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Investigation of turbulent multiphase flows in a flat panel photobioreactor and consequent effects on microalgae cultivation; using Computational Fluid Dynamics (CFD) simulation and Particle Image Velocimetry (PIV)

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Investigation of turbulent multiphase flows in a flat panel photobioreactor and consequent effects on microalgae cultivation; using Computational Fluid Dynamics (CFD) simulation and Particle Image Velocimetry (PIV) measurement

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Abstract:

Algae presents itself as a versatile feedstock for the production of fuels and chemicals ranging from ω-3 fatty acids to Jet-A or JP-8 jet fuels. Mixing of algae culture systems is vital to creating this feedstock. A review of mixing details the many algae culture systems employed to produce algae biomass. It also explores the many mixing methods utilized within the culture system and the importance for the design of these mixing methods. This importance of design has led many researchers to develop mathematical approaches to determining mixing characteristics of algae culture systems. Computational Fluid Dynamics (CFD) uses mathematical techniques to characterize fluid dynamics with the ability to designate thousands of equations to be solved by a computer processor. CFD is known for its strength in design and simulation. This technique allows a user to model a system of fluids to predict movement and therefore effectiveness of design while bypassing physical construction. Studies into this technique are presented and express the strength of CFD as a single phase solver and the current challenges of using CFD as a multiphase solver. To complete an understanding of turbulent mixing effects on algae growth performance, multiphase flows were investigated using a measurement technique of Particle Image Velocimetry (PIV). PIV was used to measure the liquid phase fluid characteristics of a Flat Panel Bioreactor (FPB) that was undergoing mixing by steady state aeration. Parameters such as flow rate (Q), mean velocity ($\bar{v}$), and mean Turbulent Kinetic Energy ($\overline{TKE}$) were characterized for each experiment that was tested across different aeration schemes. These parameters were weighted against each other to come up with a quality of mixing term, M, which was able to predict the ranking of algae growth performance amongst each experiment. As multiphase flows and their consequent effects on microalgae growth performance are further understood, techniques of CFD may be able to simulate and predict effectiveness solely using computing tools.

Chapter 1: Introduction:

1.1. Project Description

The work done in these studies explored the possibility of transitioning an understanding of algae growth systems into a modular platform that will be able to diagnose geometric and hydrodynamic effects of an algae culture system. Previous researchers were able to determine key parameters determining the effectiveness of mixing within an algae culture. These parameters include mixing ratios of algae between light and dark cycles, time which algae spend in this lighted areas, and Reynolds number. With strong increase in computing power since this previous research, it was appropriate to apply the use of current computer technologies such as Computational Fuild Dynamics (CFD) to the problem of understanding fluid effects on microalgae growth performance. CFD technology is still in development phases for multiphase flow simulation and it was therefore necessary to measure the flow with other techniques to ensure accurate hydrodynamic parameters. The measurement technique used is common in the field of aerospace engineering and it's called Particle Image Velocimetry (PIV). PIV techniques are mentioned in section 1.1.2 as well as in Chapter 4.

1.1.1. Algae Culture Techniques

First attempts to produce growth results used a genetically modified strain of *Chlamydamonas* with a medium containing organic carbon in the form of acetic acid. These tests produced high algae yields (close to 1 g/L/d) but the algae strain proved to be susceptible to bacterial contamination and the growth wasn't solely attributed to autotrophic growth. This is a necessity because the intent of the study is to maintain constant light and CO_2 concentration with hydrodynamic parameters being the sole variable. If the algae were somewhat able to consume carbon in the absence of these nutrients, the effect of hydrodynamic mixing would not be distinct.

Microalgae and contaminating bacteria both grow rapidly within the acetic acid containing medium and the genetically modified strain of algae was not robust enough to ward off cultures of invasive species. After many attempts to produce accurate algae growth results,

the wild-type algae strain *Scenedesmus Dimorphus* was used in a medium which was void of consumable organic carbon. This strain is prevalent throughout literature and outperformed the genetically modified and wild-type strains of *Chlamydamonas* in the bolds basal medium (BMM) that did not contain organic carbon.

Another important factor to avoiding contamination was procedural maintenance and cleaning (using diluted bleach) of the reactor between uses. If the reactor had been smaller and constructed of temperature-resistant materials, autoclaving the reactor would have been the best solution to the contamination issue. But because this study was designed to explore potential scale up, the reactor used was too large to be autoclaved. Furthermore, it was built primarily of polymethyl methacralyte which is not autoclavable. For these reasons, the dilute bleach clean-in-place approach was used, with good results. Figure 1 shows uncontaminated *Scenedesmus Dimorphus* in good condition after three days of growth within the bioreactor.

Figure 1.1. Microscopic examination of algae strain *Scenedesmus Dimorphus*.

Technology:

1.1.2. Fluid Dynamics Techniques

Using current technologies, we were able to gain real-time visualization of the fluid mechanical properties of a multiphase flow within a bioreactor. This was possible by joining efforts with a strong team of PIV experts, mainly Dr. Hui Hu and Dr. Zifeng Yang. Figure 1.2 is a picture taken during PIV measurements. It shows how the technique uses a laser

sheet to reflect light off of microscopic particles within the liquid. The reflected light was then captured by camera and transmitted to the computer. With time data and particle tracking, a computer code was written to define hydrodynamic properties of the liquid.

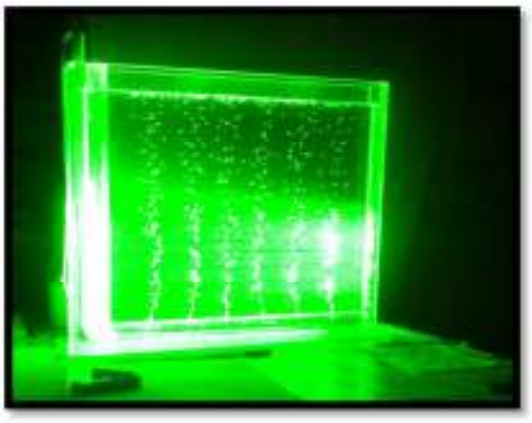

Figure 1.2. Laser sheet illumination phase of PIV.

1.2. Thesis Organization

Chapter 2, literature review, is a review of previous literature which details the study of the effects of mixing on algae bioreactors. Chapter 3, Use of computational fluid dynamics (CFD) for the design and optimization of algae culture systems, is a chapter detailing work done to explore the utility of CFD for modeling algae culture systems. Dr. Zhi J Wang and his PhD student Varun Vikas, both of the Aerospace Engineering department, provided aid with using a home-made code. Chapter 4, Characterization of Turbulent Multiphase Fluid Dynamics in Photobioreactors and Consequential Effects on Microalgae Cultivation, is a journal paper awaiting submission. It is an in-depth study of the relationship between fluid flows in the gas phase and liquid phase in an algae photobioreactor. Dr. Hui Hu and his post doc, Dr. Zifeng Yang, both of the aerospace engineering department, provided assistance with PIV measurements of the bioreactor. Dr. Zhiyou Wen, of the Food Science and Human Nutrition department provided materials and expertise in growing the algae culture. Chapter 5 is a general conclusion with suggestions for future research.

Chapter 2: Single Phase and Multiphase Fluid Dynamical Mixing Flows with Implications on Algae Culture Systems.

2.1. Introduction:

Mixing of algae is important for the distribution of nutrients inside of an algae culture. One of the most important nutrients which need to be brought in during autotrophic algae growth conditions is light.

2.1.1. Light

Under autotrophic growth conditions, algae use light energy to catalyze the photosynthesis reaction. Autotrophic conditions also allow for other cheap inputs such as nitrogen and phosphorus from waste streams, carbon dioxide from industrial exhaust, and non-potable water. Sunlight as a resource is promising because, other than the cost of the land which is used to grow algae, sunlight is an energy abundant free resource. Sunlight provides light intensities which are substantially higher than indoor lights. This is important because higher light intensity can lead to higher growth rates. However; if the light intensity provided to the algae is too high or too low, it may inhibit growth by over saturation or deprivation. Due to the Lambert-Beer's law, light intensity decays as a function of distance from the light's surface; therefore, even at high light intensity, algae cells may be light deprived if they aren't close enough to the surface. Because light is so important to algae growth, current designs favor a large surface area to volume ratio (Sastre, Csogor, Perner-Nochta, Fleck-Schneider, & Posten, 2007). This leads to higher costs (Wu & Merchuk, 2004).

To overcome photo inhibition while using high light intensities to advance photosynthesis, (Sheth, Ramkrishna, & Fredrickson, 1977) describe a flashing light effect. This effect states that high light intensities, if intermittent, are not inhibitory and may actually increase the efficiency of photosynthetic yield. Instead of flashing light onto the algae surface, algae may be moved from dark zones to light zones to simulate the intermittent (flashing) light. Marshall and Huang, (2010) explored this theory by using turbulent mixing to distribute cells systematically into lighted zones. This is a more practical solution for large scale systems

which use direct sunlight because it can utilize high light intensities to increased photosynthetic efficiency. Well-designed turbulent mixing profiles will include small elliptical swirl patterns (commonly referred to as microeddies). Optimal conditions occur when microeddies are mainly perpendicular to the light surface. This orientation allows the microeddies to bring algae from a longer distance away from the lighted surface into a region of the bioreactor which is close enough to receive adequate light. The furthest depth at which this is possible is referred to as the mixed layer depth. Assuming perpendicular orientation, an increased number and length of microeddies at the light surface will provide a deeper mixed layer. This ensures a lower surface to volume ratio, therefore increasing volumetric efficiency and reducing capital costs of materials for surface area.

Because light absorption into a culture is a critical parameter, it was important to determine influential relationships between available light at the surface and particle movement parameters. Research by Barbosa et al, (2003) calculated a parameter for the amount of light absorbed (E_{abs}) which is based on the light that gets absorbed into the reactor multiplied by the illuminated area and light fraction within light/dark cycles (ε). This fraction plays an influential role for mixing design because the other factors in the biomass yield equation are due to culture density and physical parameters. They found that when ε is smaller than 0.231, biomass production was impossible; when ε is greater than 0.869, the rate of biomass production is at almost the same rate as it is during constant illumination. Marshall and Huang, (2010) used a similar parameter, also with variable ε, for the ratio of the time in which algae are exposed to light to the specific algae's time scale of photosynthesis. They found that if algae are exposed to ε greater than 0.5, they may be able to achieve up to 90% of their maximum growth rate. Also, when ε approaches 1, further increase of mixing does not contribute to an increase in algae productivity.

2.1.2. Excess Mixing

There is a limit to realizing growth rate increases through turbulence. A balance must be achieved between being able to distribute light and nutrients throughout the culture medium and damaging cells. Many economically valuable algal strains are known to be shear

sensitive. However, the exact shear rates associated with decreases in cell growth rates is unknown, and needs to be better elucidated to help with design.

2.1.2.1. Shear

The original study which brought the effects of shear stress to attention was conducted by Bronnenmeier & Markl (1982). They state that an overcritical hydrodynamic load will damage microorganisms due to applied shear stress; microorganisms more resistant to damage are those of small spherical shape such as *Chlorella vulgaris*. Conversely, longer rod-shaped algae strains such as *Spirulina platensis* were more susceptible to mechanical forces and damaged at much lower rates of shear stress. Mitsuhashi et al, (1994) also observed significant damage to *spirulina plantensis* during relatively low shear stress and added that even cultures with unbroken trichomes showed long term effects of reduced growth.

By investigating algae strain *Dunaliella*, a strain which is vulnerable to mechanical forces because it lacks a rigid cell wall, researchers were able to isolate the damaging effects of shear on a small scale. A popular article, published by Silva et al, (1987)**,** found that an increase in hydrodynamic stress was detrimental to algae growth rates. This study focused on aeration as a method of mixing; it stated that a high Reynolds number at the bubble inlet, bubble bursting at the gas-liquid uppermost boundary, and liquid shear stress all inhibit the performance of algae growth. They also theorize that shear between the liquid-wall boundaries at U-bends ruptured cells.

2.1.2.2. Eddy size

Turbulence, a strong indicator of mixing, is defined by a fluid flow which contains eddy currents. As previously mentioned, these currents may be advantageously utilized to bring algae cells from poorly lighted areas into well lighted areas. Turbulence can accelerate algae growth up to an optimum point; thereafter algae growth will be impeded. Multiple studies conclude that decreased cell growth performance is due to decreasing size of eddy currents (microeddies on small scale) with increasing turbulence. This is because they theorize that

when the lengths of microeddies in the culture are less than the length of the cells themselves, cell damage occurs (Alias, et al., (2004); Camacho et. al, (2000); Papoutsakis, (1991)).

2.2. Moving a fluid through a reactor

2.2.1. Mixing through Pumps, Impellers, bubbling:

Liquid mixing, and therefore the ability to move fluid, is necessary to provide optimal cell culture conditions. In order to achieve efficient mixing, algae reactors should be designed to move cells periodically across a light gradient, through a small pressure gradient, and also maintain a low shear stress throughout the entire system. The two most important determining characteristics for this are the geometry, which is defined by the liquid boundaries, and the mechanical forces applied to the liquid at the site(s) of mixing.

There are three common ways to mix a bioreactor; impellers (including paddle wheels), pumps, and aeration. These methods are all associated with different degrees of sheer stress at the site of mixing.

2.2.1.1. Impellers

Throughout history, moving large amounts of fluid was accomplished by using blades. For example, air is sent into wind tunnels by large turbine blades, propeller engines and jet engines have blades thoroughly designed for fluid movement, and the movement of large ships is based on blades displacing large amounts of water from the ships boundary.

This practice of using blades to move liquid is used often for agitation inside chemical reaction vessels such as algae fermentation tanks. For this reason, Bronnenmeier & Markl, (1982) studied the effects of shear stress on algae in a stirred-tank reactor. They determined that the two critical methods of cell destruction were the shear stresses at the turbine tips and the rapid pressure change over the blade. In a study by Pruvost et al, (2006), two impeller designs were studied in great detail. They proposed that if the cultivated species was non stress-sensitive, a classical three blade impeller will provide an efficient flow circulation; if

the culture being mixed was stress sensitive, a compromise must be formed by using the two-blade impeller or other means of mixing. Because blades are so effective at moving large volumes of fluid, large scale algae production ponds use paddle wheels to move the contained culture. Alias et. al, (2004) explains that paddlewheel shear rate is a function of impeller diameter and rotational velocity. In early paddle wheel operated algae ponds, high turbulence occurs in the immediate vicinity of the wheel while laminar regimes follow downstream. Currently, some designs dampen this effect with the addition of another paddle wheel; thus providing two wheels and reducing the pressure drop between the site(s) of mixing and downstream.

2.2.1.2. Pumps

If a system is designed to use a pump for means of fluid movement, it is important to consider the shear rate which is present in the pump cavity. To benchmark multiple pump designs, Alias, et al., (2004) compared all pumps at equivalent flow rates. Pumps considered were peristaltic, diaphragm, and centrifugal pumps. In the study, peristaltic pump showed the least damaging effect; next was the diaphragm pump, and the most damaging was the centrifugal pump. Gudin & Chaumont, (1991) Also compared pumping systems and found that a centrifugal pump was the most damaging of the pumps they used. In one instance, they doubled productivity by switching from a centrifugal pump to a volumetric one. From the pumps that they compared, they listed a centrifugal pump, eccentric pump, trilobs pump, and a screw pump from most damaging to least damaging, respectively.

2.2.2. Mixing in commercial systems:

Effects of geometry on a system are said to effect hydrodynamic stress, product quality, and growth (Gudin & Chaumont, 1991; Perner et al., 2003; Pruvost et al., 2006). Thus, it is important to consider structure used to contain the culture medium. There have been many designs for growth systems ranging from highly controlled and more capital intensive bioreactors to large scale open ponds. One determining factor for the selection of containing structure is the volume of contained fluid; large amounts of fluid require more open designs. For systems using smaller volumes of contained fluid, either high biomass yields or high

value products will need to be achieved; bioreactors are necessary in this case to provide a high degree of control for operational parameters.

2.2.2.1. Mixing in Tubular bioreactors:

Tubular bioreactors' popularity evolved mainly due to their ability to provide an inexpensive enclosed system for maintaining process variables. Using small tube diameters and many tubes provides a high surface area to volume ratio which, though costly to scale up, allows for a large light surface for maximum distribution of light to the algae cells.

Due to the no-slip boundary condition, fluid velocity near a wall is restricted. In the case of tubular bioreactors, large surface area/volume ratios are present are therefore restrictive to fluid flow, causing a high pressure gradient. A rapid and large pressure drop can decrease a cell's metabolism and increase the amount of energy necessary for circulating the culture. Because fluid flow is restricted near inner walls of the tubes, faster movement occurs at the center where algae cells concentrate. As previously mentioned, a concentration of algae which is not near the surface of light will have photosynthetic inefficiencies.

Bees & Croze (2010) did an in-depth study on the concentration of algae cells in a tube. These models, including "swimming" algae which used flagella in order to move, illustrate that most of the algae cells are concentrated in the center of the tube. Pofflee et. al, (1997) studied a similar effect with non-swimming algae and concluded that a majority of cells were concentrated in the center 60% of the tube on a cross sectional area basis. In a unique approach to this effect, their study proposed a method of separation by using a series of branched tubes in order to separate this high concentration of cells in the center from the low concentration liquid near the walls.

Many researchers realize that for growth, centered concentrations of algae cells are not ideal. Determining cell placement through particle trajectory simulations, Sastre et. al, (2007) found that a static mixer can counteract a centrally located cell concentration by periodically moving cells to the radial boundaries of the tube. This is beneficial to operating conditions

because periodic movement of cells into lighted zones improves efficiency of photosynthesis and because a tube's inner fluid pattern which doesn't have slow moving velocities along the walls may decrease pressure drop. Another approach to optimizing tubular bioreactors was carried out on pilot scale as well as mathematically by Vunjak-Novakovic et al, (2005). In this study, aeration was used as to provide pumping, CO_2 induction, and random distribution of radial cell placement. This works because the tubes, oriented in a triangular pattern perpendicular to the ground, had a hypotenuse which was inclined enough for bubbles to run along the inner upper surface. While the bubble was traveling along this surface it displaced slow moving fluids with fluid from the center of the tubes which filled in the volume once the bubbles rose. This effect allowed the bubble to clean the inner surface of the tubes, distribute CO_2 into the culture, and move cells from dark zones to light zones.

2.2.2.2. Traditionally mixed systems:

Conventional open pond systems for growing algae use a paddle wheel to mix the contained fluid. These systems provide high turbulence at the wheel and provide laminar regimes downstream (Thomas & Gibson, 1990). High turbulence at the site of mechanical mixing is also seen in systems which include pumps or stirrers to move the fluids (Alias, et al., 2004). Because high turbulence can damage algae, the total volume's mixing will be limited to the high turbulent zones.

2.2.2.3. Mixing in air lift bioreactors:

Unlike conventional systems, mechanical work in aerated bioreactors occurs at the site of the air compressor, thereby reducing the shear stress within the bioreactor. The density difference between gas phase and liquid phase causes the gas to rise as bubbles and the liquid to rise with it. This is an effective way to move liquid because while a bubble is moving upward, tension at the phase boundary brings liquid along with the bubble and surrounding liquid also moves upward from the underneath and sides of the bubble to displace the volume of the bubble as it moves along its trajectory. It has been shown that an introduction of only a small amount of gas greatly influences growth (Vunjak-Novakovic et al., 2005).

Additionally, because CO_2 is most commonly in gas phase, it may be entered into the air that is used for mixing.

2.2.3. Mathematics of algae reactor systems

Because there are infinite possibilities for algae culture systems in terms of geometry and mixing, it is important to mathematically understand the growth patterns and simulate the system before scale up. Hopefully, in the future, culture systems will be designed and optimized before being built. This will reduce funding spent on empirical testing of insufficient reactor schemes.

2.2.4. Mathematical modeling of mixing:

The understanding of hydrodynamic effects on algae growth has influenced some researchers to correlate fluid dynamical properties to algae growth. One presentation used properties such as shear, viscous dissipation rates, and rate of strain in their discussion (Thomas & Gibson, 1990). Mathematical models were then developed using such properties, e.g. (Wu & Merchuk, 2004), and were later used for mathematically simulating individual bioreactors (Marshall & Huang, 2010; Vunjak-Novakovic et al., 2005).

2.2.5. CFD modeling of Mixing:

With the introduction of computational fluid dynamics (CFD), studies used variables such as turbulent kinetic energy (TKE) and dead zone percentage (DZ) (Yu, et al., 2009) to further understand the effects of hydrodynamics on algae growth. Many CFD simulations have been used to design photobioreactors; Bitog et al.(2011) has presented an analysis of 35 such cases. The basis of CFD is to extrapolate a set of operating conditions and assumptions to simulate results of a theoretical model. Though magnitude and profiles of some results have been validated, there are only few studies of fundamentals (hydrodynamic measurements) under well-defined conditions (Pruvost, Pottier, & Legrand, 2006). Others suggest to study the effects of operational parameters, varied at will (Silva, Cortinas, & Ertola, 1987).

2.2.6. Future of mixing simulation and design:

Future of simulations is that of realizing hydrodynamic principles and applying them to mathematical models, Using CFD to optimize reactor designs based on principles in literature, and which use models to predict cost and yield. An optimized bioreactor will be one that: Has a low surface area/volume ratio (cost for materials)/ Maximum surface exposed to light. Doesn't experience a high pressure drops; (metabolism, more energy for pumping) (maybe like static mixer). Long perpendicular eddy currents: Provides a deep mixed layer with light fraction greater than 0.5; eddy currents are larger than cell size as to not rupture cells Method of pumping is not shear-intensive

2.3. Conclusions:

From many empirical tests, it can be shown that if an algae production system is to have high capital costs and a low volume of algae culture, it would have to be substantially more efficient at producing a high quantity of algae biomass per land area. This may be done by using cheap inputs or novel ideas of mixing such as the triangular photobioreactor mentioned. Optimization of these systems is necessary for commercial realization. Conversely, very large scale open pond systems which require much less capital costs don't have to produce very high yields of biomass per unit land. These systems, though, also need optimizations to reduce the energy needed to move such large bodies of fluids. Slight differences in yields on this scale will translate into large gains. Therefore, for all sizes and configurations of algae culture systems, it is necessary to understand and optimize fluid mechanics to a ensure low operating energy input and to realize maximum yields.

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Chapter 3. Use of computational fluid dynamics (CFD) for the design and optimization of algae culture systems

3.1. Introduction

Because there are infinite possibilities for algae culture systems in terms of geometry and mixing, it is important to mathematically understand the growth patterns and simulate the system before scale up. Hopefully, in the future, culture systems will be designed and optimized before being built. This will reduce funding spent on empirical testing of insufficient reactor schemes.

3.1.1. Mathematical modeling of mixing:

The understanding of hydrodynamic effects on algae growth has influenced some researchers to correlate fluid dynamical properties to algae growth. One presentation used properties such as shear, viscous dissipation rates, and rate of strain in their discussion (Thomas & Gibson, 1990). Mathematical models were then developed using such properties, e.g. (Wu & Merchuk, 2004), and were later used for mathematically simulating individual bioreactors (Marshall & Huang, 2010; Vunjak-Novakovic et al., 2005).

3.1.2. CFD modeling of Mixing:

With the introduction of computational fluid dynamics (CFD), studies used variables such as turbulent kinetic energy (TKE) and dead zone percentage (DZ) (Yu, et al., 2009) to further understand the effects of hydrodynamics on algae growth.

Many CFD simulations have been used to design photobioreactors; Bitog et. al, (2011) has presented an analysis of 35 such cases. The basis of CFD is to extrapolate a set of operating conditions and assumptions to simulate results of a theoretical model. Though magnitude and profiles of some results have been validated, there are only few studies of fundamentals (hydrodynamic measurements) under well-defined conditions (Pruvost, Pottier, & Legrand, 2006). Others suggest to study the effects of operational parameters, varied at will (Silva, Cortinas, & Ertola, 1987).

Because many of the CFD codes were lacking fundamentals, models have been used to describe bioreactors with oversimplified descriptions of two phase flows; both phases were assumed as liquid but were input with large differences in density to mimic two separate phases. A novel code must be written to describe phase differences in terms of bubbles and liquid because it is only this relationship between phases which can describe realistic scenarios. Future codes should be able to simulate the bubble's movement through a liquid, and be able to model multiple bubbles through a field of geometric configurations. This novel code could be a great advancement in simulating real world problems in bioengineering and chemical engineering.

The aim of this paper was to implement a novel computer code to describe the interaction between multiphase flows. In our studies, we considered multiple bubbles, in the gas phase, moving through a two dimensional rectangular geometry containing water (liquid phase). By coupling multiple sets of momentum equations together, we were able to simulate the mechanics of the two phases with a computer code. Once validated, this will provide more in-depth knowledge into the inner workings of aerated bioreactors.

3.2. Materials and Methods

3.2.1. Fluid Assumptions

Cases were run using water as the liquid fluid. We assumed that water would be able to mimic a liquid algae culture. This assumption was made because there is only very slight density and viscosity difference between water and an algae culture. This is due to algae's specific gravity being close to 1 and the dry weight ratio of algae in water to be around 0.1%. Because this shows that algae culture is in fact mainly water and has similar fluid properties, it is a comfortable assumption that the fluids will act the same under dynamic loading.

3.2.2. Commercial Code

Initially, commercial codes (in our case: ANSYS Fluent software and Solidworks software) were run to understand the movement of fluids through typical bioreactors. Because the commercial codes were limited by oversimplifications in the multiphase flows, the bioreactors chosen to be studied were mixed through mechanical methods and assumed as single phase flows. Assumptions inputted into this software were: no slip boundary conditions at the walls, k-ε turbulence model, and single phase water as the fluid at 25 ^{0}C.

3.2.3. Novel Code

A novel CFD code was developed by Dr. Zhi J Wang and Varun Vikas, of the aerospace engineering department at Iowa State, in collaboration with Dr. Fox, of the chemical engineering department at Iowa State. This code's novelty is due to a series of four momentum equations (nicknamed QMOM) to describe the movement of a bubble through a liquid. Its initial stages of validation were those of a single bubble, at a single velocity, moving through a rectangular two dimensional mesh with the assumed liquid to be water. These validation trails proved to be successful and the code was later used by in our experiment to simulate multiple bubbles and multiple inlet velocities. This proved to be challenging because it was the first test of this type of field study for the code. Not only will the liquid movement have to be simulated for its movement around a bubble, but other bubbles in the same case would be moving liquid from their surroundings. This brings up issues of bubbles interacting with themselves and the liquid being moved in many different directions at once.

3.2.4. Mesh

To run codes using CFD, it is important to create a geometric representation of the control volume of study. It is then necessary to designate multiple points within this space to carry out calculations. The conglomeration of these calculation points is commonly referred to as a mesh, shown in Figure 3.1. This mesh was designed to scale using the software CFD-GEOM. It mimicked the flat panel bioreactor which it was meant to simulate. The

dimensions of the two dimensional mesh were 60 cm in length and 56 cm in height. The height dimension accounts for the liquid within the bioreactor not reaching the upper threshold of the flat panel's inner volumetric boundaries as well as accounting for a sparger within the bioreactor. A more dense set of calculation points are directly above horizontally similar to the inlet holes because most of the complex relationships between bubble and liquid will occur within the path of the bubble's ascent. This mesh contains over 600 calculation points which went through countless calculations and interactions until a steady state was determined. Table 1, below, shows the method used to input the velocity of the air into the system as well as the hole diameter (width in 2D) and hole placement.

Meshes for the single phase commercial code bioreactor simulations were generated using a combination of 3D geometry software (Solidworks) and a mesh generation software developed by ANSYS. ANSYS workbench was to complete the process of the simulation starting from inputting geometric configuration from a Solidworks part file (.prt) to generating a mesh, setting initial input parameters, running a case, and viewing the results.

3.2.5. Solution convergence

Once all input parameters are set for the code, the next step of the process is to run the code until a steady state is achieved. In Fluent, this is achieved through their code (which is not published). Using the novel momentum code, this is done by periodically viewing the two different outputs of the running code using Tecplot software. The two outputs are listed below:

One of the outputs of the code is called "qmom" and is used as the main bubble solver. Its main advantage is to view solutions in a flow field that detects the average concentration of bubbles in a given area of the reactor. Concentration ratio is referred to as nm. For example, 0.1 nm means that ten percent of that specific area in the bioreactor was, on average, occupied by a gas. To determine steady state for this output; we first view the graph to make sure that the bubbles had completely risen to the top, we then make sure that the bubbles' trajectory is plausible (i.e. vertically oriented), and we finally look at the time scale to see if

the pattern remained more or less the same over at least 5 seconds of "real time". This is one method of ensuring that a solution is being reached by the code.

Another one of the outputs of the code is called "pressbased". This output describes the solutions reached by the liquid (phase) solver of the code. It can be viewed in Tecplot as a graphical representation of either the pressure distribution within the reactor or the flow field visualization of velocity magnitude. While ensuring solution convergence, it is necessary to check the pressbased solution and view the pressure distribution. Distinct pressure zones should be seen throughout the reactor solely based on depth of the liquid (i.e. horizontal pattern). If this is not the case, an output from the code should not be accepted because the solution has most likely diverged.

3.3. Results

3.3.1. QMOM:

Many multiphase flow models were run using the QMOM code. These models varied by input velocity as well as inlet hole number, width, and placement. Initial testing of the code produced diverging solutions at inlet velocities which were above o.1 m/s. Because it was difficult to modify the code, it was assumed that as long as the total flow rate of the system was maintained, the results should be indicative of the real-world system. To do this, the inlet diameter of the holes was increased so we could have low enough velocity values to produce and converging solution while still maintaining the same inlet gas flow rate.

One of the first successful converging results of the code under multi-bubble loads is shown in figure 3.2. Input parameters of this case were: 12 holes equally spaced along the bottom of the reactor with a total inlet gas flow rate of 8 liters per minute. The figure represents the nm value which describes the trajectory of the bubbles in the reactor. This was visually compared to the tangible reactor which was running with a liquid medium of algae culture. The main similarity in this instance is that the trajectories of the bubbles horizontally converge towards the center of the reactor. This is because of a no-slip boundary condition at the walls of the reactor which have slow moving liquid in the immediate vicinity. This

slow moving liquid has a slightly higher pressure and is able to push the faster moving fluid, that which is along the bubble trajectory, towards the center.

Another successful representation of the code was that shown in figure 3.3. This figure also shows the "qmom" solution and is graphed in terms of nm. The initializing parameters for this case are three holes (one in the center and the other two offset by 9.2 cm) and an inlet gas flow rate of 800 ml/minute. The picture on the far left in figure 3.2 is the tangible bioreactor which had been modified for accuracy (from the previous version shown in figure 1) to have a flat sparger and identical inlet holes. The CFD study is shown in the center of the figure and presents the solution of the CFD code to compare bubble trajectory. The picture on the right in this figure shows experimental measurements of tangible bioreactor's fluid velocity profile. Each of this pictures in the figure show that the trajectory of the simulations is qualitatively identical to that visualized and measured in the tangible bioreactor. The code was able to distinguish multiphase profiles associated with this low inlet flow rate and few holes from that in figure 3.1. This is apparent due to validated bubble trajectories which are less horizontally centered in low flow rate studies (figure 3.2) and validated bubble trajectories which are horizontally centered (figure 3.1). The low gas inlet flow rate does move the liquid but not enough to make a high velocity differential between the liquid and the center and that from near the walls. Therefore, the liquid at the walls doesn't push the centered liquid inwards.

Though some of the simulations presented matched bubble trajectories with those of real-world cases, our group hasn't been able to achieve a match with the liquid velocity magnitude (vmag) and real-world scenarios. As learned from PIV experiments, liquid velocity follows an identical pattern as the bubble trajectory. This may be due to the friction at the phase boundary pulling the liquid along with it as it rises or because the liquid has to fill in the void that the bubble leaves, hence also matching trajectory. Intuitively, if the liquid has a high velocity zone in the reactor, it will affect bubble trajectory. Figure 3.4 shows two solutions, in terms of vmag, which do not seem to follow a pattern described by a bubble trajectory. This is concerning, but the most important knowledge gained from these two

cases presented in figure 3.4 is that the assumption needed to run the case is invalid. As previously mentioned, it was assumed that valid results would be generated if the flow rate of gas into the system was maintained and used the same centered placement of holes. The figure demonstrates two cases which were both initialized with equivalent inlet gas flow rates with the inlet holes being centered in equivalent positions. It is obvious that the results, given at the same time step, are much different from each other.

3.3.2. Fluent

Fluent results converged on a solution and were used as a display of flow fields within traditional bioreactors. It was important to demonstrate the power of a code for the design of bioreactors. These results were not validated by our group because we were not concerned with the development of a commercially available code.

As mentioned in Chapter 2, tubular bioreactors are very popular in the field but possess a disconcerting aspect of a centered velocity distribution. To demonstrate this theory using commercial code, a tubular geometry was designed and simulated. Results, in figure 3.5, do show this centralized velocity profile. This is problematic because the available area for fluid movement is significantly diminished and therefor, with a given flow rate, requires a higher pressure to overcome. This means that a pump would have to work harder than if the flow field was evenly distributed over the given diameter. Also mentioned in chapter 2 was the high shear stresses caused by turbulence within a pump cavity. Because there are such high stresses at the site of pumping, the pump is usually the limiting factor in design for maintaining a given turbulence. This flow field exists downstream after a period of fluid flowing in a non-centralized pattern. This initial region is commonly referred to as entry-length and is shown in figure 3.6 as the first 10 meters of tube.

3.4. Discussion

3.4.1. Velocity/bubble generation

The CFD code has few problems with input velocity into the system which forces a solution to diverge. This may be solved in two different ways; the first would be to adapt the code to run at higher velocities or that a lower velocity would scale to a real-world high velocity, and the second and more plausible method would be to incorporate a term for bubble generation. When viewing the dynamic in the tangible system, it seems that the air entering the system boundaries is not entering at the velocity specified. At low velocities, a layer of tension between the liquid and incoming gas phase holds the incoming air (generation) until the bubble's volume is large enough to have a strong buoyancy difference with the surrounding liquid. The buoyancy force will then be large enough to overcome the friction between the two phases and allow the gas to form a bubble and rise through the liquid. This bubble generation method could be designed and validated by PIV measurements taken by our group.

3.4.2. Multiphase: Incompressible and compressible.

This buoyancy force continues its presence as it rises because as the bubble increases in height, the water pressure of its surroundings decreases and the bubble expands. This expansion further increases the bubble volume and therefore the density difference.

3.4.3. Using commercial code to design optimized bioreactors

To design a tubular bioreactor in which the limit of the centralized velocity is 80% of its steady state value shown in figure 3.5 and 3.6, and thus distributing the rest of the momentum to the outer walls, a method of flow alteration will have to take place after every 3 meters. This design is shown in figure 3.7 and is commonly used in the field of fluid dynamics. This design can be seen altering the effects of supersonic air exhausted from at gun (i.e. silencer). It a design of a tubular bioreactor with circular baffles placed three meters apart. This configuration produces flow alterations before and after the baffle; therefore limiting the flow from fully developing into the flow pattern seen in figure 3.5.

Figure 3.8 shows a similar design approach to a common problem. Currently, the largest algae reactors are those of the "open pond" design and one of the problems visualized through CFD is that of high velocities along the perimeter of the contained fluid. Once again a baffle was used to disrupt fully developed flow and distribute velocity to a higher volume. In this case, the fluid is flowing counterclockwise, staring from the right of the long parallel baffle. As the fluid flows around the first bend, there exists a low velocity region at the left side and top end of the baffle. This velocity zone is therefore counteracted by a very high velocity zone which is along the perimeter of the reactor where the fluid is just exiting the first bend. To limit this high-velocity fluid flow, a baffle was placed close to the outside wall and served its purpose of distributing high velocity zones of fluid to lower velocity zones. Therefore the design of the system by using CFD enabled a more controlled velocity profile over the total volume of this common reactor-type.

3.5. Conclusion

CFD for the design and optimization of traditional and novel bioreactors is a very powerful tool. This technology allows designers to gain insight into the fluid dynamics of a bioreactor without attempting tedious mathematical equations by hand. It also allows for many geometric configurations and fluid flow rates to be tested without actually constructing the reactor. Single phase fluid flows have been validated many times and are therefore prevalent in many commercially available codes. This allows for testing reactor systems which use pumps or impellers to move liquid. The main drawback of commercial codes is due to their inability to simulate multiphase flows properly. There are many benefits of using aeration as a means for fluid movement. Hopefully, future codes will become available for the design and testing of reactor systems which utilize such multiphase flows.

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Tables

Table 3.1. Hole configurations for CFD analysis.

pi	Volume	width	depth	height	tube l.	% Vol.
	Liters	cm	cm	cm	cm	%
3.14	15.81425	61	5	61	55	0.85

hole D.	hole area	# holes	Total Area	spacing	Dist.to center	v @.5 vvm	v @ 1vvm	v @ 1.5 vvm	v @ 2 vvm
0.1	0.01	254	1.99	0.1	0.2	0.66	1.32	1.98	2.64
0.3	0.07	28	1.98	1.6	1.9	0.67	1.33	2.00	2.66
0.5	0.20	10	1.96	4.5	5.0	0.67	1.34	2.01	2.68
0.7	**0.38**	**5**	**1.92**	**8.6**	**9.2**	**0.68**	**1.37**	**2.05**	**2.74**
0.9	0.64	3	1.91	13.1	13.8	0.69	1.38	2.07	2.76
1.1	**0.95**	**2**	**1.90**	**17.6**	**18.3**	**0.69**	**1.39**	**2.08**	**2.77**
1.3	1.33	1	1.33	26.9	27.5	0.99	1.99	2.98	3.97

Figures

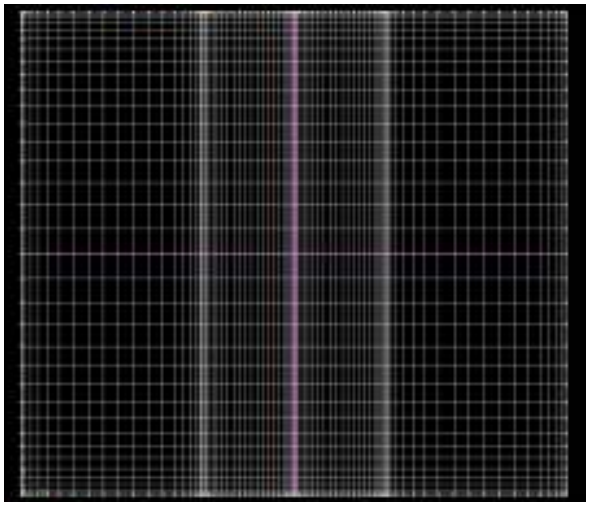

Figure 3.1. Two dimensional mesh of flat panel bioreactor for CFD

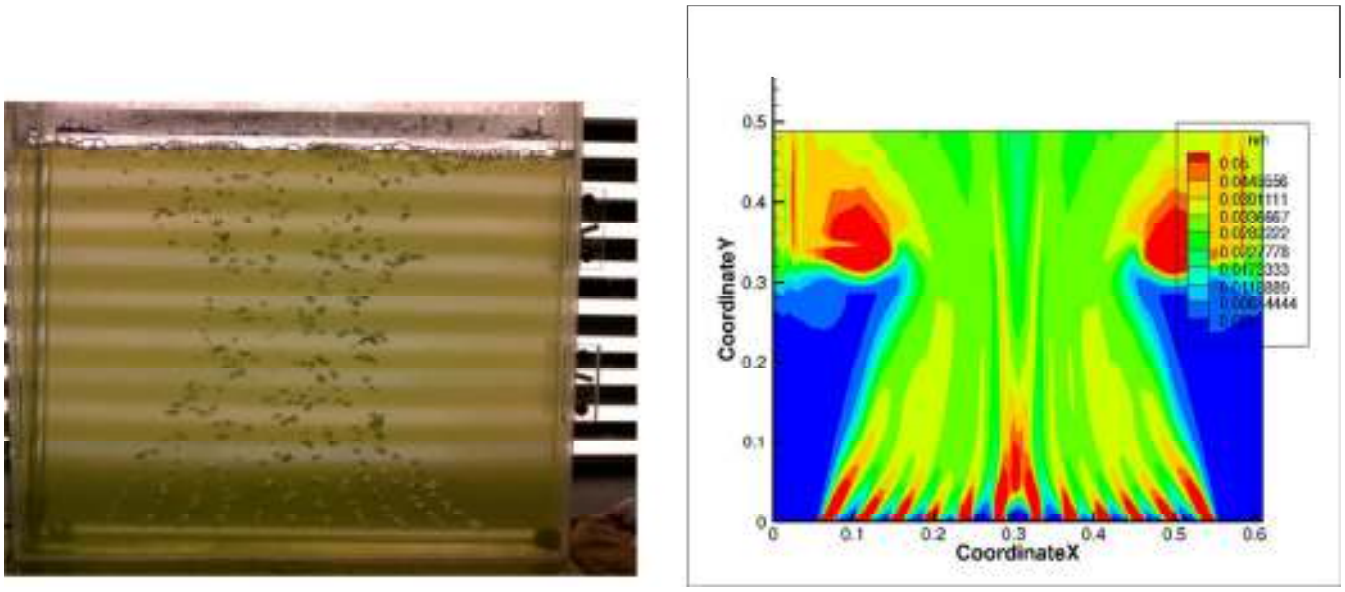

Figure 3.2. First validation case comparing a reactor using12 gas inlet holes; simulated trajectories on the right vs and real world tests on the left

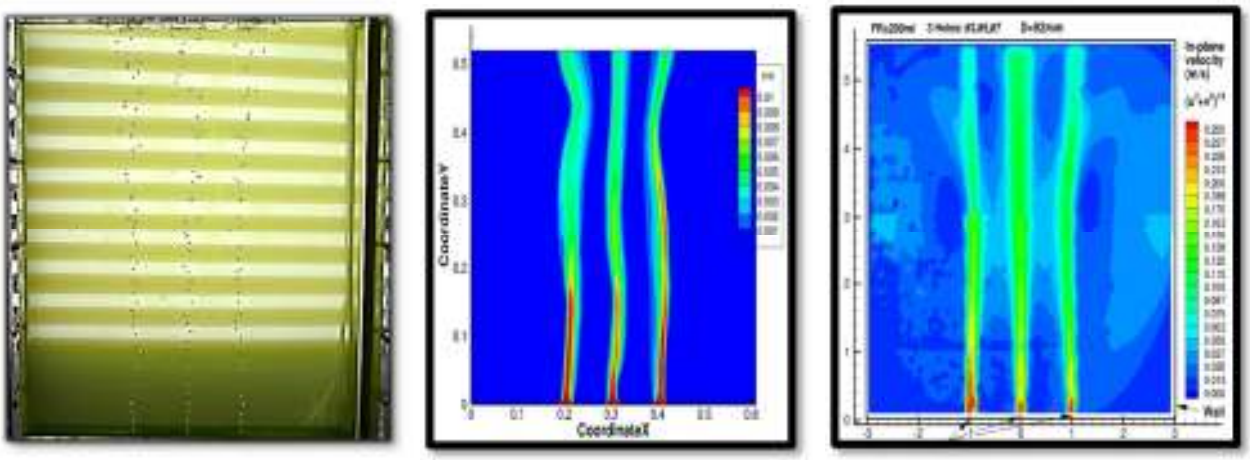

Figure 3.3. Comparison of CFD results to observation and PIV results. From left to right: live algae culture testing, CFD simulations of bubble trajectory, fluid measurements by particle imaging velocimetry.

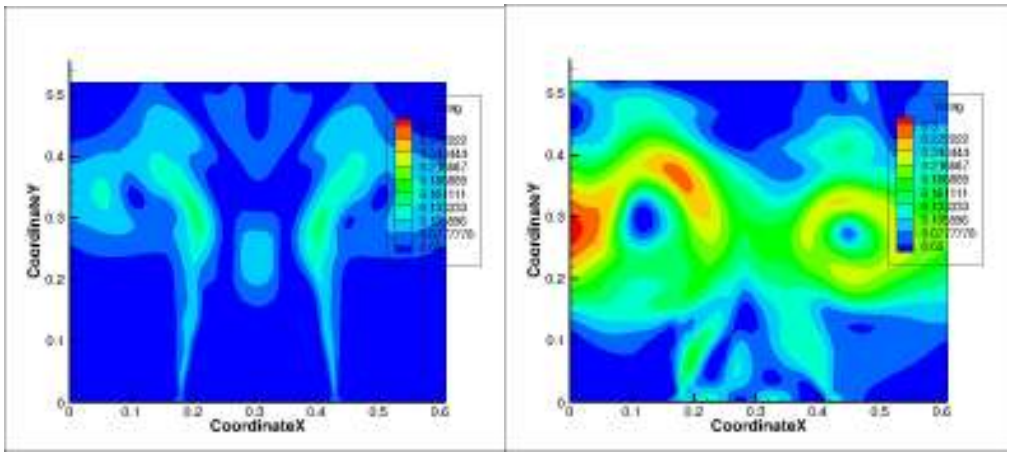

Figure 3.4. Comparison of two CFD results. Velocity magnitude displayed under equivalent flow rates but different hole inlet diameters

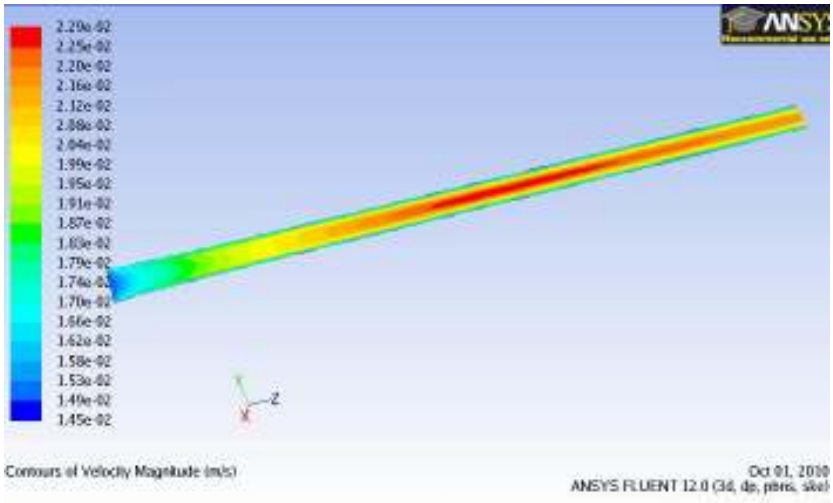

Figure 3.5. Velocity distribution within a tube. Use of a commercial single-phase solver.

Figure 3.6. Velocity of a tube along the center line.

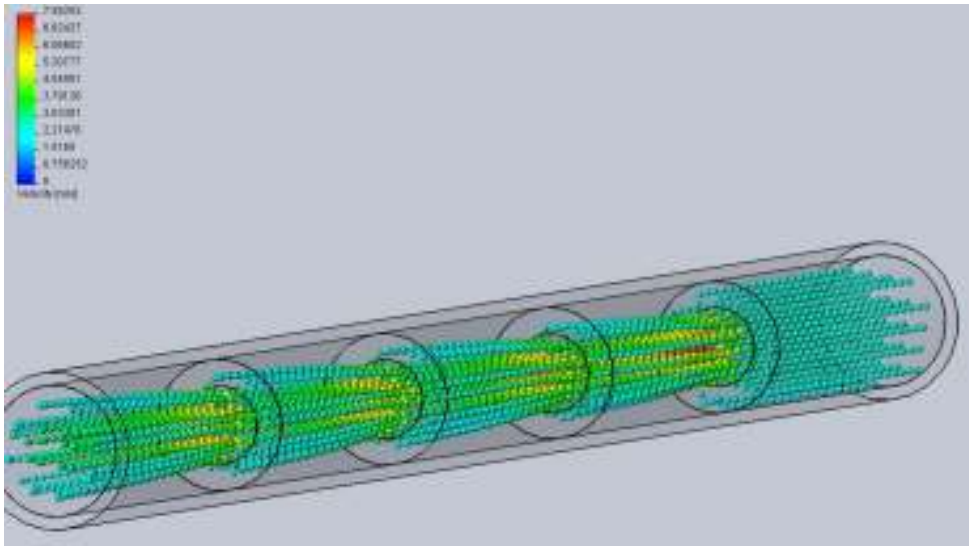

Figure 3.7. Baffled design along a tube. Liquid fluid velocities are colored from low velocity (blue) to high velocity (red)

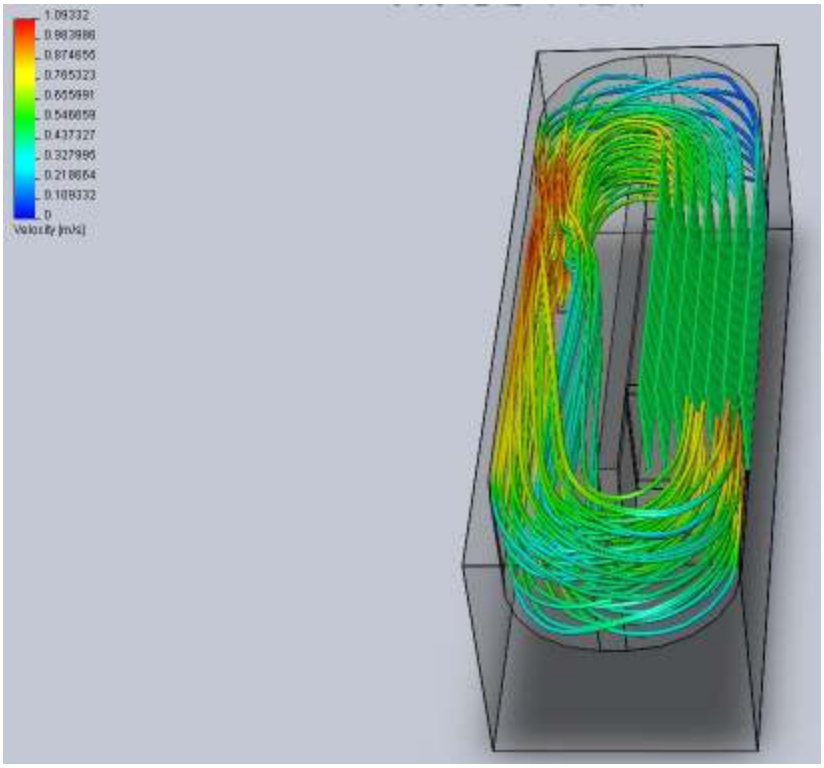

Figure 3.8. Fluid movement with baffle placed in an open pond algae culture system. Liquid fluid velocities are colored from low velocity (blue) to high velocity (red)

Chapter 4. Characterization of Turbulent Multiphase Fluid Dynamics in Photobioreactors and Consequential Effects on Microalgae Cultivation

Abstract

Researchers have discovered the importance of quantifying the performance algae bioreactors with respect to mixing in order to optimize the system for producing a high yield. Current models determine algal physiological response as a function of the input of various operational parameters. Accordingly, there is a need to provide validated in-depth understanding of algal growth and flow dynamics inside the reactor. A fundamentally based modeling approach was developed to optimize algal growth performance using principles of hydrodynamics. Particle Image Velocimetry (PIV) was used as an advanced, non-invasive, diagnostic technique; commonly used to measure liquid properties such as hydrodynamic flow field, liquid velocity, trajectory profiles, and turbulence. This work is to demonstrate the feasibility of using PIV in characterizing the multiphase flow in a flat plate photobioreactor. This was achieved by creating a preliminary effectiveness parameter "M" to describe the mixing quality inside of the bioreactor. It was used to correctly rank each of 6 different experiments into most to least effective mixing in terms of algae growth performance. More in-depth studies may lead to a more substantial equation. This equation may further be used to quantify computational fluid dynamics results, thus allowing for design based on algae growth performance to be optimized by computers before being built.

Keywords: *Multiphase flow, particle imaging velocimetry, PIV, Algae, Scenedesmus Dimorphus photobioreactor,*

4.1. Introduction

In recent years, growing microalgae as biofuel feedstock has attracted significant attention. Compared to terrestrial crops, microalgae can convert solar energy by photosynthesis to chemical energy at much higher efficiency. They can accumulate a large amount of lipid (oil) inside their cells and have very high biomass productivity (Chisti, 2007, Hu et al. 2008). Algal oil can be processed into hydrocarbons through de-oxygenation and selective cracking processes. Depending on the carbon number, these hydrocarbons can processed into different types of jet fuels (e.g., Jet A or JP-8).

Growing microalgae is often performed in closed photobioreactors, which have many inherent advantages such as well-controlled culture conditions (water, light, carbon dioxide and nutrients), the capability to maintain high populations of the desired species, and high algal cell density. This type of culture system is particularly preferred in the production of high value products such as omega-3 fatty acids and astaxanthin.

For the optimal design and operation of algal culture system, turbulent mixing of multiphase flows in photobioreactors (i.e., liquid phase - water; gas phase - CO_2 enriched air; and solid phase-algae cells) plays a very important role in determining the overall performance of the reactors. An appropriate mixing state of the multiphase flows in the photobioreactors is the key for efficiently supplying CO_2, removing generated oxygen, providing alternating periods of light/dark cycle, evenly distributing nutrients, and preventing cell sedimentation and thermal stratification. For example, in a typical photobioreactor operation, mutual shading of the algae cells is the inherent influence on light distribution which would decrease exponentially with the distance from an illuminated surface. In a well-mixed photobioreactor, local turbulences can carry the algal cells through the well-illuminated zones near the illumination sources and poorly-illuminated zones remote from the light incidence (Sheth, Ramkrishna, & Fredrickson, 1977). As a result, each individual cell will be exposed to the illuminating light in a statistical light/dark cycle. A well-mixed bioreactor is also necessary to prevent the algae cells from settling or attaching to the reactor walls Perner et al, (2003). It is also necessary to enhance gas exchange so that the algal cells will not be limited by CO_2

supply and/or inhibited by excess O_2 accumulation Alias, et al., (2004). However, a too high degree of mixing may result in a high shear stress, which may cause physical damages to algal cells, thereby limit algae growth (Thomas & Gibson, (1990); Alias et al., (2004); Silva, Cortinas, & Ertola, (1987); Sastre et al., (2007); Bronnenmeier & Markl, (1982)). It is also known that high differences in hydrostatic pressure, resulting from over-mixing, can also negatively affect algae cell metabolism. Thus, keeping an appropriate mixing state is a key issue for the optimal design and operation of a photobioreactor.

Traditional studies of the effects of mixing on algal growth were plagued by over simplistic models based on few parameters. For example, (Marshall & Huang, 2010) describe how early models were based solely on linear velocity. To improve our understanding, researchers such as Thomas & Gibson,(1990) correlated algal growth with the fluid dynamical properties such as shear stress and viscous dissipation rates. Based on such parameters, a mathematical model was developed to provide a more complete understanding of hydrodynamic effects on algae growth (Wu & Merchuk, 2004). This model was later used by many as the basis for mathematically simulating algae growth (Marshall & Huang, 2010; Vunjak-Novakovic et al., 2005). In these studies, the photobioreactors are basically treated as a black box and algal physiological response is a function of the input of various operational parameters.

Accordingly, there is a need to provide an in-depth knowledge and understanding of algal growth and flow dynamics inside the reactor. A fundamentally based modeling approach can be developed to optimize algal growth performance using principles of hydrodynamics. Particle Image Velocimetry (PIV) as an advanced, non-invasive, diagnostic technique that has been used to measure liquid properties such as multiphase flow field, liquid velocity, trajectory distribution, and turbulence. PIV has been successfully used in the field of aerodynamics. This work is to demonstrate the feasibility of using PIV in characterizing the multiphase flow in a flat plate photobioreactor. The objective of using PIV is to quantify the turbulent mixing of multiphase flows and understand its effect on algae growth. .

4.2. Materials and Methods

4.2.1 Photobioreactor setup

A flat plate photobioreactor was used in this work. The reactor configuration provides a simple structure that allows effective testing of mixing systems**.** The structure of the reactor was made using ½ inch thick sheets of Poly(methyl methacrylate), (PMMA). The dimension of the reactor will be 2 ft × 2 ft (height × length) with 4 in "gap" between the two panel plates. The working volume of the reactor was 16 L.

Fluid mixing in the reactor was achieved through introducing CO_2-rich air through a sparging system at the bottom of the reactor. As shown in Figure 4.1, a sparging system consists of eleven air inlets. The position of the holes was designed such that the gas introduced into the photobioreactor can be controlled be selecting specific combination of holes to achieve the symmetric hole distribution and equal spacing. Sparging holes inlet diameter was 0.5 mm. To ensure each hole can uniformly aerate air into the reactor, the gas was introduced to each holes and released into the reactor though an independent 0.5 mm inlet diameter tubes that are connected to a compressed air source.

4.2.2 PIV setup and measurement

Figure 4.2 shows the schematic of the PIV system used in the present study. For obtaining PIV measurements, water premixed with silver coated hollow glass spheres (Dantec S-HGS, 10 μm) at a nominal volume fraction of 10^{-5} was used to mimic the algal culture solution. Illumination was provided by a double-pulsed Nd:YAG laser (NewWave Gemini 200) adjusted on the second harmonic and emitting two pulses of 200 mJ at the wavelength of 532 nm. The laser beam was shaped to a sheet by a set of spherical and cylindrical lenses. The thickness of the laser sheet in the measurement region was set at about 1.5 mm. Two parallel high-resolution 12-bit CCD cameras (PCO1600, CookeCorp) were used for PIV image acquisition with the axis of the camera perpendicular to the laser sheet. The CCD cameras and the double-pulsed Nd:YAG lasers were connected to a workstation (host computer) via a

digital delay generator (Berkeley Nucleonics, Model 565), which controlled the timing of the laser illumination and the image acquisition.

After PIV image acquisition, instantaneous velocity vectors (u_i, v_i) and vorticity (ω_z) can be determined. The distributions of the ensemble-averaged flow quantities such as the mean velocity, normalized Reynolds Shear Stress ($\bar{\tau} = -\overline{u'v'}/U_\infty^2$), and turbulence kinetic energy ($TKE = 0.5 \times (\overline{u'}^2 + \overline{v'}^2)/U_\infty^2$) were obtained from a cinema sequence of about 1,000 frames of instantaneous PIV measurements. The measurement uncertainty level for the velocity vectors is estimated to be within 2%, while the uncertainties for the measurements of ensemble-averaged flow quantities such as Reynolds stress and TKE distributions about 5%.

4.2.3 Algal culture experiment

4.2.3.1. Microorganism, media and culture conditions

The microalga *Scenedesmus dimorphus* (UTEX #1237) was used. The strain was maintained on agar plates at 4^{o}C, and then transferred 250 Erlenmeyer flask containing 50 ml of medium, and incubated at 25 ^{o}C in an orbital shaker set to 170 rpm. The medium for the seed culture was Bolds basal medium containing (per liter) 17.5 g. KH_2PO_4, 2.5 g. $CaCl_2.2H_2O$, 7.5 g. $MgSO_4$.7H2O, 25 g. $NaNO_3$, 7.5 g. K2HPO4, 2.5 g. NaCl, 50 g. EDTA, 31 g. KOH, 4.98 g. $FeSO_4$.7H2O, 1mL H_2SO_4, 11.42 g. H_3BO_3, 0.71 g MoO_3, 8.82 g. $ZnSO_4.7H_2O$, 1.44 g. $MnCl_2.4H_2O$, 1.57 g. $CuSO_4.5H_2O$, and 0.49 g. $Co(NO_3)2.6H_2O$. The pH of the medium was adjusted to 7.0 before being autoclaved at 121 ^{o}C for 15 min. The illumination was provided by 60-W cool white plus fluorescent lights at 110-120 μmol $s^{-1}m^{-2}$ measured with an LI-250A light meter and Quantum Q40477 sensor (Li-Cor Biosciences, Lincoln, NE, USA).

4.2.3.2. Algal culture in plat plate photobioreactor

50 mL flask cultures were grown and transferred to three bubble-column photobioreactors (500 mL working volume) which were aerated by air containing 2% CO_2. The cells in the bubble column reactors were then used as inoculum for the flat plate photobioreactor. The

medium composition used was the same as flaks culture. The temperature of the photobioreactors was controlled at 25^{o}C. Multiple cool white plus fluorescent lights tubes (60-W) were placed one foot away from one of the 2'×2' faces of the flat plate photobioreactor in a parallel orientation. This was the sole source of illumination. The light intensity on this face of the photobioreactor was around 110-120 μmol $s^{-1}m^{-2}$ with uniform distribution. This value was also used evaluate effectiveness mixing on low constant light intensity by Yu, et al., (2009) and Wu & Merchuk, (2001).

The flat plate photobioreactor was operated at different combination of operational parameters including the total aeration rate, number of aerated holes, and the placement of the aeration holes (Table 1). For each operational condition, the mixing profile of the fluid flow in the reactor was determined by PIV measurements. The cell growth performance was also monitored by measuring the optical density of the solution at 685 nm.

4.3. Results

4.3.1 Effect of CO_2 concentration and total CO_2 flow rate on algal growth

The algal growth in photobioreactor highly depends on the CO_2 input. Because large scale resources offer pre-mixed air with CO_2 (i.e. exhaust from a power plant), and because mechanical characteristics for density are the same for equivalent concentrations of mixed gases at equivalent pressures, all of the air entering the flat panel bioreactor was mixed with around 2% CO_2. This value is similar to a 3% value used by Wu & Merchuk, (2001), and a 2% value used by Silva et al, (1987).

To ensure that systems were also compared with identical total induction of CO_2, cases 2-4 serve as a comparison with equal concentration (2%) as well as equal total CO_2 input (10ml/min). To test all flow rates with only 10ml/min of CO_2 input would change the mechanics of the equations as well as offer a different diffusivity rate from the bubble into the containing liquid (as we have maintained equivalent bubble sizes).

4.3.2. Effect of aeration rate on mixing property and algal growth

The flow characteristics of the flat plate photobioreactor were first investigated at different aeration rates. The flow rate was set at 200 ml/min, 500 ml/min, 800 ml/min and 1600 ml/min with the same aeration geometry of three aeration holes at the fixed position (holes # 3, 5 and 7, Figures 4.5A,C,E). Figure 5.5 shows the PIV measurements on the multiphase flow field in the photobioreactor. Because the contained liquid maintained a boundary with no inlet or exit, upward moving flows were matched by identical downward moving flows. Circular clockwise and counterclockwise motion allowed for the fluid to maintain vertical and lateral equilibrium. In aeration patterns using three center holes (cases 1, 2, 5), upward vertical movement was in the center was counterbalanced with downwards movement along the lateral walls. Experiment 4, which uses a spread aeration pattern (hole #s 0, 5, and 10), was used to provide a different mixing flow pattern with a majority of circular movement between bubble paths. With the increase of flow rate, the flow velocity in the bioreactor increases while there were no significant flow pattern changes. The interaction between bubble columns becomes evident when the flow rate is higher than 500ml/min. As a result, three columns of bubbles tend to coalesce near mid-height, and then split into three columns near the top of water. With the increase of flow rate, the flow becomes more unsteady and more sensitive to the small difference in the geometry and flow rate of each bubble column, thus the paths of bubbles tend to tilt into one direction resulting in an asymmetric flow pattern (Figure 4.5C and 4.5E). Figure 4.5B shows that even with a high flow rate, this effect is not prevalent while using the total number of holes distributed along the full length of the bottom of the reactor.

The algal growth performance was also evaluated by performing batch algal culture at different aeration rates. Using a 200 ml/min aeration rate lead to poor liquid mixing and large stagnant zones existed in the photobioreactor (Figure 4.5A) , the inoculated cells were largely settled to the bottom of the reactor within 12 hours of the inoculation. As a result, it was found the cell density in the bulk liquid decreased with the culture time (Figure 4.3). Increasing the aeration rate from 200 ml/min to 500 ml/min improved mixing performance (Figure 4.5C). However, significant zones still existed in the photobioreactor which result in

a significant sedimentation of algal cells. The cell growth and the sedimentation were balanced at this mixing condition; therefore, the algal cell density leveled off during the culture time (Figure 4.3). When the aeration rate increased to 800 ml/min, the mixing of the reactor was improved significantly (Figure 4.5E). Correspondingly, the algal growth showed a typical batch growth pattern (Figure 4.3). With further increasing of the aeration rate to 1600 ml/min, further improved algal growth occurred (Figure 4.3).

4.3.3. Effect of the aeration holes distribution on the flow characteristics and algal growth

In addition to the aeration rate, the physical placement of the aeration holes also played an important role for the flow characteristics and the algal growth in photobioreactors. To investigate the effects of aeration hole placement, the photobioreactor was aerated at a constant flow rate (500 ml/min) through different combination of locations of aeration holes.

Figures 4.5(C,D,F) show the cell growth under different physical placement of the aeration holes. As shown in these figures, aeration through the three centered sparging holes (#3, #5, and #7, Figure 4.5C) is not desireable as the low cell density was obtained (Figure 4.3). When air is areated from wider distribution, (i.e., holes #0, #5 and #7, Figure 4.5D)) amuch higher cell desntiy was achieved. However, further increasing the total number of sparging holes from three to six (while keeping ghe areation rate constant) did not further increase the cell density. The results in Figure 4.3 indicate that the geometric placement of sparging holes is a significant parameter affecting the fluid dynamics and the cell growth.

4.4. Discussion

Various studies have been performed to demonstrate the importance of mixing in the photobioreactor design and its effects on algal growth. As explained in the literature, increased mixing can improve a culture even at constant airflow (Savidge, 1981). This is important to the current study because it isolates a “mixing” parameter from other parameters such as CO_2 concentration, bubble retention time, photon flux energy, and time cycle of light

(light/dark ratio). The current work also isolates a "mixing quality" by maintaining constant algae growth parameters. Our study accomplishes this with aeration as the sole source of mixing and this understanding can therefore be used in growth systems such as air lift bioreactors.

The above results show the importance of mixing on algal growth. Both the aeration rate and the location of aeration holes significantly affected the cell growth performance. To provide a deeper insight of the effects of mixing on the algal growth, the fluid velocity profile and the turbulent kinetic energy (TKE) were determined per each experiment.

In previous studies, linear fluid velocity has been used to describe mixing performance (Marshall & Huang, 2010). This method is plagued by oversimplification of fluid dynamics because linear fluid velocity cannot take into account factors of dead zones where algae are unable to grow because they are deprived of nutrients. This parameter also doesn't take into account the light saturation, where algae can reach peak productivity, or mixed later depth. This inability to describe the total volume of fluid could be solved by separating the reactor into areas of productive and non-productive zones. In this work, the flow field measured by PIV was fractioned into four zones represented in figure 4.6; here we define $v < 0.05$ m/s as very low velocity zone; $0.05 \leq v \leq 0.10$ m/s as low velocity zone; $0.10 \leq v \leq 0.20$ m/s as medium velocity zone; and $v > 0.20$ m/s as high velocity zone. Figure 4.6a shows the velocity distribution at different aeration rates. As predicted, the low aeration rates resulted in having the highest percentage area in the lowest velocity zones. Figure 4.6b compares experiments 2-4 which have an equivalent 500 ml/min aeration rate. Differences in these zones are present and can therefore be concluded that critical parameters, other than aeration rate, are acting upon the system.

In addition to velocity, TKE of the photobioreactor at each operational condition was evaluated. The concept of TKE is often used when considering hydrodynamic properties of a system because, in general, TKE is a measure of how much energy is available for movement. In this scenario, it acts as an energy-generation (i.e. potential energy) term within

the system. Therefore, a higher TKE value will increase mixing performance within the reactor. Figure 4.7 shows the mean TKE value for different operating conditions. For equivalent inlet holes, experiments 1, 2, and 5, an increase in aeration rate led to an increased mean TKE value. This, however, is shown to be variable with a difference in mixing patterns. Because TKE is mainly a term which describes potential energy, it should be weighted with a term characterizes the effectiveness of kinetic energy terms.

The concept of mixing quality was proposed to correlate the algal growth performance and the mixing of the turbulent flow in the reactor. The relationship between the mixing quality (M) and aeration rate (Q), mean velocity (v) and mean TKE ($\overline{TKE}$) was defined as follows,

$$\mathrm{M} = \frac{Q}{\bar{v}} \times \overline{TKE} \quad (1)$$

The term $\frac{Q}{\bar{v}}$ describes the total inlet gas flow rate inversely weighted with mean velocity. This term was proposed because it is a good description of how input energy is dissipated into its surrounding volume. The aeration rate, Q, was directly proportional to the mixing quality because with our system of controlled variables, Q a good description of input energy. This is because all inlet gas flow rates enter the system at equivalent pressures and exit at equivalent pressures. All gas flows also reach steady state; after a certain amount of time (usually around 10s), the total volume of gas entering the system is equivalent to the total volume of gas exiting the system. Furthermore, because all of the gas has the same concentration of elements, the sole factor that will determine the difference in inlet energy into the system is Q, inlet gas flow rate. Also, it is beneficial for this energy to be dissipated into kinetic energy over a large volume; inversely weighting the mean velocity to mixing quality will account for this. The term $\frac{Q}{\bar{v}}$ accounts for both of these nuances; but as previously mentioned, this term describing energy and motion should be used to weight the potential energy, TKE, stored in the liquid.

Table 3 summarizes the M value for each operational condition studied in the work. As shown in the table, the final value of M correlates to growth performance very well.

To define qualitatively how to achieve a good quality of mixing, it would be described as effectiveness of the source of mixing to transfer energy into the system. The Ṁ ranking is a measure of some of these terms and is in m^4/s^2. Because the fluid and gasses were of equivalent compositions, these units could be described as energy times distance (J * m). All experiments were done modeling 2 dimensional fluid patterns over the same area and therefore the unit of distance would be insignificant when comparing Ṁ for these cases.

4.5. CONCLUSIONS

A simple relationship can be used to weigh different mixing parameters and gauge effectiveness for algae growth. It's presented here that considering all mixing characteristics is important to understanding hydrodynamic effects on algae growth. Once this is understood, CFD results can be interpreted more clearly. This testing has been done using very low flow rates and a very simple relationship has been formed. It will be important to expand this test to higher flow rates, different forms of mixing (mechanical), and come up with a more complete relationship. Mixing algae-growing-medium achieved with geometry of air inlet holes can maximize the use of light and other inputs for growth. There are a set of mathematical models in place for growth and many high powered machines for CFD. If we can understand quality of mixing related to algae growth starting from fundamentals, we can supplement algae growth models and employ CFD resources. Multiphase bubble-liquid interaction may also need to be looked at by CFD. This can also be helped by fundamental PIV studies.

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Tables

Table 4.1. Experimental design. Comparisons of CO_2 flow rate, inlet gas flow rate, number air inlets, and location.

Experiment	Inlet Gas Flow Rate	Number of Air Inlets	Location of Air Inlets
#	mL/min	#	#s
1	200	3	3,5,7
2	500	3	3,5,7
3	500	6	0,2,4,6,8,10
4	500	3	0,5,10
5	800	3	3,5,7
6	1600	11	0,1,2,3,4,5,6,7,8,9,10

Note: cases with equivalent air inlet placement are 1, 2, 5. Cases with equivalent inlet gas flow rates are cases 2,3,4.

Table 4.2. Ranking system of algae culture specific growth rate (SGR) and the Mixing Quality (M) parameter Parameters of experiment numbers 1, 2, 3, 4, 5 and 6 are listed in table 4.1.

Exp.	**SGR**	**M**	**SGR rank**	**M rank**
6	**30.5**	**81.46**	**1**	**1**
5	**4.48**	**43.96**	**2**	**2**
4	**4.27**	**32.06**	**3**	**3**
3	**2.6**	**24.14**	**4**	**4**
2	**1.2**	**18.38**	**5**	**5**
1	**-14.5**	**6.06**	**6**	**6**

Figures

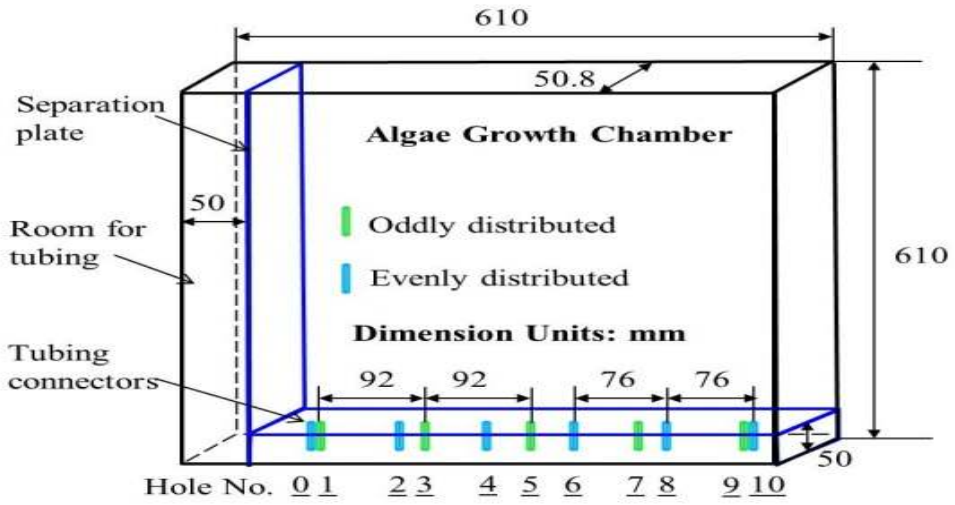


Figure 4.1. Configuration of flat panel bioreactor. sparging system and associated dimensions.

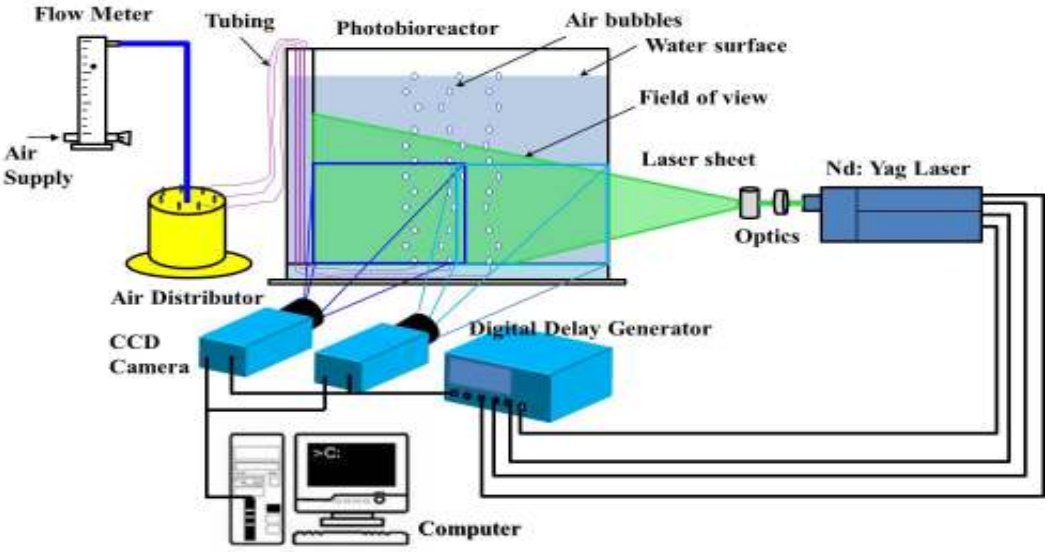


Figure 4.2. PIV instrumentation diagram. Laser and optics are used to create an illuminated sheet while two cameras capture reflected light from microscopic glass spheres. These spheres show the computer the particle placement as the fluid moves.

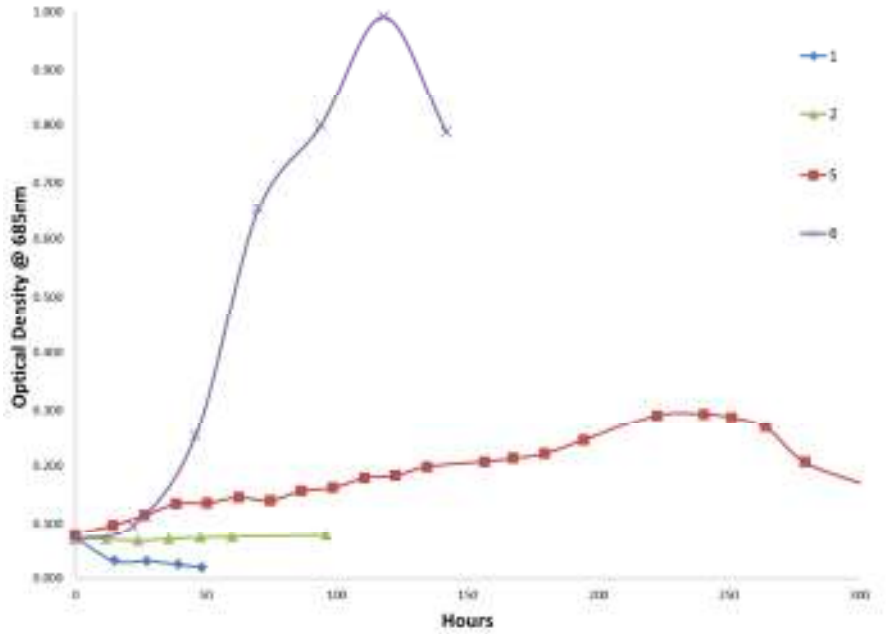


Figure 4.3. Effects of inlet gas flow rate on algae growth. Comparisons with equivalent inlet hole locations. Parameters of experiment numbers 1, 2, 5, and 6 are listed in table 4.1.

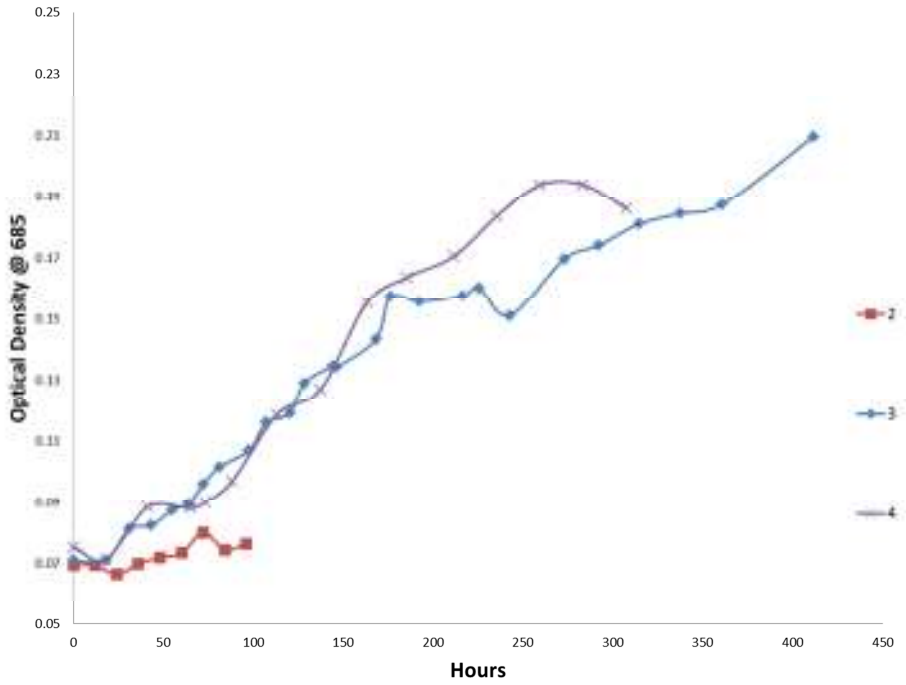


Figure 4.4. Effects of total inlet hole placement on algae growth. Comparisons with equivalent inlet gas flow rate of 500 ml/min. Parameters of experiment numbers 2, 3, and 4 are listed in table 4.1.

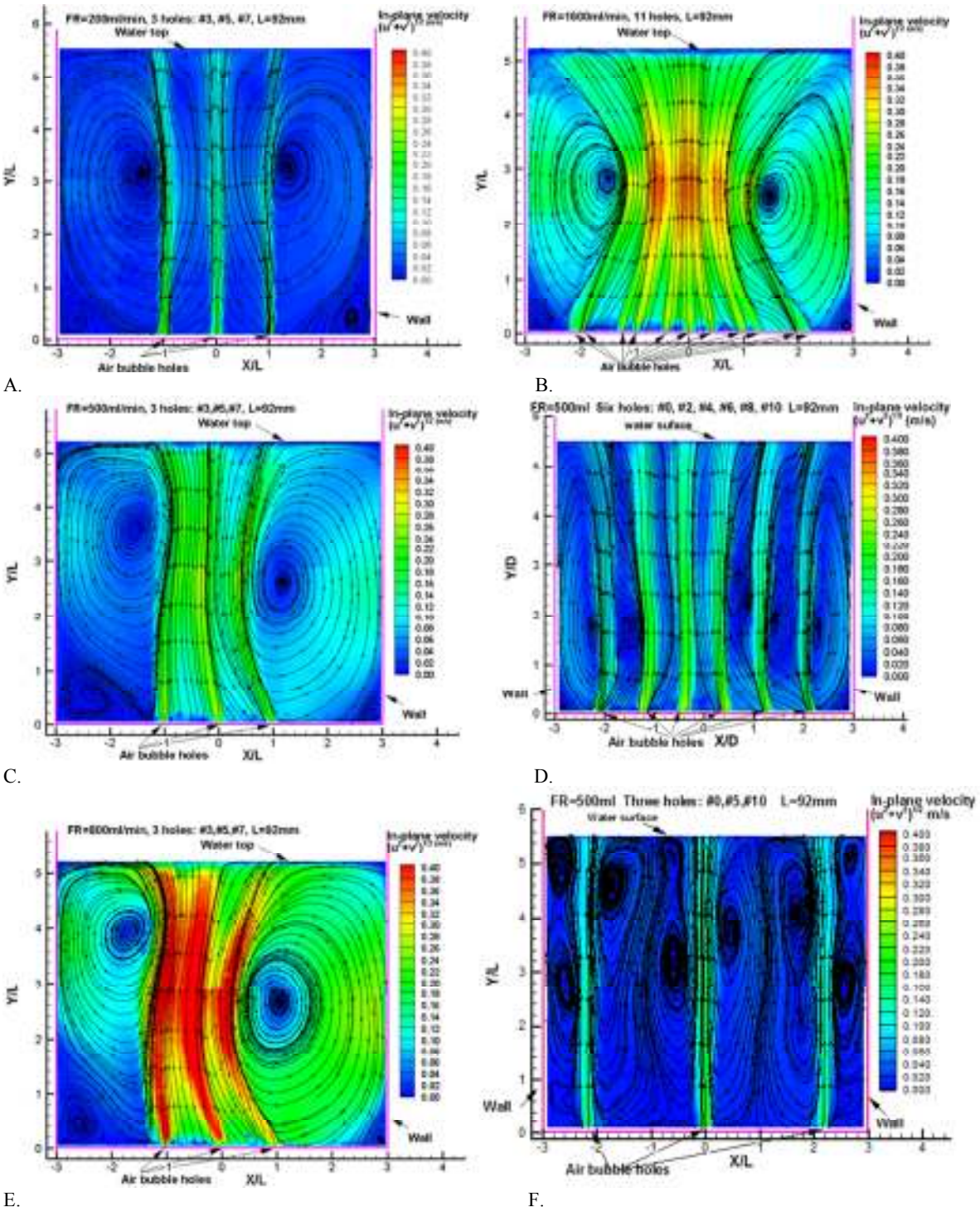
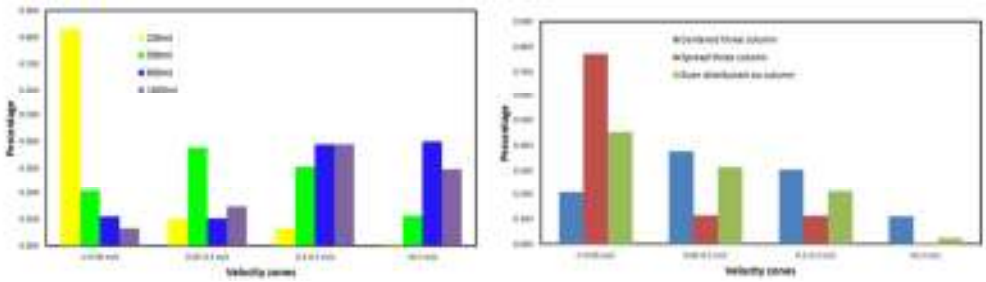


Figure 4.5. PIV results. A corresponds to experiment 1; B to experiment 6, C to experiment 2, D to experiment 3, E to experiment 5, and F to experiment 4. Each measurement shows averaged liquid velocity at steady state. Input parameters into experiments 1-6 are listed in table 4.1



6a. Velocity Zones by flow rates 6b. Velocity Zones by geometry configuration

Figure 4.6. Fluid velocity comparisons. Velocity range by percent area of volume.

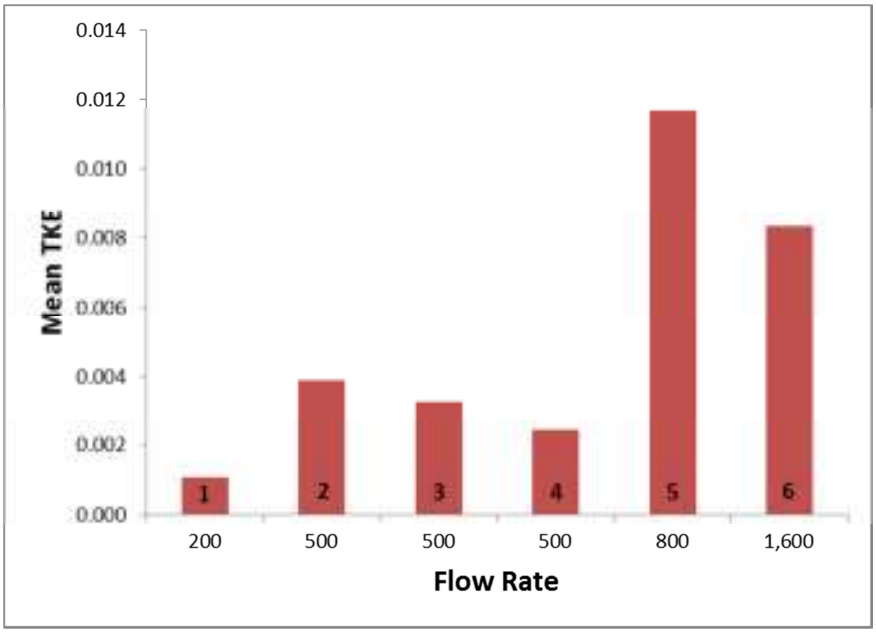


Figure 4.7. Mean TKE per experiment. Parameters of experiment numbers 1, 2, 3, 4, 5 and 6 are listed in table 4.1. Flow rate, along the x-axis, is compared against Mean TKE, on the y-axis.

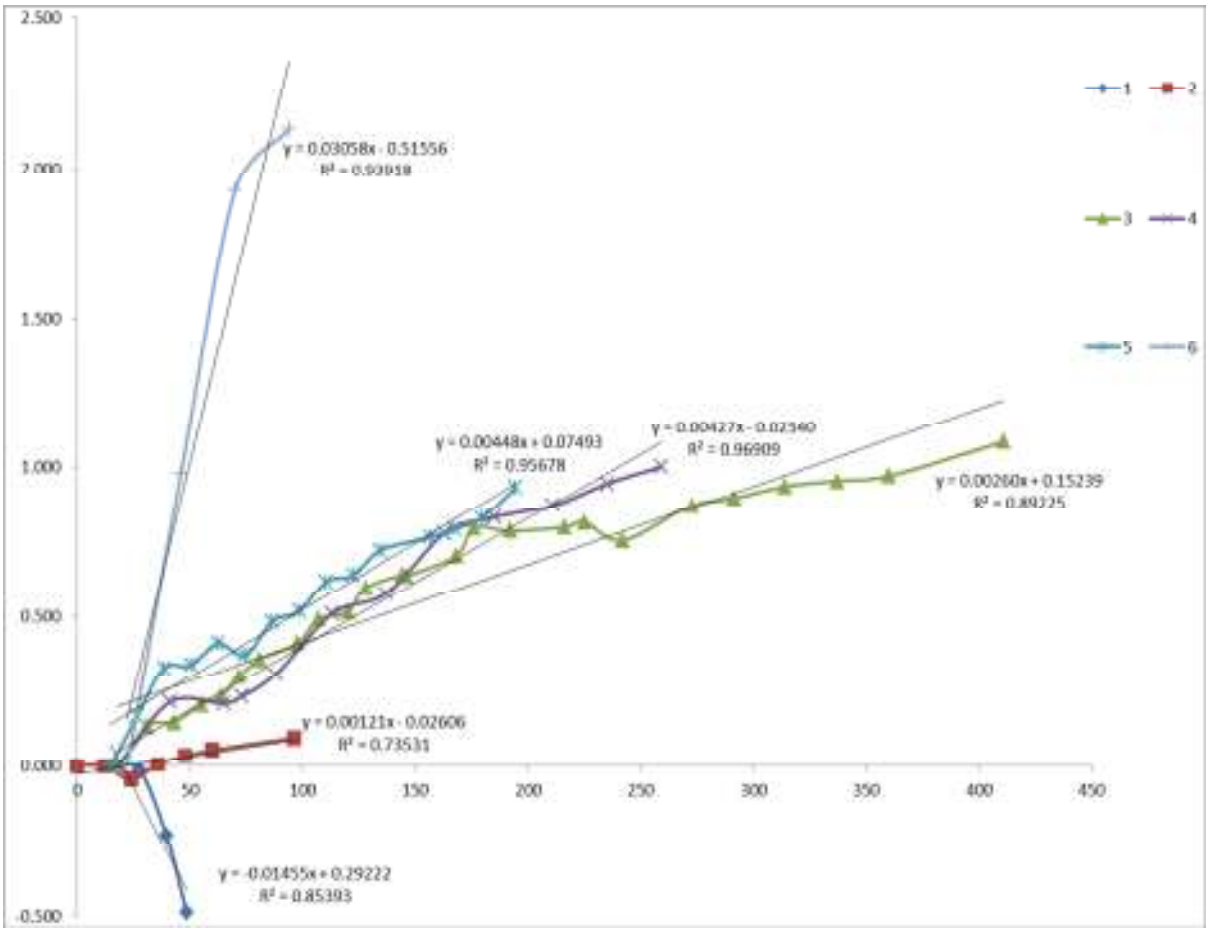


Figure 4.8. Specific growth rate of algae culture growth experiments. Parameters of experiment numbers 1, 2, 3, 4, 5 and 6 are listed in table 4.1.

Chapter 5. General Conclusions

An extensive literature review on the state of research has led our group to pursue studies towards the understanding of fundamentals of the effects of multiphase flows on algae culture systems. Cutting edge computer technologies have been used to simulate and measure algae photobioreactors; the most in-depth studies have been focused on flat panel bioreactors. Equivalent flat panel bioreactors were used for the PIV measurements and the algae growth experiments. This concept has ensured valid flow field results of the relationship between gas phase air moving through a liquid phase culture medium. Algae culture growth results were collected for each experiment that was studied using PIV. They were used to rank effectiveness of each experimental mixing system with respect to algae growth; this lead to a preliminary understanding of multiphase fluid mixing and its corresponding relevance to algae growth performance.

Commercial CFD codes were used to understand and design algae production systems which were governed by a single phase liquid flow. These studies highlight the powerful nature of using CFD code as a tool for design and optimization of an algae culture system as well as its ability to eliminate countless unnecessary empirical attempts. Commercial codes are very powerful in determining single phase flows but these codes cannot be used to describe reactors with aeration as a method of mixing (multiphase flows); these reactors include air-lift bioreactors, flat panel bioreactors, and air lift tubular bioreactors. Hence, a collaboration of researchers was formed to explore the possibility of using a user-written code to simulate the multiphase dynamic of the flat panel bioreactor used in the lab. Even though this code was not at a robust state at the time, it showed promise into the future of its science.

5.1 Recommendations for Future Research

It is recommended to expand on the understanding and preliminary relationship between the multiphase flows mentioned above and the algae culture's growth performance. Some relationships that need to be added to the code are a concentration of CO_2 in the air which is

used for aeration as well as a diffusivity of the CO_2 into the liquid phase. Initial estimates are that this is a function of bubble retention time and fluid velocity at the surrounding of the bubble. Additions to this relationship could be added through additional parameters such as mixed layer depth, light fraction, size and placement of eddy currents, and dark cycle time. These parameters have been studied many times and have been reviewed in chapter 2. They may be incorporated into the model through a further understanding using PIV to measure in-plan velocity profiles. Validations of PIV results will benefit from more growth studies at different light intensities, inlet gas flow rates, and reactor designs. They may also be improved upon by comparing them with similar studies of single phase flow systems to isolate the effect of mixing from the effect of aeration.

Once these additions to the preliminary relationship have been implemented and validated, they may be incorporated into CFD code. The platform of this should be designed around code such as the novel user-written multiphase code used in this study. CFD use has already been demonstrated to be a powerful design code; with the incorporation of algae growth dynamics, this code's utility will be much improved. This is especially true for bioengineers who will be designing photobioreactors of the future.

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Such multidisciplinary studies are necessary to completely understand the mixing effects on algae growth and couldn't have been possible without the help and support of the aforementioned people. I'd also like to thank my family and friends for support, especially my father, Carlo del Ninno, for his efforts in editing.