Automated Monitoring and Control Systems for an Algae Photobioreactor

by

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ABSTRACT

There has been considerable advancement in the algae research field to move algae production for biofuels and bio-products forward to become commercially viable. However, there is one key element that humans cannot control, the natural externalities that impact production. An algae cultivation system is similar to agricultural crop farming practices. Algae are grown on an area of land for a certain time period with the aim of harvesting the biomass produced. One of the advantages of using algae biomass is that it can be used as a source of energy in the form of biofuels. Major advances in algae research and development practices have led to new knowledge about the remarkable potential of algae to serve as a sustainable source of biofuel. The challenge is to make the price of biofuels from algae cost-competitive with the price of petroleum-based fuels. The scope of this research was to design a concept for an automated system to control specific externalities and determine if integrating the system in an algae cultivation system could improve the algae biomass production process. This research required the installation and evaluation of an algae cultivation process, components selection and computer software programming for an automated system. The results from the automated system based on continuous real time monitored variables validated that the developed system contributes insights otherwise not detected from a manual measurement approach. The implications of this research may lead to technology that can be used as a base model to further improve algae cultivation systems.

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Chapter 1

INTRODUCTION

Background

There is great interest in the development of alternative energy sources that have the potential to meet future energy demands, and to reduce society's dependence on fossil fuel. The world economy is highly dependent on fossil fuels for a diverse set of activities (Newell, 2009). Over the past several decades, oil prices have continued to climb, putting a strain on many aspects of the economy. Many believe that it is important to make transition away from oil dependency by developing new energy sources (Newell, 2009). Over several decades there have been numerous efforts that have focused on conservation as well as searching for renewable energy sources that may reduce the dependency on fossil fuels. Most recently the use of crop plants for the production of ethanol has gained attention (Newell, 2009). However, the impact on the food industry and increasing prices has created a conflict between the uses of crop plants for food versus fuel. In recent years, the nature of what was regarded as alternative energy sources has changed considerably. Today, because of the variety of energy sources and differing goals, many companies and educational institutions have been working on the possible ways of extracting energy from natural sources. There are several forms of alternative energy sources such as solar, wind, geothermal, etc.

Based on current events, it has become apparent that energy supplies can easily be interrupted worldwide (U.S Department of Energy, 2010). The U. S. Department of Energy predicted that in 2019, the demand for petroleum oil is expected to be at 19.8 million barrels per day and expected to fall to 18.9 million barrels per day (U.S. Department of Energy, 2013). The transportation sector accounts for the largest share of total consumption throughout the projection, although it is expected to fall in 2040 as a result of improvements in vehicle efficiency with the incorporation of Corporate Average Fuel Economy (CAFE) for light-duty and heavy-duty vehicles (U.S. EIA, 2013). The forces of demand and supply have caused the price of fossil fuels

to rise sporadically but continually. In the United States, oil-refining capacity is also limited. Natural disasters such as Hurricane Katrina, for example, have made key refineries in the Gulf Coast area of the U.S. inoperable for a period of time. The Gulf of Mexico oil production, for example was decreased by 56% per day. This event caused an immediate increase of oil prices due to future markets. The infrastructure and economy are both heavily dependent upon fossil fuels. As a consequence, efforts must be accelerated to develop alternative fuels and the infrastructure to support their production and distribution. The alternative to developing new energy sources is to expand the capacity of conventional energy (i.e., build more oil refineries, expand oil production and expand nuclear energy, etc.). However, the conventional energy technologies face other issues such as limited resources, pollution, and society's scrutiny. Due to these fundamental issues, alternative energy solutions will continue to be developed and pursued by government agencies, academic researches, and innovative industries.

One form of alternative energy that has been slow to develop but has gained some momentum is the development of biofuel from algae biomass. Research and development on algae as a source of biofuel began in the early 1970's in response to the energy crisis prompted by the Arab oil embargo (Sheehan, 1998). However, this technology has faced the challenge of competing with an industry that is more than one hundred years old and well developed. In the last decade university, national laboratories, and multiple companies have engaged in research and development that leads to production of biofuel from algae. However, there is a specific need to conduct further research at multiple levels in order to establish a value chain that may be competitive with the price compared to fossil fuels. The U.S. Department of Energy (Newell, 2009) is expecting biomass to play a major role in the portfolio of non-hydropower renewable sources for electricity generation as seen in Figure 1.1 from the Annual Energy Outlook 2010, the Energy Information Administration (EIA) and Richard Newell's early release presentation (Newell, 2009).

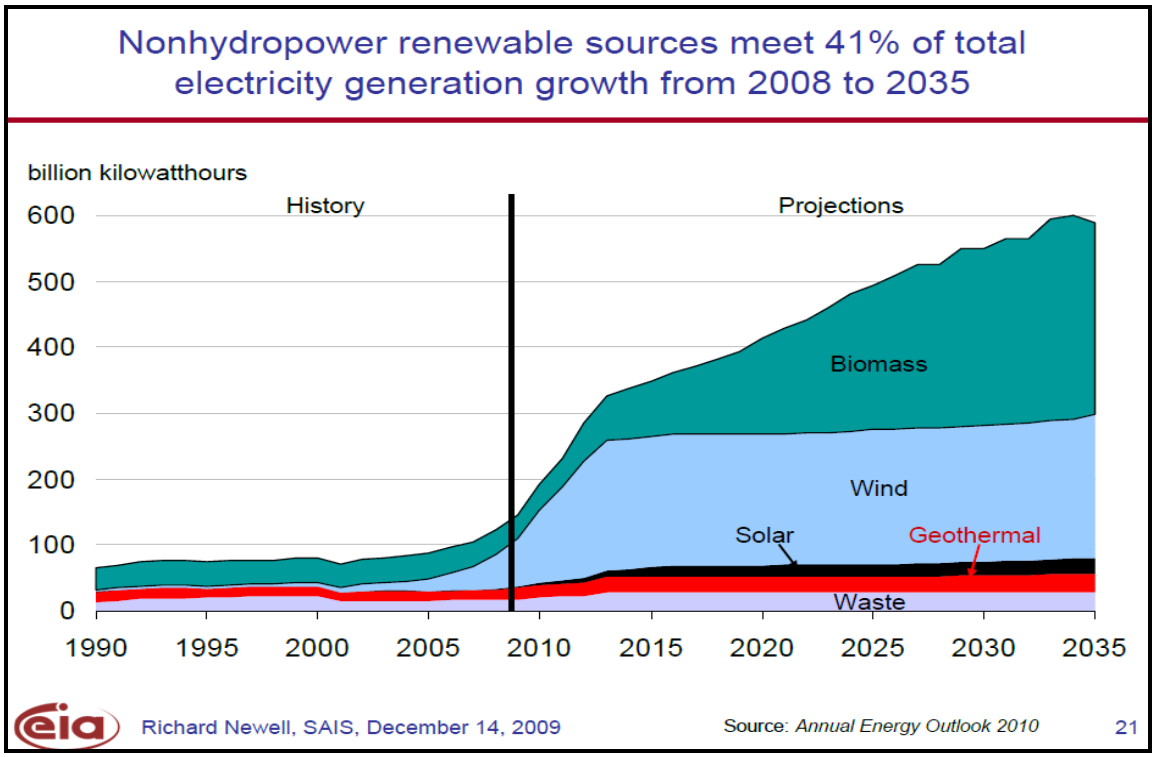

Figure 1.1. Energy Information Administration's Projections of Available Nonhydropower Renewable Energy Sources Through 2035

In response to the energy crisis of the 1970's, the U.S. Department of Energy through its Office of Fuels Development established a funded program for developing a broad range of alternative fuels such as ethanol and methanol, biogas and biodiesel. One of the research components of research within the biofuels program was aimed at developing alternative sources of renewable fuels from algae from 1978 to 1996. The program is known as the Aquatic Species Program (ASP) (Sheehan, 1998) which focused mainly on production of biofuel from high-lipid content algae by utilizing waste CO_2 from coal fired power plants.

Many technical advances were made from this program during the course of almost two decades through continuous algae strain selection and improvement by manipulating the metabolism of algae and the engineering of algae production systems or bioreactors.

Following to the close-out of The Aquatic Species Program in 1996, biomass derived fuels continued to attract attention as one of many solutions to our nation's continued and growing dependence on imported oil, which exposes the country possible risk of disruptions in fuel supply, creates economic and social uncertainties for individuals, businesses, and impacts on the national security. The establishment of The Energy Independence and Security Act of 2007 (EISA) mandated a Renewable Fuel Standard (RFS) that requires within a minimum of 36 billion gallons to be blended and sold with regular fossil fuel as transportation fuel in the U.S. (U.S. DOE, 2010). The RFS mandate also included advanced and cellulosic biofuels and biomass-based diesel and to be implemented by 2022. EISA also set new standards for fuel economy, energy efficiency and advanced research which requires the RFS to increase over time; as well as challenges to demonstrate biofuels Green House Gas emission across the life cycle that is at least 50% less than GHG emission produced by petroleum-based fuels. Table 1.1 illustrates the RFS volume requirements.

Table 1.1. Renewable fuel standard volume requirements (billion gallons) (U.S. DOE, 2010)

	CELLULOSIC BIOFUEL REQUIREMENT	BIOMASS-BASED DIESEL REQUIREMENT	ADVANCED BIOFUEL REQUIREMENT	TOTAL RENEWABLE FUEL REQUIREMENT
2009	N/A	0.5	0.6	11.1
2010	0.1	0.65	0.95	12.95
2011	0.25	0.80	1.35	13.95
2012	0.5	1.0	2.0	15.2
2013	1.0	a	2.75	16.55
2014	1.75	a	3.75	18.15
2015	3.0	a	5.5	20.5
2016	4.25	a	7.25	22.25
2017	5.5	a	9.0	24.0
2018	7.0	a	11.0	26.0
2019	8.5	a	13.0	28.0
2020	10.5	a	15.0	30.0
2021	13.5	a	18.0	33.0
2022	16.0	a	21.0	36.0
2023	b	b	b	b

[a] *To be determined by EPA through a future rulemaking, but no less than 1.0 billion gallons.*
[b] *To be determined by EPA through a future rulemaking.*

A number of next generation biofuels offer significant potential in helping to achieve EISA goals. For example, 15 billion gallons of biofuel can be produced from corn-based ethanol. Another candidate is biofuels derived from algae, which have the potential to help the U.S. meet the RFS, and at the same time advancing the nation closer toward energy independence. Despite their potential, the technology to produce biofuels from algae is considered by many in the field to be in its beginning phase, thus a considerable amount of research, development and deployment (RD&D) is needed to achieve affordable, scalable, and sustainable algae based biofuels.

To advance biofuel development the American Recovery and Renewable Act was established and announced by President Obama and Secretary of Energy Steven Chu which provided for an investment of $800M in new research on biofuels. The investment included funds

for the Department of Energy through the Office of Energy Efficiency and Renewable Energy (EERE) biomass program for research, development and utilization of biofuels.

Statement of the problem

The research and development of algae as a source of biofuel has been conducted by the Laboratory for Algae Research and Biotechnology (LARB) within the Department of Applied Biological Science (ABS) at Arizona State University (ASU) for the last eight years. The research began in the indoor laboratory using smaller scale transparent tanks (photobioreactors) to grow algae. Due to limitations of the laboratory environment to produce the quantity of algae biomass needed, larger scale transparent tank systems were developed in an outdoor facility. However, the systems developed faced challenges associated with outdoor environment variables that affect algae production. In order to compensate for these environmental variables, the designed cultivation systems had to incorporate ways to provide continuous measurement and monitoring of algae production activity and to assist in the control of some of the critical growing or cultivation parameters.

Methods typically used in the field were performed manually on each photobioreactor. With the increasing number of photobioreactor devices, there was a need for consistent and continuous measurement and control of multiple variables to avoid any uncertainty of environmental impact on the growth of the algae.

Scope of the work

The scope of the work for the research included:

- Initial data collection performed manually to monitor algae cultivation at various temperatures and pH on an early generation outdoor photobioreactor.
- Infrastructure fabrication and repair on an existing non-operable datalogging instrument (Campbell Scientific® brand).
- Data logging and monitoring for temperature, pH and dissolved oxygen values using a Campbell Scientific® datalogger.

- Installation of new industrial instrumentation system and infrastructure components at the outdoor site, including in one row of a new generation of algae photobioreactors, and in the mechanical room and greenhouse computer control room.
- Developing data correlation of monitored and controlled values on the algae biomass production system.

Limitations

The early generation photobioreactor system had a North and South orientation. In addition, one specific strain of algae was used during the initial test of the system to compare with laboratory experiments. For comparison, the new generation of photobioreactors faced East and West and was developed to meet the objectives of the supporting sponsor using a different algae strain. Both systems featured a semi-open top tank, which allows air release from the top to the atmosphere. However, the design allows both systems to be susceptible to some air borne debris and other contamination entering to the system.

Chapter 2

LITERATURE REVIEW

Overview of algae

Algae are a large and diverse group of typically autotrophic organisms, ranging from unicellular to multi-cellular forms. The largest and most complex marine forms are called seaweeds. These organisms are photosynthetic similar to land forms; however, they lack many distinct organs such as roots, stems, leaves found in other land plants. For many centuries, people throughout the world have been collecting algae for many uses (Graham, 2000). Algae biomass contains many valuable components and is currently used in some pharmaceutical grade pigments, oils, agar, foods, dietary supplements, paint, and fertilizer. Additionally, many environmentally friendly applications have been suggested for algae biomass including: bio-fuel and bio-filter components to remove toxic organic compounds and heavy metals from water (Park, 2007), bio-monitors to detect toxic contaminants (Melville, 2007), methods to remove CO_2 from flue gas (Mata, 2010), bio-filters to remove nutrients from municipal effluents and dairy manure, and as a commercial fertilizer substitute (Mulbry, 2005). Algae are increasingly being grown in laboratory based bioreactors, outdoor production ponds, and engineered off-shore environments (Chisti, 2007). More recently, a major focus of research and development on algae is related to their potential as a promising source of alternative energy.

Algae as a group of photosynthetic organisms use energy from the sun to combine water with carbon dioxide (CO_2) to produce biomass. Most algae grow in aquatic and marine environments and are usually characterized as either macroalgae or microalgae. Macroalgae are commonly known as seaweeds, and typically can be observed without the aid of a microscope. Microalgae are, as the name suggests are relatively small microscopic organisms. Most macroalgae are marine, but microalgae are common to freshwater and marine environments. Microalgae's potential oil yields, as well as the ability to be grown in a land-based facility make them one of the leading potential sources to possibly replace other crop based feedstocks such

as soybeans or corn. Microalgae are able to produce 1200 gallons/acre when grown at 10 g/m^2/day at 15 percent lipid and up to 10,000 gallons/acre when grown at 50 g/m^2/day at 50 percent lipid. (Pienkos, 2007). With a simple cellular structure and a large surface area to volume body ratio enables microalgae to uptake nutrients efficiently. Their natural environment is water which contains carbon dioxide and nutrients needed for photosynthesis. Many species are very efficient at converting solar energy to biomass. The algae biomass produced contains three main components: protein, carbohydrate, and lipids. A variety of microalgae species can be cultivated under certain conditions to accumulate large quantity of lipids. Under some conditions, lipids may represent more than 60% of the biomass (Putt, 2007).

Biologists in the field have categorized microalgae in a variety of classes based on basic cellular structure, cellular storage products, pigmentation and life cycle. The five most important microalgae groups with respect to their use as an energy source or biofuels are the:

1. Blue-green algae (Cyanophyceae). These microorganisms have the structure and organization similar to bacteria, and in some instances can play an important role in nitrogen-fixation from the atmosphere. Approximately 2,000 species are blue-green algae have been found in aquatic, marine and terrestrial habitats.
2. Green algae (Chlorophyceae). These are commonly found in both freshwater and marine environments as well as in and on soils. These algae are considered to be the evolutionary progenitors of modern plants. Their main storage compound is starch and under certain conditions such as nitrogen deficiency, lipid/oil can be produced in significant quantities.
3. Diatoms (Bacillariophyceae). These microorganisms are mainly found as phytoplankton in the oceans but are also found in brackish and fresh waters. There are over 100,000 known species (Barclay, 1984), and are the most common and widely distributed groups of algae. Cells are golden-brown in color due to high levels of a photosynthetic pigment called fucoxanthin. They also contain polymerized silica (Si) in the cell walls. Their cells store carbon in the form of natural oils or as polymer of carbohydrates.

4. Golden algae (Chrysophyceae). These algae are similar to the diatoms in biochemical composition and pigmentation; however, their pigment composition is more complex, often appearing brown, orange and yellow in color. Lipids and carbohydrates are the major carbon storage forms in this group. Primarily found in freshwater systems, there are approximately 1,000 species known to exist in the natural environment.
5. Picoplankton (Eustigmatophyceae). This group of algae has small cells approximately 2-4 μm in diameter. The genus *Nannochloropsis* is one of the marine species that belongs to this group and is common in seawater. (Sheehan et al 1998).

Overview of algae photobioreactor

A photobioreactor can be described as a culture vessel designed to capture a light controlled liquid cell suspension of photosynthetic algae. Photobioreactors can be classified as either open (to the air) or closed systems. Four major types of open air systems are shallow big ponds, tanks, circular ponds and raceway ponds (Borowitzka, 1999). Common closed systems include bag systems, flat plate reactors and tubular reactors. Each design has advantages and disadvantages with respect to capital cost, algae strain used, biomass yield, energy consumption, operating cost, temperature control and environment contamination.

Large commercial systems used today are mostly open-air systems due to simple economics. Open pond systems, also referred to as raceway ponds are commonly utilized in large scale production, as seen in figure 2.1. They are usually made of a closed loop recirculation channel that is typically about 0.3 m deep, manufactured from concrete, clay, solid plastic, and/or combination of different materials. Mixing and circulation are generated by a paddle wheel. The paddle wheel operates continuously to prevent any sedimentation of biomass and nutrients. The large horizontal surface are of the open pond is where light reaches the system and the photosynthesis process occurs and is captured by the algae. Open ponds, including mixed raceway ponds are generally economical to build and operate, can be scaled up to several hectares for even larger production and has been the method of choice for commercial

microalgae production. Approximately 98% of commercial algae biomass production is currently done with open ponds (Benemann, 2008). However, productivity in open air pond systems is much less than theoretically possible because it is difficult to control the culture conditions when the system is exposed to the environment. Various limitations arise in the operation of open ponds, such as biological invasion of other algae, algae grazers, fungi, amoeba, and limitations in colder or hot humid climates. The pond depth is always a compromise between maintaining an adequate water depth for mixing to avoid ionic composition changes due to evaporation and the need to provide light to the algae cells (the shallower the pond, the more light available to the algae cells). Further studies are being conducted on the relationship between pond depth, algae culture density and productivity for maximizing biomass output (Chisti, 2007).

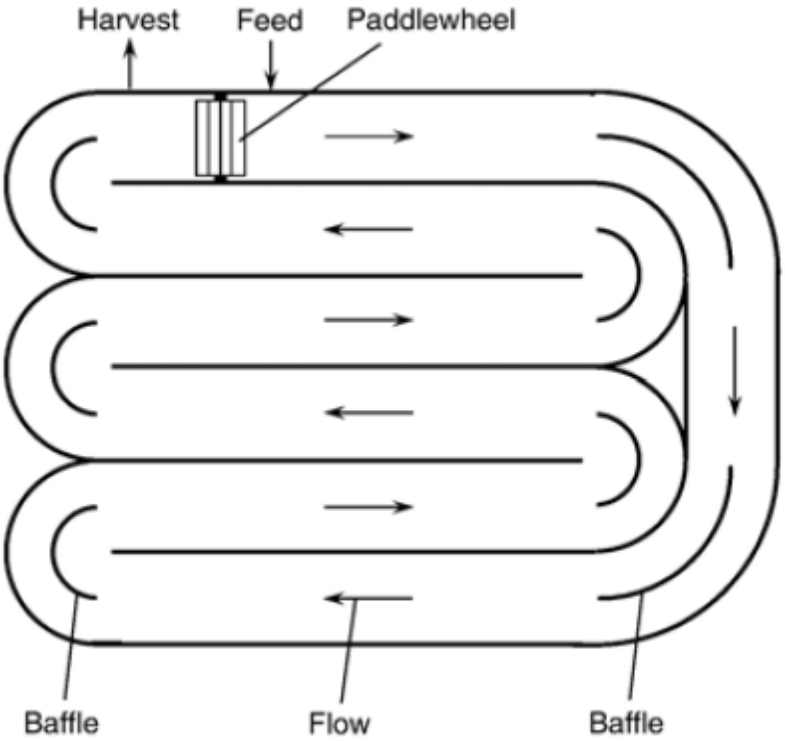

Figure 2.1. Arial view of a raceway pond (Chisti, 2007)

Beside open ponds systems, microalgae can be grown using other designs of photobioractors. The development of photobioreactors for algae production was initially done under the Research Institute of Innovative technology for the Earth (RITE) in Japan from 1990-2000 (Putt, 2007). For example, a tubular photobioreactor; shown in Figure 2.2, consists of an array of straight transparent tubes that are commonly made of plastic or glass. The tubular array acts as a solar collector where the energy from sunlight is captured. The solar collector tubes are usually designed to be 0.1 m or less in diameter. Microalgae mix is circulated from a reservoir to the solar collector section and returned to the reservoir. In a typical arrangement, the solar tubes are placed parallel to each other and flat or on various different incline angles relative to the ground.

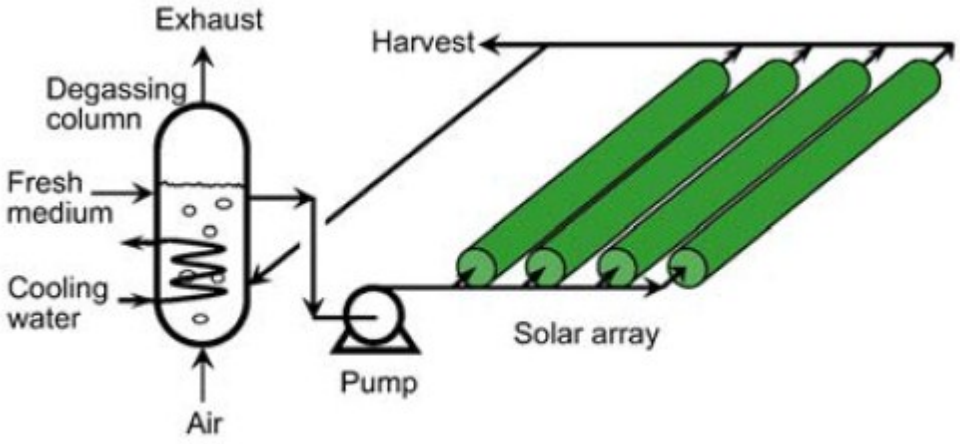

Figure 2.2. A tubular photobioreactor with parallel run horizontal tubes (Chisti, 2007).

Horizontal, parallel straight tubes might be arranged like a fence as an improvement to increase the number of tubes that can be accommodated in a given land area (Figure 2.3). Other potential improvements besides being laid flat horizontally on the ground, include some custom made tubes of flexible plastic and coiled around a supporting frame to form a helical coil tubular photobioreactors. These particular designs are potentially beneficial for growing a smaller volume

of microalgae that can be used for further inoculation process for the larger tubular photobioreactors or open ponds (Chisti, 2007).

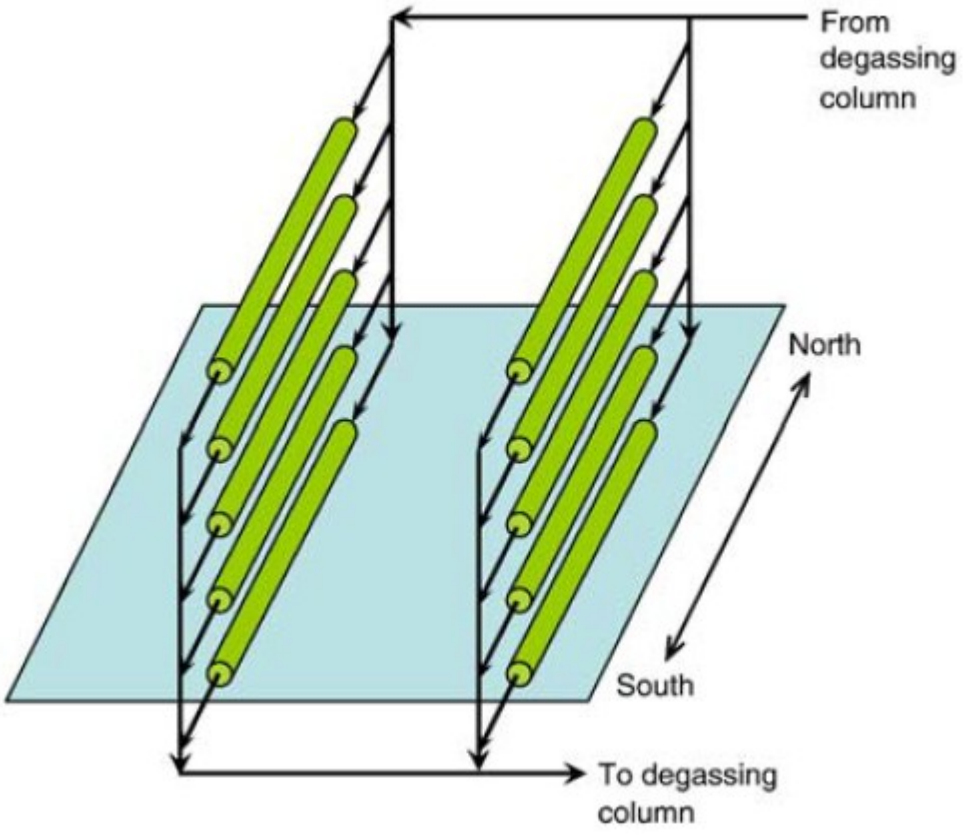

Figure 2.3. A fence-like solar collector tubular photobioreactor (Chisti, 2007).

In overall design considerations, photobioreactors depend on light, so the use of available natural sunlight is desirable. Artificial lighting of photobioreactors is technically feasible, yet expensive as compared to using natural sunlight.

Photobioreactor design is a challenge that is receiving more attention, with a focus on new technologies to reduce costs and improve efficiency. Although, in general, photobioreactors are costly, they minimize water use, energy and chemicals, making them the system of choice for

many algae biomass production facilities. The most important among their characteristics is the ability to support up to 13 times higher productivity with respect to volume as well as have a smaller footprint on a yield basis. With that perspective, it may help compensate for higher bioreactor cost (Schenk, 2008). Table 1 compares photobioreactor and raceway ponds for algae biomass production. The comparison is based on an annual production level of 100 tons of biomass for both cases, with matching carbon dioxide consumption rate, disregarding any losses to the atmosphere. These production methods represent optimal combinations of biomass productivity and concentration that have been actually achieved in large scale algae biomass production.

Table 2.1. Comparison of photobioreactors and open pond production methods (Chisti, 2007)

Comparison of photobioreactor and raceway production methods

Variable	Photobioreactor facility	Raceway ponds
Annual biomass production (kg)	100,000	100,000
Volumetric productivity (kg m^{-3} d^{-1})	1.535	0.117
Areal productivity (kg m^{-2} d^{-1})	0.048 [a] 0.072 [c]	0.035 [b]
Biomass concentration in broth (kg m^{-3})	4.00	0.14
Dilution rate (d^{-1})	0.384	0.250
Area needed (m^2)	5681	7828
Oil yield (m^3 ha^{-1})	136.9 [d] 58.7 [e]	99.4 [d] 42.6 [e]
Annual CO_2 consumption (kg)	183,333	183,333
System geometry	132 parallel tubes/unit; 80 m long tubes; 0.06 m tube diameter	978 m^2/pond; 12 m wide, 82 m long, 0.30 m deep
Number of units	6	8

[a] Based on facility area.
[b] Based on actual pond area.
[c] Based on projected area of photobioreactor tubes.
[d] Based on 70% by wt oil in biomass.
[e] Based on 30% by wt oil in biomass.

Another concept of improvement of algae biomass production is a combination of open pond systems and photobioreactors referred to as hybrid algae photobioreactors. Open ponds

are very efficient and relatively low cost for algae cultivation, yet contamination issues are major challenges, as well as the larger footprint requirement in land area. Photobioreactors are excellent in minimizing land area utilization, and have higher oil yields; however, initial costs can be ten times higher than for open pond systems. A combination of both systems may be the most feasible choice for cost effective cultivation and high yield algae biomass product. Depending on algae strains, consideration of locations, climate, and local regulations, each hybrid system needs to be custom-made to accommodate the conditions and requirements. Hybrid systems have been developed and demonstrated by several companies including Aquasearch in Hawaii, where algae cultivation is for the production of astaxanthin. In this system, the algae is initially grown in bioreactors in nutrient sufficient conditions, and then transferred to open ponds under nutrient limited conditions to induce astaxanthin production. Recently Green Star Products in Montana has utilized the Hybrid Algae Production System (HASP), a combination of closed photobioreactor and open pond system to control the cost and accelerate the growth of algae (Gordon, 2012). Large scale algae production facilities should be designed with a series of photobioreactors in various sizes, from initial culture through the final inoculum. For such a concept design to work, it is important to also use an algal strain that is both fast growing during the inoculum scale-up stage and highly productive in the final open pond stage (Schenk, 2008).

In comparison with the open air systems, closed systems of photobioreactors are significantly more expensive to build and operate, and many of them are difficult to be scaled up. However, the closed systems have advantages such as more controllable and cleaner algae culture (less potential contamination of other micro-organisms entering the system), high light distribution efficiency leading to high productivities for sustainable biomass, temperature control and the flexibility to be used outdoors in natural daylight. This would suggest that a wider range of algae strains can be grown in a more closed or contained environment to avoid or reduce contamination. Also such systems can be operated over a broader climatic range than the open air systems. These features also allow greater control of the systems, possibly allowing this type

of the system to be operated in continuous mode and yielding more consistent product composition and quality (Borowitzka, 1999). The following table (Table 2.2) illustrates some of the properties of different algal culture systems.

Table 2.2. Comparison of properties on different algal culture systems (Borowitzka, 1999).

Reactor type	Mixing	Light utilisation efficiency	Temperature control	Gas transfer	Hydrodynamic stress on algae	Species control	Sterility	Scale-up	Reference
Unstirred shallow ponds	Very poor	Poor	None	Poor	Very low	Difficult	None	Very difficult	Borowitzka and Borowitzka, 1989
Tanks	Poor	Very poor	None	Poor	Very low	Difficult	None	Very difficult	Fox, 1983
Circular stirred ponds	Fair	Fair–good	None	Poor	Low	Difficult	None	Very difficult	Tamiya, 1957; Stengel, 1970; Soeder, 1981
Paddle-wheel Raceway Ponds	Fair-good	Fair–good	None	Poor	Low	Difficult	None	Very difficult	Weissman and Goebel, 1987; Oswald, 1988
Stirred Tank reactor (internal or external lighting)	Largely uniform	Fair–good	Excellent	Low–high	High	Easy	Easily achievable	Difficult	Pohl et al., 1988
Air-Lift reactor	Generally uniform	Good	Excellent	High	Low	Easy	Easily achievable	Difficult	Jüttner, 1977
Bag Culture	Variable	Fair–good	Good (indoors)	Low–high	Low	Easy	Easily achievable	Difficult	Baynes et al., 1979
Flat-Plate reactor	Uniform	Excellent	Excellent	High	Low–high	Easy	Achievable	Difficult	Hu et al., 1996; Tredici and Zitelli, 1997
Tubular reactor (Serpentine type)	Uniform	Excellent	Excellent	Low–high	Low–high	Easy	Achievable	Reasonable	Richmond et al., 1993; Torzillo, 1997
Tubular Reactor (Biocoil type)	Uniform	Excellent	Excellent	Low–high	Low–high	Easy	Achievable	Easy	Borowitzka, 1996

Variables affecting algae biomass production

Microalgae require light, carbon dioxide, water, and inorganic nutrients for photosynthetic growth. Ideal temperature ranges are generally between 20 to 35^{o} C. Nutrient supplements in the cultivation medium must provide the required inorganic elements. Required essential elements are similar to crop plant fertilizers and typically include nitrogen (N), phosphorus (P), potassium (K), iron (Fe) and in certain cases silicon (Si). Currently, many microalgae are cultivated in open pond systems, photobioreactors, or hybrid systems around the world (Chisti, 2007).

One of the major objectives of growing algae in a controlled environment is to produce algal biomass. The biomass contains a total lipid fraction from which the neutral lipid fraction (an important precursor to biodiesel) can be separated. This neutral lipid fraction is used for the production of transportation fuels. Since the operation of photobioreactors to grow algae relies on a photosynthesis process, the availability of sunlight in certain regions like Arizona is an advantage; however, the availability of sunlight also is accompanied with increasing temperature. Currently, algae strains grown in LARB grow over a temperature range of 20^{o} to 35^{o}C. Each photobioreactor system is operated with an evaporative cooling system to control temperature with the exception of the pond photobioreactors which rely on water evaporation for cooling. During the peak temperatures of the summer season, which can reach approximately 40^{o}C, cooling is required and the cooling system must run at its maximum capacity. Otherwise, algae growth in the photobioreactors is reduced and the algae can suffer cell damage or even die. However, in the evening hours with the absence of the solar radiation, there is a significant reduction in ambient temperature that represents a suitable or tolerable range for the algae cells. Thus, a cooling system is required when algae are grown over a certain temperature range; however, the cooling system capacity can be altered based on demand, thereby increasing photobioreactor efficiency and reducing the operational cost.

Another important variable to be considered is the amount of carbon dioxide (CO_2) injected into photobioreactors. The algae grown in the photobioreactor produce biomass and also utilize CO_2 and release oxygen (O_2). Each photobioreactor was equipped with an aeration system that injects ambient air into the tank. A CO_2 supply system was also installed in parallel with the aeration system to reach a homogeneous mixture. The purpose of an aeration system is to agitate the solution, creating a well-distributed mixing of algae and the aqueous solution (culture medium) containing the appropriate nutrients and CO_2 as well as an even distribution of light exposure to the algae cells in suspension. The measure of activity of hydrogen ions in solution (pH) is another critical variable to be considered to maintain an appropriate level of acidity or basicity of the aqueous solution. As demonstrated in this research, there is a correlation between

the levels of dissolved CO_2 and pH. From a productivity standpoint, the addition of CO_2 has been known to increase algal growth rate. The relationship between algae growth and CO_2 concentration, in combination with environmental remediation has been receiving considerable attention in the search for renewable, sustainable fuels from algae (Spalding, 2007). The cultivation of photoautotrophic algae requires CO_2 to be supplied only during daylight hours when photosynthesis. The efficiency of CO_2 uptake varies depending on the algae species, algae growth rate, photobioreactor/cultivation system and incident light conditions. Therefore, the regulation of the CO_2 supply necessary to enhance or optimize algae growth is critical.

Environmental factors such as light, temperature, and nutrient status not only affect photosynthesis and productivity of the algae, but also influence the pattern, pathway and activity of cell metabolism and cell composition. Certain techniques in manipulation of algae cultures using various environmental factors could achieve specific biotechnological results. The effects of temperature, CO_2 and O_2 concentrations and light intensity on the growth of algae has been investigated to determine the optimum culture conditions for microalgae production in aquatic food production modules, including both microalgae culture and fish culture systems (Kitaya, 2005). The ambient temperature during cultivation is greatly influenced by the availability of natural sunlight. The effect of light on photosynthetic organisms is called photoacclimation or photoadaptation and can affect the biochemical composition of the organism. During this process, algae cells can undergo dynamic changes in cell composition with alterations in structural, biophysical, and physiological properties (Dubinsky, 1995). In the case of decreasing light intensity, the algae cellular response is to increase their chlorophyll a and other light-harvesting pigments (chlorophyll b, chlorophyll c, phycobiliproteins and primary carotenoids). In contrast, with the increase of light intensity, chlorophyll a and other pigments for photosynthesis decrease, while the secondary carotenoids (astaxanthin and beta-carotene), which serve as photoprotective agents, increase. Carotenoid accumulation may result from the alteration of carbon and nitrogen flows within the cells under stressful conditions (Ben-Amotz, 1982). This is critical information necessary to optimize cultivation techniques particularly when the algae being cultivated is for

higher value products such as carotenoids. For biofuel production, light intensity plays equally important roles during which lipid content and composition are the essential components. Increasing light intensity has been found to be inversely related to algae cellular lipids and total polyunsaturated fatty acid (PUFA) content (Cohen, 1999). However, in other studies, strong light intensity was observed to increase PUFA levels in certain algae species, resulting from an increase in oxygen-mediated lipid desaturation under high light conditions (Molina Grima, 1999).

Temperature effect is another major factor influencing algae biochemical composition. The effect of temperature on membrane lipid content and composition has been well-studied. A decrease in temperature below an optimum growth temperature level generally increases the content of unsaturation of lipids in membrane systems. In addition, it also results in increasing enzyme production as an adaptive mechanism for maintaining rates of photosynthesis and respiration (Thompson, 1992). Another effect of temperature on algae growth is in the co-production of other compounds.

In a study on *Haematococcus*, cell numbers increased threefold when the growth temperature was increased from 20^{o}C to 30^{o}C (Tjahjono, 1994). Similar result was observed with the alga, *Chlorococcum*, in addition to the observation that the total carotenoid content almost doubled when growth temperature was increased to 35^{o}C. These findings suggested that by increasing the temperature above that required for optimum growth can induce the formation of active oxygen radicals within algae cells, and stimulate an enzymatic reaction which results in the increase in carotenoid composition (Liu & Lee, 2000). With the complex correlation of environment variables and the resulting algae biomass, there is a clear need for consistent monitoring and control of those variables to establish an optimal condition and to avoid uncertainty that can impact the growth of the algae and the composition of the algae biomass.

Overview of automation system

According to Merriam-Webster dictionary (www.merriam-webster.com), automation is defined as the technique of making an apparatus, a process, or a system to operate

automatically; the state of being operated automatically; and automatically controlled operation of an apparatus, process, or system by mechanical or electronic devices that take the place of human labor. Simply, automation can be described as the construction and application of technology to monitor and control activities for the delivery of products and services. The technology application involves the utilization of a complete system that includes design considerations, sensors, programmable controllers, program algorithm and controlled devices.

Historical background of automation

The introduction of automation was applied to the manufacturing enterprise in the 1960's to replace bulky and challenging electromechanical relay technology being used in factory systems at that time. The primary goal was to eliminate the high cost of inflexible, relay controlled systems. Microprocessor technology as a programmable control or programmable logic controller (PLC) was quickly adopted in the form of a solid state control due to many advantages over more conventional electromechanical technology. In comparison to electromechanical control, programmable control is generally relatively inexpensive, provides a higher level of flexibility, offers smaller size components, comes industrially reinforced for factory environment and is modular and reusable to reduce the time and labor required for process changeovers (Morriss, 2000).

The implementation of an automation system to a processing system needs to be well thought out in order for each system to work reliably together for a relatively long period. The installation processes, improvement, as well as troubleshooting, are simplified through the use of software reprogramming instead of costly and labor intensive rewiring upgrades. The result is the reduction of downtime, increased yields and an improvement in product quality. The success of U.S. industries in the global market has been the result of implementing programmable control for manufacturing automation (Gintz, 2004)

Basic PLC principles and operation

A programmable logic controller consists of two basic sections; the central processing unit and the input/output interface system as illustrated in Figure 2.4.

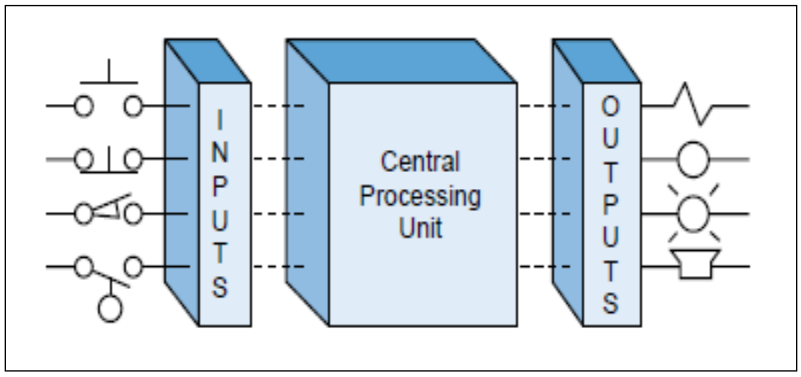

Figure 2.4. Programmable controller block diagram (Bryan, 1997)

Referring to Figure 2.4 above, the central processing unit (CPU) manages all of PLC activities. The CPU consists of three major components such as processor, memory and power supply.

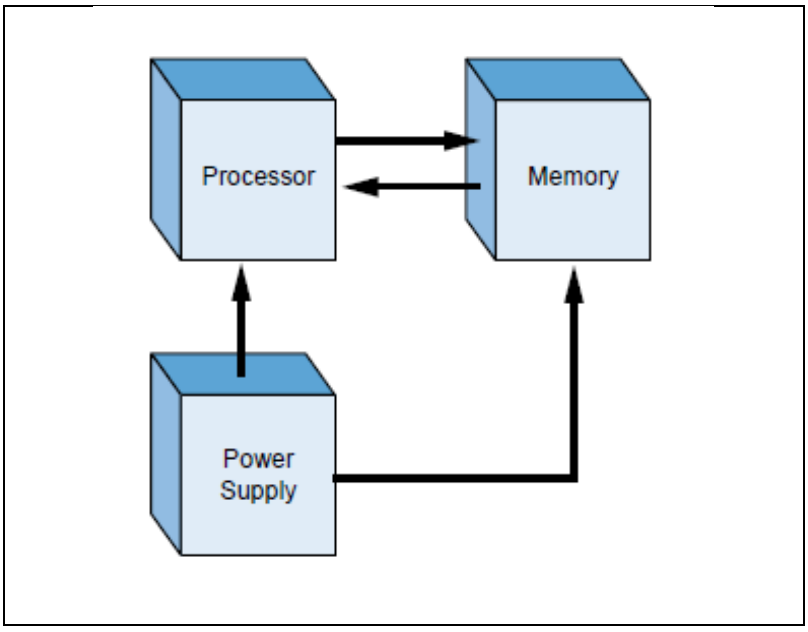

Figure 2.5. Major CPU components block diagram (Bryan, 1997)

The operation principle of a PLC is relatively simple. The input/output (I/O) component of the system is physically connected to the devices on the field that are encountered in the machine or ones that are used in the control of a process. Examples of these field devices can be discrete or analog input/output devices, such as limit switches, pressure transducers, push buttons, motor starters, solenoids, etc. The I/O interfaces provide the correlation between the CPU and the information providers (inputs) and controllable devices (outputs). Figure 2.5 illustrates major CPU components block diagram and the correlation. During its CPU operation, it performs three processes such as:

1. Reading or accepting the input data from the field devices via the input interfaces.
2. Executing or performing the control program stored in the memory system.
3. Writing or updating the output devices via the output interfaces.

The process of sequentially reading the inputs, executing the program in memory and updating the outputs is known as scanning.

The I/O system forms the interface at the point where the field devices are connected to the controller. The main function of the interface is to structure various signals received from or sent to external field devices. Incoming signals from sensors such as push buttons, limit switches, analog sensors, and selector switches are connected to the terminals on the input interfaces. Field devices that are being controlled such as motor starters, solenoid valves, pilot lights, and position valves, are connected to the terminals of the output interfaces. The system power supply provides the entire electrical voltages requirement for proper operation of various CPU sections. A personal computer equipped with PLC software is usually used to program the PLC.

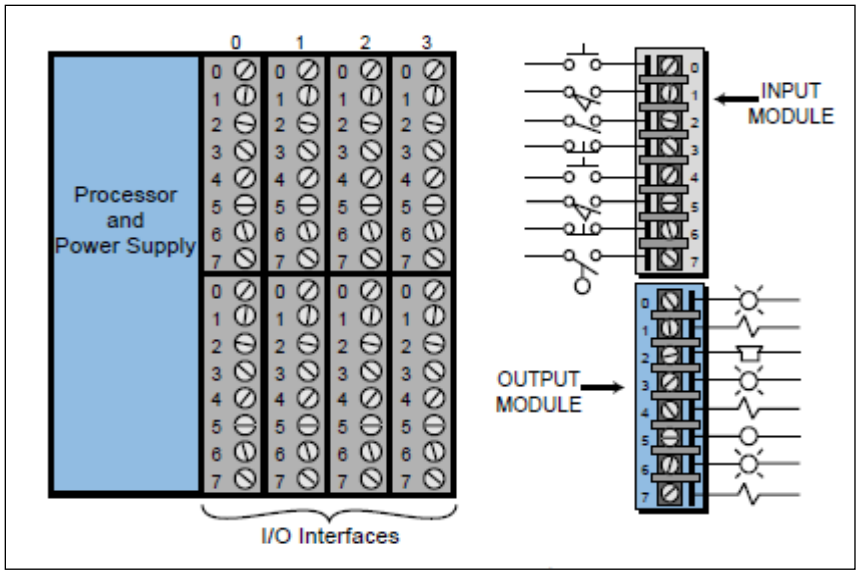

Figure 2.6. I/O system interface (Bryan, 1997)

Summary

Product development for biotechnology using an algae photobioreactor requires a longer time than the development of other technologies leading to products such as consumer goods. There are many unknown factors, combined with the requirement of teamwork of many people with different disciplines and expertise. Consequently, the research and development of algae cultivation systems at LARB must be designed to implement current knowledge and to be able to adapt based on future insight, innovation, and new devices/tools, and techniques. A high degree of flexibility is needed to include and integrate concepts and equipment designs for potential upgrades. The advances in the fields of electronics, information, and physical sciences must be incorporated into this biotechnology field.

The application of an automated monitoring and control system for an algae photobioreactor eliminates the need for constant manual measurement techniques and the labor necessary to obtain the required data on either a semi-continuous or continuous or interval basis. In addition, potential errors can be prevented assuming the automated system is well-calibrated

and maintained. Overall, the process, product and environmental control can be significantly enhanced and the value of the scientific research and data obtained can be improved.

The significance of an automated system to the field is the increased precision of activity monitoring and control over an extended period. The measurement accuracy and speed are improved and can be expected to be more advanced in the future. The design for the adaptability of an automated system with other components for future updates should always be considered. The system must be easy to upgrade in order to keep up with technology advances in analytical, electronics and informatics, including improved software and other component upgrades. This approach guarantees interactive operating systems that allows for maximum ease of use and efficiency. Other possible advancements include window-based human machine interfaces (HMI) that guarantees secure user recognition, including graphical representation that reduces probability of misinterpretation; and continuous training of the user personnel (Sonnleitner, 1991).

The intent of this research is to design a conceptual automated monitoring and control system that will enable the researchers to conduct biological research with real time datalogging, monitoring, and control. The PLC, as the processor of the system, for example, has the capability to be programmed to specific needs based on the scope of the experiment or project performed.

Chapter 3

METHODOLOGY

Overview

This chapter discusses the design, construction, operation and data collection for the photobioreactors used in this research. At the time this document was written, there were three stages of monitoring system design and experimentation. The first stage used the Campbell Scientific® system on existing photobioreactor tank systems. The second stage was similar to the first stage with the exception that a new generation bioreactor prototype was incorporated. The third stage was the design, installation and setup of various industrial instrumentations, including a Programmable Logic Controller system on the revised new generation of photobioreactor. The project began with the initial stage of evaluating and assessing the Campbell Scientific® datalogger capability and overall performance of an older generation photobioreactor.

Stage 1: Initial photobioreactor data collection

The initial data collection for the algae photobioreactor monitoring system was started by rebuilding an existing non-operated Campbell Scientific® CR-1000 datalogger that was available at LARB. The objective of this stage was to determine whether this particular system was operational due to the fact that the system was part of an existing bioreactor system and exposed to outdoor environmental conditions. Based on the sensors used the system was capable of measuring and datalogging temperature and pH values. Once the system was operational, its overall performance for data collection on an older bioreactor system was evaluated in relation to the algae biomass produced.

Datalogger installation

The first step in testing the datalogger involved repairing any wiring damage on the system. The damage was due to direct exposure of components to the environment conditions.

After the damage was repaired, a sealed control box was purchased to protect the datalogger components (processor, receiver/transmitter and power supply) from environmental conditions such as sunlight, impact, moisture and temperature.

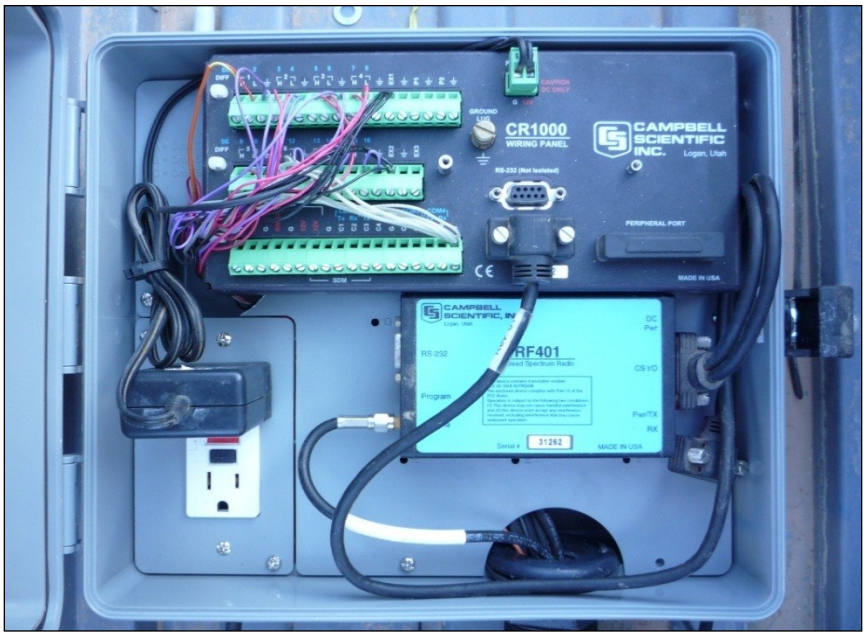

Figure 3.1. Processor and other components inside a sealed control box

In order for the datalogger system to have the mobility to collect data for various photobioreactor systems for research purposes, the system was mounted on a plastic mobile cart purchased from a local hardware store. A software package supplied by the datalogger manufacturer called Loggernet was also installed on the laboratory computer along with same type of a receiver/transmitter installed in the control box for data collection.

Three sensors were used with the datalogger for measuring two different photobioreactor tanks including content temperature, ambient temperature and one pH sensor measuring the pH on one of the tanks. Manual measurement techniques using a handheld instrument were also performed for data comparison. The experiment was conducted for a period of one month (May 2009). The following pictures show the sensors used during the experiment.

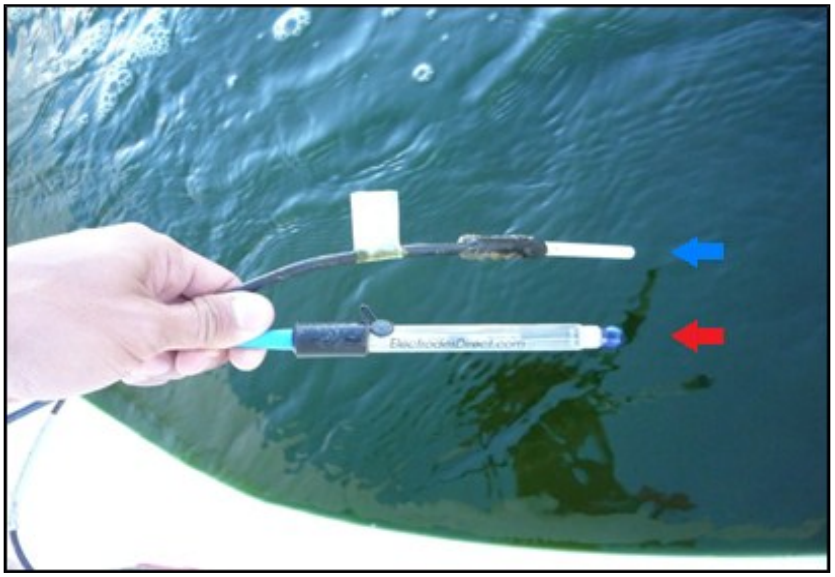

Figure 3.2. Temperature (blue arrow) and pH (red arrow) probes

Photobioreactor systems and content used for data collection

Three types of photobioreactor systems were used for this experiment. One was a pond photobioreactor. A pond photobioreactor is a race-track shaped tank that consists of a paddle wheel to keep the algae solution circulating in the tank and to enhance cooling through evaporation. A photograph of the reactor is included in Appendix (Figure A.1). The tank measured 12'L x6 W'x1.25'D, with a radius of 3' on each end. A concentration of 1.5 g/L of one algae strain type and water with an approximate depth of five inches was used as part of an ongoing growth experiment conducted by LARB researchers. Two ponds, labeled Pond B and Pond D, were positioned North-South to each other, and an East-West orientation relative to their radius. Both were used for duplicate samples.

The second type of photobioreactor used was a mobile flat panel photobioreactor with the surface area facing an East-West orientation. The algae strain and concentration used was the same as the one contained in the pond photobioreactor. The tank measured 48"L x48"Wx1.5"D. The cooling system incorporated a water evaporative system with water circulating in a cooling

loop heat exchanger inside the tank. Two tanks were mounted on a fixed main frame, with both tanks positioned East-West to each other and labeled Mobile SE #5 and Mobile SW #6. A photograph of the mobile flat panel photobioreactor system is included in Appendix (Figure A.2).

The third type of photobioreactor was the outdoor column reactor. This system was not used for the algae inoculation process at the time of the study due to the scheduled cleaning stage. However, temperature measurements in two columns were taken as references to determine the temperature when they were only filled with plain water.

The following page shows the graph plot of temperature measurements and pH taken from Loggerrnet software (Figure 3.3). Temperature units were in degrees Celsius.

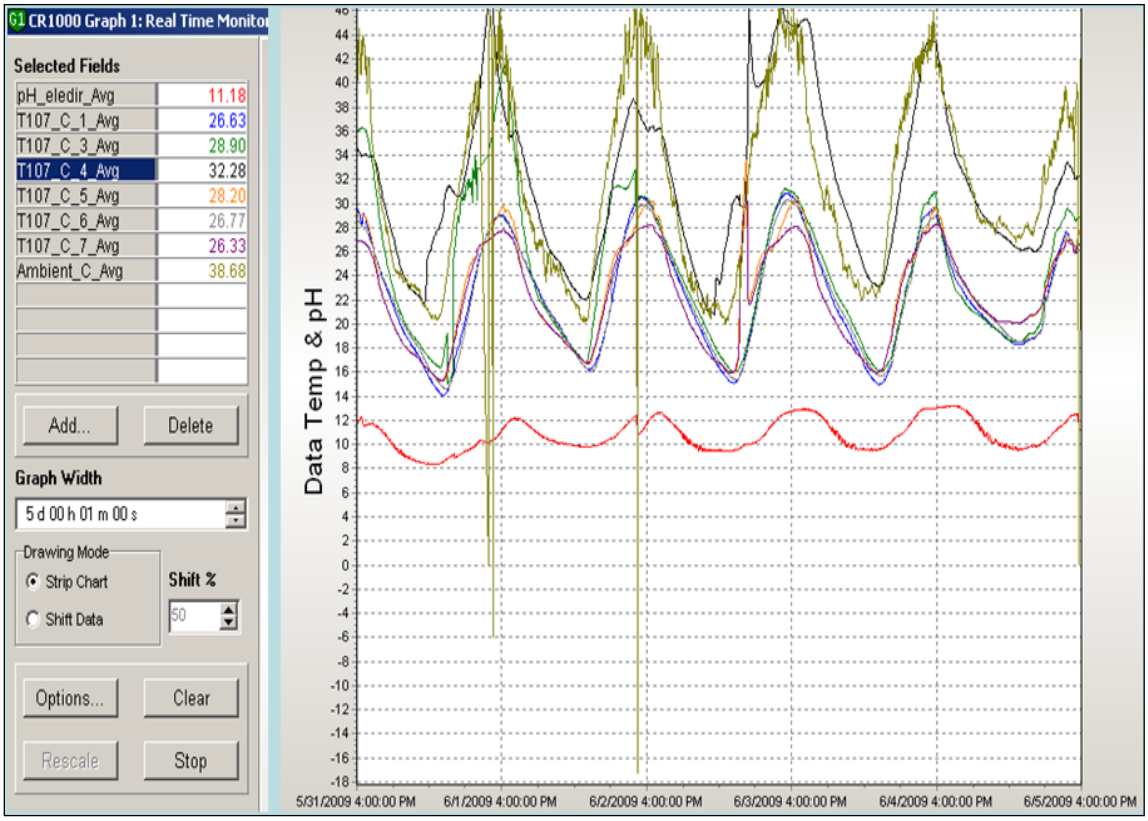

Figure 3.3. Loggernet graph plot of temperature and pH

The following table shows the graph colors corresponding to the photobioreactor systems being tested for temperature based on the window display on the left side.

Table 3.1. Photobioreactor systems monitored for temperature.

No.	Graph color	System	Temp (deg. C)
C1	Blue	Pond D	27.3
C3	Green	Column (water only)	30
C4	Black	Column (water only)	30
C5	Orange	Mobile SE #5	27.3
C6	Grey	Pond B	27.5
C7	Purple	Mobile SW #6	27
	Light Green	Ambient	38

Stage 2: Data collection on new generation photobioreactor prototype

In July of 2009, a new generation panel photobioreactor prototype was constructed. The tank was a continuous system that measured 4'Hx4'L with a width of 2". A preliminary test of its performance was needed in terms of cooling system and its influence on the algae solution. This was the same datalogger system, algae strain type and concentration for the growth experiment that was used previously.

The experiment was conducted over a two month period: July to August 2009. Variables measured were ambient temperature, aeration, algae solution, cooling system inlet and outlet temperatures. The purpose of this experiment was to determine the temperature and pH ranges necessary for parts specification and configuration that were needed on Stage 3 of the research. A photograph of the prototype tank is included in Appendix section (Figure A.3 and A.4).

Due to a problem encountered with the Loggernet activation software, the datalogging values could not be plotted within the software. Instead, values were plotted using Microsoft Excel. Figure 3.4 illustrates the performance of the cooling system during the peak temperature. The output temperature was higher by around 3^{o}C than the input temperature, which indicates that the water absorbed the excess heat from inside the tank. Another interesting observation

from the graph was the fact that the aeration system introduced higher air temperature than the ambient air temperature by almost 10^{o}C higher. The algae solution reached 39^{o}C during peak temperature. Because of this finding, it was concluded that there was a need for higher heat capacity evaporative cooler to lower the algae solution temperature by ca. 10^{o}C. Figure 3.4 shows the temperature trends over two days.

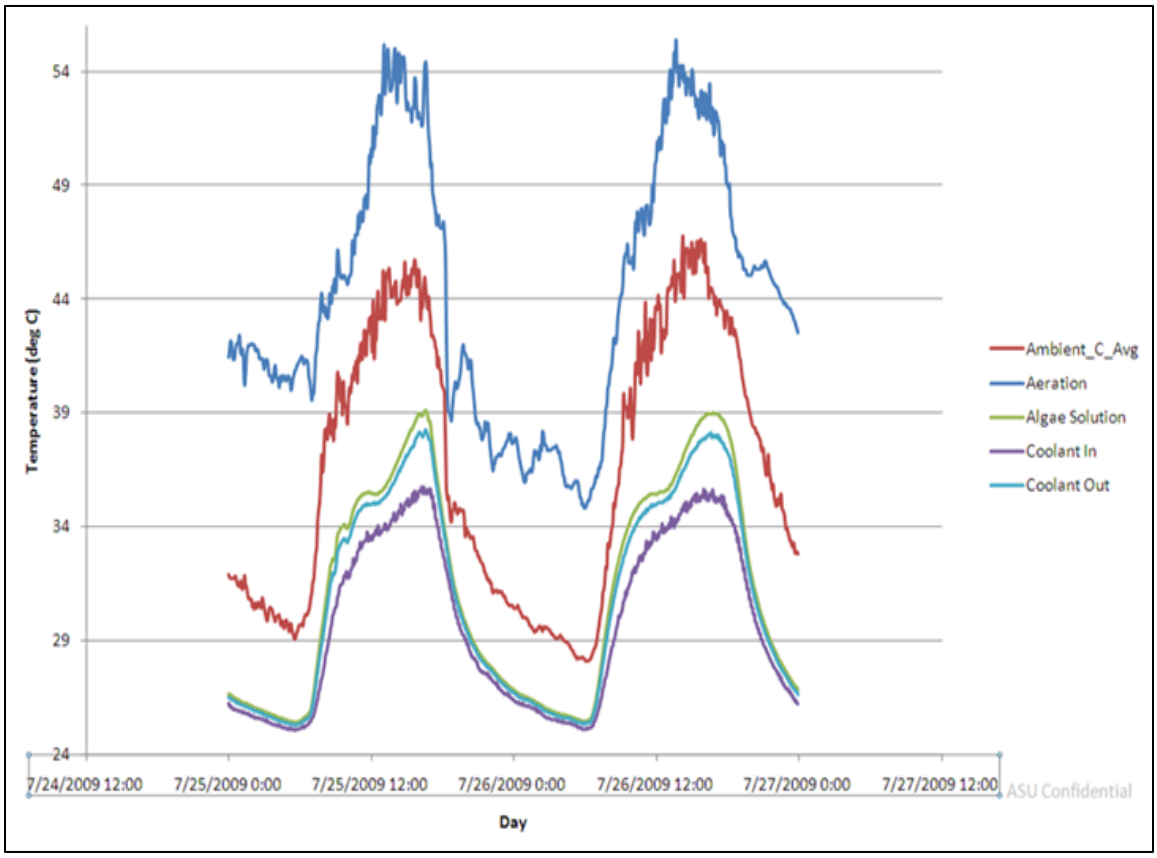

Figure 3.4. Partial temperature readings plotted for stage 2 experiment

Stage 3: Design and construction of industrial monitoring and control system

In November of 2009, a revision of the new generation bioreactor was completed. A larger capacity evaporative cooler having twice the size of the previous one was installed. The unit was to be a model for an algae commercial production system. The same variables measured on previous experiments were also considered for this design; such as temperature and pH. A new variable measurement for consideration in this system was the addition of a dissolved O_2 probe along with an analyzer capable of analyzing the signals from pH and dissolved O_2 probes. A Programmable Logic Control (PLC) system was a new addition to the design scope.

Several critical temperature points were considered for measurement on this photobioreactor. Performance evaluation of the new evaporative cooling system was needed to establish overall photobioreactor performance. One row of the new generation photobioreactor consisted of 12 stainless steel cooling loops, one loop being on each 4' length section of the photobioreactor tank. Each inlet of the cooling loops was connected to a supply manifold, while each outlet was connected to a return manifold. Important points for temperature monitoring measurements were:

- In-tank on East end
- In-tank on West end
- Cooling supply manifold
- Cooling return manifold
- Inlet of cooling loop center pair
- Outlet of cooling loop center pair
- Ambient air

A total of seven resistance temperature detectors (RTD) were used as temperature sensors. Two of these were 18" long and used for in-tank measurement, while the rest were 6" long and used for other applications as mentioned above. The RTD was chosen over the use of a thermocouple

due to its narrower temperature range and to yield higher accuracy and repeatability. Two stainless steel brackets were custom fabricated to support in-tank RTDs, while the shorter ones were fitted with brass T-fitting in series with the cooling system plumbing. Figures 3.5, 3.6, and 3.7 show the RTDs fitted on the photobioreactor system.

Figure 3.5. In-tank use RTD (red arrow) fitted with a bracket (blue arrow)

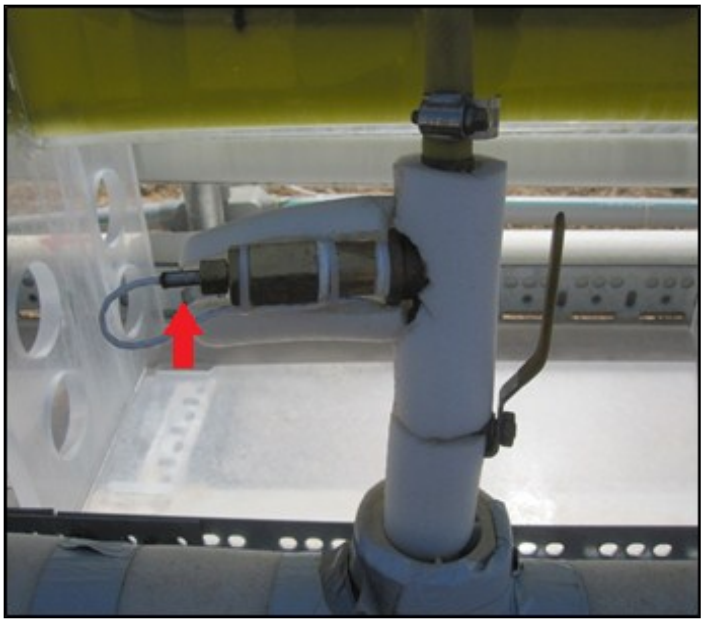

Figure 3.6. RTD (red arrow) installed on aeration plumbing

Figure 3.7. RTD (red arrow) installed on cooling system plumbing

Beside RTD installation for temperature measurement, pH and dissolved O_2 probes along with an analyzer were also installed. All of the sensors' wirings were connected to a

dedicated sealed enclosure containing a data communication interface. Both pH and dissolved O_2 probes were used by submerging them directly in the tank. Additional photographs of other equipment installation are included in the appendix section. Figures 3.8 and 3.9 illustrate the pH and dissolved O_2 probes.

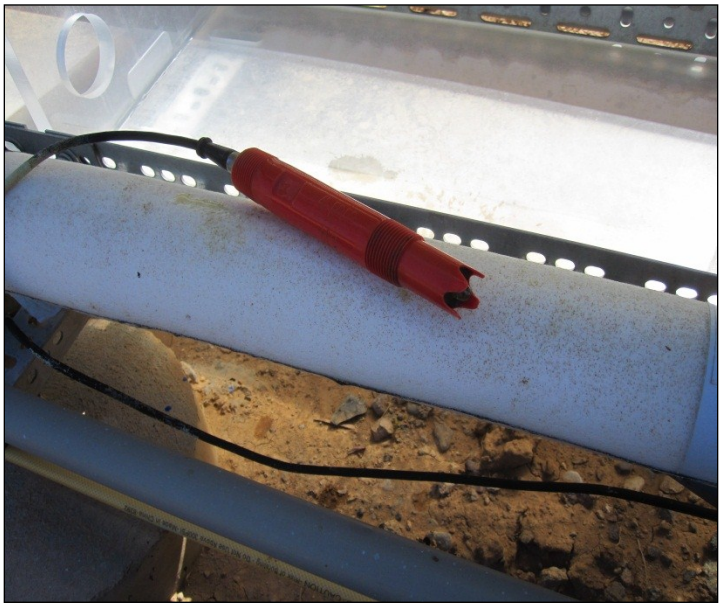

Figure 3.8. pH probe utilized

Figure 3.9. Dissolved O_2 probe utilized

Infrastructure construction, components installation, parts selection and negotiation with parts suppliers were also tasks performed during the performance and completion of the project. PLC programming with the use of software from Rockwell Automation such as RSLogix 5000, RSLinx Classic and FactoryTalk View Studio was included in order for a PC computer to be utilized to program and control the PLC. Continuous development and improvement of this project included the following:

- Mass flow meters for measuring aeration and CO_2 supplies.
- Control valve for CO_2 supply regulation.
- Control valve for cooling water regulation.
- Relay/switching device for activation and deactivation of cooling and heating system.
- Update on PLC software and program to accommodate the additional devices.

Chapter 4

RESULTS AND DISCUSSION

Overview

In this chapter, the results obtained from the latest experimental run are presented along with a discussion of the results in relation to the published literature. From the previous chapter, three design stages were used as experimental discoveries to develop experience with different environment conditions, photobioreactor designs, equipment, and other challenges encountered while conducting the study. This provided a better understanding for designing a complete system that takes into consideration of environment conditions, algae strain selection, photobioreactor system, and existing infrastructure.

The experiment was conducted with available resources, in consideration of variables involved in the algae culturing process (algae strain selection, equipment availability, labor support) and monitoring and control setup (infrastructure design and build up, programming and IT support), and simplified to comply with the time frame for research completion. In this chapter, challenges in understanding the biological mechanisms related to algae growth, the production system for algae cultivation, and automation system infrastructure build up are presented to provide a guide for the steps required in integrating an automation system with an existing algae photobioreactor system.

Photobioreactor type utilized for the experiment

The photobioreactor system chosen for the experimental run was a flat panel photobioreactor system. The orientation of the photobioreactor system was in a North-South orientation, consisting of four rows with each row having twelve tanks of flat panel photobioreactors. Each tank measured 48”Hx48”Lx1.5”W yielding a total operational volume approximately of 3,456 cubic inches or 55 liters. Pictures of the entire photobioreactor system arrangement including basic infrastructure, flat panel rows, and cooling system are included in the

Appendix A. Figure 4.1 shows the actual tanks utilized for the experiment with the photograph taken facing toward the South; the two green color panels are on the West side and the two brown color panels are on the East side.

Figure 4.1. Flat panel photobioreactors

Design of the experiment

The primary objective of the experiment was to compare algae growth rates when cultivated for a conventional production run with a continuous supply of CO_2 during the day compared to a controlled CO_2 supply based on select environment variables within the entire photobioreactor system. The conventional system of CO_2 supply was activated with a timer

controller with the activation and deactivation timing adjusted based on the sunrise and the sunset of the season. The experimental design for the research used a total of 4 flat panel tanks; 2 operated with the conventional continuous method and 2 operated with monitoring and control system integration. The system boundary considered includes the entire photobioreactor system components, including flat panel tanks, cooling system and aeration system. Figure 15 shows the two brown colored flat panels on the East side that were being operated in the conventional way without having any monitoring and control system integration. The two green colored flat panels on the West side were monitored for system variable values. Concurrently to obtaining the input values for those variables, the controlled variable was the CO_2 supply to the aeration system. The CO_2 was contained in a large aluminum gas cylinder installed within the field site. Appendix Figure A.5 shows the large CO_2 storage cylinder used to supply CO_2, to all types of photobioreactors within the LARB cultivation facility.

All four flat panels retained the shared cooling system operational infrastructure including evaporative cooling tower (Appendix Figure A.6), underground cooling water storage tank, water supply and return piping, and cooling coils inside each flat panel tank. The original design infrastructure of the flat panel photobioreactor system had 2 blower motors installed for the aeration system of all 4 rows of panels.

Since the CO_2 supply is transported by blending with a stream of air from the aeration system by a blower, a secondary blower was utilized specifically for the two West side flat panels, providing the capability to control the CO_2 supply to the West side flat panels through a monitoring and control system. A stand-alone aeration system was arranged by fabricating a CO_2 supply line obtained by providing a separate piping line from the main CO_2 line supply that was already being controlled by the timer. Hence, a CO_2 supply was always available inside the piping line whenever the timer was activated. From that pipeline, an air pressure regulator capable of regulating CO_2 (0-100 psi) was installed in order to match the operating pressure set for the East side flat panel tanks. In-line with the output flow of the pressure regulator, a normally closed 2-way 24VDC solenoid valve was fitted. The solenoid acted as a valve that allowed the CO_2 to be

routed. The next part installed was a manual flow meter that was used to adjust the CO_2 flow rate to match the operational flow rate set on the east side flat panel tanks. With this configuration, CO_2 could be supplied on demand for the West side flat panel tanks based on the programmed function demand. Figure 4.2 and 4.3 show the arrangement and modification for an independent stand-alone aeration system for the West side flat panel tanks.

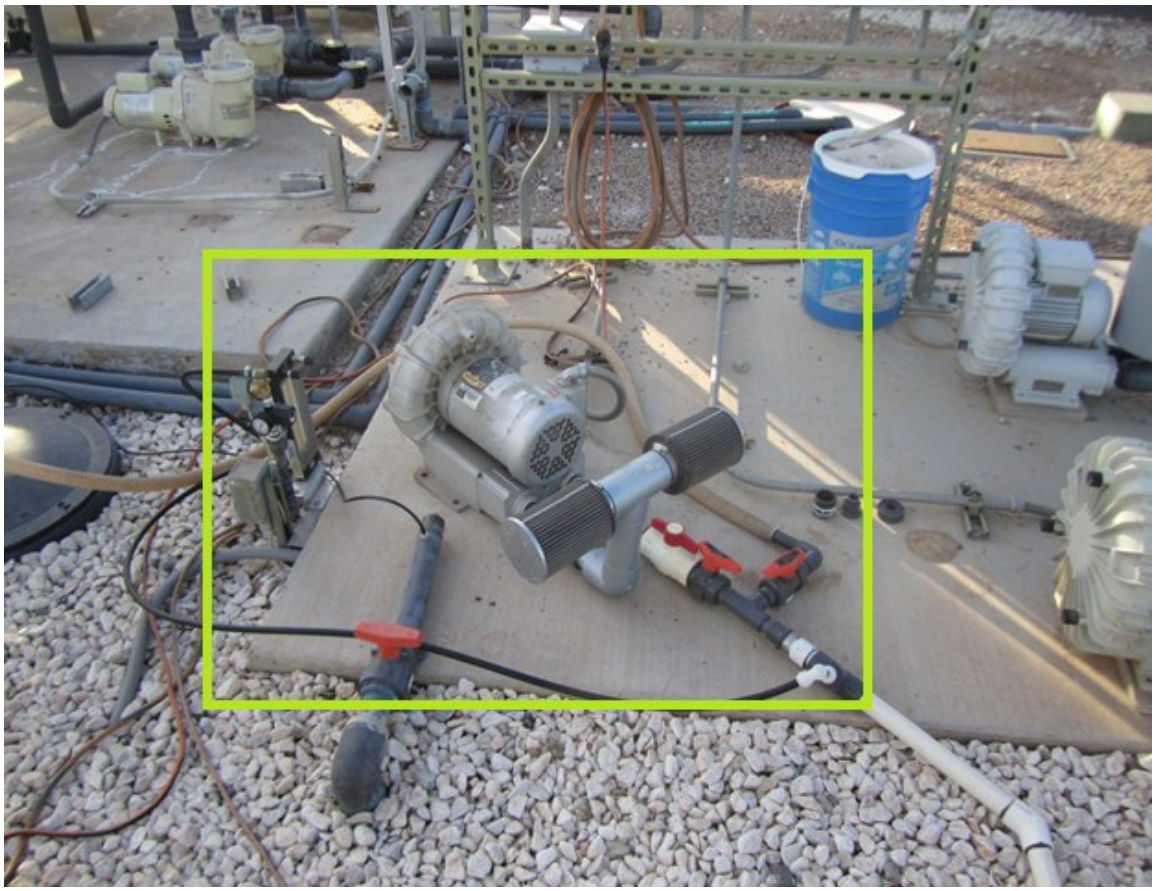

Figure 4.2. Stand-alone aeration system with supporting parts assembled (inside green box)

Figure 4.3. CO_2 regulator, solenoid and flow meter as part of stand-alone aeration system

The system's operational components assessment was based on the earlier experiment setup and data generated. Even though different photobioreactor designs may exhibit different performance results, there were other variables that were not completely understood along with other uncontrollable and unpredictable occurrences. For the two West side flat panel tanks with the integrated automation system, the experimental variables were:

Inside flat panel tanks:

- Temperature reading: 2 RTD probes for algae culture temperature
- pH reading: pH probe
- Dissolved O_2 reading: Dissolved O_2 probe

Outside flat panel tanks:

- Ambient temperature
- One cooling loop inlet temperature for West side flat panel tanks
- One cooling loop outlet temperature for West side flat panel tanks
- Main manifold cooling loop inlet temperature for East and West side flat panel tanks
- Main manifold cooling loop outlet temperature for East and West side flat panel tanks
- Aeration temperature for West side flat panel tanks

The following figures (4.4 and 4.5) show the RTDs installed on aeration and cooling systems.

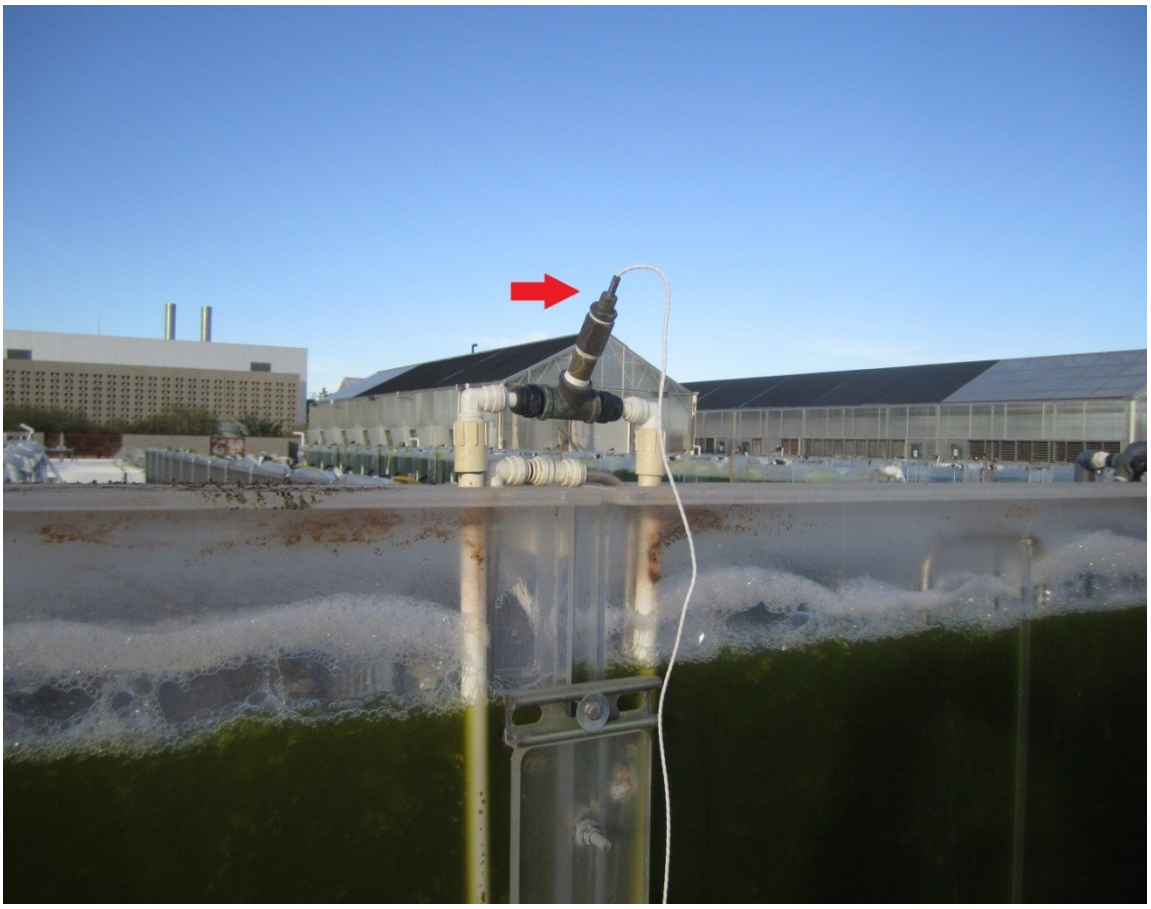

Figure 4.4. RTD installed on aeration system piping

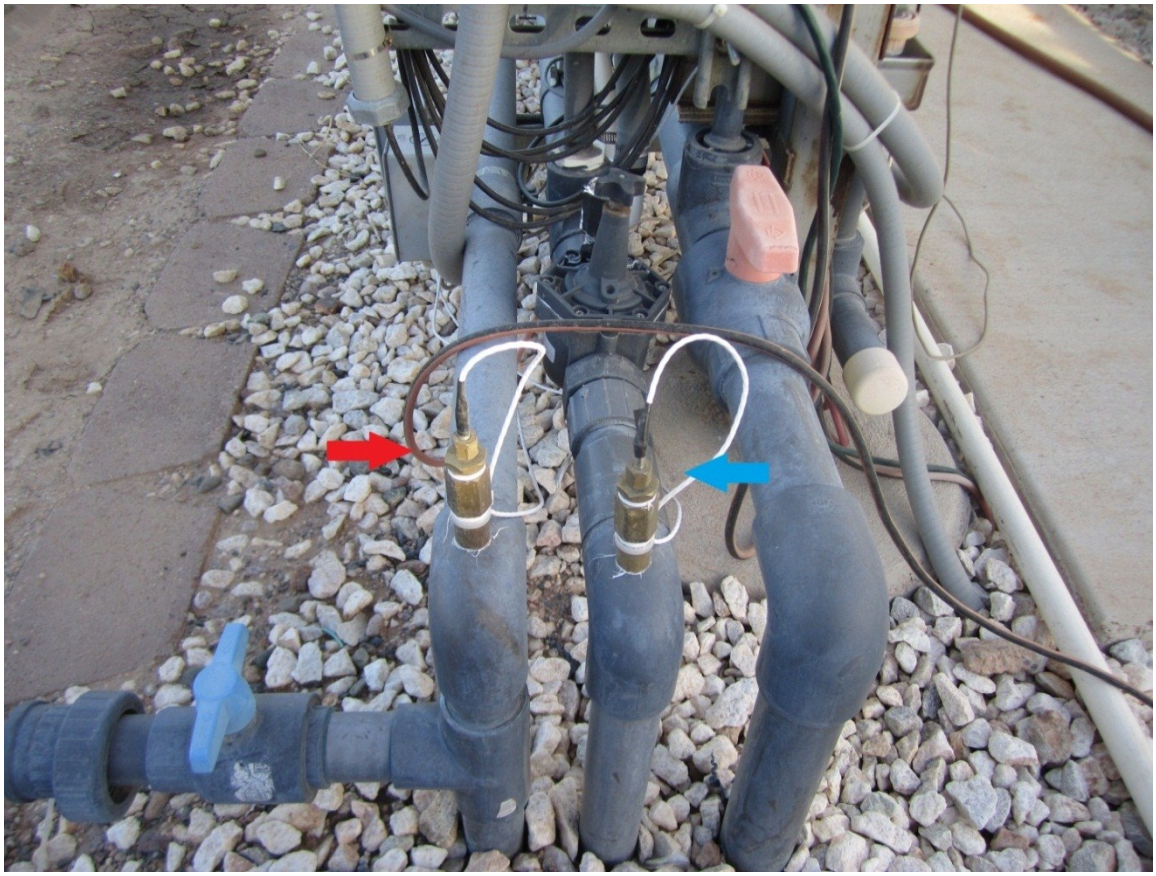

Figure 4.5. RTD installed on cooling system (blue arrow for supply and red arrow for return)

Among the variables being monitored, the cooling system and pH readings could be controlled based on several temperature readings and regulation of CO_2 addition in the aeration supply stream. In order to minimize ambiguity in variable values, the cooling system was fitted with a controller activation using time-based adjustment. The regulation of CO_2 addition through the aeration system was retained as the only controlled variable.

In order to enable continuous development of this research effort, some components were upgraded to meet the research interests and/or scalability of the photobioreactor system. Some of the areas of interest were:

- **Algae culture pH:** this was done by metering of CO_2 supply to the aeration supply stream. Algae culture pH reading is affected by culture media, temperature and CO_2

content. Appendix Figure A.7 illustrates pH analyzer installed on prototype photobioreactor. The analyzer has a build in capability to interpret signal from a dissolved O_2 sensor initially installed as a test. The dissolved O_2 value was planned to be used as a baseline to determine correlation with the dissolved CO_2 content in the algae culture. There was a need for further experimentation on the correlation of the dissolved O_2 data in relation to dissolved CO_2 content. The main part for CO_2 regulated supply is a normally closed solenoid valve. For future precise metering, an electronically controllable mass airflow metering device with a mass air flow sensor could be fitted. To complement the mass airflow metering device, an additional dissolved CO_2 sensor with an analyzer could be installed. Dissolved CO_2 input parameter would be better utilized if operated together with an already installed dissolved O_2 sensor. From those two sensors, input variables of dissolved O_2 and CO_2 would assist in defining the correlation between dissolved gases, volumetric displacement in a liquid media, as well as the algae culture's capacity to capture CO_2 supplied in the flat panel tanks.

- **Cooling system:** the main manifold supply for the cooling system can be controlled by utilizing a regulating bypass valve to allow excess cooling water that is not needed for cooling to be returned back to the reservoir. Continuous regulation of water supply to cooling coils and bypass return path to reservoir will affect the cooling system performance, allowing for better control resolution based on the defined algae culture temperature. A major improvement for controlling flat panel tanks temperature is to install an electronically controllable 3-way bypass valve; one port for inlet water and two ports with one port for cooling water supply and one port for cooling water return.

Algae strain selection

The algae use for this research was a green microalga *Scenedesmus* sp. (LRB-0414). The culture was initially grown in an indoor laboratory in several small glass tubes. The algae culture grown indoors utilized BG-11 culture growth media and was illuminated with cool white

fluorescent lamps to enable doubling the cell concentration within approximately 3 days. The cells were grown in glass tubes with the following dimensions: internal diameter 5.0 cm, length 60 cm, and maximum volume 850 mL. Light intensities provided by the fluorescent lamps ranged from 15 to 350 µmol photons $m^{-2}s^{-1}$. The algae culture was aerated by compressed air containing 1% CO_2 at a flow rate of 2 Liters/second. The mixture of air and CO_2 was regulated through a rotometer muti-tube flowmeter device. Cells were grown at a constant temperature of 25^{o}C. This initial step is critical in order to determine overall algae culture health and prepares for sufficient culture density required prior to transferring algae culture to be inoculated for outdoor cultivation. From this stage, an algae culture density of 1.5 g/L was prepared to be used for outdoor inoculation.

Automation system configuration and results

The initial step to utilize an automation system is to configure supporting components within the infrastructure. Supporting components were installed outdoor (field site) and indoor (control room) which include PLC unit, power supply and communication junction box. Integration of select components to photobioreactor system required attention to detail to ensure that components can function consistently with minimum problems. Supporting components are shown in Appendix section Figure A.8-11.

The software used for the monitoring and control programming algorithm was obtained from Rockwell Automation (www.rockwellautomation.com). The software package includes several components that enable multiple function variables to be integrated in a designed program. The main software is FactoryTalk View; including other software such as FactoryTalk View Site Edition (SE), FactoryTalk View Machine Edition (ME) and FactoryTalk View Studio. These are Human Machine Interface (HMI) software products designed with a common look and navigation to assist application development and training time.

Supportive of the Rockwell Automation Integrated Architecture, FactoryTalk View is part of scalable and unified set of monitoring and control solutions designed to extend stand-alone machine-level applications up through supervisory level HMI applications that can be developed

through a series of networks. This offers a common development environment for application, utilization, architecture productivity increases, long term operation costs, and to achieve quality improvement. Figure 4.6 shows FactoryTalk View Studio window from the training software.

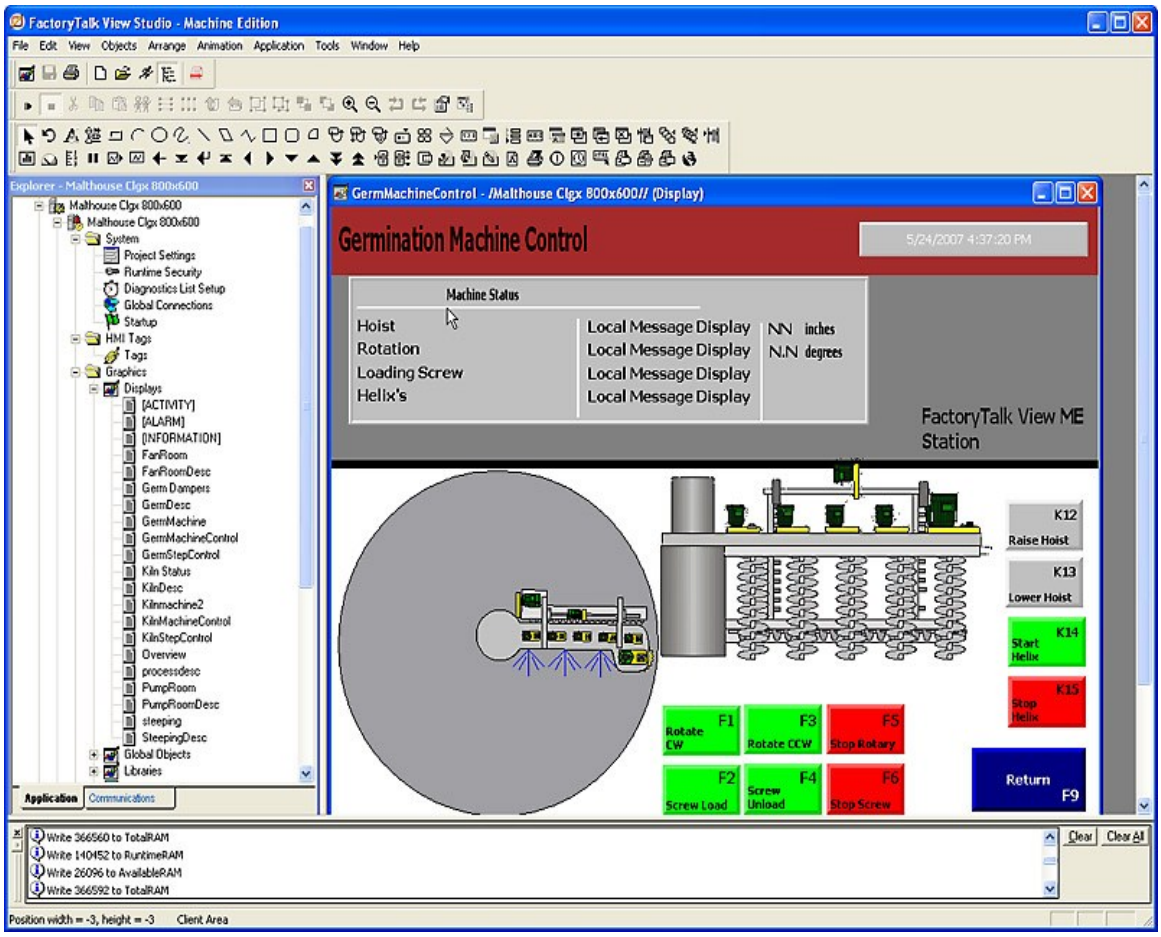

Figure 4.6. FactoryTalk View Studio window

Rockwell FactoryTalk Activation software is essential to initiate any use of Rockwell licensed products. It is part of the FactoryTalk Services Platforms and provides components that allow FactoryTalk-enable products to use activated files generated by Rockwell and distributed over the system network or internet. The activation uses a file over Rockwell website that is digitally signed, plain-text file that activates software products and locks the activation to a

designated computer's hard disk, Ethernet card or a secured website. The activation file contents are confined by a signature generated by Rockwell that is based on machine specific information provided when installing the software. This greatly enhances the system's security in the event of any Intellectual Property know-how concerned.

Support for the operational system of FactoryTalk View software input and output data management is essential to enable system monitoring and control algorithm. Also from Rockwell, software RSLinx Enterprise is utilized for operating the data server. It communicates via FactoryTalk data using systems client/server communication protocol with FactoryTalk products. FactoryTalk products and RSLinx Enterprise share FactoryTalk capabilities of system diagnostics, redundancy, and security. RSLinx Enterprise is included with all FactoryTalk software package. Figure 4.7 illustrates RSLinx software window.

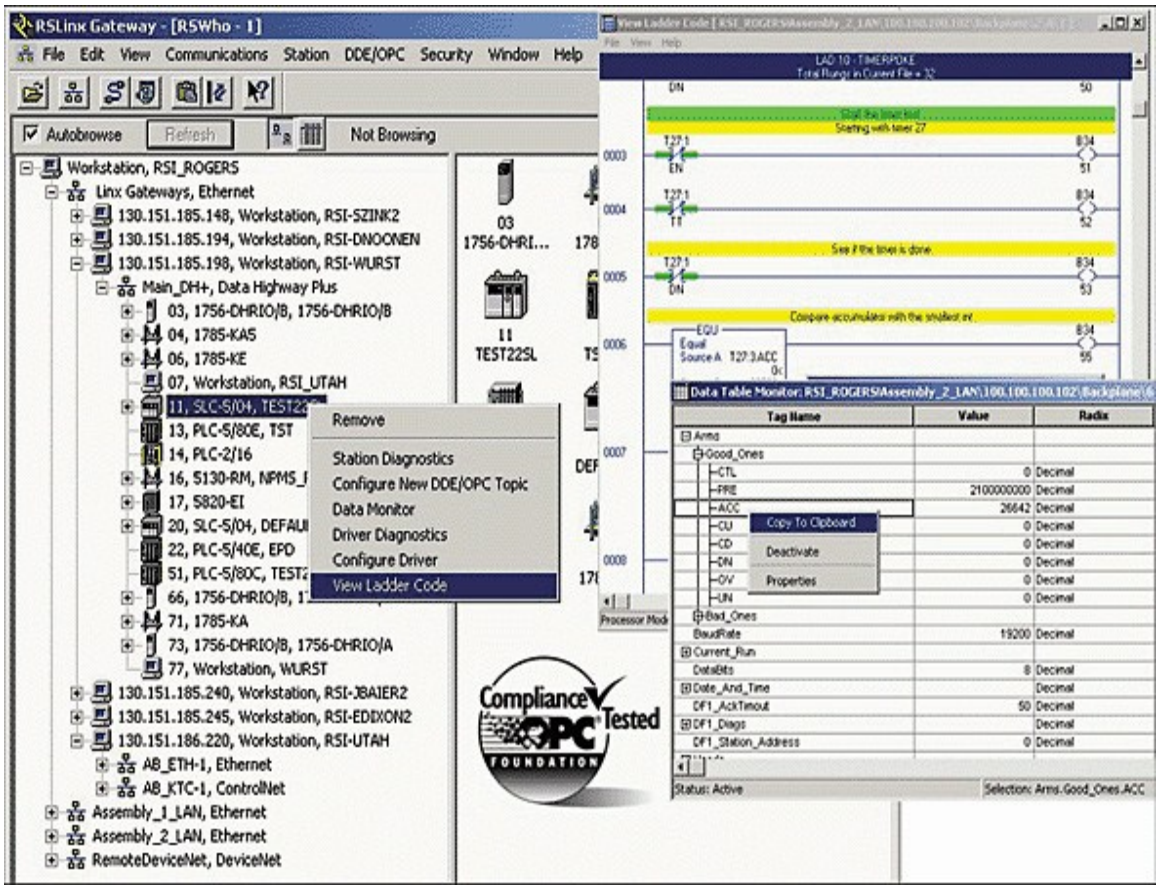

Figure 4.7. RSLinx Gateway window

The operation software that enables algorithm programming of monitoring and control systems was performed through Rockwell RSLogix 5000 software for design and configuration. RSLogix 5000 uses of protocol IEC61131-3 compliant interface, symbolic programming with structures and arrays and a comprehensive instruction set that serves many types of applications. It provides ladder logic, structured text, function block diagram and sequential function chart editors for program development as well as support for batch and machine control applications. Any program configurations completed from RSLinx and RSlogix 5000 software could then be included as a programmed operating system for FactoryTalk View Studio. Figure 4.8 illustrates the HMI template being configured in FactoryTalk View Studio.

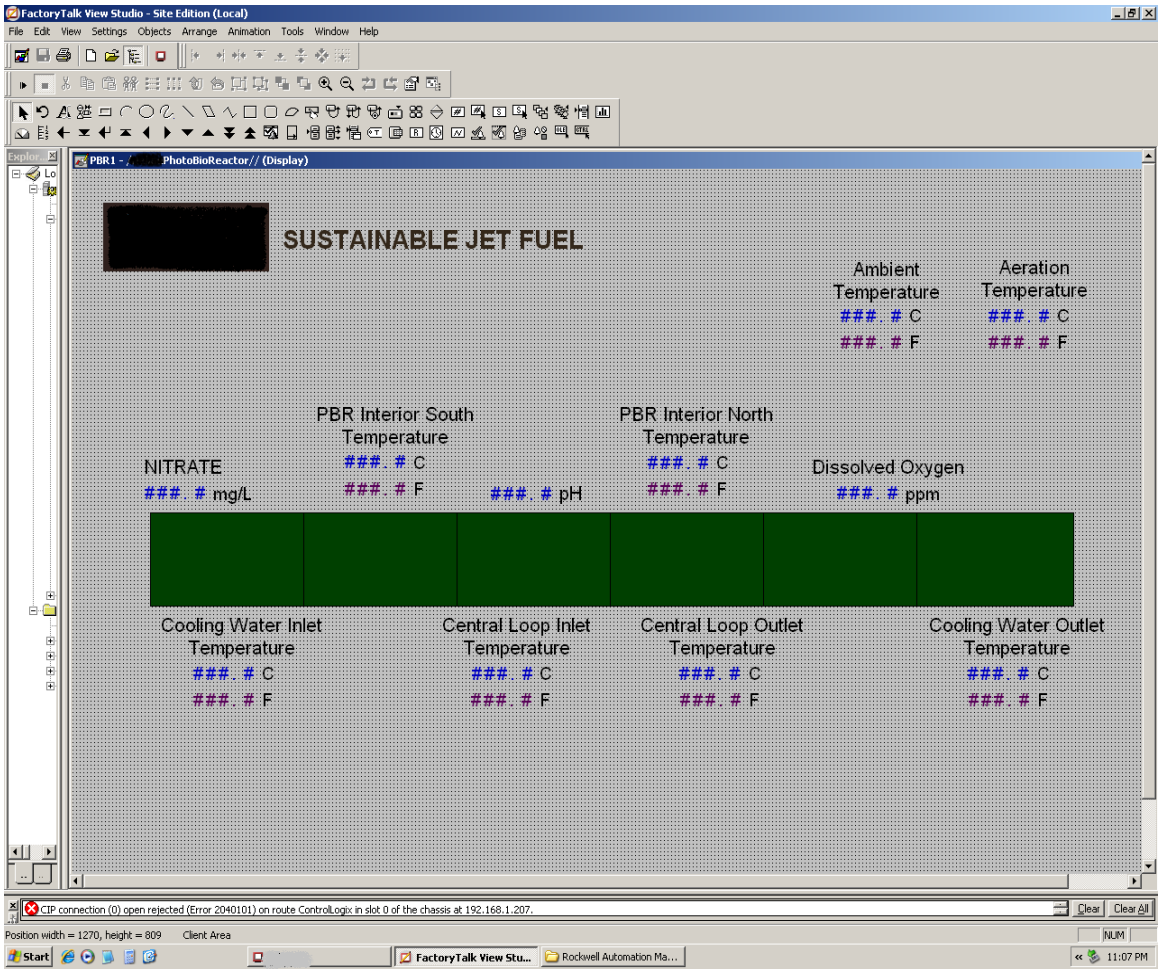

Figure 4.8. HMI template configuration in FactoryTalk View Studio

The study was conducted in parallel with the research scope under EPA P3 (Environment Protection Agency, People, Prosperity, and the Planet) sponsored project in developing commercially viable culture media from wastewaters optimized for the emerging microalgae-based biofuel industry. The experiment was performed over two weeks starting on the second week of January 2012, with the monitored data obtained from the run over the first five days. The flat panel photobioreactor utilized for conducting the monitoring control study was used as a control study using standard BG-11 Growth Medium. In contrast, other flat panels were used for experimental algae cultivation using growth media processed from various wastewaters obtained

from dairy, poultry and municipal sources. Due to time constraints and limited assistance in algae cultivation process, the monitoring and control system progress covered only up to the programming of the data communication and PLC to obtain input variable values (temperatures values on various points and pH).

The information obtained from sensors was processed through PLC with Rockwell Automation software programmed to correlate input values to be useful for the further programming routines needed for the control variable outputs. The raw data processing from PLC was transferred to a data management system (Microsoft Access), which enabled the raw data to be stored in its own format based on the Access Jet Database Engine. The support of Access is by Visual Basic for Applications (VBA), an object oriented programming language that can reference a variety of data generation such as from Rockwell Automation. The integration of Access greatly minimizes the size of data memory space utilization as compared to storing Rockwell Automation data to the computer desktop hard drive. The stored data from Access was then tabulated through Microsoft Excel enabling the values to be better interpreted in the form of organized spreadsheet and graphical forms. Starting time of the recording was at 10:00 PM of the day 0, and continued to 6:00 AM of day 5. The programmed real time measurements were taken every fifteen minutes. The graphical plots in this report have been simplified to provide the five day monitoring into hourly data points. Figure 4.9 illustrates ambient and aeration temperature values versus time.

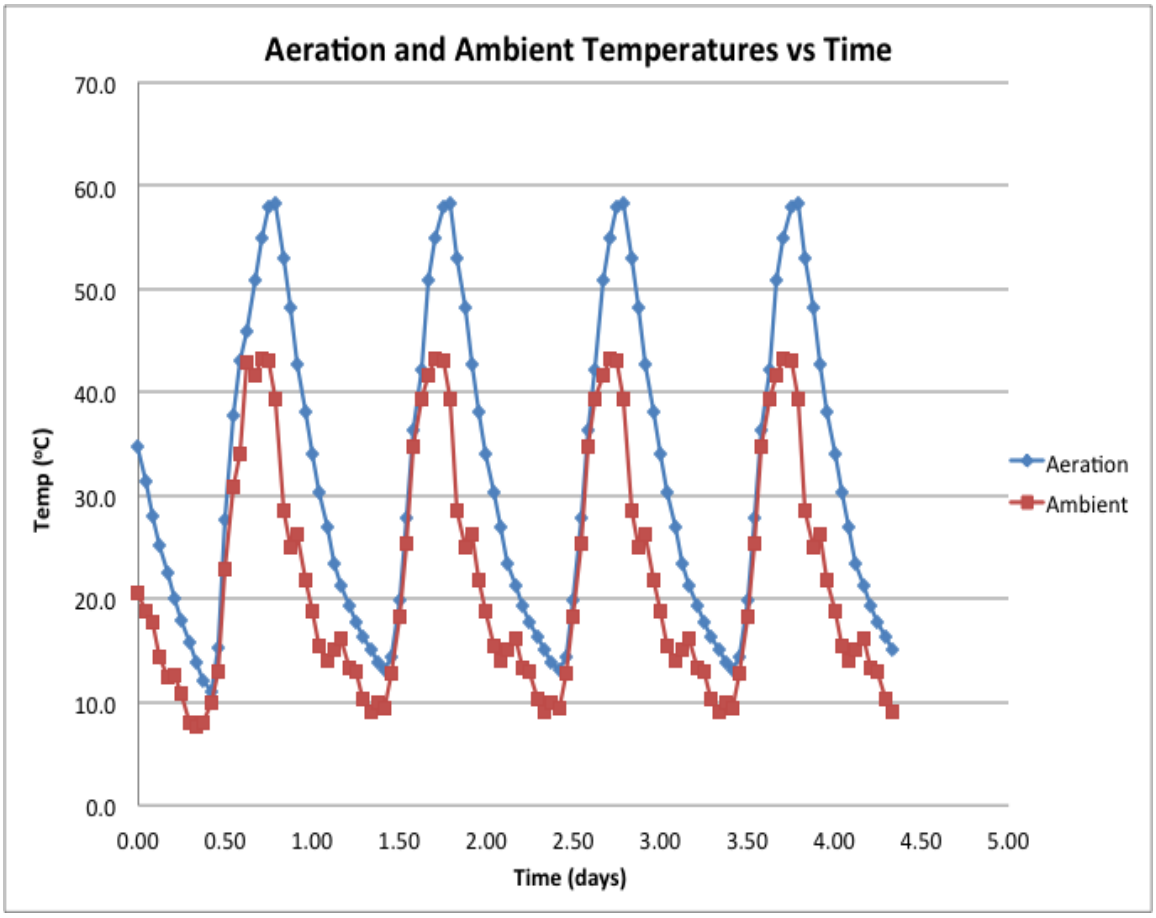

Figure 4.9. Aeration and ambient temperatures versus time

Referring to the graph, the red plot is for the ambient temperature, and the blue plot is for the aeration temperature. At the highest temperature of the day, the ambient temperature shows readings that are higher than the actual temperature value. This was due to the fact that the RTD used was exposed directly to the sunlight, thus the radiant heat from the sun increased temperature values during the peak time of the day. The solution was to relocate it to the point where it could obtain actual ambient air temperatures while avoiding direct sunlight exposure during the day. The blue plot of the aeration shows that during the highest temperature of the day, the air and CO_2 mix supplied to the photobioreactor reached 58^{o}C. This is normal due to the air supply being forced by a blower at a high flow rate (rated at 110 cubic feet per minute from

www.aquaticeco.com). This greatly affects the in-tank culture temperature and cooling system efficiency.

The next graph is the plot of in-tank algae culture temperature for the east and west flat panels under the monitored system. Figure 4.10 shows the comparison of the two flat panel temperature variations.

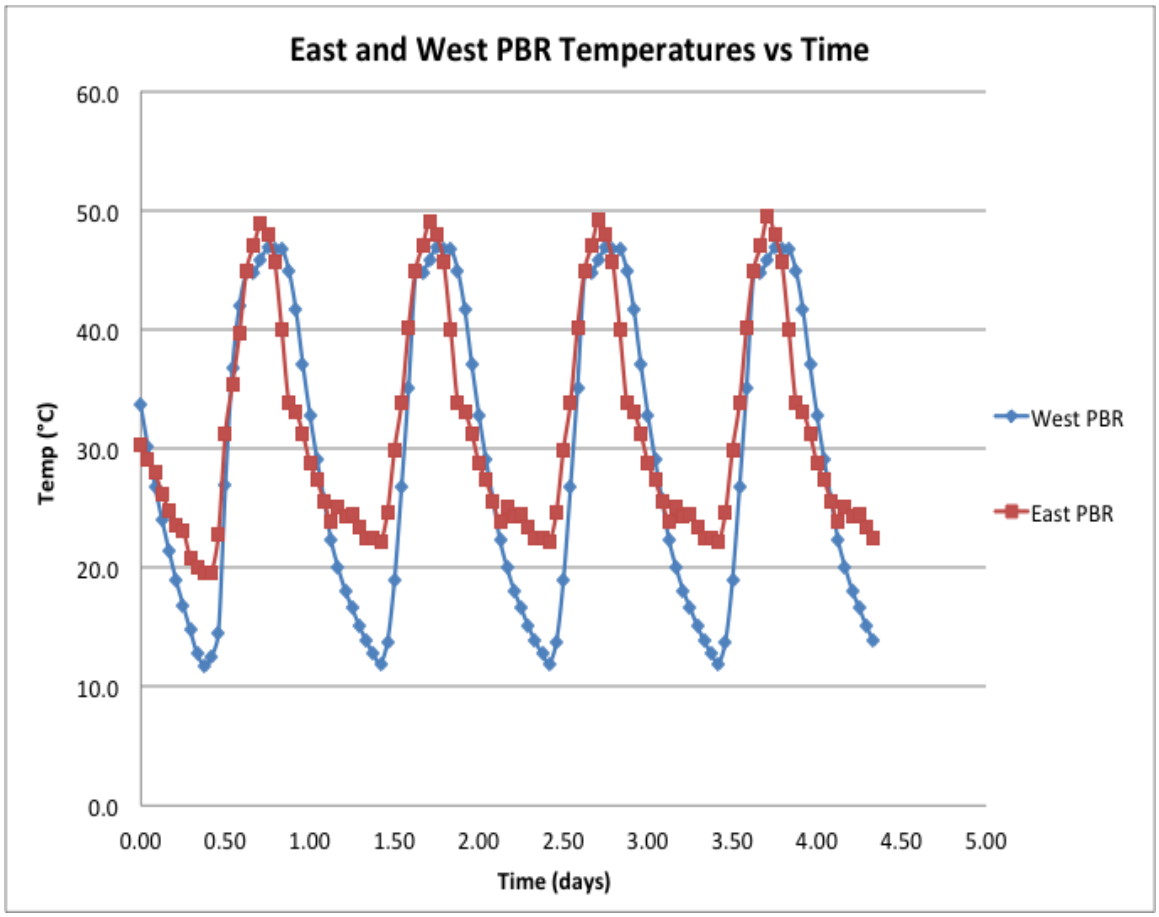

Figure 4.10. East and west flat panel temperatures versus time

In-tank algae culture temperature is influenced by many factors. Environment factors are ambient temperature and sunlight radiation. Other factors influenced are the overall system integrations and cultivation preparation such as aeration system, cooling system and culture density. From the

graph it can be observed that the west side overall temperature values were lower than the east side due to the cooling water supply of fresh water from the cooling tower. The excess water that was already used to cool the west side through its cooling loop was circulated to be used for the east side flat panel cooling loop, thus a temperature difference between west and east in-tank algae culture temperatures. Figure 4.11 illustrates the temperature values for the cooling loop inlet and outlet. The cooling loop described for the plot is a combination of two cooling loops of the west and east flat panels connected in series.

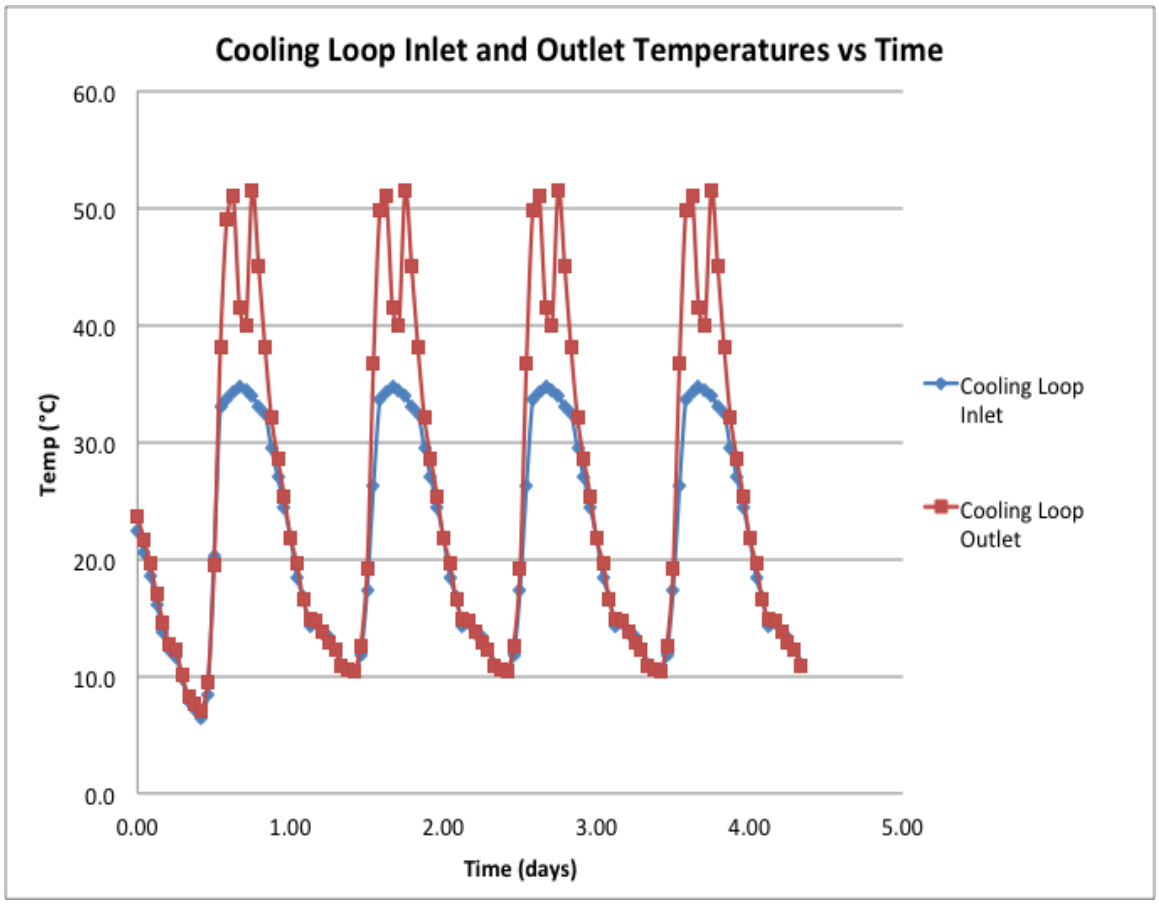

Figure 4.11. Cooling loop inlet and outlet temperatures versus time

The cooling loop inlet temperature reading was based on the lowest water temperature capable of being supplied by the cooling system. The cooling loop outlet temperature was based on the reading of cooling water circulated from west and east flat panel cooling loops. There were slight variations in temperature readings due to the RTDs exposure to the sunlight. To remedy this, a UV resistance insulation material could be added to cover the RTDs.

Monitoring the main manifold supply and return water temperatures can also assess the cooling system efficiency for the entire cooling system circuit. Two RTDs integrated within main manifold provided the temperature values. Figure 4.12 illustrates the cooling system performance.

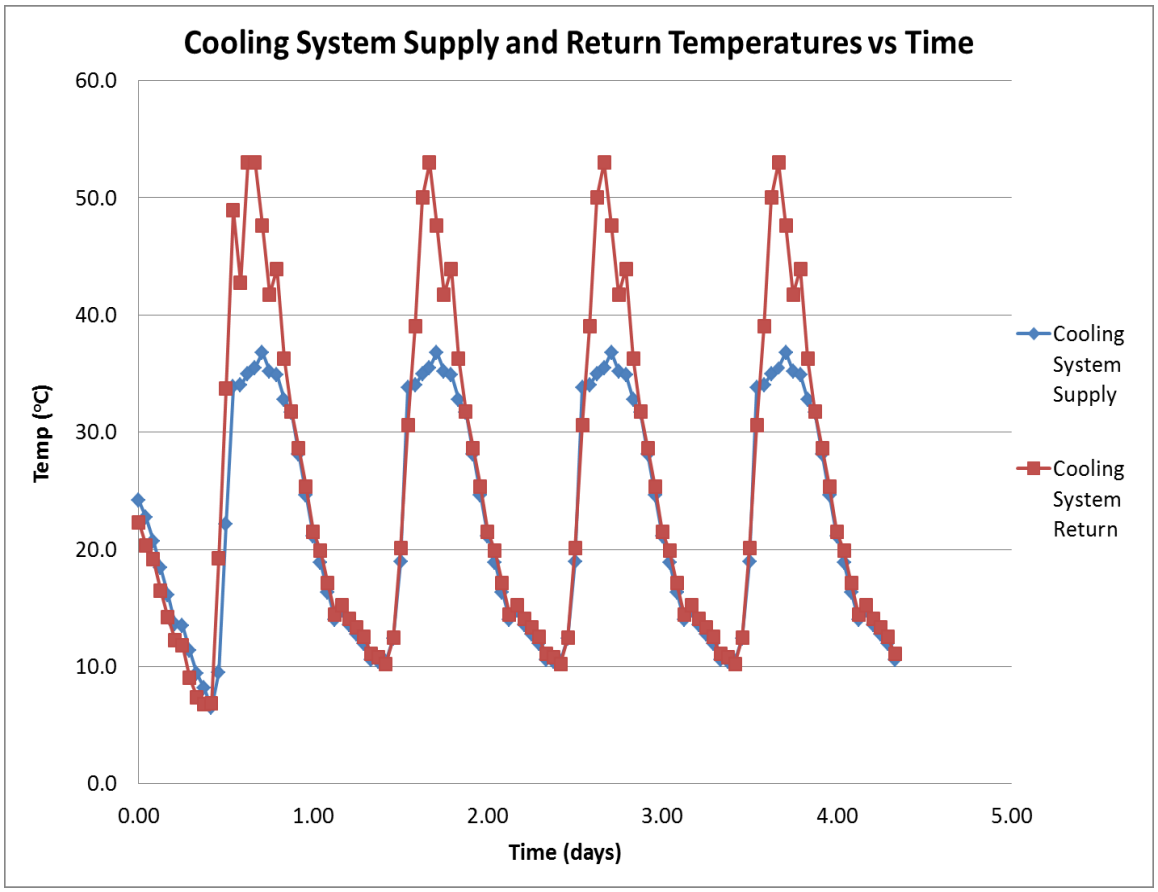

Figure 4.12. Cooling system supply and return temperatures versus time

The cooling system supply temperature provided the lowest temperature reading for the cooling system capability based on the ambient temperature. The cooling system return temperature reading represents the overall temperature of the flat panel photobioreactors in a row and provides an example of how the twelve flat panels arranged in series affect the cooling water temperature as it was returned to the evaporative cooling tower. The overall cooling system temperature readings can assist in detecting any cooling system problems during the cultivation process, as well as predict the components maintenance requirements and service life, and provide seasonal cooling system performance should the existing cooling system need to be utilized for additional photobioreactors.

The other monitored values beside temperature readings were the pH readings. Figure 4.13 shows the pH data (red plot) taken manually with a hand held pH meter, compared with pH measurements taken by the monitoring system. Due to the availability of only one pH probe unit for the monitoring system, the west side flat panel was chosen to be the sampling unit.

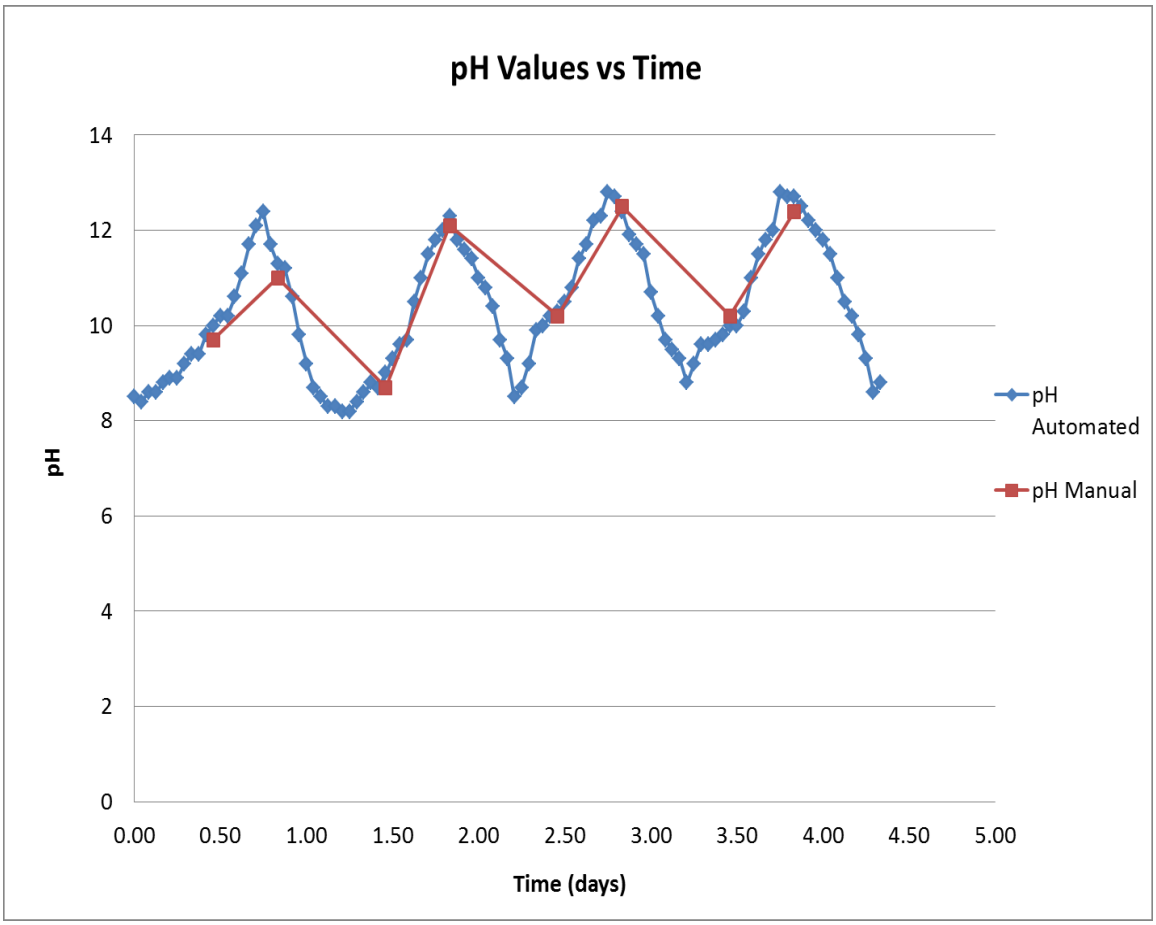

Figure 4.13. pH values from manual measurements and system monitored versus time

The manual pH measurement was taken two times a day; first at 9:00 AM and second at 6:00 PM. The eight manual pH measurements were compared against the monitoring system measurements. All eight yielded comparable pH values to that obtained with the monitoring system at the same time. The system monitored plot shows other pH values, including the highest and lowest values, otherwise not detected by the manual methods. This data illustrates that continuous real time system monitoring can assist in determining the pH, CO_2 supply status, and photobioreactor cooling system efficiency as well as other parameters to maintain appropriate algae culture conditions.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

An algae cultivation system, in general, is similar to agricultural crop farming practices. Plants are grown on an area of land for a certain time period (season) with the goal of harvesting part of or all the biomass produced by the plants. One of the advantages of using algae biomass is that it can be grown as a source of energy in the form of biofuels. Additionally, algae-based biofuels do not compete with other agriculture food crops. Significant advances in algae production practices, photobioreactor technology and strain selections, have led to additional knowledge about the remarkable potential of algae to serve as a sustainable source of biofuel.

Although a scalable, commercially viable algae cultivation system has not yet emerged; numerous approaches in research have been conducted to make the price of biofuels from algae to become cost-competitive with fossil-based petroleum fuels. Continuous improvement in the algae production process is required in order to obtain the desired quality and quantity of product and reduce the overall cost to obtain biofuels and co-products from algae. One of the improvement efforts needed is the design of an automated monitoring and control system specifically for an algae photobioreactor system. This is of great importance to research organizations and industries that wish to exploit the use of algae for various products.

The results from this research indicate that in a diverse world there can be no set of absolute components for designing a universal ”fits-all” automated system. Some systems may require more functionality and/or flexibility, some may require less. The balance between cost and functionality will vary from project to project. This research focused on an evaluation of outdoor photobioreactor types and was conducted using an existing datalogger system. In order to improve datalogging repeatability and upgradability, robust industrial components were evaluated and integrated with the photobioreactor system. In addition, a PLC was configured and validated using Rockwell Automation software.

The following recommendations are based on the monitoring capabilities provided by the automation software and the results from the field testing.

Recommendations

This study should be further developed to implement the automated monitoring and control system with more functionality and adaptability for various algae photobioreactor systems. However, any steps taken should observe some of the following recommendations to ensure the ultimate goal can be achieved.

- Planning should include collaboration of researchers from various disciplines such as biology, chemistry and engineering.
- Planning must include a thorough study of field site, including environment conditions, existing infrastructure systems and other supporting equipment available.
- Planning team should have a thorough understanding of algae cultivation process/production systems and photobioreactor system dynamics.
- Design of any automated system must be custom specific to the planned photobioreactor system and its infrastructure.
- Knowledge of algae strain or strains to be used, environmental effects on the strain and nutrient/treatment sources supporting the algae cultivation will enhance the productivity and value of any planned system.
- Photobioreactor and pond systems need additional research and development to improve overall production capabilities.
- Continuous analysis of the cost of production systems (including monitoring and control) is necessary to make cultivation systems operational, competitive, and sustainable. Integration of other sustainable energy sources such as solar, wind and natural gas with algae cultivation systems need to be evaluated for long-term potential benefits.

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APPENDIX:

FIGURES OF PHOTOBIOREACTORS AND SUPPORTING COMPONENTS

Figure A.1. LARB Medium Pond Raceway System

Figure A.2. LARB Mobile Photobioreactor

Figure A.3. Prototype Flat-panel Photobioreactor Production Row

Figure A.4. Prototype Flat-panel Photobioreactor Production Row

Figure A.5. Outdoor CO_2 Storage Cylinder

Figure A.6. Evaporative Cooling Tower

Figure A.7. Outdoor pH Analyzer and Communication Junction Box Installed on Prototype Photobioreactor

Figure A.8. Outdoor Electrical Junction Box with 120VAC-to-24VAC Power Supply

Figure A.9. Outdoor Communication Junction Box in the Harvest Room

Figure A.10. Communication Junction Box with Power Supply in Control Room

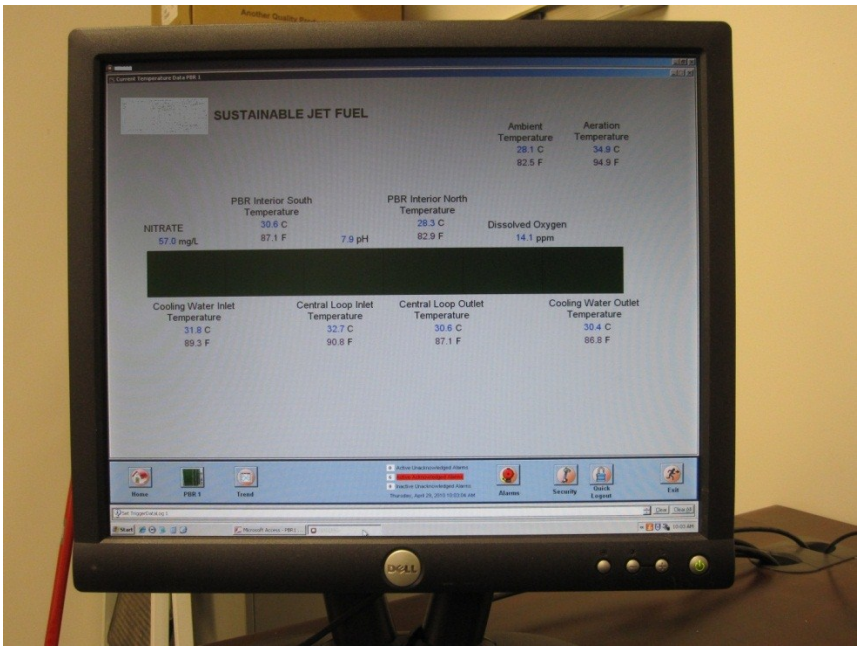

Figure A.11. Early Prototype Human Machine Interface (HMI) Window for Photobioreactor Monitoring