私立東海大學化學工程暨材料工程研究所

碩士論文

Master Thesis

指導教授：顏宏偉博士

Advisor：Hong-Wei Yen, Ph.D.

探討應用 computational fluid dynamics (CFD)於微藻培養之渠道式反應器設計

Application of computational fluid dynamics (CFD) on the raceway design for the cultivation of microalgae

研究生：**古艾迪**

Graduate student：Adi Kusmayadi

中華民國 108 年 7 月

July, 2019

Master's Thesis Recommendation Form

Department: Department of Chemical and Materials Engineering

Student's Name : ADI KUSMAYADI

Thesis Tittle : Application of computational fluid dynamics (CFD) on the raceway design for the cultivation of microalgae

This is to certify that the thesis submitted by the student named above, has been written under my supervision. I hereby approve of this thesis to be applied for the examination.

Advisor: Hong-Wei Yen., PhD

Advisor's Signature :

Date : / / / (yyyy/mm/dd)

ACKNOWLEDGEMENTS

In the Name of Allah, the most Gracious, the most Merciful All praises be to Allah, king of the king, the Lord of the world, and the master of the day after, who has given us blessing and guidance. Because of His graciousness and mercifulness the writer able to finish this research.

In this chance, my deepest appreciation goes his profound gratitude, more than he able to express, to:

1. Prof. Hong-Wei Yen, who advisor of this thesis for his supervision, guidance, and advice from the beginning of this research.
2. Great appreciation to all lectures in the Department of Chemical and Material Engineering giving the valuable insightful during I studied in this university.
3. Special thanks to my colleagues both Indonesian Student Association and Bioprocess Engineering laboratory at Tunghai University that always full support this research.
4. Special dedicates to my family who always given the suggestion and motivation as well as I studied in the master program.
5. All my friends at Tunghai University who have spent the incredible moment for two years.

Finally, I would like to thank everybody who is not mentioned because their guidance, support, and motivation this research could be finished.

Taichung, July 2019

Adi Kusmayadi

ABSTRACT

The present study investigated the effect of light intensity and mixing on microalgae growth in a raceway by comparing the performance of a paddlewheel to a combination of paddlewheel and CO_2 spargers in a 20 L raceway. The increase of light intensity was known to be able to increase the microalgal growth rate. Increasing paddlewheel rotation speed from 13 to 30 rpm enhanced *Chlorella vulgaris* growth by enhancing culture mixing. Simulation results using computational fluid dynamics (CFD) indicated that both the turnaround areas of the raceway and the area opposite the paddlewheel experienced very low flow velocities (dead zones) of less than 0.1 m/min, which could cause cell settling and slow down growth. The simulated CFD velocity distribution in the raceway was validated by actual velocity measurements. The installation of CO_2 spargers in the dead zones greatly increased flow velocity. The increase of paddlewheel rotation speed reduced the dead zones and hence increased algal biomass production. By complementing the raceway paddlewheel with spargers providing CO_2 at 30 mL/min at 20 rpm, we achieved an optical density of 3.83, which was 1.9 times that obtained without CO_2 sparging.

Keywords: CFD, raceway, *Chlorella vulgaris*, paddlewheel, CO_2 sparging

摘要

本研究探討 20 L 軌道中葉片旋轉速度和提供 CO2 流量對於微藻生長的影響，實驗結果顯示了光照強度和增加混合對反應器中微藻生長有正面影響。率。CO2 的提供來增加混合，增加葉片轉速從 13 到 30 rpm 增加了小球藻的生長速度。計算流體動力學（CFD）的流速模擬結果表明，反應器中軌道的轉向區域和與葉片相對的區域都經歷了小於 0.1 米/分鐘的低流速（死區），這可能導致細胞沉降並減緩生長。通過實際速度測量驗證了在跑道中模擬的 CFD 速度分佈。在死區安裝二氧化碳分佈器可以有效的增加混合並提高該區域的流速。葉片轉速的增加也會降低死區的範圍，從而增加了藻類濃度。實驗結果顯示搭配 CO2 30 ml/min 的提供與 20 rpm 葉片轉速，菌體 OD 可以增加至 3.83，大約是沒有額外 CO2(控制組)的 1.9 倍。

关键词：CFD，滚道，小球藻，水轮，CO_2喷射

TABLE OF CONTENTS

LIST OF FIGURE

LIST OF TABLE

CHAPTER 1

INTRODUCTION

1.1 Research background

The threat of global warming has encouraged the development of renewable energy to replace carbon-intensive fossil fuels [1]. Microalgae are a promising source of renewable transportation fuels thanks to their high growth rate, which enables them to double in mass within hours, and their high content of lipids that are used for biofuel production [2]. In addition, microalgae can serve as renewable sources of chemicals used in a wide range of applications, including cosmetics and nutraceuticals [3]. Algal biomass productivity is influenced by light intensity, CO_2 provision, temperature, pH, and nutrient supplementation [4].

The cultivation of microalgae can be conducted in both closed and open systems [5]. Closed photobioreactors (PBR) can provide an environment that fosters fast growth and high biomass productivity, as they allow tight control of cultivation conditions and minimize the risk of contamination. However, their high capital and operating costs are major disadvantages, especially for commodity products, such as biofuels [6]–[8]. Moreover, PBRs are not easy to scale-up, which impedes commercialization [3].

The open system of raceways is often utilized for large scale cultivation of microalgae [9]. It has the simplicity of design and operation and is easy to scale-up [10]. However, adequate mixing in the raceway is required to avoid settling of microalgal biomass that, in turn, leads to lower cell growth and biomass productivity due to limited cell exposure to light and nutrients. Thorough mixing provides good light distribution and nutrient availability, as well as heat dissipation and increased CO_2 utilization, making the process of photosynthesis more effective and leading to higher biomass productivity [11]. The lack of rigorous culture mixing has been reported to lead to cell membrane breakdown for *Spirulina* [12].

As a result, preventing cell settling through thorough mixing is of paramount importance to raceway algae cultivation. Recently, this goal has been aided by the use of computational fluid dynamics (CFD) in the design and operation of raceways [10]. Researchers have investigated the effect of mixing on the hydrodynamics of raceways to minimize energy utilization [7]. CFD simulations have been used to investigate paddlewheel rotation speeds and baffle installation in raceway systems [13,14]. The light/darkness (L/D) cycles applied on microalgae cells cultivated in a raceway based on a Lagrangian particle tracking method have been studied by identifying the cell trajectories and their hydrodynamic characteristics. The results indicate that L/D cycles can be decreased with an increase in paddlewheel rotational speed in the range of 5-12 rpm. Moreover, the introduction of flow-deflector baffles in raceways can greatly increase the light time and the ratio of light time to L/D cycle for microalgae cells [15].

CFD simulations have also been performed on a novel ARID (Algae Raceway Integrated Design) system to obtain velocity profiles [16]. This raceway was positioned on the ground at a small slope, so that water could flow in laterally-laid serpentine channels at a low rate driven by gravitation. The low flow rate of water overflowed the lateral channel walls and mixed with the main flow in the next lower channel, thus creating better mixing. Even in such a complex raceway system, measurements and CFD simulation results matched in a satisfactory way, indicating that CFD simulations are a reliable tool in designing raceways for algae cultivation.

1.2 Objective

The purposes of the present study were to investigate the effect of mixing and the light intensity to achieve the high optical density (OD) and biomass production on microalgae in the raceway system. Initially, the variation of the light intensity was investigated in this research. The performance by comparing mixing provided by a paddlewheel at a variable rotation speed with mixing provided by a combination of paddlewheel and CO_2 spargers was also evaluated. The response parameters measured were the optical density and biomass production. Subsequently, to simulate the flow velocity of microalgal culture at the variation of the paddlewheel rotation speeds was performed by CFD simulation. The results of flow velocity predictions were compared to real velocity measurement using the flow velocity measurement at several points of the areas in the raceway.

1.3 Thesis organization

In Chapter I, the research background, objective and thesis organization were explained. Chapter II, introduces all information on microalgae. Chapter III, review experimental section was utilized in the research such as the materials, instruments, microalgae and the culture of the medium, algal concentrations, the configuration of the raceway system, the velocity and the light measurement. In Chapter IV, the data are shown under the effect of light intensity, the paddlewheel speed, combining paddlewheel and gas spargers on algal growth, and the applied CFD analysis in the raceway operation. In Chapter V, general conclusion was explained are drawn.

CHAPTER 2

LITERATURE REVIEW

2. 1 Microalgae

Microalgae are the group of plants distributed not only in the terrestrial but also in the marine environments. The familiar necessary group of microalgae includes *Chlorophyta* (green algae), *Xanthophyta* (yellow-green algae), *Bacillariophyta* (diatoms), *Rhodophyta* (red algae), *Chrysophyta* (dinoflagellates), and *Eustigmatophyte* (pico-plankton) [17].

Microalgae might be come across all over the world. Microalgae are not only notably spread in the waters but also on the surface of all kind of soils [18]. In everywhere the aquatic microalgae are mostly found from freshwater to salt lakes, with the tolerance condition for pH, temperature, turbidity, O_2, and CO_2 [19].

In general, under good culture condition, microalgae have the composition of protein (30-50%), lipids (8-15%) and carbohydrates (20-40%) [17]. Besides, most species of microalgae contain oil level as 20-50% whilst several species oil content in microalgae such as *Schizochytrium sp.* able to outpace 80% of dry biomass weight. The high of oil in the microalgae is appropriate for the production of biodiesel. It is the main to have the capability to economically yield the number amount of oil-rich microalgae biomass to generate the oil of microalgae [20]. **Table 1** explained that the growth rate and the lipid contents in some microalgae species.

Species	Growth rate (d^{-1})	Lipid contents (% dry wt)	References
Scedesmus	0.54–0.82	30-53	[21]
Neochloris oleoabundans	1.06–1.36	35-54	[22]
Nannochlropsis sp.	0.04–0.72	15-70	[23]
Isochrysis sp.	0.10–0.60	6-50	[24]
Dunaliella viridis	0.22–0.80	17-32	[25]
Chlorella sp.	0.58–0.87	18-66	[26]
Botryococcus braunii	0.24	20–55	[27]

Table 1 The growth rate and the lipid contents in some microalgae species

Actually, the photosynthetic microorganism utilized the water as the source of the electron, sunlight as the source of energy, and CO_2 as a source of carbon. Microalgae count for 50% of photosynthetic that occur on the earth [28]. They will produce oxygen and carbohydrates, protein, and lipids [29]. The reaction of photosynthesis is performed as follow:

$$CO_2 + H_2O + light \longrightarrow (CH_2O)n + O_2$$

The detail of the photosynthetic process in the microalgae had described in [30]. The microalgae perform C3 photosynthesis that is similar to C3 photosynthesis of common terrestrial plants. In C3 photosynthesis the first product of assimilation of CO_2 is 3 carbon sugar, glyceraldehyde-3-phosphate (G3P) [31]. In the process of photosynthesis, the antenna complex of the photosynthetic apparatus is utilized for capturing the light sources and transferring to the neighboring chlorophyll molecules present in the chloroplast. This light energy (four photons) distributes water molecules to reduce four electrons from two water molecules. It results in both H^+ ions and O_2 is liberated as a by-product. For completing the reaction of photosynthesis a total of 8 photons are obtained. This process yields ATP (adenosine triphosphate) and NADH. ATP (with NADPH) is employed as the source of energy to fix the CO_2 to three carbons organic compound, glyceraldehyde-3-phosphate (G3P). The three carbon sugar (G3P) in the chloroplast is transformed into starch and saved as the large granules as long as photosynthesis. The innumerable enzymes locating in the chloroplast control the biochemical reactions of photosynthesis. G3P from them the chloroplast stroma is dispatched into the cytosol to provide as the basis for the biosynthesis of any organic molecules and metabolites. Basically, several G3P will be utilized for the biosynthesis of carbohydrate, several G3P molecules are converted into pyruvate for protein synthesis and some G3P are utilized for fatty acid synthesis for the accur … ı is used … ıed in **Fi**

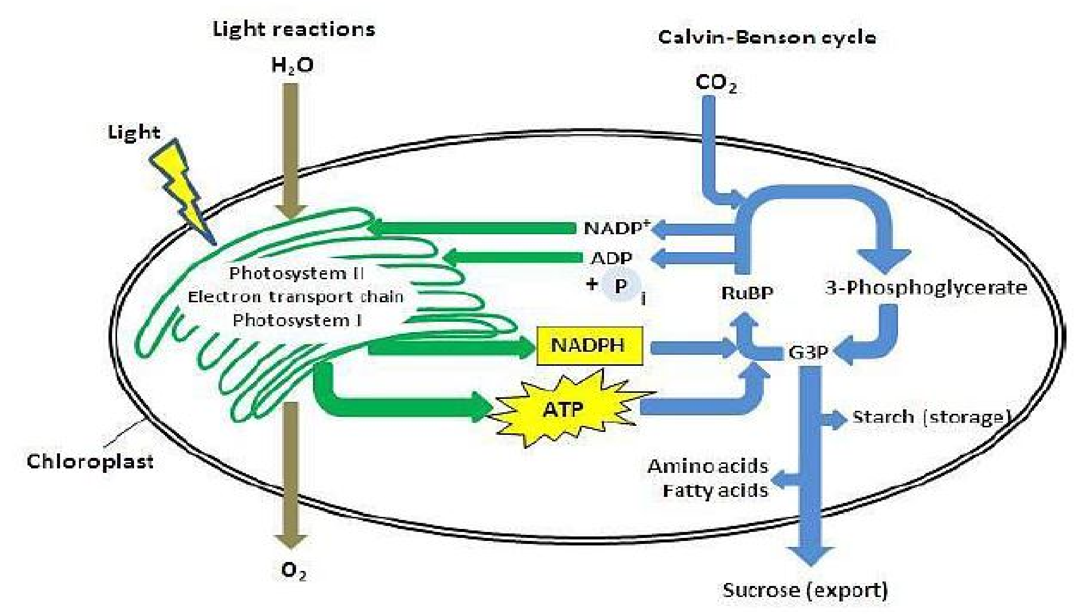


Figure 1 The conversion of solar energy into chemical energy by oxygenic photosynthesis in the chloroplast [32]

Additionally, microalgae have a wide range of applications in various industries including, pharmaceuticals, cosmetics, bioremediation, aquaculture feed, bioplastics production, nutraceutical (nutritional ingredients), high-value molecules like pigments, and also as nutritional supplements for humans and animals [33]. The application of microalgae in various fields is presented in **Fig 2**.

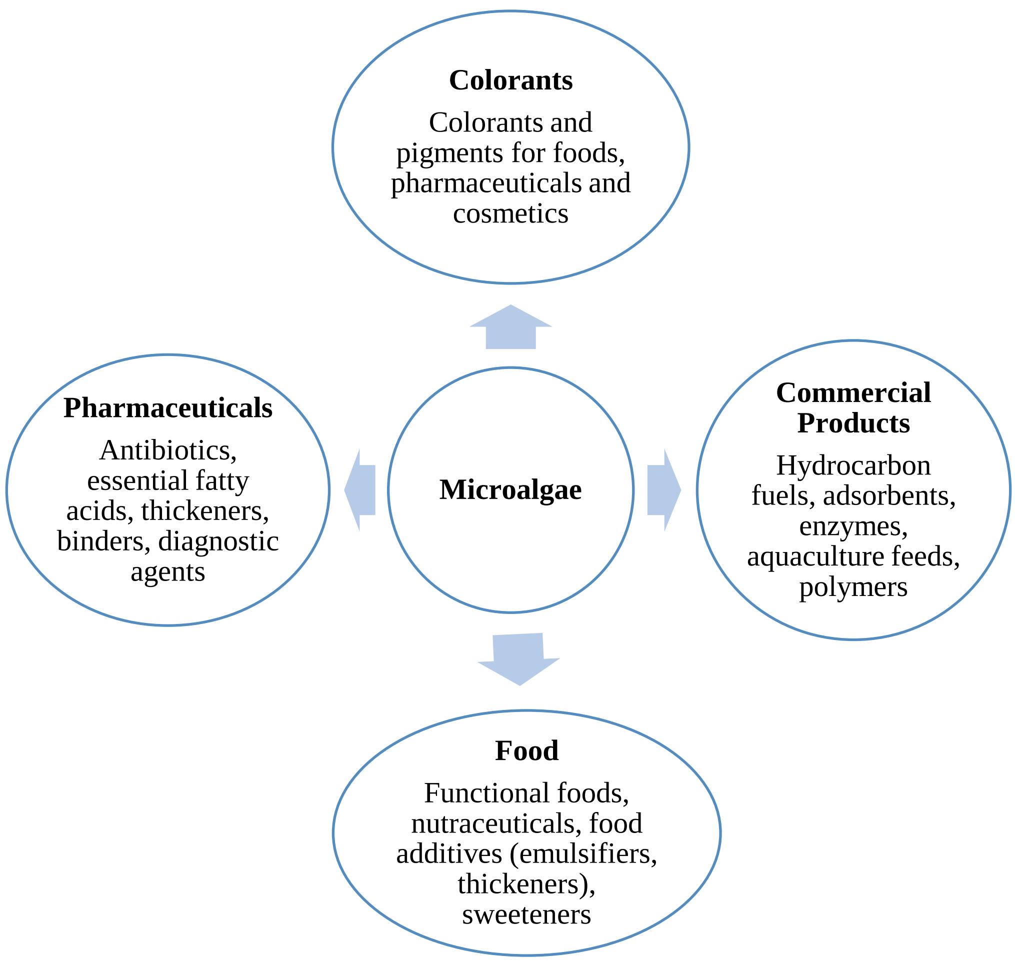


Figure 2 The application of microalgae in various fields. Modified from [33]

2.1.1 *Chlorella Vulgaris*

Microalgae reflect the plentiful biodiversity from 40.000 are explained or analyzed [17]. One of the types of microalgae is familiar in the green microalgae namely *C. vulgaris*. Basically, the name of *Chlorella* origins from the Greek word *chloros*, it's meaning green, and the Latin suffix Ella has the meaning of microscopic size. The microalgae are unicellular microalgae growing in fresh water and already performed since the period of 2.5 billion years ago [34].

C. vulgaris has the spherical microscopic cell with 2-10 μm diameter and is without flagella [35], [36]. The structural elements of *C. vulgaris* are similar to the plants and also it contains the pigments chlorophyll-a and –b in its chloroplast. The process of photosynthetic might make the multiplies rapidly, needing carbon dioxide, water, sunlight and the small the number of minerals to reproduce [34]. The Schematic ultrastructure of *C. vulgaris* representing different organelles shown in **Fig 3**.

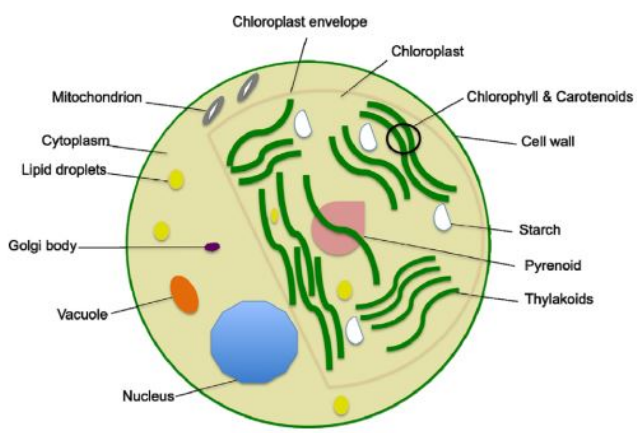


Figure 3 Schematic ultrastructure of *C. vulgaris* representing different organelles [34]

Basically, it contains the main elements such as glycolipids, waxes, hydrocarbons, phospholipids, and small amounts of free fatty acids [17]. They will be synthesized by the chloroplast locating on both cell wall and organelle membranes. Therefore, in favorable term of growth conditions, the producing of lipids (especially triacylglycerols) will achieve 58% [37]. The magnified of *C. vulgaris* is shown by **Fig 4**.

C. vulgaris is in most cases most utilized for large-scale production of microalgae inasmuch as its capacity is not only rapidly growing but also convenient to cultivate [38] and withstand to a contaminant [39]. In addition, another characteristic of *C. vulgaris* is both competitive nature under distinct growth conditions [40] and tolerance toward pH range of between 5 and 10 [41]. Actually, *C. vulgaris* already cultivated since 1950 [42] and is generated by more than 70 commercial factories [43].

The biomass of *C. vulgaris* involves about 50-58% protein, 12-17% carbohydrate and 14-22% lipids [44]. In other studies confirmed that in under nutrient poor, the lipid compounds are about 14-25% [23]. Moreover, the compound of lipid up to 58% of dry weight can be reached [45].

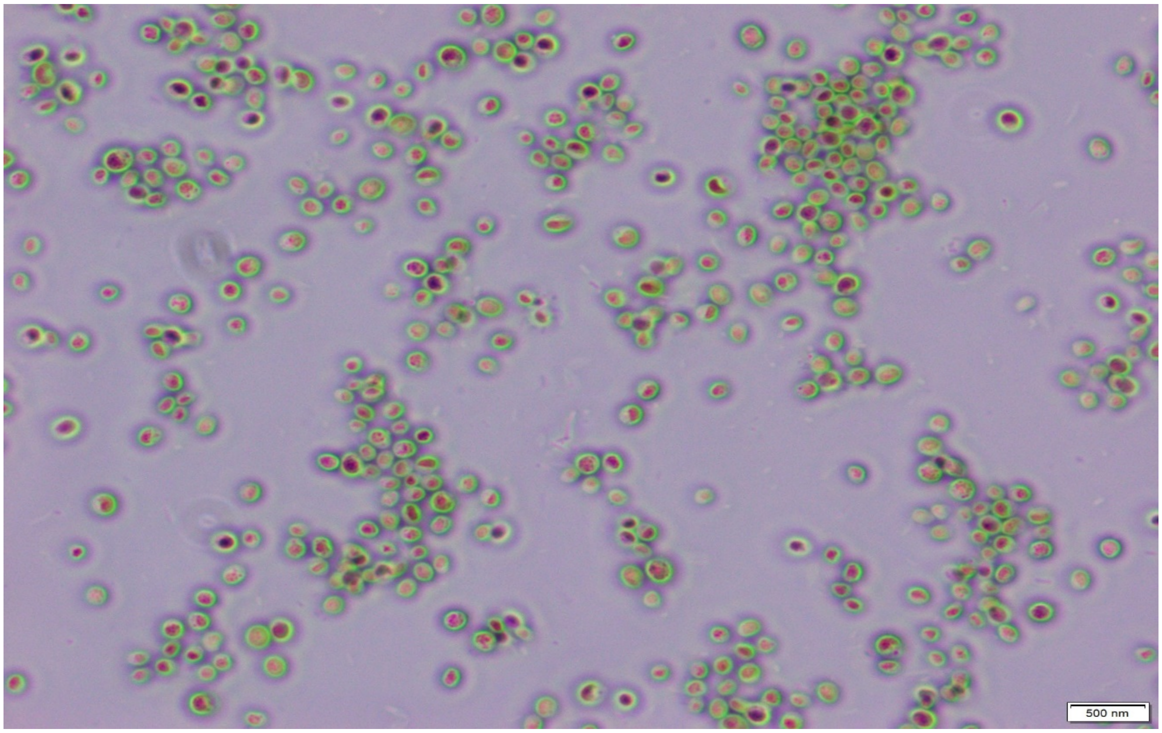


Figure 4 Magnified details of *C. vulgaris*

2.2 Rheology-related factors affect the cultivation of microalgae

2.2.1 Light availability

Light energy significantly influences the cell growth and biomass production in a photoautotrophic microalgal cultivation system since light is essential for photosynthesis [46]. Both low exposure to light and excessive irradiation can negatively influence cell growth rate by decreasing the level of certain proteins [46]. The wavelength range of solar radiation that can be optimally utilized by microalgae is in the range of 400-700 nm. This is also called photosynthetic active radiation (PAR). The geographical location of the cultivation system can affect the intensity of influent solar irradiation [47]. The peak of sunlight intensity at a tropical location can be as high as 2000 µE m^{-2} s^{-1}, but photosynthesis saturates at 10-20% of the peak PAR value. Therefore, photosynthesis rate does not attain the optimal theoretical rate [48].

The ability of microalgal cells to receive light in a raceway system relies on the turbulent area, pond depth, and biomass concentration due to the specific degree of light attenuation and movement of cells between photic and dark zones [49]. The culture near the surface of the raceway experiences photoinhibition or light saturation, but light limitation occurs deeper in the culture vessels. Nevertheless, the shallow nature of raceway ponds will aid the culture to receive optimal light. Lambert-Beer's Law equation describes the intensity of light as the function of the distance to the surface in a raceway system [50].

$$I_L = Io e^{-ka\, CxL},$$

where Io is light level on the surface of the raceway system; ka is the microalgae-dependent light absorption coefficient of the biomass; Cx is the concentration of biomass; L is the depth from the surface, and I_L is the local irradiance.

2.2.2 Temperature

Temperature is one of the environmental factors which affects the growth of microalgae as it is related to the activities of many enzymes and metabolites [49], [50]. In addition, temperature highly affects respiration and photorespiration than photosynthesis. Increase in the temperature will significantly increase respiration, but the flux through the Calvin cycle increases only marginally. Therefore, the increase in temperature decreases the efficiency of photosynthesis. This effect can influence the suspension cultures by the difference in the decrease of CO_2 and O_2 solubility at elevated temperatures [51]. The temperature range for optimal microalgal growth rates is between 20^oC - 25^oC for mesophilic species, up to 40^oC for thermophilic strains and up to 17^oC for psychrophilic strains [52].

2.2.3 CO_2 sparging

Carbon is one of the major nutrients that constitute around 50% of microalgal biomass by weight. It is utilized for respiration, as an energy source, and as the building blocks for the generation of new cells during cell division [52]. Being photosynthetic in nature, microalgae usually use CO_2 as the source of carbon, supplied as pure CO_2 or an air-CO_2 mixture [52]. The production of 1 kg of microalgal biomass requires approximately 1.5 to 2 kg of CO_2 [53]. In addition, sodium bicarbonate ($NaHCO_3$) can also be used as a carbon source. It maintains the medium pH conditions as well [54]. Higher CO_2 concentrations lead to growth inhibition, while lower concentrations limit cell growth. Therefore, the range of CO_2 concentration suitable for optimal microalgal growth is from $2.3x10^{-2}$ M to $2.3x10^{-4}$ M [55].

One of the environmental global issues in this decade is emerging from CO_2 emission. The plentiful studies have conducted research for reducing CO_2 emissions. One approach is using CO_2 as a source of carbon for cultivation the microalgae [41]. Microalgae are able to rapidly grow in the waste waters containing the valuable compounds [56]. The types of microalgae utilized for the mitigation of CO_2 are *C. vulgaris* [54], *Botryococcus braunii* [57] and *Scenedesmus* sp. [17]. The flue gas of industry contains 10-20% CO_2 and the microalgae tolerance to the high concentration of CO_2, and toxic compound (NOx and Sox) are *Nannochloris* sp and *C. vulgaris* [58].

2.2.4 Medium pH

The culture pH can significantly influence the growth rate of microalgae and alkaline conditions promote better carbon capture, producing high biomass. With an increase in pH, CO_2 will dissolve in water to form HCO_3 which is the predominant form of CO_2 in weakly alkaline solutions. Several microalgal species are sensitive towards culture pH value, hence it might define the dominant species in mixed cultures. The optimal pH for microalgal growth is in the range of 7-8 [56]. The chlorophyll content will decrease when the pH increases to 8.5 - 9.5[57].

2.2.5 Culture media

a. Nitrogen

Nitrogen is the most notable element that was obtained for microalgae nutrition. It will give for approximately 5-10% of cell dry weight (103) and is a necessary component of whole structural and functional proteins in microalgae cell [59]. Innumerable studies explained that nitrogen-limited give the effect for increasing the accumulation of lipids [59]. The pH of the medium is related to the assimilation of nitrate and ammonia so that the pH will change with the phenomena of nitrogen absorption. When ammonia is utilized as the only nitrogen source, the pH of the medium will exsiccate [60].

b. Phosphorus

Phosphorus is one of the primary macronutrient that has the necessary role in the metabolic process to form the enormous structural and functional constituents which is obtained for the growth of microalgae. The main form where microalgae obtain phosphorous is as inorganic phosphate, either as H_2PO_4 or $HPO^{2-}{}_4$. Each species of microalgae has phosphorus tolerance of optimum concentration in the medium but the average tolerance is about 50 μ g/L-20 mg/L [60].

2.3 Microalgae culturing in open system

Open systems for microalgal cultivation have been extensively utilized in the past few years [61]. The most common open systems are unstirred shallow ponds, stirred circular ponds, and paddlewheel stirred raceway ponds. The design for open systems is shown in **Fig 5**.

Open systems are generally used for commercial microalgal cultivation and are accepted for biofuel production because of several advantages. The primary benefits of open cultivation systems are lower production costs than closed systems or photobioreactors and the fact that they are relatively convenient to maintain and easy to scale up [62]. Nevertheless, the main limitations of such systems are water loss by evaporation, poor light utilization, diffusion of CO_2 to the atmosphere, large land requirements, and the fact that they are highly prone to contamination [63]. In addition, the mass transfer in this system is relatively poor due to the inefficiency of the stirring mechanism, thereby resulting in lower biomass productivity [63]. Table 5 shown detail of comparison of microalgae cultivation in open raceway and photobioreactor.

A few alternative ways to optimize open systems involve using wastewater and reclaimed water as the medium, recycling water and nutrients, complete and proper use of the entire microalgae biomass, use of indigenous strains for cultivation, and optimization of harvesting techniques [64]. The comparison of microalgae cultivation in open raceway and photobioreactor is shown in **Table 2**.

Table 2 Comparison of microalgae cultivation in open raceway and photobioreactor

Factor	Open Raceway	Photobioreactor
Risk of contamination	High	Low
Biomass productivity	Low	High
CO_2 utilization	Low	High
Cultivation of large scale	Yes	No
Light	Natural	Artificial/Natural
Cost of operation	Low	High
Cost of capital	Low	High

Figure 5 Open systems: (A) raceway pond, (B) circular pond, (C) unstirred pond [65]

2.3.1 Circular pond

Circular ponds are one of the open microalgal cultivation systems that have been often utilized in South East Asia for the culture of *Chlorella sp* and wastewater treatment [37], [66]. Generally, the diameter of the circular pond is up to 45 m and 0.3-0.7 m in depth, with a pivot agitator in the center. The design of circular ponds is limited to less than 10 ha because of the improper mixing provided by the rotating pivot arm. Actually, this system has efficient mixing if compared with the unstirred system, but it has the potential of contamination. The main of drawback with this cultivation system is both the shortage the temperature control and vulnerable algal to the parasite and another kind of microalgae overcoming the weaker strains [67].

In recent years, some studies used the difference of impeller for cultivation in this system. The widely used impeller in industrial production, especially in South China, is grid plates. Because of the strongly the axial flow mixing is in the three-blade hydrofoil impeller and four-pitched blade turbine (PBT) agitators so that they usually are implicated in the industrial applications [68].

A lot of companies in Taiwan and Japan use the circular pond for the cultivation of *chlorella sp* to generate β-carotene [69]. The entangling of a hydrofoil impeller with the down-flow operation can optimize biomass concentration of *Chlorella pyrenoidosa* about 65.2 and 88.8 % higher than those of grid plate (with double arms and four-pitched-blade turbine) in the circular pond [70]. The cultivation of *Oscillatoria* in circular ponds using diluted wastewater attained biomass productivity of about 15 gm^{-2} d^{-1}, with 80% ammonia removal and 50% total organic carbon from the wastewater [2].

2.3.2 Unstirred pond

The unstirred pond is the simplest open system for the cultivation of microalgae. It establishes in the natural water having the half meter of the depth for the permeability of the light with the absence of the stirring unit [67]. This system is usually fit to build at the lagoon ponds or lakes. It is the most economical method of all commercial culture methods. The disadvantage of this cultivation of microalgae is the limiting of microalgae growth, for a carbon dioxide dissolution from the air to water. Another shortage of this system is extremely poor mixing so that the lack of mass transfer, distribution of nutrient and light, even they are obtained for the photosynthesis process of microalgae [67]. It is being used commercially for several of microalgae species such as *Dunaliella salina* [2]. In Australia, unstirred ponds are utilized for the cultivation of *Dunaliella salina* for β-carotene production. Dried microalgal biomass from natural lakes in South-East Asia contributes to more 30 ton $year^{-1}$ [66].

The application of unstirred pond is solely restricted to the kind of microalgae which have the ability of aggregation in poor conditions. In addition, it can overcome several contaminants such as protozoa, other microalgae, viruses, and bacteria that give influence to pH and alkalinity of culture medium [71]. Some the ways to solve the culture contaminations such as the filtration of water might to bring down the certain kind of contaminants, covering the raceway with translucent membranes to avoid the contaminants and placing the screen in the water flow with the fitly sized so that the heavy contaminants will be drowned to the bottom and then it might be removed from the sediment traps [72]. Several industries have developed methods for the cultivation of microalgae in unstirred ponds to yield the product of interest [73]. For instance, the industry in Whyalla, South Australia generates about 7 to 10 tons $year^{-1}$ β -carotene in 460 ha open ponds and the industry in Hutt Lagoon, Western Australia also generates about 6 tons $year^{-1}$ β -carotene in 250 ha.

2.3.3 Raceway pond

Since 1950, raceway ponds have been used for microalgae cultivation. It is built as a single unit or as a group of continuous units joined together. The depth of raceway ponds is normally limited to 15-40 centimeters. The raceway channels are probably constructed in concrete or compacted earth or lined with plastics. The paddlewheel, pump, and airlift drive water continuously for agitation and circulation of the mixture to avoid sedimentation of microalgal culture [65]. The main factor in the design and operation of a raceway system is the mixing efficiency that optimally exposed microalgae cells to sunlight and CO_2. A velocity setting at 10-20 $cm.s^{-1}$ is effective for preventing the microalgal cells from deposition and settling. If the mixing is poor, it will generate inadequate oxygen removal during active photosynthesis. If the mixing velocity is greater than or equal to 30 $cm.s^{-1}$, the energy inputs are extremely high [2]. A lot of studies have reported successful microalgal cultivation in raceway systems and some of them are summarized in **Table 3.**

Cyanotech Corporation in USA has the largest number of raceway units (> 60), each of which is around 2.900 m^2. They also declared that a cell concentration of up to 1 gram dry weight per m^2 per day can be reached and productivities of 10 to 25 grams dry weight per m^2 per day are achieved [69]. The productivity of biomass in the raceway system yielded about 60–100 mg dry weight L^{-1} d^{-1} [74]. On the other hand, the main challenge for reaching the optimal productivity for microalgae is to maintain the temperature and incident sunlight intensity [2].

Basically, the most popular that was utilized open systems for commercial of microalgae cultivation is raceway, for it is lower construction and the costs of maintenance [75]. Another reason making the raceway is most commonly used due to in the raceway has the paddlewheel for mixing not only to expose the cells of microalgae to sunlight and CO_2 so that the photosynthesis is more optimal but also avoiding microalgae sedimentation. In addition, inefficient mixing in the circular pond and no mixing in the unstirred pond have the poor mass transfer rates so that produced the low biomass of microalgae [76].

Table 3 Mass cultivation of microalgae in the raceway

Strain	Design of raceway	Focus of study	Reference
Spirulina platensis	0.7 m in length, 0.075 in depth, 0.2 m width	The cultivation of *Spirulina platensis* in open raceway	[77]
Botryococcus braunii	1.13 m in length, 0.3 in depth, 0.6 in width	The cultivation of green alga *Botryococcus braunii* in open raceway	[78]
Chlorella sp	1.5 m in length, 0.7 m in depth, 1 m in width	The cultivation of *Chlorella sp* in open raceway	[79]
Graesiella sp	20 m in length, 0.2 m in depth,12 m in width	Effective cultivation of a novel oleaginous microalga *Graesiella sp*. WBG-1	[80]
Scenedesmus sp	1.13 m in length, 0.2 m in depth, 0.9 in width	Influence of water depth on *Scenedesmus sp* production	[71]
Isochrysis galbana	1.4 m in length, 0.3 m in depth, 0.4 in width	Raceway pond design for *Isochrysus galbana* culture for biodiesel	[81]
Nannochloropsis. salina	3.66 m in length, 0.65 m in depth, 1.31 m in width	Effect of outdoor conditions on *Nannochloropsis salina* cultivation	[82]
Phaeodactylum. tricornutum and Isochrysis. galbana	300 m in length, 0.3 in depth, 1 m in width	A dynamic optimization model for designing open-channel raceway ponds for algal biomass	[83]
Chlorella vulgaris.	7.5 m in length, 2.5 m in width	Unveiling algal cultivation using raceway ponds for biodiesel production	[84]

2.4 Environmental effect on microalgae culture using open raceway system

2.4.1` Evaporation

Evaporation is one of main concern with the cultivation of microalgae in the dry tropical district is the high rate of evaporation from the surface of the raceway system up to 10 L/m2/day. The location that usually was selected to build the microalgae plant has to the plenteous source of fresh or low salt content makeup water. In another hand, the specific tropical areas having the monsoon rains might inhibit the culture dilution, hence removal nutrients and microalgae biomass might occur. Therefore, the pond has to been accomplished with the overflow spillways and to serve covered deep retention ponds into that the cultures to be able pumped tentatively [60].

2.4.2 Climate

The climatic conditions also give negative effects on the temperature of medium cultivation. The condition of low air humidity and the high of evaporation will have a cooling effect on the medium. The medium will heat up until $40^{o}C$ in the condition of both the high relative air humidity and no winds, this condition will make the lethal of microalgae. Therefore, the convenient areas to be chosen for the cultivation of microalgae is the location having the average humidity below 60% [18].

2.5 Important design aspects of the open raceway system

2.5.1 Mixing and energy consumption

The mixing is one of the main element in the raceway system. Good mixing will provide some advantages such as enhancing the distribution of the light to the cells so that the photosynthesis process is to be optimal, preventing the sedimentation of microalgae, the good distribution of carbon dioxide and nutrients, and the removal of photosynthetically resulted oxygen and so on [72]. Therefore, it will result in biomass productivity of microalgae around 10 fold [1].

The power consumption is obtained depending on the flow velocity, the depth of raceway and the performing of baffles [73]. The range of power consumption in the open raceway is about the 1.5-8.4 Wm^{-3} [73]. The operating of raceway at 20 cm depth is another way to go easy on energy loss [74]. The energy consumption will increase if the depth of raceway will increase or decrease from 0.2 m [85]. If the ends of the raceway system are installed the semicircular flow deflector baffles, it can minimize the energy consumption [86]. Besides, the increase of baffle number in raceway system also enhances the energy consumption, but the insufficient baffles will reduce the mixing and lead to the reduction of cells growth rate in raceway system [73].

2.5.2 Depth

The depth relates to the temperature, the efficiency of light utilization, the good mixing, and energy consumption so that has the main role in obtaining the optimized productivity of microalgae [2]. It leverages not only the amount of light but also the intensity of microalgae cell exposed to get maximum light [49]. This study investigated that obtaining the optimal biomass productivity at the low-level the depth [71]. The depth at 20 cm resulted in the highest biomass production, for the water permeability of the sunlight. The penetration will decrease with the increase in water depth. The depth at 20 cm resulted in approximately 38% higher biomass and also needed lower nutrients and power consumption than that of the depths at 30 cm and 40 cm [71]. Moreover, the microalgae biomass in the raceway system of the depth under 20 cm generalized the higher settle ability that the settling ability is about 83.6% within 5 min [71].

Therefore, the water depth becomes the crucial parameter in the raceway system design for the cultivation of microalgae.

2.5.3 Bend geometry

Energy is needed to circulate the paddlewheel for mixing the fluid especially at the bends and causes the energy will be a loss [87]. The design of raceway has to solve the dead zones developing near the midst wall downstream of bends due to they will enhance the improvidence of energy and remove the holding capacity of the pond [1]. Two approaches for designing of the bend to be taken into consideration for instance the keeping channel width the same, but lineal the flow to the outer side of the bend by varying the depth from superficial in the center to deep at the outside, and cramping the channel width and enhancing the depth, but maintain the depth uniform across the width [87].

2.6 Computational fluid dynamics (CFD) modeling in open raceway system

2.6.1 General concept

Computational fluid dynamics (CFD) is a powerful tool used to analyze fluid flow, heat and mass transfer, chemical reactions, and related phenomena [61], [88]. There are physical and chemical indicators in the CFD software display that can be used to develop process system models. This software also can be utilized to simulate a variety of conditions as well as the liquid and gas flows in turbulent and laminar regimes, heat transport, chemical reactions, multiphase flows, and the interactions of fluids and solid structures. As a result, CFD makes it possible to predict the performance of new designs before they are tested for their performance [88].

CFD has numerous applications in many industries, including aeronautics, automotive, building HVAC (heating, ventilation, and air conditioning), petrochemicals, energy/power generation, process engineering, oil and gas, product design, optimization, and turbomachinery, among many others. Besides, the application of CFD also has several advantages and limitations that were shown in **Table 4**.

CFD has numerous benefits compared to experimental optimization, particularly time and economic resources. In fact, it has commercial codes as well as STAR-CD, PHOENICS, CFX, FLUENT, and others, with three principal tasks, which are as follows:

- **Pre-processing**

  This step is the learning and characterization of a problem, including geometric illustration, the building of fit grid, adding the chemical and physical characteristics of the phenomenon, estimation of materials and boundary condition.

- **Solving**

  This step is to solve the mathematical equations that establish the system. This software will resolve the equations by adjusting the meshing and estimating the model input until the admirable convergence is reached. This step will perform equation discretization, integration of equation and the implication of the boundary condition, and this is time-consuming due to the repetition of calculations to achieve a thorough analysis.

- **Post processing**

  The next step after getting the results is to analyze the simulation result. The software can visualize fluid properties, the track of particles and study numerous particular variables at certain points in the regime. Some of the popular post-processing software include ANSYS CFD-Post, EnSight, FieldView, ParaView, Tecplot 360 and so on.

  Basically, CFD has the strong ability to simulate the flow pattern in the complicated conditions [89]. To achieve the goals such as reducing the cost of production and improving the high productivity of microalgae has to consider several factors such as the water loss and make-up, the management of salt (especially for the culture of marine), and the management of thermal [7]. CFD is utilized for analyzing the cultivation of microalgae in the photobioreactor, hence the ability of this software is suitable to optimize the simulation of two-phase turbulent flow in several applications of engineering especially the chemical engineering. In recent years, some studies carried out the simulation of CFD in the cultivation of microalgae using the raceway system [4,7,88].

To make the model CFD is more precision for simulation so that need to validate it with the data of the experiment. The purposing of this way is useful for determining a few parameters namely, the paddlewheel velocity, the medium depth, the design of construction, and the great operating conditions in the raceway system. Nevertheless, the effective strategy depends on good modeling of not only drag coefficients but also momentum exchange among the phases of liquid and gas [52]. In addition, the implementation of CFD modeling in the raceway system generally includes explaining the geometry and mesh generation, setup of the model, the run of simulation and the results post-processing.

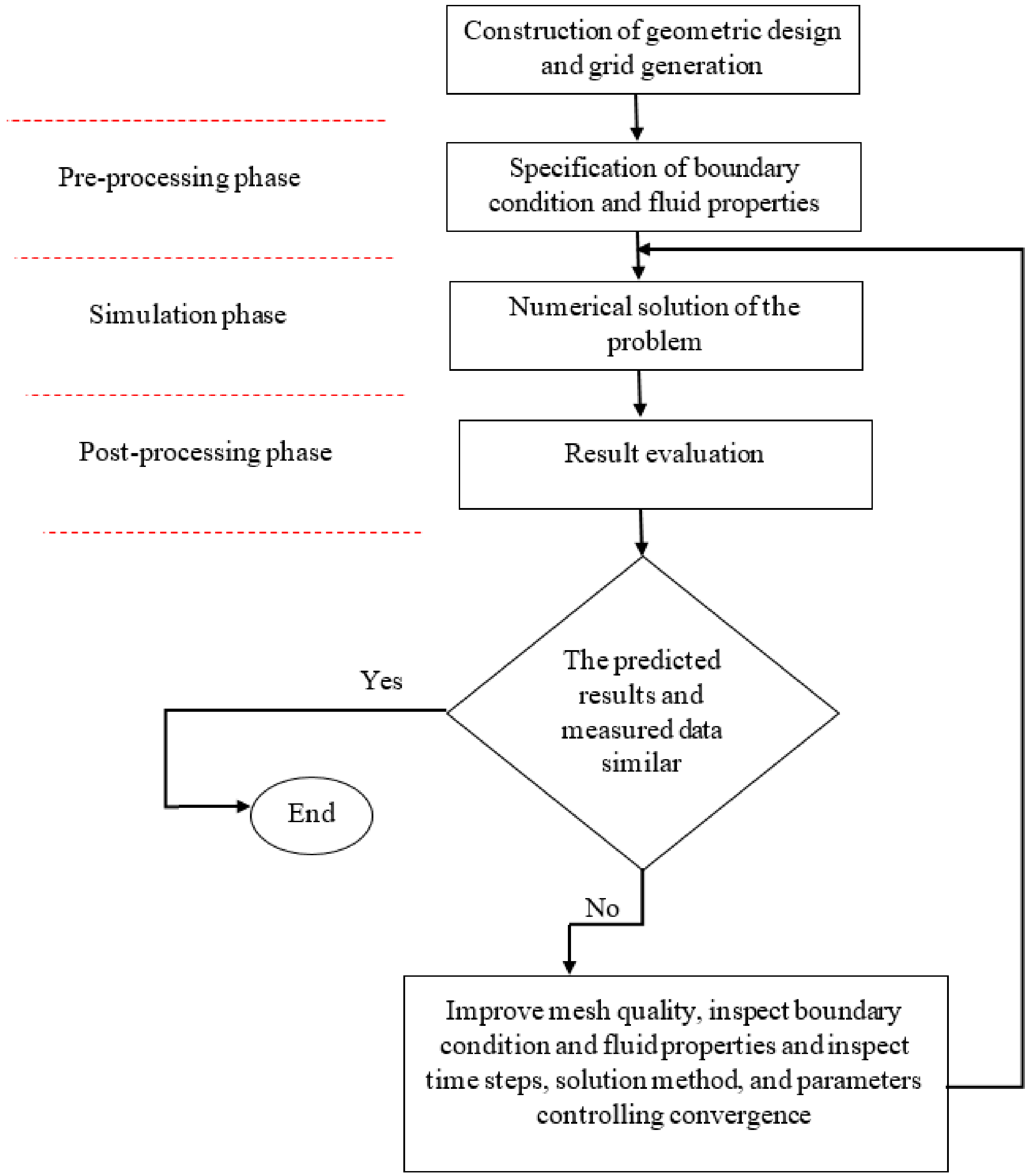


Figure 6 CFD modeling

The improving of CFD results can be governed by increasing of the number of cells in the grid. The optimal meshes are non-uniform. The good mesh is built in the areas in which the spacious variations happen from spot to spot and a coarser grid is utilized in the regions with the relatively slight change.

Table 4 Advantages and limitations of CFD application

Advantages	Limitations
1. The physical boundary of the system can be considered in disconnection type. 2. The simulation can provide the calculated data at some specific location points within the system that cannot be measured by the device. 3. A lot of flow parameters can be collected from the simulation results before performing the practical experiments. 4. The simulation results can contribute to more	1. The deviations of simulation results from the real data might be significant for the simple flow pattern and for the undermined boundary flow. 2. All the characteristics of microalgal cells have been assumed to be the same, including the light availability. Whereas the real microalgal cell had different characteristics. 3. It could spend much simulation time for the

understanding of flow problem than that of the experiments	complex model. A supercomputer might be required for such a complex model.
5. The time and cost consuming is lower than that of experiments	

2.6.1 Turbulence fluid dynamics model in CFD

Turbulence plays a vital role in the movement of microalgal cells in raceway ponds, and it also influences light distribution. Turbulence is taken into account for precise prediction of the hydrodynamics in the raceway system, along with other factors such as grid resolution and the turbulence model preference. The Reynolds-averaged Navier-Stokes (RANS) model is commonly used for a multiphase turbulent reacting flow simulation in a raceway system. There are three methods for liquid-gas turbulence simulations: the dispersed turbulence model, the mixture turbulence model, and the per-phase turbulence model. However, they use the same model constants but have distinct equations to estimate the turbulence viscosity [76]. The dispersed turbulence model is a turbulence model that utilizes the eddy viscosity model or the Reynolds stress model for modeling liquid phase turbulence, where the low flow is usually conducted so that the gas phase is assumed to be in a laminar regime. The two-phase k-ε model is the turbulence model used to determine the set of k and ε transport equations for each phase [88]. The mixture k-ε is convenient to use since the phases separate for terraced multiphase flows, and the value of the density ratio between phases is about 1.

2.6.2 Multiphase fluid dynamics model

Computational fluid mechanics has advanced and can provide useful insights into the dynamics of multiphase flows. Three multiphase simulation approaches are commonly utilized for hydrodynamics, which includes the Eulerian-Eulerian, the Lagrangian-Eulerian, and volume of fluid approaches.

2.6.2.1 Eulerian-eulerian approach

This approach uses the mass and momentum equation to solve the solid and fluid phases and volume fraction. However, if the phases are either dispersed or continuous, they will be solved using a single pressure field. The Eulerian multiphase model enables the modeling of multiple, separate, yet interacting phases. The phases can be liquids, gases, or solids in almost any combination. In addition, the Eulerian approach is utilized for each phase, different from the Eulerian-Lagrangian approach, which is utilized for the discrete phase model. The interaction term, attraction force, and the virtual mass effect will be used for making the interaction model between the average flows of phases. This approach is convenient for modeling systems with liquid-liquid or liquid-gas phases, and its various applications include aeration boilers, evaporation, and separators. On the other hand, this approach is not recommended for stratified free-surface flows due to its need for a precise explanation of the interface boundary.

2.6.2.2 Lagrangian-eulerian

In this approach, the influence of small-scale motions around individually dispersed phase particles is solely modeled circumstantially while viewing the particle motion in the dispersed phase. In addition, the Eulerian and Lagrangian frame is used for modeling particle movement in the continuous and dispersed phases. The modeling in the continuous phase requires detailed information, thereby the operation of putting particle trajectories in the flow will be conducted to get some information for the model establishment. Moreover, this approach is appropriate to simulate the reaction, mass transfer, and heat processes for each particle. The simulation of a huge number of particle trajectories will be held in the turbulent flow to obtain valuable averages. This approach, therefore, is also fit for the simulation of dispersed multiphase flow that has a low volume fraction of approximately $<10\%$ of the dispersed phase. To improve the simulation of the raceway with CFD, the studies approached the modeling for the growth of microalgae in raceway utilizing the Lagrangian particle tracking enabling the establishment of the accepted light scheme in the association with Han's model of both photo production and photoinhibition [69].

2.6.2.3 Volume of fluid (VOF)

This method can be used to estimate whole phases of fluids by formulating local and instantaneous conservation equations for mass, momentum, and energy. Using a boundary at the interface is a way to solve the local instantaneous conservation equations, but it cannot solve the interface between diverse phases. Therefore, this method will track the motion of the whole phases. Various volumetric forces are needed to displace whole interfacial phases. This approach is limited solely to several dispersed phase particles that can be modeled. Therefore, it is not an appropriate approach for use in a simulation of dispersed multiphase flows in huge equipment because the estimation of the flow process in each dispersed phase particle involves the use of enormous computational resources. This method gives much valuable information that can improve the other models, such as the Eulerian-Lagrangian and Eulerian-Eulerian methods.

CHAPTER 3

EXPERIMENT SECTION

The outdoor raceway was performed on a large scale to create the biofuels. The microalgae cultivation was influenced by the mixing, light intensity, CO_2, nutrients, and temperature. A few studies investigated the optimal effect of mixing and the light intensity for microalgae cultivation in the raceway. These effects were tested in this research as the primary of experimental purposes. Moreover, using CFD simulations were explored to calculate the flow velocity of the microalgal culture in the raceway. These CFD simulations were developed and its performance compared to actual velocity measurement. This chapter explained the microalgae and the culture of the medium, the configuration of the raceway system, and CFD modeling of the velocity profile.

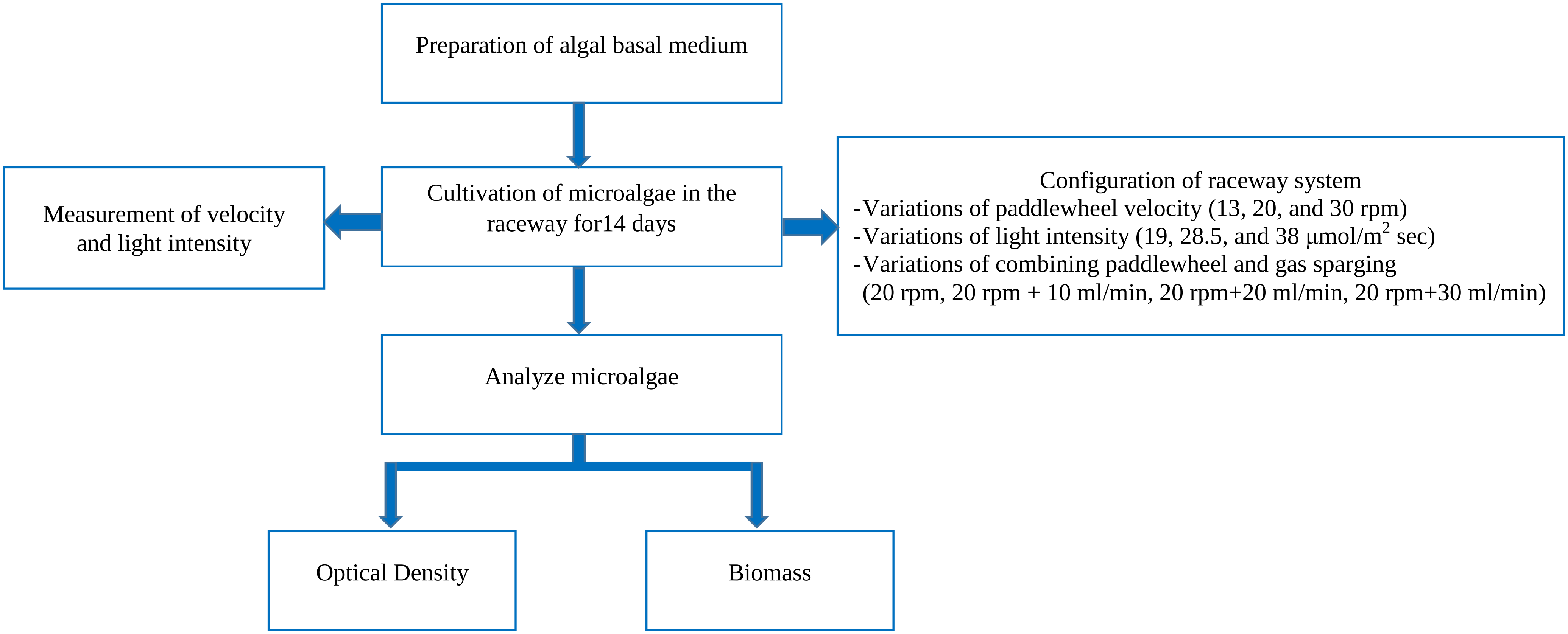


Figure 7 Schematic of research

3.1 Materials

Table 5 Materials

No	Materials	Source/Vendor
1	KNO_3	Tokyo Chemical Industry
2	KH_2PO_4	Showa Chemical
3	$MgSO_4.7H_2O$	Showa Chemical
4	EDTA	Showa Chemical
5	H_3BO_3	Showa Chemical
6	$ZnSO_4.7H_2O$	Strem Chemicals
7	$FeSO_4.7H_2O$	Osaka Hayashi Pure Chemical
8	$CaCl_2.2H_2O$	Showa Chemical
9	$MnCl_2.4H_2O$	Tokyo Chemical Industry
10	MnO_3	Steam Chemicals
11	$CuSO_4.5H_2O$	Showa Chemical
12	$Co(NO_3).6H_2O$	Showa Chemical

3.2 Instruments

Table 6 Instruments

No.	Instruments	Specification
1	Spectrophotometer	Model Genesys 150, Thermo Fisher Scientific Corporation
2	Moisture Meter	Model MA-35 Moisture Analyzer, Denver Instrument Corporation
3	The velocity measurement device	Model FW450, JDC Corporation
4	The light intensity measurement	Model LI-1400, LI-Cor Incorporation

3.3 Microalgae and the culture of medium

The strain utilized in this study was *Chlorella vulgaris*, which was kindly provided by professor Jo-Shu Chang, National Cheng Kung University, Taiwan. Algal basal medium was used to cultivate the microalgae in the raceway system. The cultivations were performed at room temperature of 25-30℃. The composition of the algal basal medium will be presented in **Table 7**.

Table 7 The composition of algal basal medium

No.	**Component**	**Component Concentration (g/l)**
1.	KNO_3	1.25
2.	KH_2PO_4	1.25
3.	$MgSO_4.7H_2O$	1.00
4.	EDTA	0.5
5.	H_3BO_3	0.1142
6.	$ZnSO_4.7H_2O$	0.0882
7.	$FeSO_4.7H_2O$	0.0498
8.	$CaCl_2.2H_2O$	0.111
9.	$MnCl_2.4H_2O$	0.0142
10.	MnO_3	0.0071
11.	$CuSO_4.5H_2O$	0.0157
12.	$Co(NO_3).6H_2O$	0.0049

3.4 Algal concentrations

Algae concentration was determined using optical density. 10 mL sample was collected from the raceway system and placed in a spectrophotometer (Model Genesys 150, Thermo Fisher

Scientific Corporation). The culture's absorbance (optical density) at 560 nm was monitored and used moisture analyzer (Model MA-35 Moisture Analyzer, Denver Instrument Corporation) to measure of biomass concentrations. The spectrophotometer and moisture meter were shown in **Fig 8**.

(A) (B)

Figure 8 (A) Spectrophotometer (B) Denver Instrument (Moisture Meter)

3.5 Configuration of the raceway system

The experiments were conducted in a lab-scale raceway system made of fiberglass with dimensions of 50 cm length x 30 cm width x 14 cm depth. The paddlewheel was constructed of stainless steel and consisted of 4 blades with 18 cm length and 10 cm width. The paddlewheel velocity for mixing was set at 13, 20, and 30 rpm for 14 days. All the raceway experiments were carried out with 20 L of medium resulting in a culture depth of 7 cm. Continuous light intensity was provided by using 2-4 fluorescent lamps at 9.5 ($\mu mol/m^2.sec$) each lamp. Over that period measurements of light penetration, algae concentration by optical density, and fluid velocities were made. The cultivation of microalgae and design of raceway were shown in **Fig 9** and **10**.

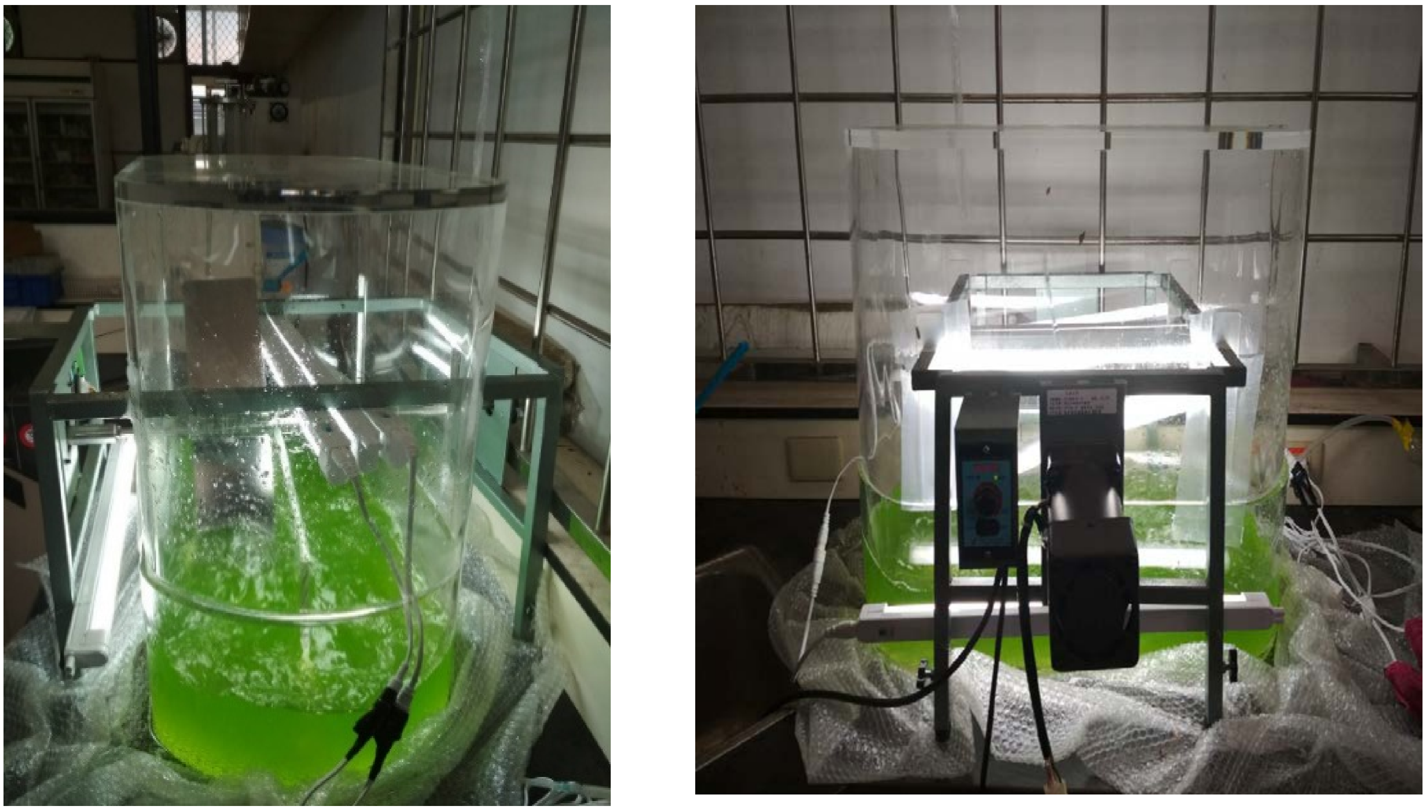


Figure 9 Cultivation of microalgae

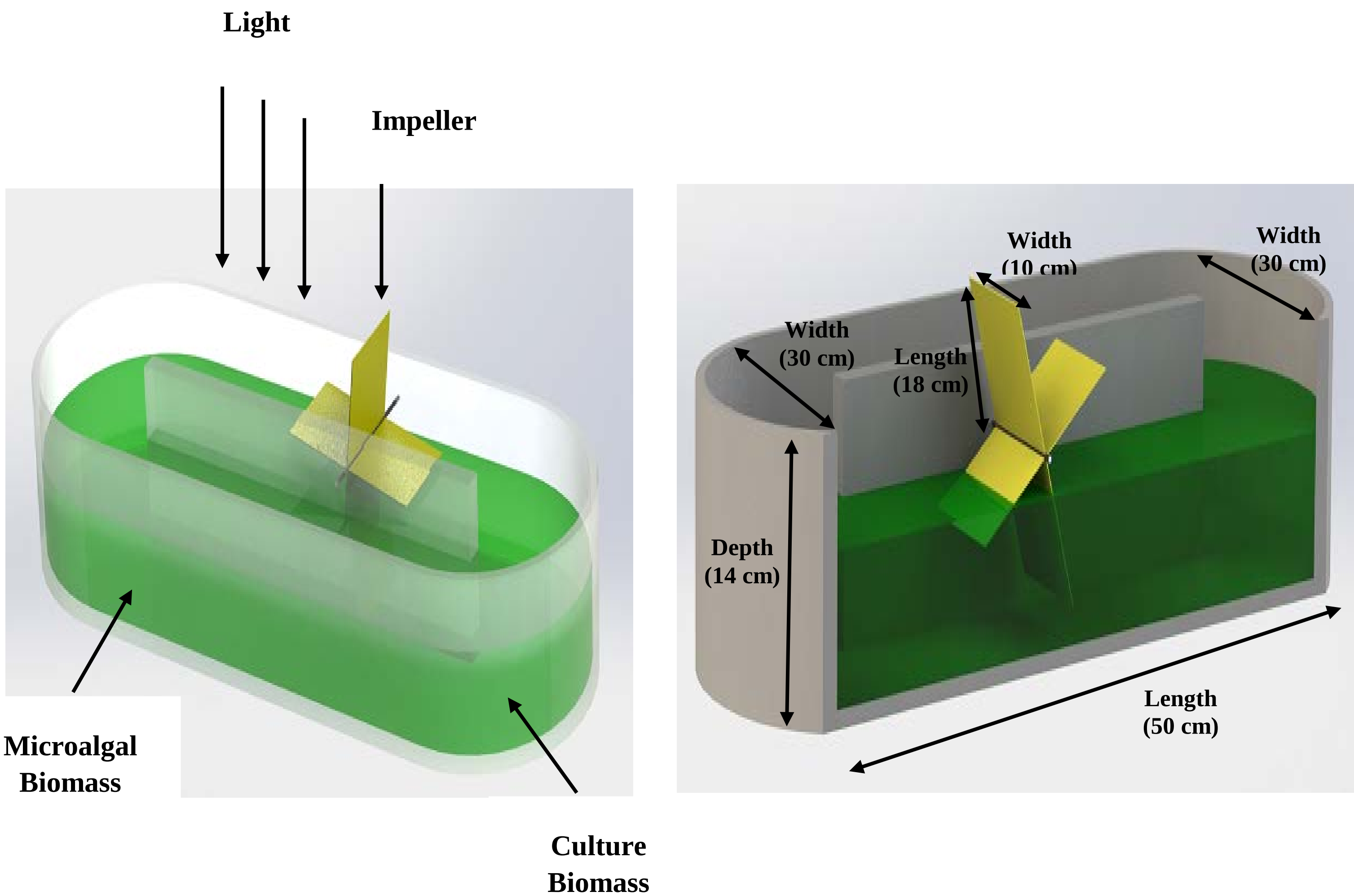


Figure 10 Design of raceway

3.6 Velocity measurement

The flow velocity measurement device (model FW450, JDC Corporation) is an accurate measurement device for water flow and air speed, as well as temperature. It is water proof, has a backlight, and can be set to measure average speed between 3 seconds and 24 hours. The impeller is magnetized, producing a magnetic field when rotating which is passed through the cable to the display unit. This velocity measurement was utilized to determine the velocities at 6 specific locations without algal biomass in the raceway system as shown in **Fig 11**. The velocity measurements were conducted at the top surface, middle of depth and the bottom. In order to examine the ability of the measured velocities, the measurement was repeated three times.

Figure 11 The velocity measurement device (model FW450, JDC Corporation)

3.7 Light measurement

The light measurement (model LI-1400, LI-Cor Incorporation) in **Fig. 12**, was utilized in this experiment to determine the light intensity at the water surface, middle and bottom in the raceway at the six specific locations. The units of this light device are μmol $m^{-2}.s^{-1}$. The fluorescent light intensity was measured in to examine the effect of microalgal growth on the light available.

Figure 12 The light intensity measurement (model LI-1400, LI-Cor Incorporation)

3.8 CFD modelling

The CFD package ANSYS 19.2 was employed to simulate algae culture flow in the raceway system. The CFD simulation required the construction of a geometric model in the ANSYS Design Modeler. The raceway system was divided into a paddlewheel movement zone and a culture medium zone, which intersect at the cylindrical interface [90]. The tetrahedral structural mesh was selected in ANSYS Design Mesh with 209.960 nodes and 183.615 elements for the simulation [91]. The mesh was divided into two parts: a sliding mesh for the cylindrical area surrounding the paddlewheel and a stationary mesh for the remaining domain of the computation. **Fig 13** presented geometry and mesh of the raceway system. The simulator used a multiphase model to attain steady state and select a transient simulation. The turbulent flow was calculated by a standard k-ε turbulence model, which was selected because of its wide range of applications. The volume of fluid (VOF) method is commonly used to track the free interface of water and air with a coefficient of surface tension of about 72 mNm^{-1} at 25°C. The selection of the QUICK scheme was discretized for convective terms and the diffusions terms were central-differenced. The setting of time size in the solution tab of the ANSYS FLUENT was 0.01 s [92]. Finally, the walls a [illegible] on.

The sc [illegible]

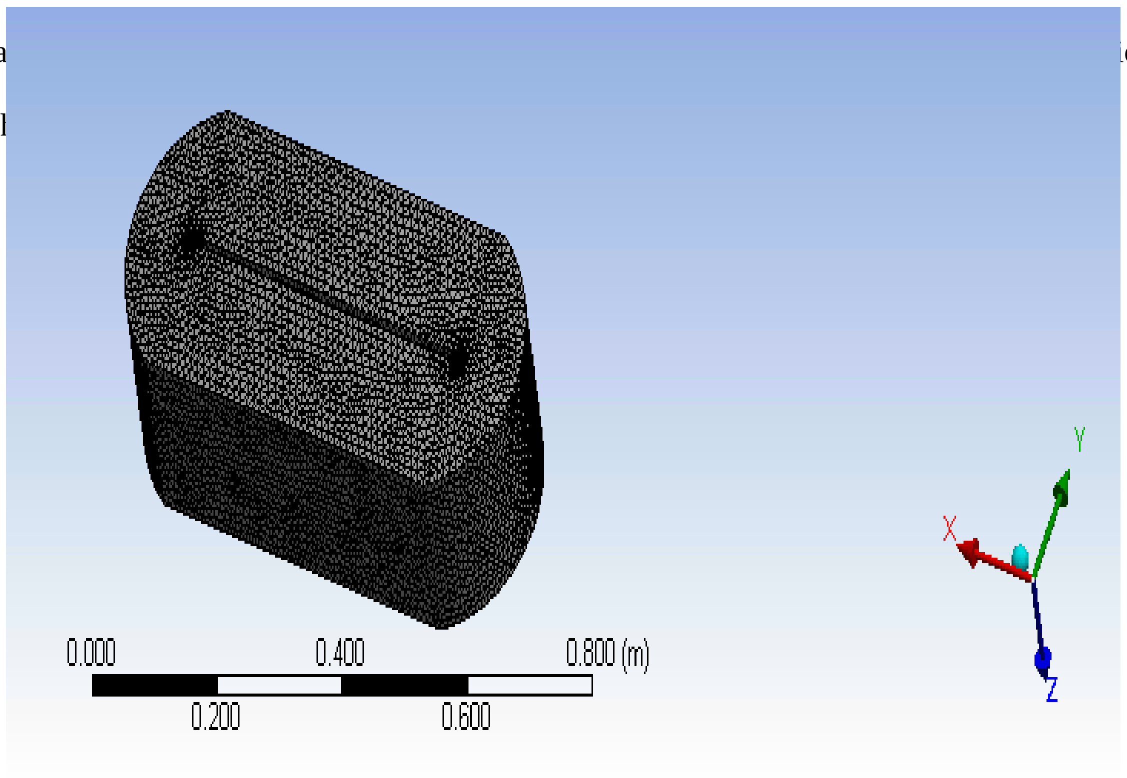


Figure 13 Geometry and mesh of the raceway system

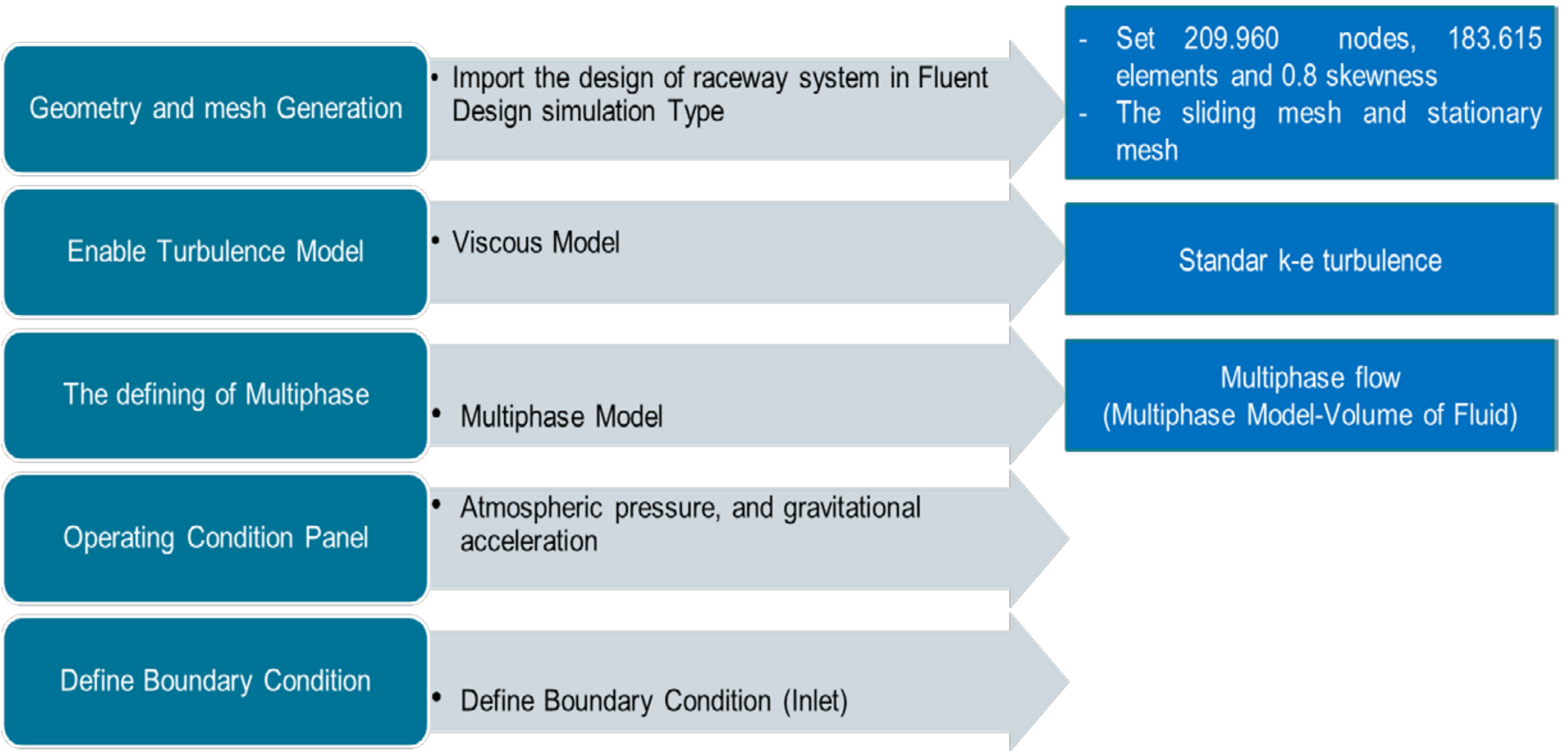


Figure 14 CFD Modelling

CHAPTER 4

RESULTS AND DISCUSSION

These results explained the effect of the light intensity and mixing to achieve the high optical density (OD) and biomass production on microalgae in the raceway system. The simulations of CFD are compared with the fluid flow at the paddlewheel rotation in the real raceway systems. This chapter is hand out into four sections explaining this study. The first part elucidated the details algal growth with the different of light intensity. The second part performed the effect of paddlewheel in the raceway system. The third part clarified the combining of paddlewheel and gas sparging on algal growth. The forth part demonstrated the CFD application in the raceway operation.

4.1 Effect of light intensity on algal growth in a raceway

For the growth of microalgae, the effect of light intensity on the microalgal concentration is significant while the light intensity is less than the saturation level. The dimensions of the raceway, in general, are relatively shallow but with wide illumination surface as compared to the characters of the stirred tank. Therefore, while providing sufficient light intensity can significantly enhance the growth of microalgae. In stirred PBRs, the light availability of microalgal cultivation usually switches between the photosynthesis (near the surface) area and light-limitation areas (down to the bottom), while mutual shading of cells causes the steep gradients to decrease of light intensity [93]. Therefore, the effects of light intensity on the growth of *Chlorella* in a raceway were examined in this study.

As shown in **Fig 15** and **16**, the growth and biomass of *Chlorella* in this raceway can be obviously enhanced by the increase of light intensity at 20 rpm of paddlewheel speed. The final biomass concentration will be almost proportional to the light intensity within the range of 19 to 38 μmol/m^2 sec. The results indicated that the light intensity will be the critical factor in the raceway operation with the fixed paddlewheel rotation speed. Even the paddlewheel can only provide the horizontal flow that might be not sufficiency for the vertical flow. And also the maximum light intensity providing of 38 μmol/m^2 sec providing in this study has not achieved the saturation level. Therefore, the increase of light intensity will be almost proportional to the biomass concentration. Algal cultures become photoinhibited once the PAR value exceeds the saturation threshold. It was reported the rate of photosynthesis does not increase beyond photosynthetically active radiation (PAR) value of about 100–200 μmol/m^2 sec and all the excess light is wasted [94]. An increasing incident irradiance level generally increases raceway productivity, as the local irradiance level in the broth declines rapidly with culture depth and a high surface irradiance generally means a larger illuminated culture volume.

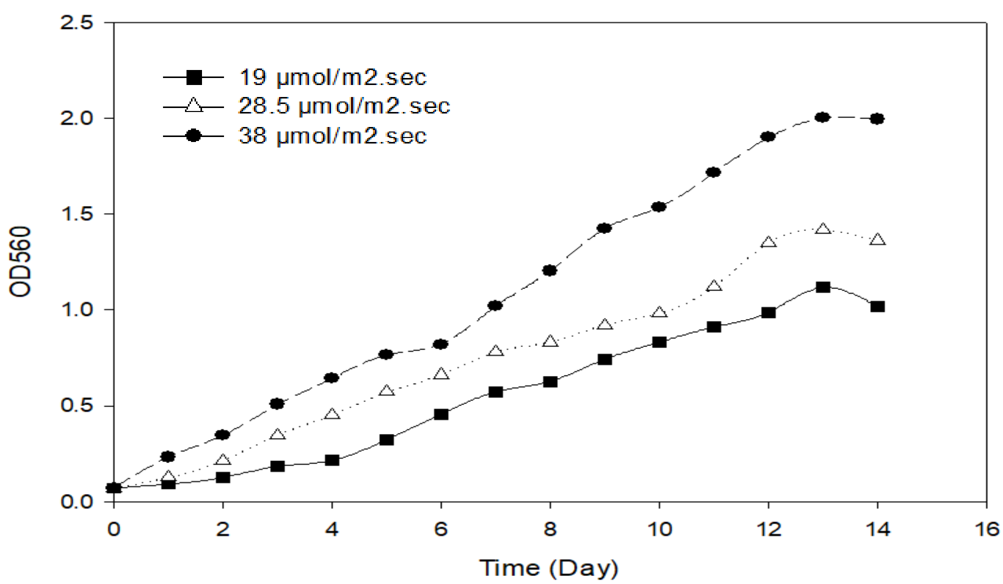


Figure 15 OD with different of light intensity on *C. vulgaris* growth in the raceway

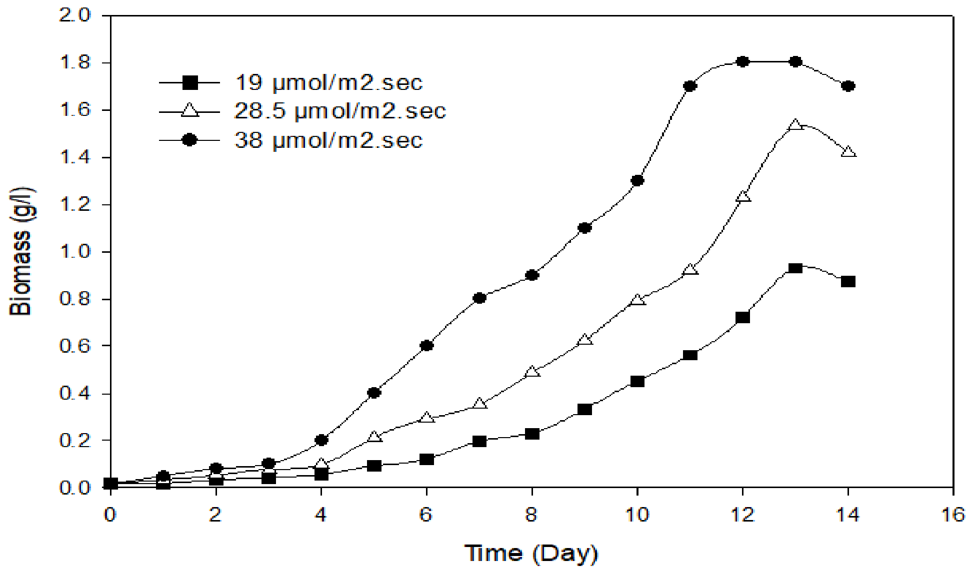


Figure 16 Biomass with different of light intensity on *C. vulgaris* growth in the raceway

4.2 Effect of the paddlewheel on the growth

In the raceway operation, the paddlewheel rotation speed is an important parameter due to the requirement for hydrodynamic flow across the length of the raceway to support the growth of microalgae. Thorough culture mixing enhances CO_2 dissolution and prevents the cells from settling to the bottom of the raceway, which leads to poor growth due to light and nutrient limitations. Three paddlewheel rotation speeds were tested at 13, 20, and 30 rpm and the results are shown in **Fig 17 and 18**. The paddlewheel rotation speed of 30 rpm resulted in the highest terminal OD_{560} of 2.1 (about 1.85 g/L of dry biomass), which is higher than that obtained at 13 rpm and 20 rpm. Apparently, high rotation speed leads to intense hydrodynamic flow and potentially better CO_2 dissolution in the culture medium that enhances cell growth. Higher speeds, however, may lead to culture overflow outside the raceway and will incur higher energy consumption, which will increase operating costs at commercial scale. To reduce energy consumption in raceway cultivations, researchers have tried to modify the paddlewheel design to enhance flow dynamics and cell growth [6]. As a result of inclining the paddlewheel blades by 15 degrees, *Chlorella pyrenoidosa* achieved a higher growth rate in a raceway than with a traditional paddlewheel. Maximum attained biomass concentration was 11% higher at 0.92 g/L and areal productivity was 17% higher at 11.89 $g/m^2/day$ [6].

Our results suggest that stronger mixing resulting from high paddlewheel rotation speeds can enhance cell growth. They are in agreement with previous reports on the need to enhance nutrient distribution in the culture and prevent cell settling and shortage of light and carbon dioxide [69]. In addition to growth inhibition resulting from insufficient mixing, it has been reported that oxygen supersaturation can also lead to a reduction in biomass productivity in raceways [73]. To avoid oxygen accumulation in the culture, CO_2 sparging can be used during raceway operation to rapidly remove oxygen. As mentioned previously, increasing paddlewheel rotation speed has its limitations from a flow and energy consumption standpoint. As a result, we next examined the introduction of CO_2 spargers at several points in the raceway to assess the effect of a combination of horizontal and vertical mixing on microalgal growth.

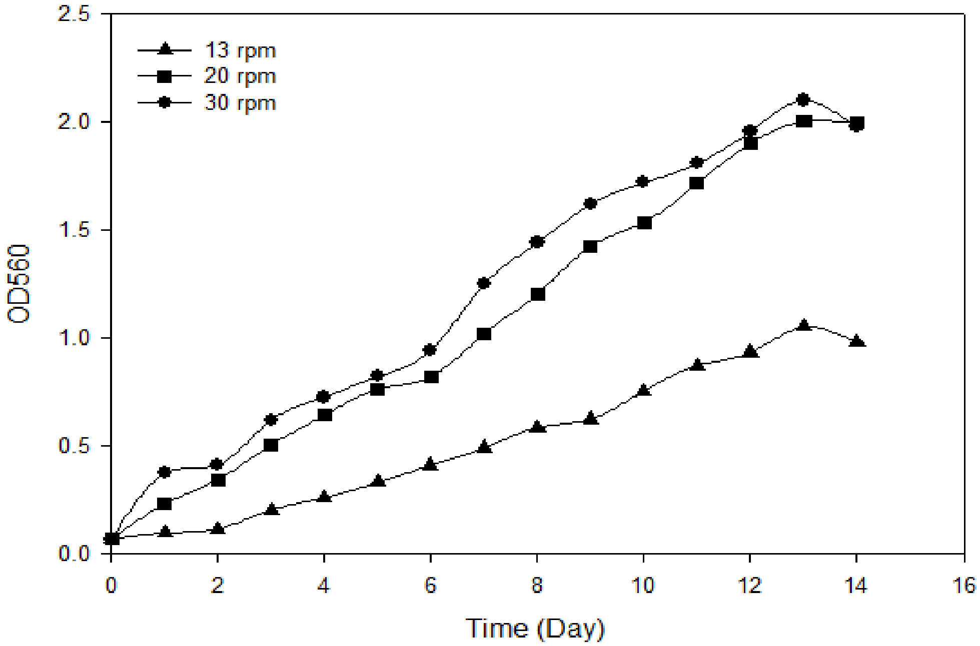


Figure 17 OD with different of paddlewheel on *C. vulgaris* growth in the raceway

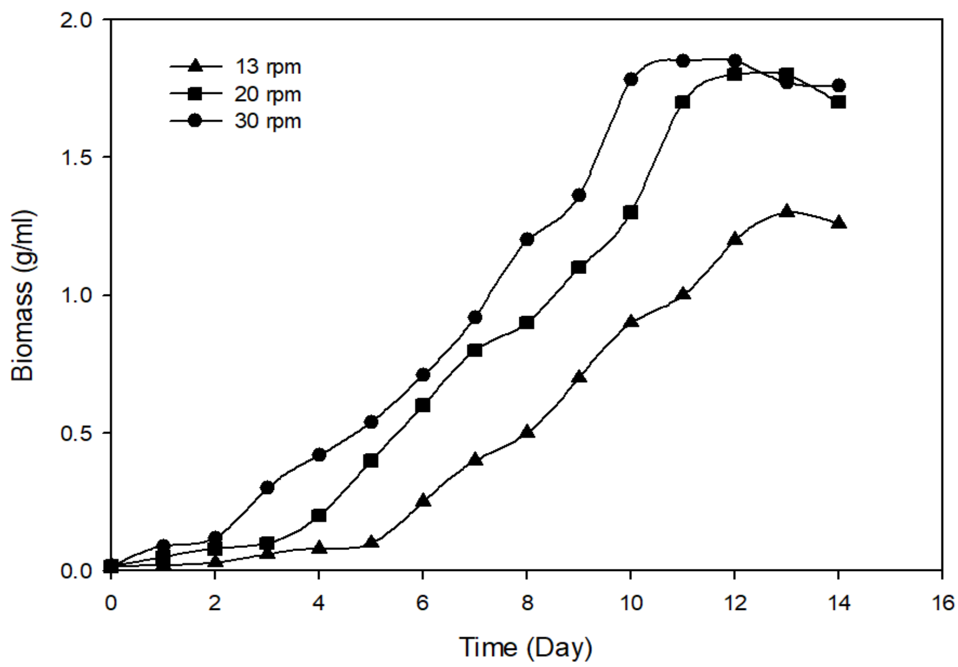


Figure 18 Biomass with different of paddlewheel on *C. vulgaris* growth in the raceway

4.3 Effect of combining paddlewheel and gas sparging

Two CO_2 spargers were installed in the two areas of the raceway with the lowest flow rate, (turnaround area of the raceway after the paddlewheel and on the side of the raceway opposite the paddlewheel) as shown in **Fig 21**, as identified by the CFD simulations presented in the next section. This way, in terms of mixing, the horizontal culture flow created by the rotation of the paddlewheel was complemented by the vertical flow force of the gas spargers, as intense mixing in the raceway can lead to the higher growth rate of microalgae [12]. Nevertheless, excessive shear stress can cause increased cell mortality, decreased growth rate and cell viability, or even cell lysis. For the strain-*Chlorella* used in this study, the tip-speed of 0-5.89 m/s is the suggested range of shear stress [95].

In this part of the study, the paddlewheel rotation speed was fixed at 20 rpm. The two gas spargers were supplied with a mix of air and CO_2 and were operated at 5 mL/min pure CO_2 each (total 10 mL/min of gas), 10 mL/min (total 20 mL/min), and 15 mL/min (total 30 mL/min). The results of the rotational speed of paddlewheel at 20 rpm with CO_2 sparging at total 10, 20 and 30 mL/min of gas. As seen in **Fig 19 and Fig 20**, the introduction of CO_2 spargers enhanced cell growth significantly. A maximum OD of 3.83 was obtained at 30 mL/min CO_2, as compared to 2.84, 2.32, and 2.0 in the raceway runs with 20, 10, and 0 mL/min CO_2 sparged and the maximum biomass of 2.52 g/l was obtained at 30 mL/min CO_2, as compared to 2.33, 2.1, 1.8 in the raceway runs with 20, 10, and 0 mL/min CO_2 sparged respectively. Hence, providing CO_2 at the selected two areas of the raceway appeared to have a noticeably positive effect on cell growth, which is in agreement with cell growth enhancement reported in the literature [11]. Vertical mixing influences microalgal growth as it affects the frequency at which cells will travel from the bottom of the raceway (dark zone) to the surface of the raceway (light zone), which is crucial for photosynthetic efficiency. Efforts have been reported on designing raceway ponds in ways that enhance vertical mixing and CO_2 residence time [69]. It should be noted that given the shallow depth of the culture in our raceway (7 cm), sparged CO_2 at low flow rates does not have sufficient residence time in the liquid culture to dissolve and become available to the cells. This may be the reason why at 10 mL/min CO_2 the cell OD_{560} achieved was statistically indistinguishable from that without any CO_2 sparging.

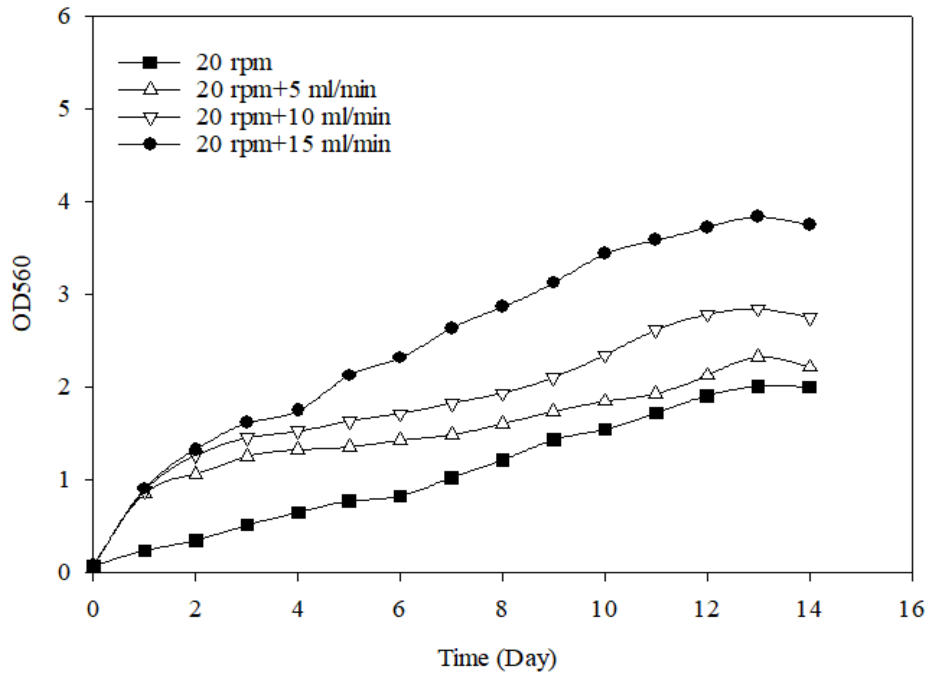


Figure 19 OD with the combined effect of paddlewheel (at 20 rpm) and spargers at various CO_2 flow rates on *C. vulgaris* growth in the raceway

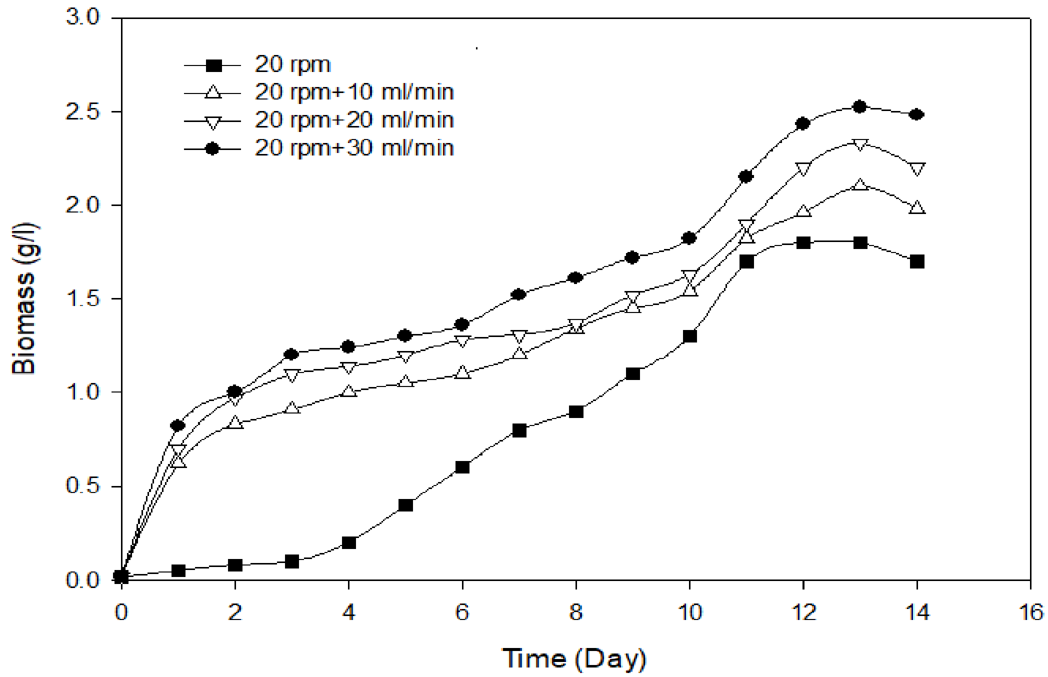


Figure 20 Biomass with the combined effect of paddlewheel (at 20 rpm) and spargers at various CO_2 flow rates on *C. vulgaris* growth in the raceway

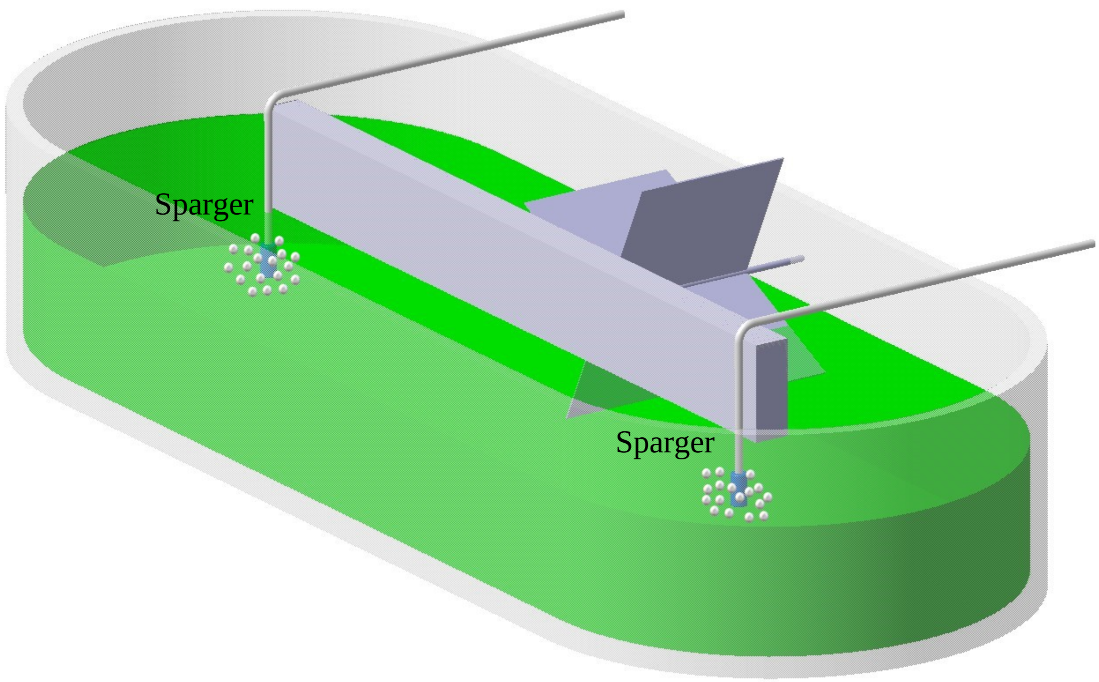


Figure 21 The combining paddlewheel and sparger in the raceway

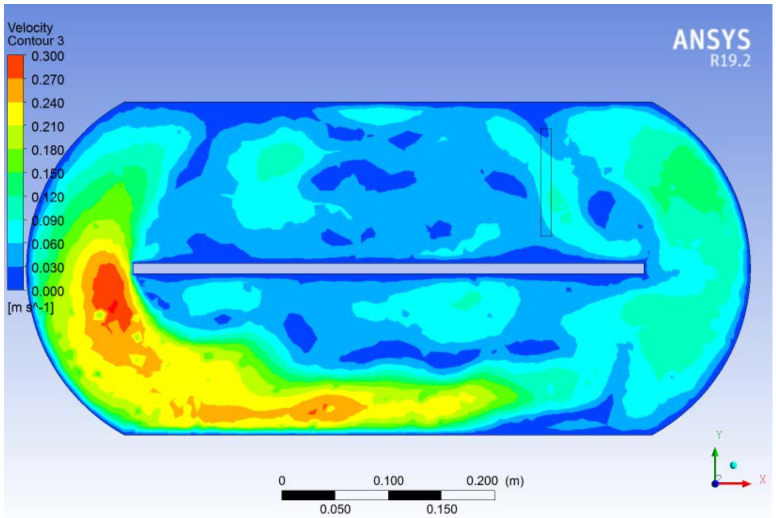
4.4 The applied CFD analysis in the raceway operation

Given the complexity of fluid flow in a raceway, CFD simulations were performed to calculate the flow velocity of the algal culture throughout the raceway at various paddlewheel rotation speeds. The flow velocity predictions of the CFD model were compared to actual velocity measurements taken with the use of a flow velocity meter at several points in the raceway. The results of the validation of CFD results with flow meter measurement results performed in **Table 8**. As shown in **Fig 23**, the correlation between predictions (y) and measurements (x) was strong, respectively. Hence, the CFD-simulated depiction of the raceway appears to provide a good representation of its actual operation. The CFD simulations were conducted at five settings of paddlewheel speed (13, 20, 30, 40 and 50 rpm) and the resulting flow velocity profile of the raceway is shown in **Fig 22**.

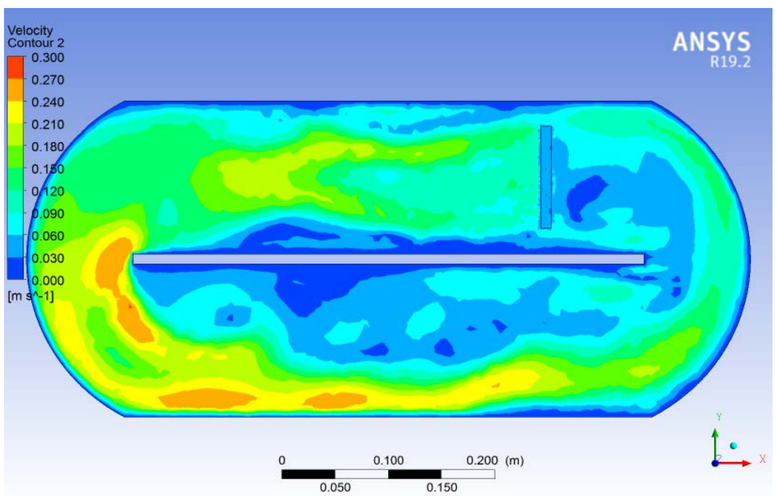
As seen in **Fig 22**, the areas with the slowest velocity, less than 0.1 m/s, are located in the turnaround area of the raceway after the paddlewheel and on the side of the raceway opposite the paddlewheel. A minimum channel velocity of 0.2 m/s has been suggested to ensure that the velocity everywhere in the raceway is sufficient to keep the cells suspended in the culture [94]. Areas having a fluid velocity of less than 0.1 m/s have been termed "dead zones", as cell settling may occur there due to the inadequacy of culture flow to maintain cells in suspension [7], [86]. In such dead zone, cell growth rate will be retarded due to insufficient light intensity and possibly limited nutrient availability. Therefore, CO_2 provision through spargers and the resulting vertical mixing can play an important role in enhancing cell growth [96].

As clearly seen in **Fig. 22**, increasing paddlewheel rotation speed decreases the dead zone areas (blue areas), especially in the turnaround area of the raceway. Due to friction at the bends of the raceway, flow velocity drops in the turnaround area. This drop, in turn, results in low velocities also in the central area of the raceway opposite the paddlewheel. With the increase in rotation speed, the blue areas shrink significantly as paddlewheel speed rises from 13 to 50 rpm, although this improvement comes at the expense of higher power consumption [10]. Regarding the suggested minimum velocity value of 0.2 m/s [94], it seems that a paddlewheel rotation speed of 50 rpm can adequately achieve a velocity profile in excess of that value practically everywhere in the raceway **(Fig. 22E**). Since high paddlewheel speeds will result in higher energy use and possibly in operational issues, such as culture spillage outside the raceway, an optimization analysis should be performed before selecting the best paddlewheel speed value for a particular raceway system. For the geometry of our raceway reactor carrying 20 L of culture at a depth of 7 cm, a paddlewheel rotation speed of 20 rpm combined with CO_2 spargers at the previously cited two areas was deemed to be the most suitable selection for proper operation. **Table 9** presented the comparison of experimental data with the literature data.

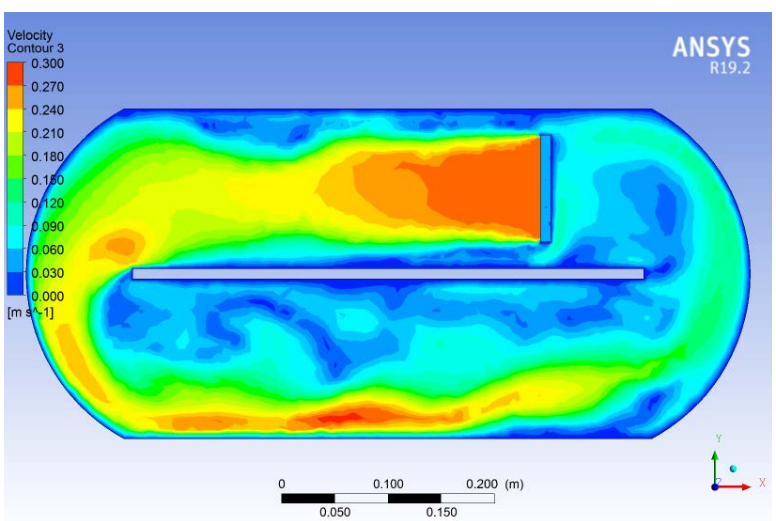
Bottom surface



Middle surface

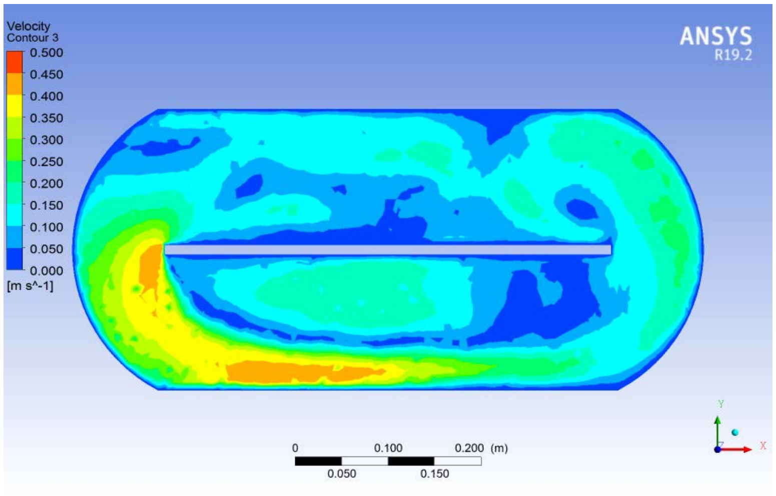


Top surface

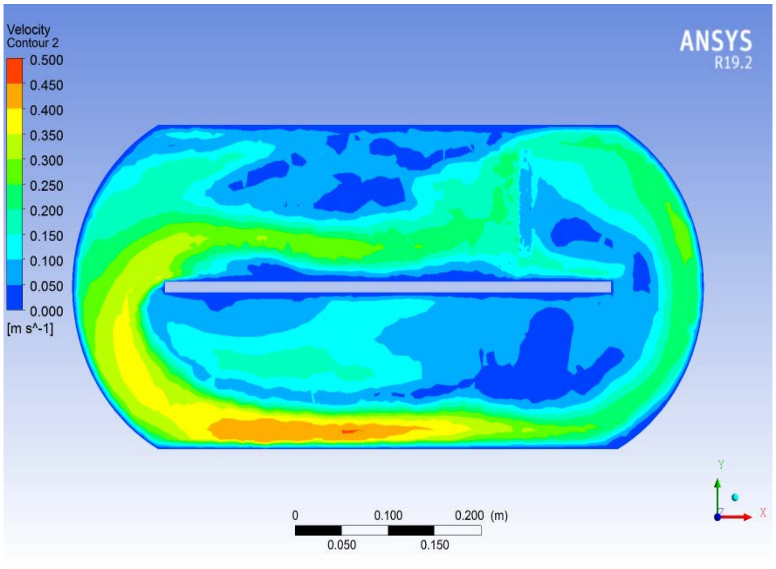


(A)

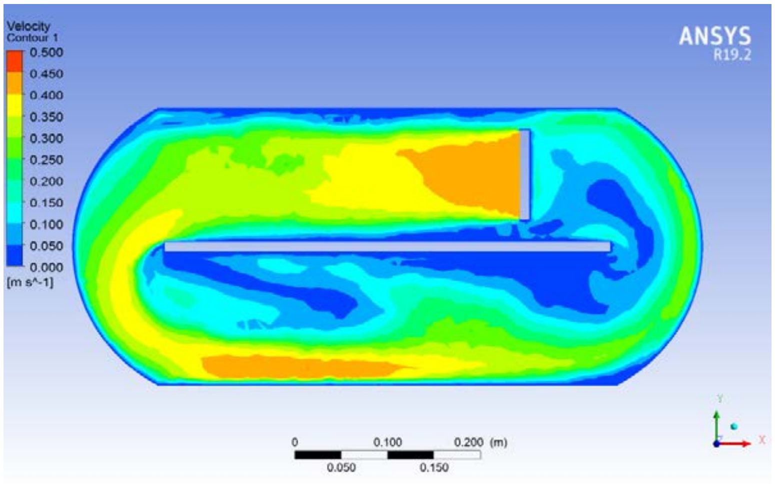
Bottom surface



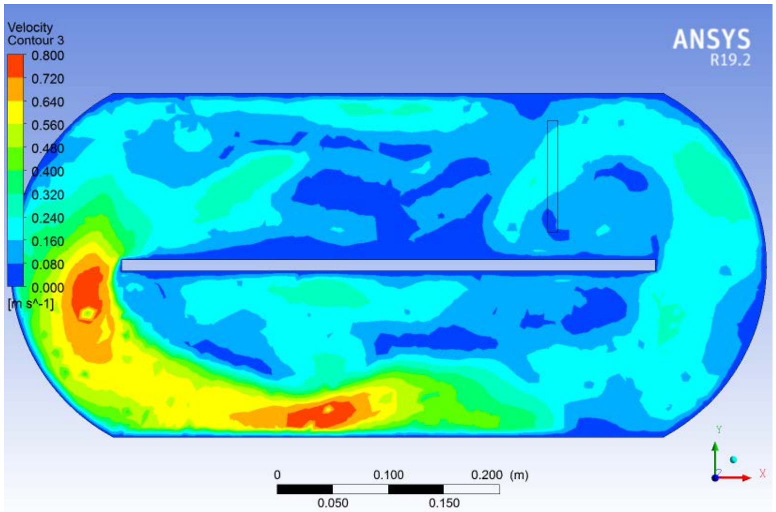
Middle surface



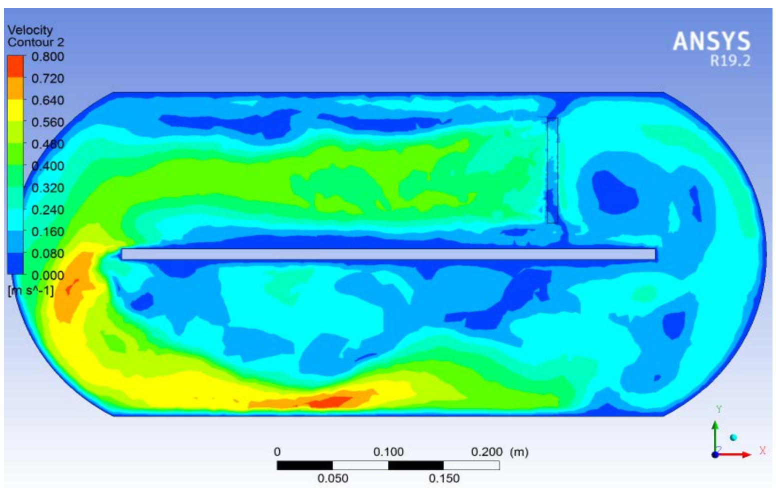
Top surface



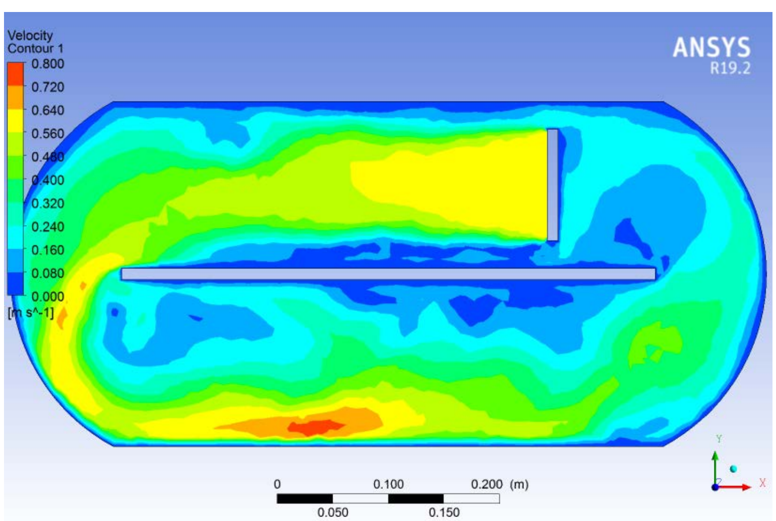
Bottom surface



Middle surface

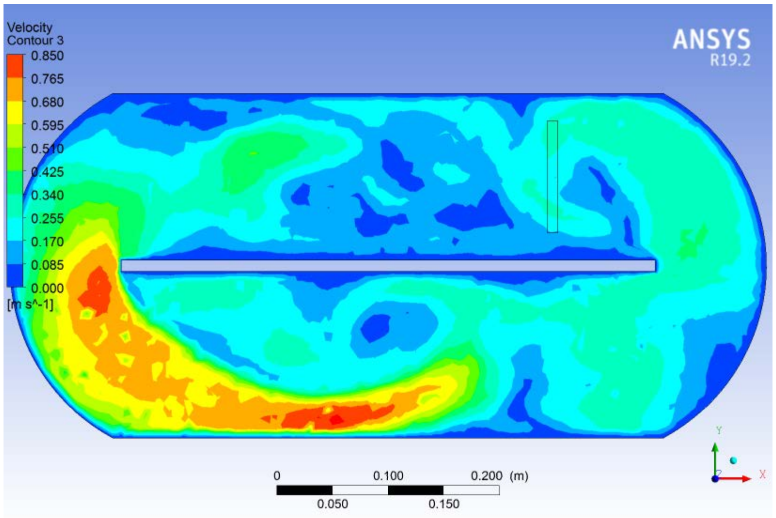


Top surface

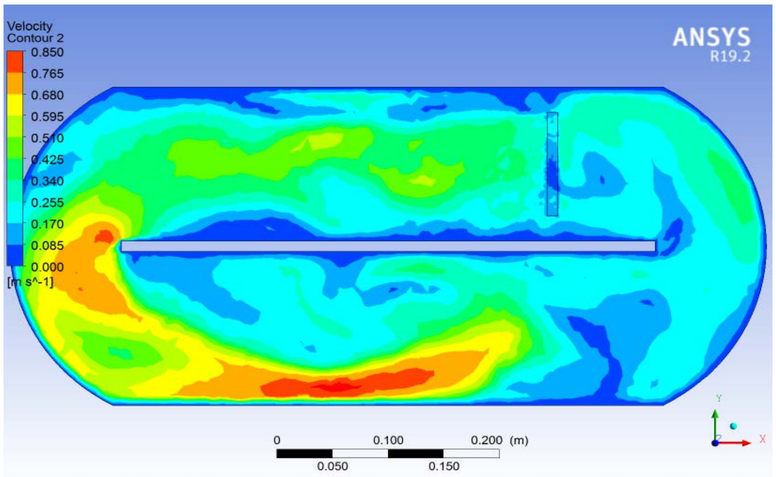


(C)

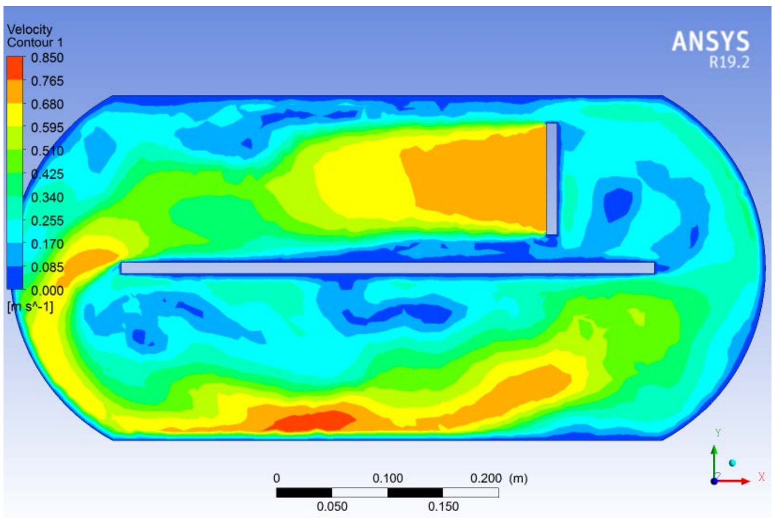
Bottom surface



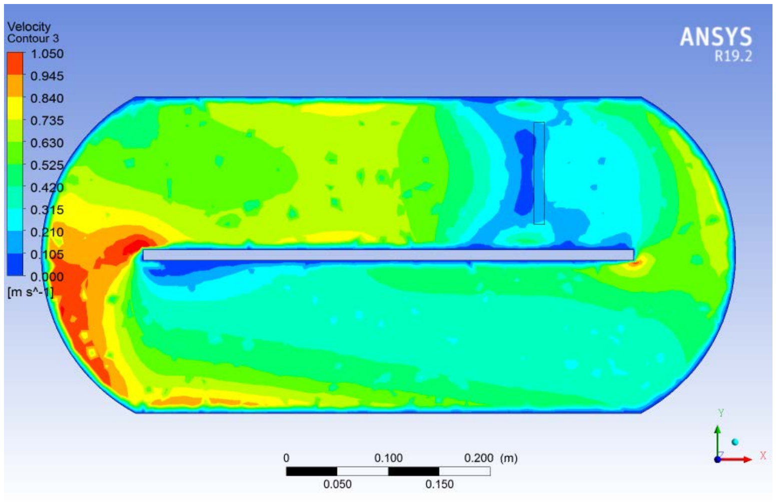
Middle surface



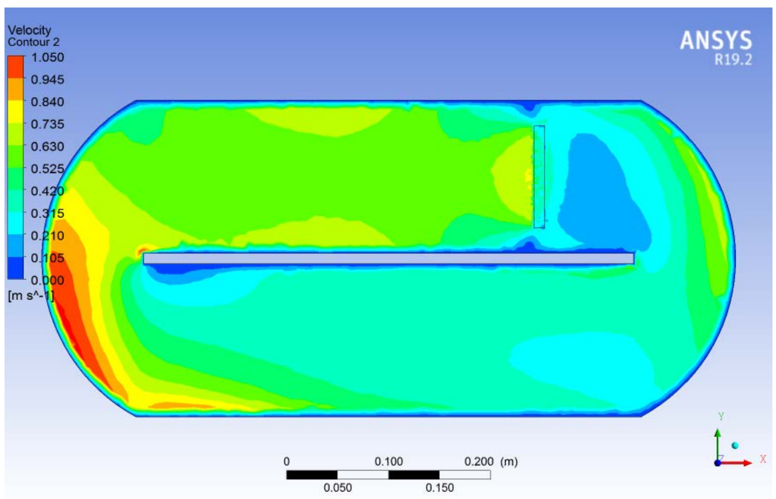
Top surface



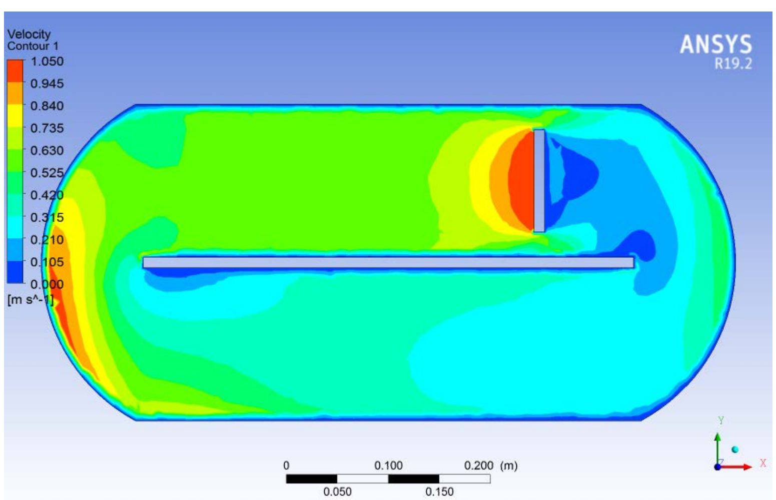
Bottom surface



Middle surface

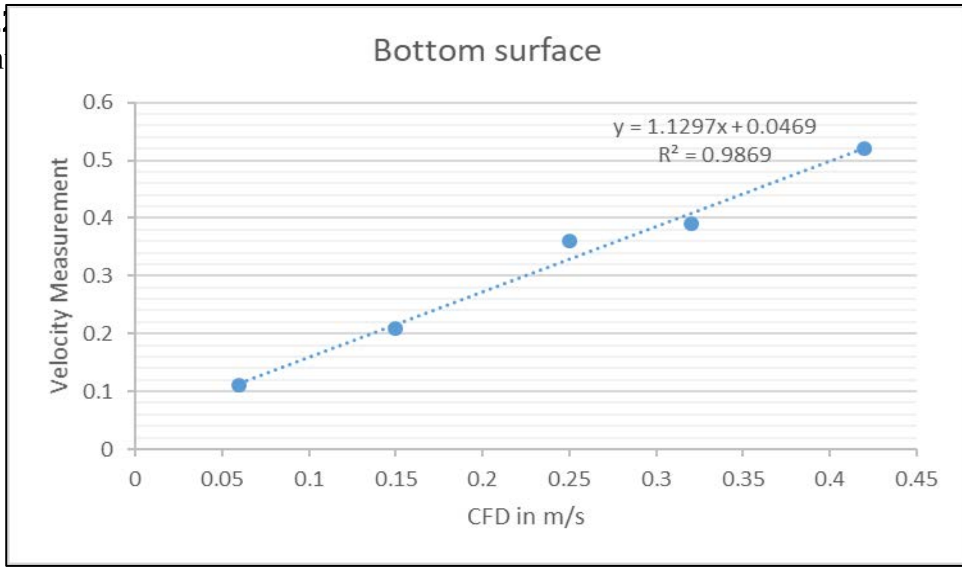


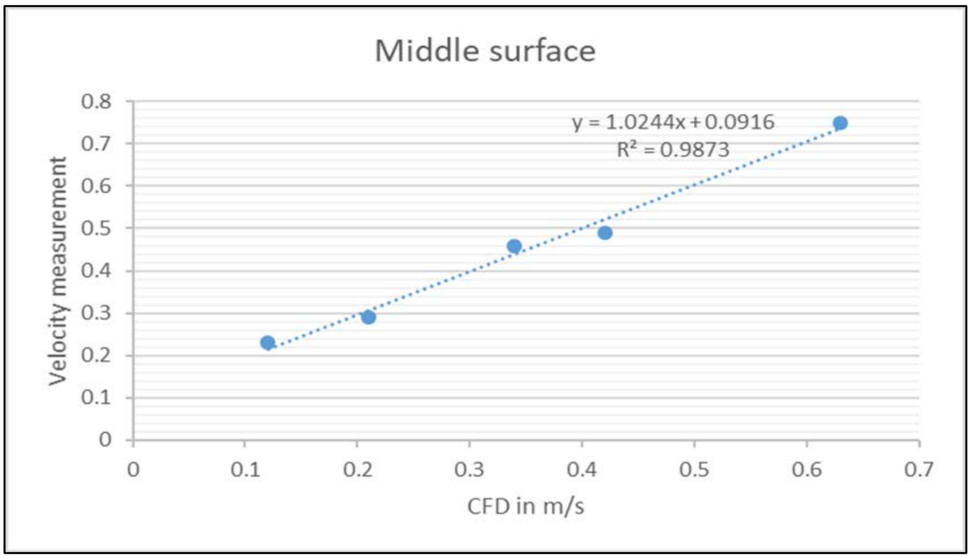
Top surface



(E)

Figure 2 ... mined by
CFD sim ... m (D) 35





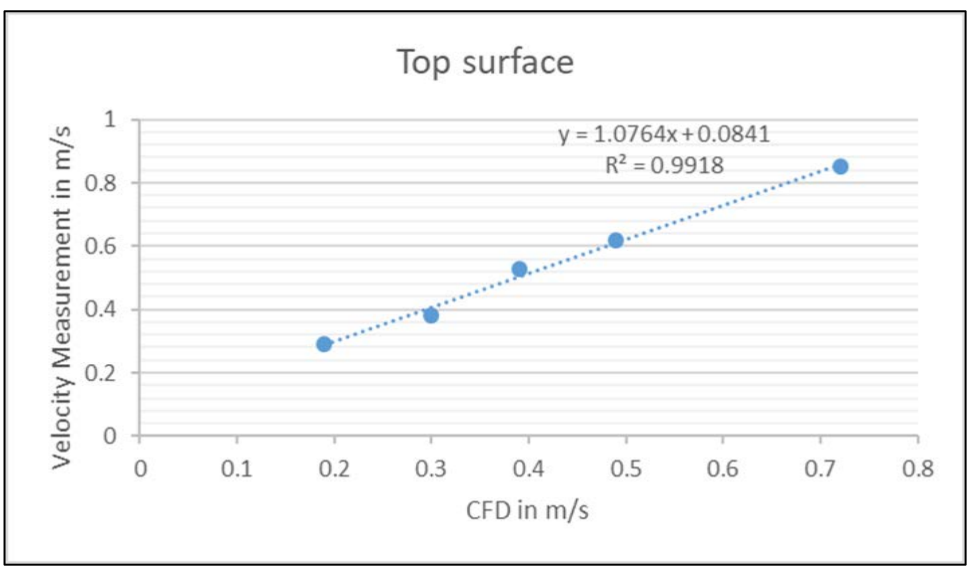


Figure 23 Correlation between CFD-simulated flow velocities and actual flow velocities determined with the use of a flow measurement device in the raceway at a paddlewheel rotation speed of 20 rpm

Table 8 The validation of CFD results with flow meter measurement results

Paddlewheel speed (rpm)	Location	Velocity measurement (m/s)	CFD (m/s)
	Top	0.29	0.19
13	Middle	0.23	0.12
	Bottom	0.11	0.6
	Top	0.38	0.30
20	Middle	0.29	0.20
	Bottom	0.20	0.15
	Top	0.53	0.39
30	Middle	0.49	0.42
	Bottom	0.39	0.32
	Top	0.62	0.49
35	Middle	0.46	0.34
	Bottom	0.36	0.25
	Top	0.85	0.72
50	Middle	0.75	0.63
	Bottom	0.52	0.42

Table 9 The comparison of experimental data with the literature data

Strain	Dimension of Raceway	CFD Code	Turbulence Model	Paddlewheel Velocity (rpm)	Focus of Study	Cultivation Biomass (g/l)	Reference

C. vulgaris	1.4 m in length, 0.5 m depth, 0.35 m width	FLUENT	k-ε	10	Investigated the algal productivity in open raceway ponds with CFD	0.48	[10]
Nannochloropsis gaditana	10 m in length, 0.3 m depth, 4.1 m width	FLUENT	k-ε	10	Analyzed microalgae growth in raceway ponds with CFD	0.62	[58]
Chlorella sp	0.7 in length, 0.2 m depth, 0.2 m width	FLUENT	k-ε	8	Simulated the light/dark cycle of microalgal cells with CFD to improve microalgal growth	1.75	[97]
Spirulina	0.2 m in length, 0.35 m in depth, 0.6 m in Width	FLUENT	k-ε	30	Improved the baffle for increasing the microalgal productivity with using of CFD simulation	3	[98]
Arthrospira platensis	2 m in length, 0.15 m in depth, 0.5 m in width	FLUENT	k-ε	6	Integrated CFD model for raceway cultivation of *Arthrospira platensis*	0.425	[99]
Chlorella vulgaris	1.4 m in length, 0.5 m in depth, 0.35 m in width	FLUENT	k-ε	10	Investigated the hydrodynamics and light transfer for getting the biomass production with CFD	0.41	[9]
N. salina	57 m in length, 0.25 m depth, 4.1 m width	FLUENT	k-ε	16.7	Integrated computational fluid dynamics (CFD) model for open pond cultivation of *Nannochloropsis salina*	0.8	[100]
Chlorella pyrenoidosa	4.5 m in length, 0.35 m depth, 1.9 m width	CFX	k-ε	10	Compared the paddle wheels speed in simulation and microalgae culture experiments	0.9	[68]
Chlorella vulgaris	0.5 m in length, 0.14 in depth, 0.3 m in width	FLUENT	k-ε	30	Application of computational fluid dynamic (CFD) on the raceway design for the cultivation of microalgae	2.52	[101]

CHAPTER 5

CONCLUSION

In this study, the predicted flow velocity profile by using CFD model in the raceway system was verified by the flowmeter measurement, denoting that the simulation results can be represented as the real data in the established raceway. The increase of paddlewheel rotation speed can certainly enhance the cells growth rate. The increase of light intensity was known to be able to enhance the microalgal growth rate. Based on the CFD simulation results, two spaces in the turnaround area of the raceway after the paddlewheel and at the edges of the central paddle were observed to have the low flow rate less than 0.1 m/s. The spargers with CO_2 supplemental installed in those area can avoid the sedimentation and efficiently enhance the microalgae growth. The increase of paddlewheel velocity can lead to receive higher the average velocity and reduce the dead zone. The effect of paddlewheel velocity in the raceway was validated by the experiments with the cultivation of *Chlorella vulgaris*. The results presented that high biomass production was achieved at 30 rpm of the paddlewheel velocity setting. In addition, the mixing of microalgae with using the combining of the paddlewheel and sparger in the raceway system resulted in the higher growth rate rather than with solely using the paddlewheel.

REFERENCES

[1] R. Hreiz, B. Sialve, J. Ô. Morchain, R. Escudié, J. P. Steyer, and P. Guiraud, "Experimental and numerical investigation of hydrodynamics in raceway reactors used for algaculture," *Chemical Engineering Journal*, vol. 250, pp. 230–239, 2014.

[2] P. M. Slegers, M. B. Lösing, R. H. Wijffels, G. van Straten, and A. J. B. van Boxtel, "Scenario evaluation of open pond microalgae production," *Algal Research*, vol. 2, no. 4, pp. 358–368, 2013.

[3] J. C. M. Pires, M. C. M. Alvim-Ferraz, and F. G. Martins, "Photobioreactor design for microalgae production through computational fluid dynamics: A review," *Renewable and Sustainable Energy Reviews*, vol. 79, no. November 2016, pp. 248–254, 2017.

[4] T. M. Mata, A. A. Martins, and N. S. Caetano, "Microalgae for biodiesel production and other applications: A review," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 1, pp. 217–232, 2010.

[5] M. S. Wigmosta, A. M. Coleman, R. J. Skaggs, M. H. Huesemann, and L. J. Lane, "National microalgae biofuel production potential and resource demand," vol. 47, pp. 1–13, 2011.

[6] F. Zeng, J. Huang, C. Meng, F. Zhu, J. Chen, and Y. Li, "Investigation on novel raceway pond with inclined paddle wheels through simulation and microalgae culture experiments," *Bioprocess and Biosystems Engineering*, vol. 39, no. 1, pp. 169–180, 2016.

[7] H. Hadiyanto, S. Elmore, T. Van Gerven, and A. Stankiewicz, "Hydrodynamic evaluations in high rate algae pond (HRAP) design," *Chemical Engineering Journal*, vol. 217, pp. 231–239, 2013.

[8] I. Dogaris, M. Welch, A. Meiser, L. Walmsley, and G. Philippidis, “A Novel Horizontal Photobioreactor for High Density Cultivation of Microalgae,” *Bioresource Technology*, vol. 198, pp. 316–324, 2015.

[9] H. Amini *et al.*, “Numerical and experimental investigation of hydrodynamics and light transfer in open raceway ponds at various algal cell concentrations and medium depths,” *Chemical Engineering Science*, vol. 156, pp. 11–23, 2016.

[10] J. Huang *et al.*, “Investigation on the performance of raceway ponds with internal structures by the means of CFD simulations and experiments,” *Algal Research*, vol. 10, pp. 64–71, 2015.

[11] R. Putt, M. Singh, S. Chinnasamy, and K. C. Das, “Bioresource Technology An efficient system for carbonation of high-rate algae pond water to enhance CO 2 mass transfer,” *Bioresource Technology*, vol. 102, no. 3, pp. 3240–3245, 2011.

[12] H. Ali, T. A. Cheema, H. S. Yoon, Y. Do, and C. W. Park, “Numerical prediction of algae cell mixing feature in raceway ponds using particle tracing methods,” *Biotechnology and Bioengineering*, vol. 112, no. 2, pp. 297–307, 2015.

[13] T. Pirasaci, A. Y. Manisali, I. Dogaris, G. Philippidis, and A. K. Sunol, “Hydrodynamic design of an enclosed Horizontal BioReactor (HBR) for algae cultivation,” *Algal Research*, vol. 28, no. November, pp. 57–65, 2017.

[14] B. Xu, P. Li, and P. Waller, “Study of the fl ow mixing in a novel ARID raceway for algae production,” *Renewable Energy*, vol. 62, pp. 249–257, 2014.

[15] Z. Chen, X. Zhang, Z. Jiang, X. Chen, H. He, and X. Zhang, “Light/dark cycle of microalgae cells in raceway ponds: Effects of paddlewheel rotational speeds and baffles installation,” *Bioresource Technology*, vol. 219, pp. 387–391, 2016.

[16] B. Xu, P. Li, and P. Waller, “Study of the flow mixing in a novel ARID raceway for algae production,” *Renewable Energy*, vol. 62, pp. 249–257, 2014.

[17] Q. Hu *et al.*, “Microalgal triacylglycerols as feedstocks for biofuel production: Perspectives and advances,” *Plant Journal*, vol. 54, no. 4, pp. 621–639, 2008.

[18] A. Powell and A. Silkina, “Microalgal Biotechnology in Wales,” no. November, 2016.

[19] J. D. WEHR, “Algae: Anatomy, Biochemistry, and Biotechnology by Barsanti, L. & Gualtieri, P.,” *Journal of Phycology*, vol. 43, no. 2, pp. 412–414, 2007.

[20] Y. Chisti, “Biodiesel from microalgae beats bioethanol,” *Trends in Biotechnology*, vol. 26, no. 3, pp. 126–131, 2008.

[21] L. Xin, H. Hong-ying, G. Ke, and S. Ying-xue, “Effects of different nitrogen and phosphorus concentrations on the growth, nutrient uptake, and lipid accumulation of a freshwater microalga Scenedesmus sp.,” *Bioresource Technology*, vol. 101, no. 14, pp. 5494–5500, 2010.

[22] C. Sousa, L. De Winter, M. Janssen, M. H. Vermuë, and R. H. Wijffels, “Bioresource Technology Growth of the microalgae Neochloris oleoabundans at high partial oxygen pressures and sub-saturating light intensity,” vol. 104, pp. 565–570, 2012.

[23] L. Rodolfi *et al.*, “Microalgae for oil: Strain selection, induction of lipid synthesis and outdoor mass cultivation in a low-cost photobioreactor,” *Biotechnology and Bioengineering*, vol. 102, no. 1, pp. 100–112, 2009.

[24] M. Yoshioka, T. Yago, Y. Yoshie-stark, H. Arakawa, and T. Morinaga, “Effect of high frequency of intermittent light on the growth and fatty acid pro fi le of Isochrysis galbana,” *Aquaculture*, vol. 338–341, pp. 111–117, 2012.

[25] F. J. L. Gordillo, M. Goutx, F. L. Figueroa, and F. X. Niell, “Effects of light intensity , CO

2 and nitrogen supply on lipid class composition of Dunaliella viridis," pp. 135–144, 1998.

[26] C. Hsieh and W. Wu, "Bioresource Technology Cultivation of microalgae for oil production with a cultivation strategy of urea limitation," *Bioresource Technology*, vol. 100, no. 17, pp. 3921–3926, 2009.

[27] S. Ruangsomboon, "Bioresource Technology Effect of light , nutrient , cultivation time and salinity on lipid production of newly isolated strain of the green microalga , Botryococcus braunii KMITL 2," *Bioresource Technology*, vol. 109, pp. 261–265, 2012.

[28] S. Purton, "Algal Chloroplasts," *Encyclopedia of Life Sciences*, no. July 2001, 2001.

[29] L. Pilon, H. Berberoĝlu, and R. Kandilian, "Radiation transfer in photobiological carbon dioxide fixation and fuel production by microalgae," *Journal of Quantitative Spectroscopy and Radiative Transfer*, vol. 112, no. 17, pp. 2639–2660, 2011.

[30] Douglas. S.E.. Larkum. A. W. D.. and Raven. J.A, "Photosynthesis in Algae. Dordrect: Kluwer Academic, pp. 479," p. 10811, 2005.

[31] J. R. Ehleringer and T. E. Cerling, "C 3 and C 4 Photosynthesis James R Ehleringer and Thure E Cerling Professor Harold A Mooney and Dr Josep G Canadell Editor-in-Chief," no. July, 2014.

[32] M. P. Johnson, "Photosynthesis," *Biochemistry*, vol. 60, pp. 255–273, 2016.

[33] L. Dufosse *et al.*, "Microorganisms and microalgae as sources of pigments for food use : a scientific oddity or an industrial reality ?," vol. 16, pp. 389–406, 2005.

[34] C. Safi, B. Zebib, O. Merah, P. Y. Pontalier, and C. Vaca-Garcia, "Morphology, composition, production, processing and applications of Chlorella vulgaris: A review," *Renewable and Sustainable Energy Reviews*, vol. 35, pp. 265–278, 2014.

[35] A. . Illman, A. H. Scragg, and S. W. Shales, "Increase in Chlorella strains calorific values,"

Enzyme and Microbial Technology, vol. 27, pp. 631–635, 2000.

[36] M. Yamamoto, M. Fujishita, A. Hirata, and S. Kawano, "Regeneration and maturation of daughter cell walls in the autospore-forming green alga Chlorella vulgaris (Chlorophyta, Trebouxiophyceae)," *Journal of Plant Research*, vol. 117, no. 4, pp. 257–264, 2004.

[37] A. L. Stephenson, J. S. Dennis, C. J. Howe, S. A. Scott, and A. G. Smith, "Influence of nitrogen-limitation regime on the production by," vol. 1, pp. 47–58, 2010.

[38] J. M. Lv, L. H. Cheng, X. H. Xu, L. Zhang, and H. L. Chen, "Enhanced lipid production of Chlorella vulgaris by adjustment of cultivation conditions," *Bioresource Technology*, vol. 101, no. 17, pp. 6797–6804, 2010.

[39] M. E. Huntley and D. G. Redalje, *CO2mitigation and renewable oil from photosynthetic microbes: A new appraisal*, vol. 12, no. 4. 2007.

[40] K. E. Wilson and N. P. A. Huner, "Batterbury & Bebbington 1999 Environmental histories Access to resources and Landscape change.pdf," 2000.

[41] S. H. Ho, C. Y. Chen, D. J. Lee, and J. S. Chang, "Perspectives on microalgal CO2-emission mitigation systems - A review," *Biotechnology Advances*, vol. 29, no. 2, pp. 189–198, 2011.

[42] M. Görs, R. Schumann, D. Hepperle, and U. Karsten, "Quality analysis of commercial Chlorella products used as dietary supplement in human nutrition," *Journal of Applied Phycology*, vol. 22, no. 3, pp. 265–276, 2010.

[43] and A. I. Pauline Spolare, Claire Joannis-Cassan, Elie Duran, "Commercial Application of Microalgae," *Journal of Bioscience and Bioengineering*, vol. 101, no. 2, pp. 87–96, 2006.

[44] C. J.-C. Pauline Spolare Elie Duran, and Arsene Isambert, "Commercial Application of

Microalgae," *Journal of Bioscience and Bioengineering*, vol. 101, no. 2, pp. 87–96, 2006.

[45] H. M. Amaro, A. C. Guedes, and F. X. Malcata, "Advances and perspectives in using microalgae to produce biodiesel," *Applied Energy*, vol. 88, no. 10, pp. 3402–3410, 2011.

[46] F. Rubio Camacho, F. García Camacho, J. M. Fernández Sevilla, Y. Chisti, and E. Molina Grima, "A mechanistic model of photosynthesis in microalgae," *Biotechnology and Bioengineering*, vol. 81, no. 4, pp. 459–473, 2003.

[47] R. Reyna-Velarde, E. Cristiani-Urbina, D. J. Hernández-Melchor, F. Thalasso, and R. O. Cañizares-Villanueva, "Hydrodynamic and mass transfer characterization of a flat-panel airlift photobioreactor with high light path," *Chemical Engineering and Processing: Process Intensification*, vol. 49, no. 1, pp. 97–103, 2010.

[48] R. W. Thimijan and R. D. Heins, "Photometric, radiometric, and quantum light units of measure: a review," *HortScience*, vol. 18, no. 6, pp. 818–822, 1983.

[49] D. L. Sutherland, M. H. Turnbull, and R. J. Craggs, "Increased pond depth improves algal productivity and nutrient removal in wastewater treatment high rate algal ponds," *Water Research*, vol. 53, pp. 271–281, 2014.

[50] T. Sato, D. Yamada, and S. Hirabayashi, "Development of virtual photobioreactor for microalgae culture considering turbulent flow and flashing light effect," *Energy Conversion and Management*, vol. 51, no. 6, pp. 1196–1201, 2010.

[51] F. Chen and Y. Zhang, "High cell density mixotrophic culture of," *Enzyme*, vol. 0229, no. 96, pp. 221–224, 1997.

[52] Z. Chen, Z. Jiang, X. Zhang, and J. Zhang, "Numerical and experimental study on the CO2gas-liquid mass transfer in flat-plate airlift photobioreactor with different baffles," *Biochemical Engineering Journal*, vol. 106, pp. 129–138, 2016.

[53] T. M. Sobczuk, F. Garcı, and F. C. Rubio, "Carbon Dioxide Uptake Efficiency by Outdoor Microalgal Cultures in Tubular Airlift Photobioreactors," 2000.

[54] C. Y. Chen, K. L. Yeh, H. M. Su, Y. C. Lo, W. M. Chen, and J. S. Chang, "Strategies to enhance cell growth and achieve high-level oil production of a Chlorella vulgaris isolate," *Biotechnology Progress*, vol. 26, no. 3, pp. 679–686, 2010.

[55] A. F. Barajas-Solano, A. Guzmán-Monsalve, and V. Kafarov, "Effect of carbon-nitrogen ratio for the biomass production, hydrocarbons and lipids on botryoccus braunii UIS 003.," *Chemical Engineering Transactions*, vol. 49, no. 2011, pp. 247–252, 2016.

[56] C. V. González López, F. G. Acién Fernández, J. M. Fernández Sevilla, J. F. Sánchez Fernández, M. C. Cerón García, and E. Molina Grima, "Utilization of the cyanobacteria Anabaena sp. ATCC 33047 in CO2removal processes," *Bioresource Technology*, vol. 100, no. 23, pp. 5904–5910, 2009.

[57] C. Yoo, S. Y. Jun, J. Y. Lee, C. Y. Ahn, and H. M. Oh, "Selection of microalgae for lipid production under high levels carbon dioxide," *Bioresource Technology*, vol. 101, no. 1 SUPPL., pp. S71–S74, 2010.

[58] A. Malek, L. C. Zullo, and P. Daoutidis, "Modeling and Dynamic Optimization of Microalgae Cultivation in Outdoor Open Ponds," *Industrial and Engineering Chemistry Research*, vol. 55, no. 12, pp. 3327–3337, 2016.

[59] A. Richmond, E. Lichtenberg, B. Stahl, and A. Vonshak, "Quantitative assessment of the major limitations on productivity of Spirulina platensis in open raceways," *Journal of Applied Phycology*, vol. 2, no. 3, pp. 195–206, 1990.

[60] B. Jha *et al.*, "Global Phosphorus Scarcity and Full-Scale P- Recovery Techniques : A Review," *Water Research*, vol. 46, no. 4. pp. 1–7, 2016.

[61] R. Hase, H. Oikawa, C. Sasa, M. Morita, and Y. Watanabe, “Photosynthetic Production of Microalgal Biomass in a Raceway System under Greenhouse Conditions in Sendai City,” vol. 89, no. 2, pp. 157–163, 2000.

[62] R. Baxter, N. Hastings, A. Law, and E. J. . Glass, *Algal culturing techniques*, vol. 39, no. 5. 2008.

[63] C. U. Ugwu, H. Aoyagi, and H. Uchiyama, “Photobioreactors for mass cultivation of algae,” *Bioresource Technology*, vol. 99, no. 10, pp. 4021–4028, 2008.

[64] T. Y. Zhang *et al.*, “Promising solutions to solve the bottlenecks in the large-scale cultivation of microalgae for biomass/bioenergy production,” *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 1602–1614, 2016.

[65] E. M. Y. Shen, W. Yuan, Z.J. Pei, Q. Wu, “Microalgae Mass Production Methods,” *American Society of Agricultural and Biological Engineers*, vol. 52, no. 4, pp. 1275–1287, 2009.

[66] K. Kumar, S. K. Mishra, A. Shrivastav, M. S. Park, and J. W. Yang, “Recent trends in the mass cultivation of algae in raceway ponds,” *Renewable and Sustainable Energy Reviews*, vol. 51, pp. 875–885, 2015.

[67] K. W. Chew, S. R. Chia, P. L. Show, Y. J. Yap, T. C. Ling, and J. S. Chang, “Effects of water culture medium, cultivation systems and growth modes for microalgae cultivation: A review,” *Journal of the Taiwan Institute of Chemical Engineers*, vol. 91, pp. 332–344, 2018.

[68] C. Meng, J. Huang, C. Ye, W. Cheng, J. Chen, and Y. Li, “Comparing the performances of circular ponds with different impellers by CFD simulation and microalgae culture experiments,” *Bioprocess and biosystems engineering*, vol. 38, no. 7, pp. 1347–1363,

2015.

[69] K. Kumar, S. K. Mishra, A. Shrivastav, M. S. Park, and J. W. Yang, “Recent trends in the mass cultivation of algae in raceway ponds,” *Renewable and Sustainable Energy Reviews*, vol. 51, pp. 875–885, 2015.

[70] R. Qiu, S. Gao, P. A. Lopez, and K. L. Ogden, “Effects of pH on cell growth, lipid production and CO2addition of microalgae Chlorella sorokiniana,” *Algal Research*, vol. 28. pp. 192–199, 2017.

[71] B. H. Kim *et al.*, “Influence of water depth on microalgal production, biomass harvest, and energy consumption in high rate algal pond using municipal wastewater,” *Journal of Microbiology and Biotechnology*, vol. 28, no. 4, pp. 630–637, 2018.

[72] M. Prussi *et al.*, “Experimental and numerical investigations of mixing in raceway ponds for algae cultivation,” *Biomass and Bioenergy*, vol. 67, no. 0, pp. 390–400, 2014.

[73] J. L. Mendoza *et al.*, “Oxygen transfer and evolution in microalgal culture in open raceways,” *Bioresource Technology*, vol. 137, pp. 188–195, 2013.

[74] D. Chiaramonti *et al.*, “Review of energy balance in raceway ponds for microalgae cultivation: Re-thinking a traditional system is possible,” *Applied Energy*, vol. 102, pp. 101–111, 2013.

[75] E. Suali and R. Sarbatly, “Conversion of microalgae to biofuel,” *Renewable and Sustainable Energy Reviews*, vol. 16, no. 6, pp. 4316–4342, 2012.

[76] Z. Do-Quang, A. Cockx, A. Liné, and M. Roustan, “Computational fluid dynamics applied to water and wastewater treatment facility modeling,” *Environmental Engineering and Policy*, vol. 1, no. 3, pp. 137–147, 1998.

[77] C. J. Kim, Y. H. Jung, S. R. Ko, H. I. Kim, Y. H. Park, and H. M. Oh, “Raceway

cultivation of Spirulina platensis using underground water," *Journal of Microbiology and Biotechnology*, vol. 17, no. 5, pp. 853–857, 2007.

[78] A. Ranga Rao, G. A. Ravishankar, and R. Sarada, "Cultivation of green alga Botryococcus braunii in raceway, circular ponds under outdoor conditions and its growth, hydrocarbon production," *Bioresource Technology*, vol. 123, pp. 528–533, 2012.

[79] D. Karthikeyan, M. Muthukumaran, and B. S. Balakumar, "Mass Cultivation of Microalgae in Open Raceway Pond for Biomass and Biochemicals Production," *Int J Adv Res Biol Sci*, vol. 3, no. 2, pp. 247–260, 2016.

[80] X. Wen *et al.*, "Effective cultivation of microalgae for biofuel production: A pilot-scale evaluation of a novel oleaginous microalga Graesiella sp. WBG-1," *Biotechnology for Biofuels*, vol. 9, no. 1, pp. 1–12, 2016.

[81] A. Sanchez Bermudez, A. Gonzalez Perez, R. Maceiras, M. Cancela, and S. Urrejola, "Raceway Pond Design for Micoalgae culture for Biodiesel," *Chemical Engineering Transactions*, vol. 25, pp. 845–850, 2011.

[82] T. Cai, X. Ge, S. Y. Park, and Y. Li, "Comparison of Synechocystis sp. PCC6803 and Nannochloropsis salina for lipid production using artificial seawater and nutrients from anaerobic digestion effluent," *Bioresource Technology*, vol. 144, pp. 255–260, 2013.

[83] S. Yadala and S. Cremaschi, "A Dynamic Optimization Model for Designing Open-Channel Raceway Ponds for Batch Production of Algal Biomass," *Processes*, vol. 4, no. 2, p. 10, 2016.

[84] E. Baldev *et al.*, "Unveiling algal cultivation using raceway ponds for biodiesel production and its quality assessment," *Renewable Energy*, vol. 123, pp. 486–498, 2018.

[85] J. L. Mendoza *et al.*, "Fluid-dynamic characterization of real-scale raceway reactors for

microalgae production," *Biomass and Bioenergy*, vol. 54, pp. 267–275, 2013.

[86] K. Sompech, Y. Chisti, and T. Srinophakun, "Design of raceway ponds for producing microalgae," *Biofuels*, vol. 3, no. 4, pp. 387–397, 2012.

[87] K. Liffman, D. A. Paterson, P. Liovic, and P. Bandopadhayay, "Comparing the energy efficiency of different high rate algal raceway pond designs using computational fluid dynamics," *Chemical Engineering Research and Design*, vol. 91, no. 2, pp. 221–226, 2013.

[88] S. C. James and V. Boriah, "Modeling Algae Growth in an Open-Channel Raceway," *Journal of Computational Biology*, vol. 17, no. 7, pp. 895–906, 2010.

[89] R. M. Daniel Fishman, R. P. Joanne Morello, and and J. Yang, "National algal biofuels technology roadmap," *National Renewable Energy Laboratory*, no. May, 2010.

[90] Z. Yang, J. Cheng, Q. Ye, J. Liu, J. Zhou, and K. Cen, "Decrease in light/dark cycle of microalgal cells with computational fluid dynamics simulation to improve microalgal growth in a raceway pond," *Bioresource Technology*, vol. 220, pp. 352–359, 2016.

[91] A. Nikolaou, P. Booth, F. Gordon, J. Yang, O. Matar, and B. Chachuat, "Multi-Physics Modeling of Light-Limited Microalgae Growth in Raceway Ponds," *IFAC-PapersOnLine*, vol. 49, no. 26, pp. 324–329, 2016.

[92] H. Amini *et al.*, "An integrated growth kinetics and computational fluid dynamics model for the analysis of algal productivity in open raceway ponds," *Computers and Electronics in Agriculture*, vol. 145. pp. 363–372, 2018.

[93] A. P. Carvalho, S. O. Silva, J. M. Baptista, and F. X. Malcata, "Light requirements in microalgal photobioreactors: An overview of biophotonic aspects," *Applied Microbiology and Biotechnology*, vol. 89, no. 5, pp. 1275–1288, 2011.

[94] Y. Chisti, "Large-scale production of algal biomass: Raceway ponds," *Green Energy and Technology*, pp. 21–40, 2016.

[95] C. Wang and C. Q. Lan, "Effects of shear stress on microalgae – A review," *Biotechnology Advances*, vol. 36, no. 4, pp. 986–1002, 2018.

[96] I. Perner-Nochta and C. Posten, "Simulations of light intensity variation in photobioreactors," *Journal of Biotechnology*, vol. 131, no. 3, pp. 276–285, 2007.

[97] Z. Yang, J. Cheng, Q. Ye, J. Liu, J. Zhou, and K. Cen, "Decrease in light/dark cycle of microalgal cells with computational fluid dynamics simulation to improve microalgal growth in a raceway pond," *Bioresource Technology*, vol. 220, pp. 352–359, 2016.

[98] J. Cheng, W. Guo, C. Cai, Q. Ye, and J. Zhou, "Alternatively permutated conic baffles generate vortex flow field to improve microalgal productivity in a raceway pond," *Bioresource Technology*, vol. 249, no. August 2017, pp. 212–218, 2018.

[99] P. Ranganathan, J. C. Amal, S. Savithri, and A. Haridas, "Experimental and modelling of Arthrospira platensis cultivation in open raceway ponds," *Bioresource Technology*, vol. 242, pp. 197–205, 2017.

[100] S. Park and Y. Li, "Integration of biological kinetics and computational fluid dynamics to model the growth of Nannochloropsis salina in an open channel raceway," *Biotechnology and Bioengineering*, vol. 112, no. 5, pp. 923–933, 2015.

[101] A. Kusmayadi, G. Philippidis, and H. Yen, "Application of computational fl uid dynamics to raceways combining paddlewheel and CO 2 spargers to enhance microalgae growth," *Journal of Bioscience and Bioengineering*, pp. 6–11, 2019.