ABSTRACT Renewable energy is interesting as a countermeasure for the fossil energy depletion and carbon dioxide reduction. Biodiesel using vegetable oils is one of the most desirable renewable energy because it can be an alternate diesel to petroleum. However, the biodiesel from soybean or corn, etc. can be confronted with food crisis. Microalgae have recently been researched as a new biodiesel source which not only contain high oil lipids with high growth rate but also offer value-added products such as cosmetics, health functional food or pharmacy from the residue. Because pond production system has limitations in unstable weather conditions and insufficient land availability especially in Korea, photo-bioreactors (PBRs) is essential for their cultivation. More so, controlling the suitable environments such as light, nutrients, carbon dioxide, temperature, etc. in the PBR is possible. Despite the availability of PBRs at present, only a few can be practically used for mass production due to some limitations. In this study, computational fluid dynamics (CFD) was used to design an optimum bubble-column PBR for mass production of microalgae. Multi-phase models including bubble movement, meshes and time step independent tests were considered to develop the three-dimensional CFD model. The model was enhanced and validated through Particle Image Velocimetry (PIV) tests. Various types of PBRs were simulated and compared quantitatively with consideration of the microalgae’s growth model adaptable for the CFD model and an evaluation method of mixing efficiency in the PBRs has been done. This research can be used as a basic technique for microalgae production on a large scale.

Keywords: Bio-diesel, computational fluid dynamics (CFD), microalgae, photo-bioreactor

INTRODUCTION

Climate change and exhausting of petroleum have been a global problem. Renewable and carbon neutral energy source are necessary for environment and economic sustainability. Natural energy from solar, wind and biomass are now being watched with keen interest to solve the problem. Among the mentioned energy sources, biodiesel derived from biomass and oil crops is a potential renewable and carbon neutral alternative.
Biodiesel is already a proven technology and very attractive alternative fuel source. Biodiesel is clean and carbon-dioxide-neutral fuel and now becoming more and more popular considering that so far it has the promising potential to completely replace petroleum fuel (Chisti, 2007). At present, most of the current biodiesel are from soybean and corn oil. However, as supply and demand grows, so does the price of soybeans and corn. Thus its major drawback is that producing a significant amount of oil requires a vast surface of land which competes with food production and food supply. Meeting the increasing demand would require the world to use virtually all of its arable land.

The most promising alternative source of biodiesel is from microalgae. Microalgae are photosynthetic organism that has high oil content up to 30-70% of its dry weight. Contrary to the fast growing and uniform composition of microalgae which can complete one life cycle every few days, plant and animal origin biomass suffer several limitations such as slow growing rate, relatively low oil contents, limited production capacity, high cost, etc. High oil content algae species could produce oil as much as 1000 times of soybean on a same size land. The major factors for the maximal growth of microalgae are light and CO₂.

Over the past forty years a great deal of research has been carried out with similar concepts for microalgae fuels production and CO₂ utilization. The only practicable methods of large-scale production of microalgae are raceway ponds and tubular PBRs. In PBRs, maximum production is possible when the environmental conditions for growing microalgae are attained. Introducing CO₂ in PBRs is usually done through bubbles. With this mechanism, stress of microalgae during their growth stage is minimized. However, to maximize growth rate of microalgae in PBRs, several factors are to be considered like PBR size and shape including the mixing mechanism to provide the optimum environmental conditions for the microalgae’s growth.

To study main factors for the growth of microalgae, field experiments are necessary. However, conducting field experiments, although it is the ideal method offers us many limitations. Field experiments are very costly and time consuming. More so, the factors that can be determined are very limited. However, the advent of computational fluid dynamics (CFD) in the 70’s and its continuous development paved the way to study many aero and fluid dynamic phenomena in a more realistic way. CFD technology has been successfully applied in huge number of areas, including many which are of interest to engineers. The range of applications is broad and encompasses many different fluid phenomena. Studying the main factors for the growth of microalgae in PBRs using CFD has many advantages. Various size and shape of the PBR can be studied with varying internal conditions. Several boundary conditions to determine optimum environmental factors for the maximum growth of microalgae can be studied. Also, several approaches of introducing bubbles can be looked into and the mixing mechanism can be analyzed. Considering these advantages of CFD aside from minimizing the cost and time in this research, we will use this technology to determine the optimum size and shape of the PBR and also analyze the approaches in introducing CO₂ in the PBR and mixing characteristic inside the PBR. To achieve our final goal, the objectives of our research at the first year were to establish criteria for CFD simulations to include realizing bubble and movements inside of PBR by bubble injection and suitable mesh and time-step size.

MATERIALS AND METHODS
CFD simulation was utilized to study the hydrodynamics of flow inside the PBR. To design the geometry, Gambit (Fluent Co. New Hampshire, USA, ver. 2.4) was used as a
pre-processor to make grids and meshes. Fluent (Fluent Co. New Hampshire, USA, ver. 6.3) was used to solve the fluid dynamic equations as a main solver. Ensight was chosen as a post-processor to visualize the flows and the changing parameters in PBR.

To realize bubble acting in the PBR, using multi-phase model is inevitable. Therefore, for the approach of the research we had to decide the exact model for PBR simulation. There are four possible multi-phase models which are MPM (Multi-Phase Mixture) Model, DPM (Discrete Phase Model), Eulerian-Eulerian Model and the VOF (Volume of Fluid) Model. The main equations of each model are similar because they are made of continuity (1) and momentum (2) equations except for the DPM method which is governed by the force balance equation (3).

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m \tag{1}
\]

\[
\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla P + \nabla \cdot \vec{T} + \rho \vec{g} + \vec{F} \tag{2}
\]

\[
\frac{\partial u_i^p}{\partial t} = F_D(u_i - u_i^p) + \frac{g_i(\rho_p - \rho)}{\rho_p} + F_i \tag{3}
\]

where, \( \rho \) is the density, \( t \) is the time, \( \vec{v} \) is the velocity, \( S_m \) is the source term, \( p \) is the static pressure, \( \vec{T} \) is the stress tensor, \( \rho g \) is the gravitational body force, \( \vec{F} \) is the external body forces, \( u_i \) is the fluid phase velocity, \( u_i^p \) is the particle velocity, \( F_D(u_i - u_i^p) \) is the drag force per particle mass, and \( F_i \) is an additional acceleration term.

This research focused on the development of a three dimensional CFD model in order to quantitatively analyze the efficiency of bubble-column PBRs for mass production of microalgae. Multi-phase models including bubble movement, meshes & time step independent tests were considered to develop the three dimensional CFD model. The surface tension on the CFD model was decided following the comparison of bubble rising time from the laboratory experiments. Particle Image Velocimetry (PIV) test was conducted to validate and enhance the CFD model. For quantitative comparison between different types of PBRs, a new method was developed using particle traces and its statistical analysis. Using the new method to calculate the efficiency of PBRs, productivity and uniformity were estimated according to various structures of 20 L PBRs.

**RESULTS & DISCUSSION**

Results showed that the MPM & Eulerian models failed to realize bubbles. Eulerian model is the widely used multi-phase model in chemical reactions because it offers advantage over other models. However, to realize bubbles, we had to assume the gas bubbles as solid with a fix diameter which is not appropriate. In the case of DPM, initial inputs like the number and diameter of bubbles were limited. Simulation using the VOF model realized the bubbles and considered to be more appropriate because it considers surface tension factor. This prompted us to favor the VOF model for our PBR simulation.
Various sizes and types of meshes were tried with the VOF model in 3D simulation. This model has been previously used by Li et al. (2000) and Akhtar et al. (2007). After trials and errors, we determined a suitable grid size and mesh type for the PBR simulation which is not only accurate, but also able to shorten the calculating time. The final mesh is hexahedron type with basically 4 mm size. Time step size was tested using courant number (Eq.4). Courant number is a non-dimensional number to evaluate a convergence of the CFD model according to time step size, mesh size and velocity difference between meshes. The better the quality of the mesh structure, which is being enhanced, the lesser is the courant number. With 4 mm size is used as a basic size of the meshes, in a 2-L PBR model, 0.005 seconds of time step is appropriate by the test with range of 0.001 to 0.1 seconds. The VOF model had shown to realize bubbles as presented in Fig. 2.

\[
\Delta t = \frac{2CFL \times V}{\sum \lambda_{f}^{\text{max}} A_f}
\]

where, \(V\) is the cell volume, \(A_f\) is the face cell, and \(\lambda_{f}^{\text{max}}\) is the maximum of the local eigenvalues.

Surface tension is one of the main factors to decide a size of bubble in the culture fluid. As the surface tension is larger, the resistance of bubble is increased resulting in the increase of bubble rising time. The bubble rising times of the CFD models using different values for surface tension were compared with 1.13 seconds in average which was calculated with the video analysis of same structure of PBR in the laboratory experiments.
Using a trend curve from various CFD results, the surface tension in the PBR was decided as 0.048 Nm\textsuperscript{-1}.

![Figure 2](image1.png)

**Figure 2.** Bubble movement in the laboratory experiment and a 3-D PBR simulation

The three dimensional CFD model was also validated by PIV test which is known as the most accurate method for fluid flow analysis among field experimental methodologies. PIV tests were conducted to trace micro particles in the fluid inside of a manufactured 20 L PBR according to the locations of bubble injection, size of injector and injecting volumes. Figure 3 shows the results of the PIV test and the CFD simulation.

![Figure 3](image2.png)

**Figure 3.** Averaged flow of culture fluid of the PIV test and the CFD simulation.

The mixing efficiency of PBRs is needed to quantitatively evaluate how long the microalgae stay at the space where light source is enough. It is challenging to calculate an integrate value for mixing efficiency in the PBRs which do not have both inflow and outflow. Therefore, particle tracer for each microalgae particle was used in the CFD model. Light intensity model presented by Steele (1977) was used by comparing between various numerical models and field experiments (Eq 5). Light transmittances by the age of microalgae measured by field experiments were adapted in the light intensity model.
This was designed by C language and applied to the CFD simulation by UDF (User defined function) for each particle.

\[
I = I_E \exp\left[-(k_x \cdot x + k_n)\times d\right] = I_E \exp(a \times d) \tag{5}
\]

\[
a = -0.1 \times \exp(0.3682 \times D) \tag{6}
\]

where, \(I_E\) is the optimum light intensity with 300 \(\mu\text{E m}^{-2}\text{s}^{-1}\), \(a\) is the constant by age of microalgae, \(d\) is the depth from the surface where the light source is available, and \(D\) is the day of the microalgae grow.

2,500 particles were uniformly distributed in the PBRs and their trajectories were traced with three dimensional coordinates according to the time steps. The coordinate data were used to time-dependently calculate the light absorption. The entire data for each particle’s light absorptions were statistically analyzed in order to evaluate the mixing efficiency for PBR structures. Figure 4 shows the daily decrease of light absorption for each particle according to the age of microalgae using CFD simulation. The statistical analysis was helpful to calculate quantitative values for the average absorption of light and its uniformity from the standard deviations.

![Figure 4. Distributions of light absorption by microalgae’s daily ages](image)

The mixing efficiency was analyzed according to the various types in a 20 L PBR. The size of plate and tubular type PBRs were illustrated in Fig. 5. For the optimum fluid flow, the uniformity of inlets, depth & gap size of the baffles for guiding the internal flow were considered.
Table 1 shows the mixing efficiency of various types of PBRs divided into light absorption and uniformity. In the day 1, the light absorption was not significant according to the PBR due to low concentration of the microalgae. In the day 7, when the light absorbable area was limited with high concentration of microalgae, it could be increased by 17 % in light absorption and increased by 55 % in uniformity according to the structure of PBRs which could lead appropriate fluid flow inside the PBRs comparing with basic tubular PBR. Additional baffles inside the tubular PBRs is helpful to increase both light absorption by 11 % and uniformity by 15 % while plate type PBRs shows better uniformity by 38 % than tubular type PBRs.
Table 1. Uniformity (U) and light absorption (LA) for each types of PBRs according to the age of microalgae

<table>
<thead>
<tr>
<th>Label</th>
<th>Inlet type</th>
<th>Baffle depth</th>
<th>Baffle gap</th>
<th>Day 1 LA</th>
<th>U</th>
<th>Day 4 LA</th>
<th>U</th>
<th>Day 7 LA</th>
<th>U</th>
</tr>
</thead>
<tbody>
<tr>
<td>AX</td>
<td>Basic</td>
<td>No baffle</td>
<td></td>
<td>3 %</td>
<td>-4 %</td>
<td>6 %</td>
<td>-5 %</td>
<td>13 %</td>
<td>-4 %</td>
</tr>
<tr>
<td>SX</td>
<td>Side</td>
<td>No baffle</td>
<td></td>
<td>2 %</td>
<td>8 %</td>
<td>5 %</td>
<td>12 %</td>
<td>11 %</td>
<td>10 %</td>
</tr>
<tr>
<td>S313</td>
<td>Side</td>
<td>3 cm</td>
<td>1&amp;3 cm</td>
<td>2 %</td>
<td>19 %</td>
<td>5 %</td>
<td>21 %</td>
<td>12 %</td>
<td>14 %</td>
</tr>
<tr>
<td>S333</td>
<td>Side</td>
<td>3 cm</td>
<td>3&amp;3 cm</td>
<td>2 %</td>
<td>18 %</td>
<td>4 %</td>
<td>20 %</td>
<td>10 %</td>
<td>8 %</td>
</tr>
<tr>
<td>S513</td>
<td>Side</td>
<td>5 cm</td>
<td>1&amp;3 cm</td>
<td>1 %</td>
<td>19 %</td>
<td>4 %</td>
<td>23 %</td>
<td>7 %</td>
<td>18 %</td>
</tr>
<tr>
<td>S533</td>
<td>Side</td>
<td>5 cm</td>
<td>3&amp;3 cm</td>
<td>1 %</td>
<td>19 %</td>
<td>5 %</td>
<td>23 %</td>
<td>13 %</td>
<td>19 %</td>
</tr>
<tr>
<td>4x</td>
<td>4</td>
<td>No baffle</td>
<td></td>
<td>-7 %</td>
<td>13 %</td>
<td>-15 %</td>
<td>22 %</td>
<td>-32 %</td>
<td>30 %</td>
</tr>
<tr>
<td>4213</td>
<td>4</td>
<td>2 cm</td>
<td>1&amp;3 cm</td>
<td>-3 %</td>
<td>4 %</td>
<td>-2 %</td>
<td>11 %</td>
<td>17 %</td>
<td>20 %</td>
</tr>
<tr>
<td>4413</td>
<td>4</td>
<td>4 cm</td>
<td>1&amp;3 cm</td>
<td>-7 %</td>
<td>37 %</td>
<td>-11 %</td>
<td>45 %</td>
<td>4 %</td>
<td>41 %</td>
</tr>
<tr>
<td>4253</td>
<td>4</td>
<td>2 cm</td>
<td>5&amp;3 cm</td>
<td>-5 %</td>
<td>17 %</td>
<td>-8 %</td>
<td>30 %</td>
<td>4 %</td>
<td>35 %</td>
</tr>
<tr>
<td>8253</td>
<td>8</td>
<td>2 cm</td>
<td>5&amp;3 cm</td>
<td>-15 %</td>
<td>34 %</td>
<td>-28 %</td>
<td>49 %</td>
<td>-30 %</td>
<td>55 %</td>
</tr>
<tr>
<td>8413</td>
<td>8</td>
<td>4 cm</td>
<td>1&amp;3 cm</td>
<td>-10 %</td>
<td>10 %</td>
<td>-19 %</td>
<td>32 %</td>
<td>-18 %</td>
<td>47 %</td>
</tr>
</tbody>
</table>

Figure 6. Distributions of light absorption at the 7th day according to the structure of PBRs.

CONCLUSION

Light absorption affects the overall productivity of microalgae in the PBRs. However, uniformity of culture fluid flow is also important not only to reduce the stagnated area or eddies where slurry can be easily accumulated but also to enhance the viability of microalgae passing the light absorption area due to its photosynthesis especially to the large scaled PBRs. In this research, the quantitative evaluation method for mixing efficiency was developed with three dimensional CFD simulation model. This can be effectively used to design an appropriate PBR for mass production of microalgae with consideration of the importance of both light absorption and uniformity.
REFERENCES