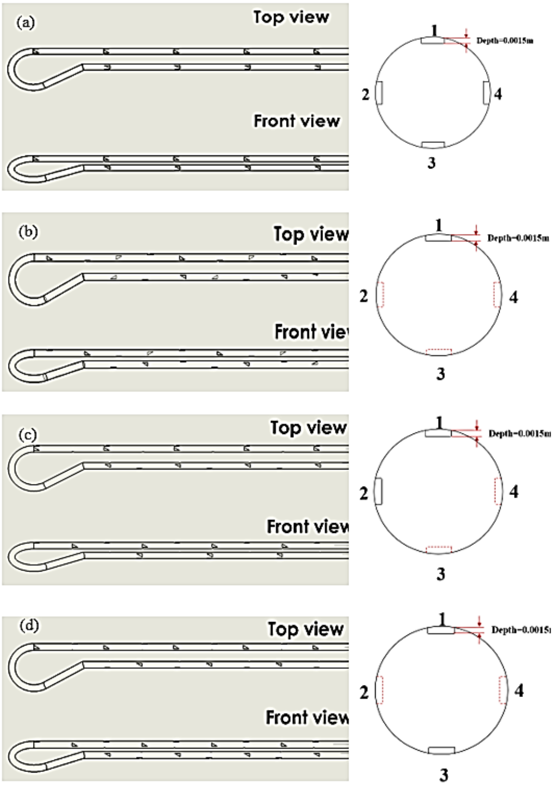

Fig. 2: The modification of a 60-degree one-stacked layer by attaching the fins: (a) case 1234, (b) case 1-2-3-4, (c) case 12-34, and (d) case 13-24, where 1 is the position of the fin at the top, 2 left, 3 bottom, and 4 right sides.

seawater flow inside the tubular photobioreactor using two-fluid models: average velocity and average swirling velocity, pressure drop, and energy consumption. Regarding the 3-dimension meshing discretization, the tetrahedron structure is suitable. ANSYS FLUENT CFD software is the main simulator, and all the results are presented with ANSYS CFD-Post. (Pinyaporn et al. 2012)

Hydrodynamics

The two-phase flow model was selected to study the seawater and microalgae system's hydrodynamics in a 60-degree one-stacked tubular photobioreactor and modified 60-degree with fins. Seawater and microalgae were represented as the continuous and dispersed phases, respectively.

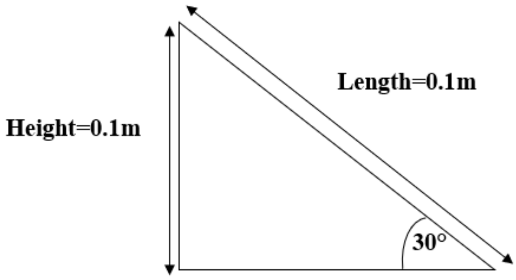

Fig. 3: The dimension of each fin.

Mathematical Model

The Eulerian–Eulerian, Lagrangian-Eulerian, and Volume of Fluid (VOF) multiphase models have been generally used for hydrodynamic research (Bitog et al. 2011). In this work, the behavior of modified tubular photobioreactors used the Eulerian-Eulerian model to predict the flow. This model can model the separated interacting phase by solving the mass and momentum for each phase. The Eulerian model in ANSYS FLUENT can function to model multiple separate. The phases can be liquids, gases, or solids in nearly any combination for studying the behavior of particles, which corresponds to the objective of this work to study the flow behavior of microalgae with water, air, and other gas. Eulerian is a flow description of fluid with a time that uses momentum and continuity calculation, which calculates the volume fraction of microalgae.

The continuity equation for phase i is expressed by Eq. (1).

$$\frac{\partial}{\partial t}(\alpha_i\rho_i) + \nabla\cdot(\alpha_i\rho_i\vec{u}_i) = 0 \quad (1)$$

where the subscript i stands for seawater and microalgae, α_i is the volume fraction, ρ_i the density, and $\vec{u}_i$ the velocity.

The momentum conservation equation for the i phase is expressed by Eq. (2).

$$\frac{\partial}{\partial t}(\alpha_i\rho_i\vec{u}_i) + \nabla\cdot(\alpha_i\rho_i\vec{u}_i\vec{u}_i) = -\alpha_i\nabla p + \alpha_i\rho_i\vec{g} + \nabla\cdot\bar{\bar{\tau}}_i + \sum_{i=1}^{n}\vec{R}_{ji} + \alpha_i\rho_i(\vec{F}_i) \quad (2)$$

where p is the pressure, $\vec{g}$ acceleration due to gravity, $\bar{\bar{\tau}}_i$ stress tensor, $\vec{R}_{ji}$ the interaction force between phases, and $\vec{F}_i$ the external body force as a drag force.

The boundary conditions were as follows: the velocity inlet boundary was specified at the inlet pipe condition with a uniform inlet velocity. A No-slip boundary condition was selected at the wall. The pressure outlet boundary condition was chosen for the outlet

The properties of the microalgae and seawater are shown in Table 1. Seawater was represented as a continuous phase, while microalgae were in the dispersed phase. Moreover, microalgae and seawater inlet velocities were set at 0.17 m/s with a dispersed phase volume fraction of 0.05.

Table 1. Fluid properties (Theerawat, 2012)

Properties	Seawater	Microalgae
Density, (kg/m^3)	1020	1300
Viscosity, $(kg/m\cdot s)$	0.001	0.001

Microalgae Growth Kinetic Model

The proposed growth model in this work was based on that of Aiba et al. (1982), and expanded by van Leeuwen et al. (2012). This model covers all the required parameters, shown in Eq. (3).

$$\mu = \frac{\mu_{max} I}{K_s + I + \frac{I^2}{K_i}} \quad (3)$$

With μ_{max} being the maximum growth rate [h^{-1}]. The actual maximum growth rate is defined by μ_{max}. μ_{min} is the negative growth rate from respiration [h^{-1}]. I is the light intensity [$\mu mol m^{-2} s^{-1}$] at a given location. K_s is the light intensity [$\mu mol m^{-2} s^{-1}$] where half of the maximum growth rate is reached. K_i is the photoinhibition steering parameter [$\mu mol m^{-2} s^{-1}$].

RESULTS AND DISCUSSION

Fluid Dynamic Simulation Results

The seawater density is 1020 kg/m^{3,} while microalgae density is assumable at 1300 kg/m^3. Therefore, the Eulerian multiphase model can consider the microalgae cells to be another continuous phase. Both seawater and microalgae viscosities are assumed to be equivalent at 0.001 kg/m.s. Two boundary conditions (inlet and outlet) were simulated. For the inlet boundary, both water and microalgae phases have a velocity of 0.17 m/s. Also, the microalgae inlet volume fraction was 0.05, the same as the inside one.

Figure 4 shows the streamlined micro-algae velocity of the 60-degree stacked layered model with fin. There are 4 different cases. All are performed by ANSYS FLEUNT and CFD-Post software. The velocity field is illustrated by arrow vectors and streamlines according to fluid behavior in a cross-sectional view. The streamlined colors represent the velocity intensity (red is high-velocity, yellow is medium-velocity, and blue is low-velocity).

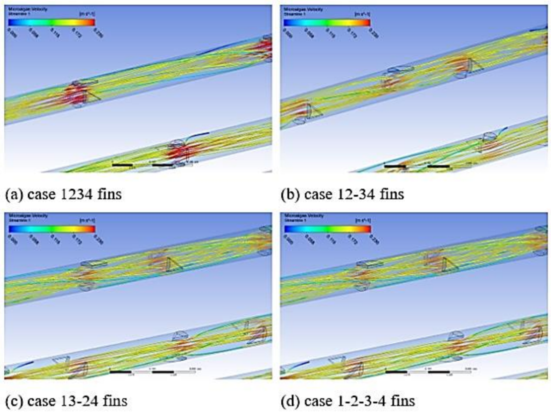

Fig. 4: The different microalgae velocity profiles among 4 cases.

The results observed that the streamline of case 1234 was the highest velocity in the z-direction because microalgae flow through the fin swirling velocity will increase, leading to microalgae growth. The microalgae phase flowed through the fin swirl flow and provided the circulated microalgae in the tubular photobioreactor. This means that the velocities in the radial and tangential axes were also high. As a result, microalgae can receive more light. However, high velocity provides a high-pressure drop, which requires more energy.

The pressure drop per meter along the tube length at various velocity flows is illustrated in Figure 5. As expected, the application of the fin-mixer has generated a high-pressure drop. Case 1234 resulted in a remarkable increase, while cases 1-2-3-4 and case 12-34 gave an analogous effect on the pressure drop. Alternatively, cases 13-24 exhibits the lowest pressure drop. However, at an average flow velocity of 0.5 m/s, the pressure drop in case 13-24 is 164.82 Pa/m, two times the pressure drops in case without-fin (81.22 Pa/m).

Figure 5 shows the relationship between energy consumption and flow velocity. At 0.2 m/s, the pressure drop in the 60-degree stacked layered model with 13-24 fin is the same as in the classical Tubular photobioreactor (without fin). At lower average velocities, pressure drop behavior looks like a classical Tubular PBR at standard conditions. Figure 6 shows energy consumption at various flow velocities. Because this energy is relational to pressure drop, the 60-degree Stacked layered model with 13-24 fin requires the lowest energy consumption. Notice that a 60-degree stacked layered model with 1234, 1-2-3-4, and 12-34 fin allows more energy conservation at proper average flow velocity. However, the system might transform from turbulent to laminar in the very low flow velocity regime. Therefore, the present pressure drop relation does not satisfy.

Suitable conditions for mixing this Tubular PBR must be prolonged at turbulent behavior to force the excellent mass transfer and light-harvesting. This tubular flow with a mean velocity of 0.5 m/s has a Reynolds number of 25,000 (over 4000 at the turbulent regime). Hence, the high average velocity allows the right conditions for mixing.

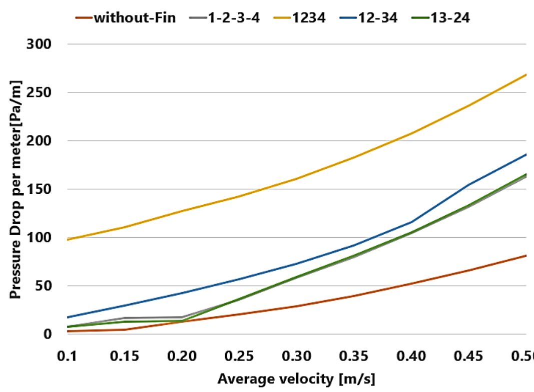

Fig. 5: Pressure drop of TPBR with the different average velocity

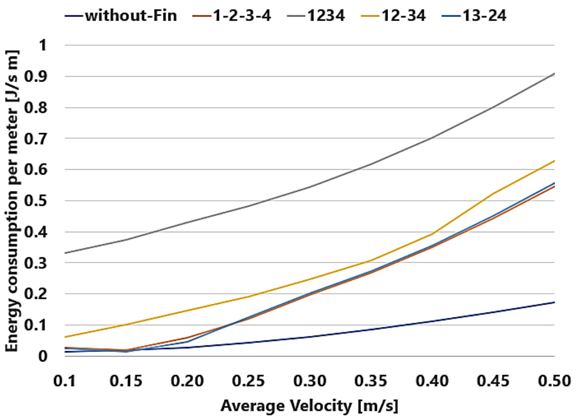

Fig. 6: Energy consumption with a different average velocity

Once the mean velocity decreases to 0.1 m/s, the Reynolds number decreases to 5000. Although Reynolds number is still in turbulent flow, it comes too close to the transient boundary. The mixing condition is unpredictable. Therefore, the best practice is to keep a small mean velocity change in real PBR operation. 60-degree Stacked layered model with 13-24 fin can conserve energy by reducing the flow velocity to 0.15 m/s. The energy consumption can then reduce by 68% of the actual one at the flow velocity of 0.2 m/s.

Swirling Velocity

The swirl number is computed by the profile of velocity at the cross-sectional area. Figure. 7 showed the average swirling velocity. High average swirling velocity is obtained by 1234 with 60-degree stacked layers tubular photobioreactor. In comparison, 12-34 and 13-24 tubes show moderate swirl numbers. The high swirl can increase the light exposure area for algae. As a result, algae growth can be promoted; efficiently.

Light Intensity Zone

The global position consists of latitude, longitude, and time zone (relative to GMT). The default solar irradiation method is Fair Weather Conditions. The shading calculation for solar ray tracing is a straightforward application of vector geometry. A ray is traced from the centroid of a test face in the direction of the sun, presented in Figure 8.

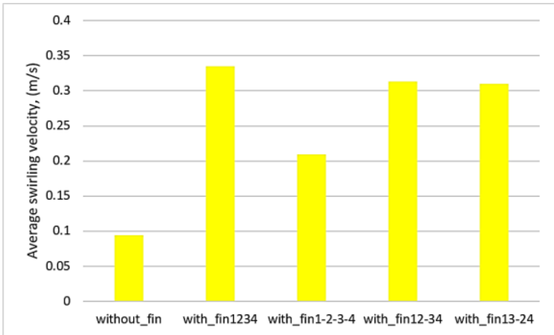

Fig. 7: Average Swirling velocity on each design of fin with 60 degrees stacked layers tubular of photobioreactor

The modeling approach is the option for light distribution. The zone numbers and the corresponding growth of microalgae are determined in the light-intensity zone. 60-degree stacked layered with fin case 13-24 consists of 15 parts. Parts 1, 3, 5, 7, 9, 11, 13, and 15 are straight tubes presented in Figure 9.

Each part is divided into 3 zones: the top, middle, and bottom tubes presented in Figure 10. In geometry, preferences can design for the number of zones. The specific light intensity zone is used to calculate the growth and the incident light intensity.

The top tube will receive full light intensity middle, and the bottom tube will receive half of the light intensity. The average light intensity base in Bangkok, Thailand, is 577.5 $W/m^{2,}$ presented in Figure 11.

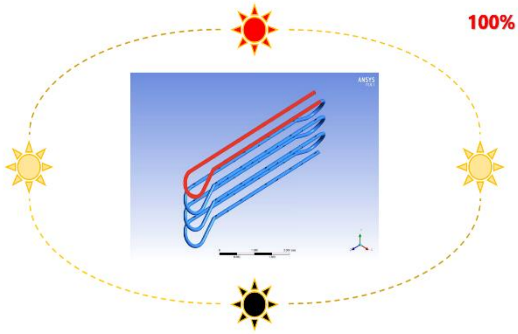

Fig. 8: Global position (latitude, longitude, and time zone)

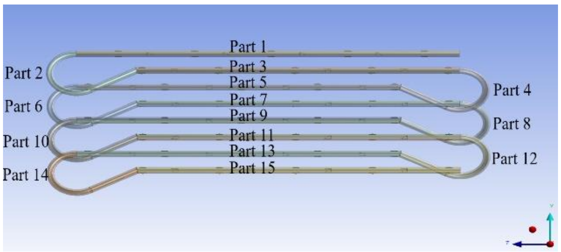

Fig. 9: light intensity zone on 60-degree stacked layered with fin case 13-24 for calculating the growth of microalgae

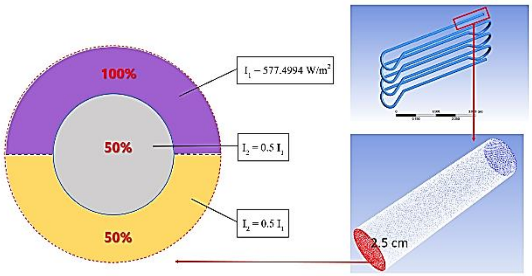

Fig. 10: light intensity zone on 60-degree stacked layered with fin case 13-24 in the straight tube (parts 1, 3, 5, 7, 9, 11, 13, and 15)

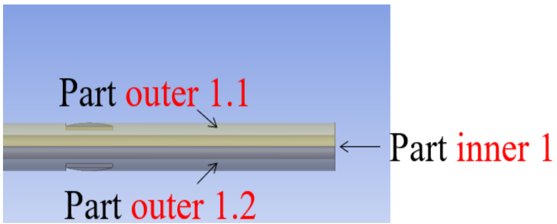

Fig. 11: light intensity zone in part 1 consists of a top tube, middle tube, and bottom tube

As shown in Figure 9, parts 2, 6, 10, and 14 are the front U-tube, and parts 4, 8, and 12 are the back U-tube both are divided into 2 zones, which are the inner and outer tubes shown in Figure 12.

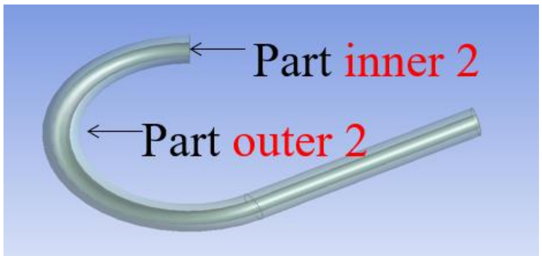

Fig. 12: light intensity zone in part 2 consists of the inner and outer tubes

The inner part of the tube will receive half of the light intensity; the outer part of the tube will receive full light intensity, as presented in Figure 13. The average light intensity in Bangkok, Thailand, is 577.5 W/m^{2}, as described.

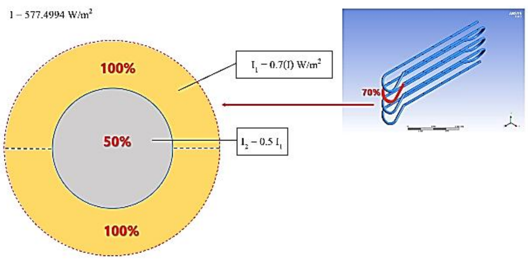

Fig. 13: light intensity zone on 60-degree stacked layered with fin case 13-24 in U-tube (parts 2, 6, 10, and 14 are front U-tube and parts 4, 8, and 12 are back U-tube)

Biomass Production

Despite this variation in the light intensity zone, they all show a similar trend; productivity increases with the amount of sunlight received. Biomass production depends on the reaction rate of microalgae in the function of local light intensity performed in this system using the User Defined Function (UDF). A user-defined function, or

UDF, is a function that you program that can be dynamically loaded with the FLUENT solver to enhance the standard features of the code. This study has compared 60-degree stacked layered with fin case 13-24 and without fin.

Figure 14 shows the volume fraction contour of microalgae in a 60-degree stacked layered without a fin, in which the microalgae distribution was poorer than the case with a fin. The biomass concentration without fin was 0.675 g/L.

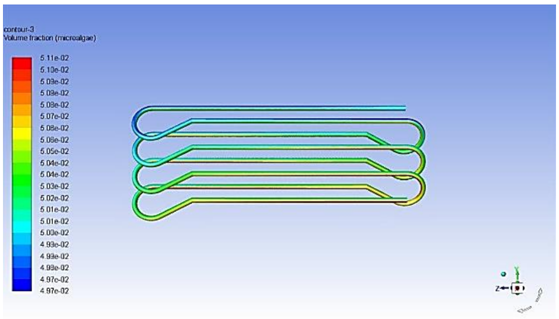

Fig. 14: Volume fraction of microalgae in 60-degree stacked layered without fin

Figure 15 shows the volume fraction contour of microalgae in 60-degree stacked layered with fin case 13-24, which has a better mixing than 60-degree stacked layered without fin. The biomass concentration with 13-24 fin was 0.806 g/L. The growth of microalgae as the reaction rate depends on the direction of the tube; when microalgae can stay in the tube for a long time, the growth will be even higher, as presented in Table 2.

Table 2: Biomass for each species in Tubular Photobioreactor with 13-24 fin

Species	Simulation	Biomass, (g/L)
Spirulina	CFD	0.806
Porphyridium	CFD	1.56
Oscillatoria	CFD	3.54

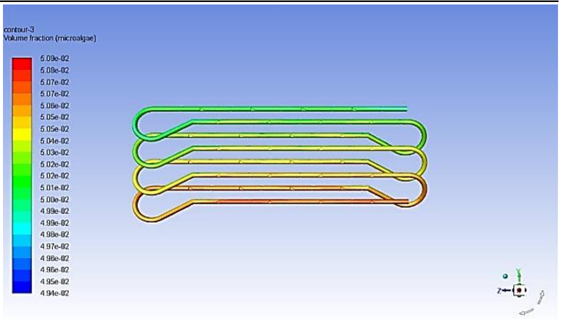

Fig. 15: Volume fraction of microalgae in 60-degree stacked layered with fin case 13-24

CONCLUSIONS

This work aims to design and develop Tubular Photobio-reactor to increase light exposure and biomass production efficiency. The tubular photobioreactor geometry has a diameter, and the length of the solar receivers are 0.05 and 40 m in 93.4 liters. Potential configurations are proposed and simulated in commercial CFD software for the flow behavior in the tubular photobioreactor. The simulation result of tubular photobioreactor with 12-34, 1-2-3-4, 1234, and 13-24 showed the Pressure drop at 0.15 m/s was 29.82, 17.03, 110.63, and 12.9 Pa/m, respectively. Energy consumption was 0.1, 0.019, 0.374, and 0.0145 J/s, respectively, and the swirling velocity was 0.2929, 0.2093, 0.3346, 0.2903 m/s. Hint, the tubular photobioreactor with 13-24 fin has a low-pressure drop and low energy consumption. The tubular photobioreactor with 1234 fin has a high swirling velocity but consumes more energy and increases the shear stress to the microalgae (swirling velocity did not exceed 0.3 m/s). Thus, the tube with 13-24 fin was the best.

In the next step, we brought the 13-24 fin-type to insert the Growth rate equation into the FLUENT software to simulate the microalgae's growth and movement using the User Defined Function (UDF) technique, which compares a tubular photobioreactor between without fin and with fin. The results showed that the tubular photobioreactor without fins had lower biomass than the 13-24 fin-type, which were 0.675 and 0.806 grams per liter, respectively because the 13-24 fin-type will make well microalgae distribution led to an increase in the light distribution too. Tubular Photobioreactor fins type 13-24 had more biomass production, up to 19.4 percent.

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