Hydrogen from Microalgae and the Collection and Sensing Systems

Midterm report

Team 9

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Abstract

Although it may not be readily apparent, energy directly correlates with the quality of life and technological resources that are available to people. As societies grow and become more advanced, the consumption and need for more energy increases. The augmented demand can put a strain on available resources which is why there has been a heightened interest in alternative energy. This project will focus on hydrogen as an alternative energy source. A photobioreactor has been developed which uses the hydrogen gases produced by microalgae to create energy. This project seeks to improve microalgae cultivation and develop a sensor to accurately measure the amount of hydrogen production.

1 Introduction

Hydrogen gas has become an ideal fuel source for the future since it burns clean and generates a large amount of energy per unit mass allowing it to be more fuel efficient than other resources[1]. Using hydrogen in renewable energy processes has become of greater interest due to the depletion of natural oil reserves. However, because of low concentrations at its pure form, hydrogen is not cost efficient for everyday use, making the study of biohydrogen one of great interest[2]. This calls for the exploration of hydrogen generation as a waste product of anaerobic respiration of green and blue algae from a photo bioreactor. When a controlled environment enables and regulates the proper anaerobic conditions necessary for the cultivation of algae, a photobioreactor is constructed to allow larger amounts of bio hydrogen to be produced and utilized as clean energy[3]. This occurs through biophytolysis of water by algae. The presence of light irradiation catalyzes the event and water is broken down into its hydrogen and oxygen components[4]. The phenomenon in which hydrogen is created as a waste product during the photosynthesis of algae must be promoted in a way that overcomes various issues[5]. These issues include creating a system that enables steady and continuous microalgae growth that is cost effective. The evolution of hydrogen results in an amount of fuel that is useable in commercial applications. The scope of this project will be directed toward the design and development of microalgae and measuring and collecting the hydrogen produced.

2 Project Definition

2.1 Background research

In today's world the need for renewable/sustainable energy has never been greater. Coal, petroleum, and other types of non-renewable sources provide much of the energy used today. Within the next century, these energy resources are projected to be fully depleted. Hydrogen is at the top of the list of biofuels that can solve the energy crisis that future generations face. Hydrogen in the simplest element known to man and it is usually combined with other elements. For example, hydrogen combines with oxygen to form H_2O, the most abundant resource on our planet[1]. However, it has proven difficult and expensive to split hydrogen from water to use as an energy source[2]. The most common form of this element is found as hydrocarbons, a product of organic compounds, which makes up gasoline, methanol, and propane. Hydrogen can be extracted from hydrocarbons through the application of heat, a process known as reforming[1]. The downside of reforming is the byproduct CO2, which contributes to the greenhouse effect.

One alternative for hydrogen production comes from algae. Using sunlight as their energy source, and under the right conditions, algae can give off hydrogen. The research that is currently being done is aimed at two types of algae: Scenedesmus sp. and Chlamydomonas reinhardti, figure 1a and 1b, respectively. These types of algae are favored due to their high degree of adaptability and fast reproductive cycle[3]. Our sponsor has given us the primary tasks of designing and developing an H_2 producing photobioreactor, and designing and developing an electronic H_2 mass measuring sensor to test such systems.

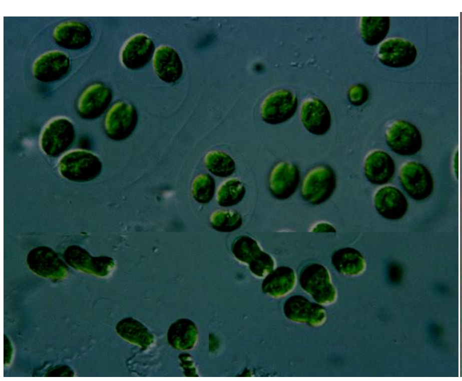

Figure 1a: Scenedesmus sp

Figure 1b: Chlamydomonas reinhardti

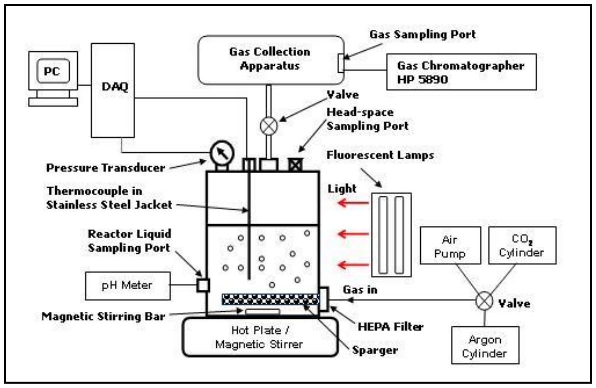

Figure 2: Schematic of a Photobioreactor.

In order to produce H_2 from algae, the algae must be cultivated in a controlled manner. There are two ways to cultivate algae: open ponds and photobioreactors. Photobioreactors (PBRs) are closed systems that provide a controlled environment where algae productivity is high. PBRs are used to better control CO_2 supply, water supply, temperature, etc[4]. Figure 2 shows a basic schematic of a PBR. The main components of such a system include a light source, hot plate, thermocouple, container, and a gas collection apparatus. Previous senior design teams at Florida State University have built working photobioreactors. One such team was team 7 from 2013 who was successful in designing and fabricating a bioreactor, which can be seen in figure 3. Their bioreactor has sensors that can monitor algae concentration, mass flow rate, and CO_2 concentrations. The bioreactor is installed in the AME building at the FAMU-FSU engineering school.

Figure 3: Team 7's 2013 photobioreactor

2.2 Need Statement

Florida State University and the Federal University of Parana have joined together to sponsor this project. There is need for a scalable and sustainable process for producing hydrogen from microalgae cultures such as Scenedesmus sp. and Chlamydomonas reinhardtii to demonstrate the feasibility of photobioreactors in the field of alternative energy. Additionally, an automated sensing system will be needed to monitor the hydrogen content of the resulting PBR system.

2.3 Goal Statement & Objectives

The goal of this project is to further the development of alternative energy with the use of a sustainable process for producing hydrogen from microalgae. To consider this project as successfully completed, there are several goals that need to be met. Below are the main objectives that must be accomplished:

- Design and construct operational H_2 producing units
- Design and construct an electronic H_2 mass measuring sensor
- Provide enough experimental data to test the operation of the H_2 producing designed units
- Provide mechanical drawings of the entire system and sensor for future product scale up
- Write an invention disclosure (FSU team) to be submitted to the USPTO by the OTT/FSU, and a patent request (Brazilian team) to be submitted to the Brazilian INPI, for the H_2 producing photo bioreactor system developed

2.4 Constraints

There are many engineering issues such as appropriate bioreactor designs and scaling-up the system, preventing interspecies hydrogen transfer to non-sterile conditions, and the purification and separation of hydrogen. The photobioreactor should be designed in such a way that it is easily scalable. The workspace in the lab is small which means the size of our bioreactor will be smaller. However, if this type of system is to potentially be used as a major source of energy in the future, a much larger bioreactor is needed. The bioreactor also cannot be used until a gallon of algae is grown. Until then, the algae will initially be grown in small glass bottles or beakers.

Our team is working with a budget of roughly $1000. This creates issues when it comes to growing and maintaining healthy algae. The food for the algae is very expensive to buy premade so it is important for the team to learn how to make the food. The biggest constraint for this project deals with maintaining a large amount of healthy algae and the time is takes to produce that amount. It can take months to grow an adequate amount of algae and without a large amount, hydrogen production won't be maximized. Many of the students working on this project have little background in the growth processes of microalgae and microorganisms in general. This insufficient knowledge could lead to a lack of understanding on how to integrate hydrogen production with other processes. The processing of biomass feed stock is also very expensive. If this it to become a widespread energy source in the future, the cost of production must be reduced.

The hydrogen mass sensor must have three different colored LED lights that correspond with different percentage levels (5%, 10%, 20%) of hydrogen mass. The lights will light up according to the mass percentage detected. It will also make a sound once the hydrogen mass percentage level is above 5%.

3 Design and Analysis:

3.1 Functional Analysis

H2 Sensor

The sensor is a MQ – 4 sensor with a sensitivity of 200 – 10,000 ppm and is controlled through an Arduino Uno microcontroller board. The board has 14 digital input/output pins, 6 analog inputs, and a 16 MHz clock. The H2 sensor and board requires programming and calibration for a correct readout. Figure A shows the prototype that has been assembled by the team in Brazil at UFPR. The system will operate on 5V with an input voltage of 7 – 12V, which will be supplied by an appropriate power adapter. When hydrogen is present, the system will alert the user through a chain of LEDs that light depending on the percent concentration, e.g. one LED for 5% concentration, two LEDs for 10% etc.

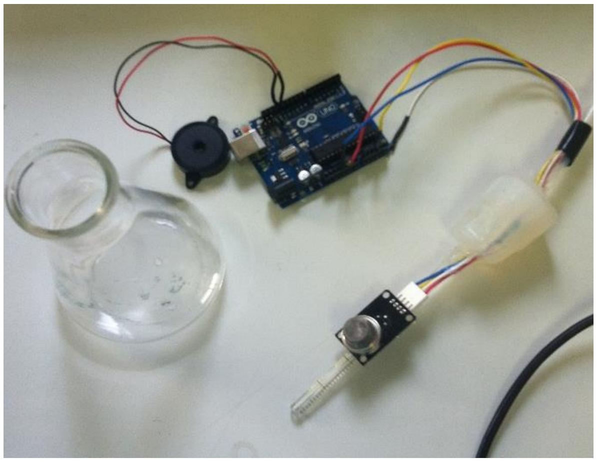

Figure A: Prototype of H2 sensor system.

Photobioreactor

The basic components of photobioreactors include the housing for the algae, CO2/air supply, and a light source. For our purposes, the light sources will be 3’ long T8 fluorescent tube lights. These lights use 25 Watts of power and output 2000 lumens at a color temperature of 5000 Kelvin. Bi-pin cable harnesses and 30 Watt ballasts will be connected together (for multiple light sources) and plugged into a commercial power strip. Polymethyl methyl acrylate was chosen as the material for the housing of the algae. This clear plastic has a density of 1.19 g/cm^3, a transparency of 92%, and is low cost. Some advantages of this plastic are good impact strength, high transmittance, and excellent environmental stability. Pumps and/or compressed CO2 will also be used to maintain the algae and as a means of circulation. The pump considered is a commercial portable compressor, which operates at 100 PSI and a volume flow rate of 10

CFM. In order for the algae to have the appropriate concentration of CO2, a 20 cubic ft. cylinder will be considered.

3.2 Design Concepts

Some important design criteria to consider when choosing a bioreactor design include surface area to volume ratio, mass transfer of CO_2, and the net energy ratio. The surface area to volume ratio ($\frac{A}{V}$) determines the amount of light entering the system per unit volume. A higher $\frac{A}{V}$ ratio will result in a higher cell concentration and greater productivity[10]. This ratio was evaluated for each of the bioreactor designs show below in *figures 4-6.*

Airlift PBR:

$$\frac{A}{V} = \frac{2\pi rh + 2\pi r^2}{\pi r^2 h} = 1.388$$

Flat Plate PBR:

$$\frac{A}{V} = \frac{2hw + 2hl + 2wl}{whl} = 0.639$$

Fermenter PBR:

$$\frac{A}{V} = \frac{2\pi rh + 2\pi r^2}{\pi r^2 h} = 0.369$$

Where the volume was determined from the liters of medium present in each of the bioreactor systems:

Airlift PBR:

$$V = \pi r^2 h = 254.5 \, x \, 4 = 1018.4 \, in^3 = 16.7 \, L$$

Flat Plate PBR:

$$V = whl = 3456 \, in^3 = 56.6 \, L$$

Agitator PBR:

$$V = \pi r^2 h = 3694 \, in^3 = 60.5 \, L$$

From previous studies, it was shown that the photosynthetic photon flux density was ultimately lower for bioreactors with higher $\frac{A}{V}$ ratios. A higher $\frac{A}{V}$ ratio results in greater radiation distribution over a larger surface area. Thus, a higher volumetric productivity is the result[10].

Algae specimens require inorganic carbon in order to produce biomass. Inorganic carbon exists in various forms in liquid environments when the temperature and pH levels are right. Resistance to CO_2 diffusion can be a limiting factor during mass transfer[10]. The rate of mass transfer can be calculated from:

$$N_{CO2} = k_L a(C_{CO2}^{*} - C_{CO2})$$

Where k_L is the liquid-phase mass transfer coefficient and a is the area available for mass transfer.

The net energy ratio (NER) is defined as the ratio of total energy produced in terms of biomass and hydrogen divided by the operation energy:

$$\text{NER} = = \frac{\Sigma\ \text{Energy Produced}}{\Sigma\ Energy\ Input}$$

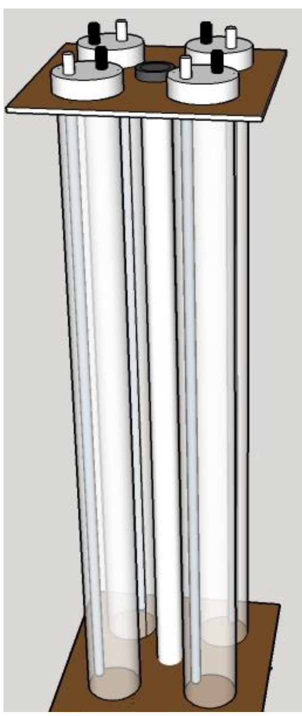

Figure 4: Chamber Airlift Bioreactor

Airlift and flat plate bioreactors are advantageous systems because they use compressed air to mix as well as control the temperature of the system. This results in a more efficient NER.

The first bioreactor design our team has considered is that of the chamber airlift bioreactor (depicted in *Figure 1*). This consists of a light source in the middle and tubes of algae arranged around the outside of the light forming a chamber. Advantages to this design include its simplicity and there are no moving parts like an agitator. This results in less risk of defects and lower overall maintenance. Because this design doesn't include an agitator, the system is easier to sterilize and clean. It also requires less energy since there are no moving parts. This design has a greater heat-removal than most other bioreactor because of the draught tube inside the bioreactor can be used as an internal heat exchanger. Some disadvantages include the need for higher air pressure. Because there is no mechanical agitator, this design uses an air supply to agitate the algae. The air supply is adjusted by raising the air pressure. If higher air pressure is needed to agitate the specimen, then more energy consumption results which leads to a higher operating cost.

The second design is a flat plate bioreactor which is depicted in *Figure 2*. This design has an open gas transfer system which reduces O_2 buildup. It uses air to produce bubbling at the bottom or the sides of the system to create circulation and agitate the system. However, due to the intense bubbling that occurs, there is a shear that acts upon the cells until the bubbles burst. The temperature of the system is controlled by heat exchange coils.

Figure 5: Flat Plate Bioreactor

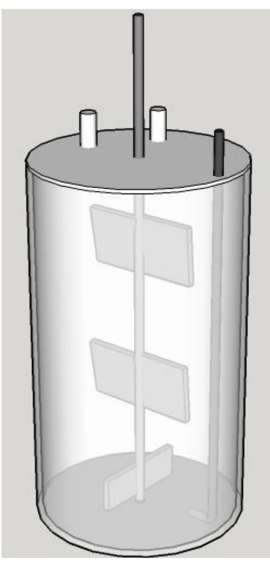

Figure 6: Fermenter Bioreactor

The third design of a fermenter bioreactor is shown in *Figure 3*. This design incorporates paddles or impellers to agitate the system. The temperature control method uses heat exchange coils which is identical to the flat plate bioreactor. This system can be very beneficial when a great degree of control is needed. However, because the system has a larger volume in terms of depth and width, the light efficiency is very low.

3.3 Evaluation of designs

Table 1. Design decision matrix

Criteria	Photobioreactor Design		
	Chamber Airlift	*Flatplate*	*Fermenter*
Affordability	6	8	7
Safety	9	9	9
Automated Operation	8	7	5
Weatherproof	9	9	9
Low-Maintenance	9	8	6
Continuous Operation	9	7	7
Ease of Use	8	6	4
Gas Output	9	7	5
Weighted Sum	**67**	**61**	**52**

3.3.1 Criteria, Method

A design matrix is used to evaluate which design would be optimum when designing the photobioreactor to be used for this senior design project. Due to budget limitations affordability is a very important criterion to judge. The completion of the project depends heavily on how much we can get and how much we can do for the amount of money we have been allocated. The safety of the person using the project to be designed is one of the most important aspects when engineering a particular design. Since combustible gases will be produced in this project we have to make sure that the proper components are in place to prevent any catastrophic damages to anyone in the vicinity of photobioreactor. Automated and continuous operation is also criteria since this is a time sensitive project. The more automated and continuous the operation the less human interference is present lending to complications and/or lost and wasted time. Due to the size of the design and the fact that it can be sufficiently lit by the sunlight provided during the day time it may be viable to place the photobioreactor outside. Therefore, if the system were not weatherproof there could be malfunctions of components that make up the design which would be detrimental to the project. The easier the photobioreactor is to use the less likely it will be that complications arise due to issues with actually using the device. Furthermore, the easier it is for the user to use the better the results will be when handling the algae and transporting it from one place to another. Finally, the amount of gas produced is probably one of the most important criterions to judge since it is essentially the main goal of the entire project. We want the design that will yield the highest amount of gas produced by the algae in order to optimize on the goals of the project.

3.3.2 Selection of optimum designs

After review of the design matrix it is evident that the chamber airlift photobioreactor design is the design that scored the highest and therefore, will be the best design for the goals of this project. As stated earlier, it is one of the most efficient of the designs when it comes to cultivating the algae and yielding hydrogen output. It is simple and has no moving parts making it relatively inexpensive in regards to the budget. Furthermore, it uses compressed air to control the temperature of the system as well as mix the medium and aggravate the algae so it is a automated, continuation, and low maintenance system that can easily be made weatherproof.

4 Methodology

Creating a set schedule and organization of tasks is essential to ensuring a successful project. The first tasks include researching microalgae. It is important to understand how to grow and maintain healthy algae so that enough hydrogen will be produced. Without a substantial amount of hydrogen, testing will be inadequate. Data will be collected periodically in order to determine how well the system is working. Team members will also work on designing and constructing a sensor which will aid in determining the amount of hydrogen being produced. The collected results will be analyzed and used to determine how the current system can be improved. The final results and suggestions for improvement will be presented during the final presentation.

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4.1 Schedule

The Gantt chart shown in Appendix A breakdowns the team's assignments for the fall semester. It is broken down into four sections: initial planning, microalgae growth, sensor development, and photobioreactor development. The initial planning phase has been completed; however, many assignments in the remaining three sections will continue to be worked on throughout the semester. Algae growth research will be ongoing throughout the semester in order to ensure maximum growth and hydrogen production. Roughly a week will be spent evaluating current equipment and equipment needed as well as cost analysis. Once this is complete, supplies will be ordered. Algae growth will begin as soon as the supplies arrive and the lab is fully set up. A similar approach has been used for the sensor and photobioreactor development. Research began at the beginning of the semester but will continue as improvements need to be made. Following research, an equipment evaluation was performed as well as cost analysis and ordering of parts. There are currently parts for the sensor but it needs to be reprogrammed to meet the performance specifications. This began ahead of schedule (week of September 29). Once it has been fully programmed, the sensor will be test and recalibrated as needed. The photobioreactor follows a similar schedule. After the current photobioreactor has been evaluated, it will be updated with any additional parts needed. Once this is complete and there is enough algae grown in the small manual bioreactors, the algae will be moved to the automated photobioreactor.

4.2 Resource Allocation

The FSU team will be handling most of the algae growth as well as the photobioreactor development. The UFPR team will work on creating a functional sensor. The entire FSU team has researched algae growth in order to explore multiple ideas and perspectives. The group has currently been talking with the sponsor to determine what equipment and parts are needed. Ariel Johnson will handle the cost analysis and Jonatan Elfi will handle ordering parts. The FSU team as a whole will work on the lab set up as well as maintaining algae growth. Jonatan has performed the majority of the bioreactor research. The team will evaluate the current bioreactor together to determine what adjustments should be made. Ariel will again perform cost analysis and Jonatan will handle ordering parts. The initial cost analysis should only take 2-3 days. Ordering parts will immediately follow the completion of cost analysis. Some equipment like the algae may take up to 4 weeks to arrive. Because of this, the team will be working on setting up the lab and experimenting with medium solutions.

5 Conclusion

The continuous development of renewable energy sources like that of hydrogen can make a positive impact on society. Decreasing society's dependency on fossil fuels will not only create a cleaner atmosphere by reducing greenhouse gas emission, but it is also an economically viable energy option. This design project is focused on developing a more efficient way of cultivating microalgae as well as maximizing the amount of hydrogen that is produced and extracted in order to develop an effective energy alternative.

6 References

1. Masukawa, Hajime. "Genetic Engineering of Cyanobacteria to Enhance Biohydrogen Production from Sunlight and Water." *Ambio* 41.Supplement 2. Special Report: Capturing the Sun (2012): 169-73. *Formatex.org*. Web.

2. Demirbas, Ayhan. *Biohydrogen: For Future Engine Fuel Demands*. London: Springer, 2009. Print.

3. "Cultivation of Algae - Photobioreactor: Oil from Algae." *Cultivation of Algae - Photobioreactor - Oil from Algae*. N.p., n.d. Web. 24 Sept. 2014.

4. “Project 9: Bioh2.” *Campus.fsu.edu.* Web. 24 Sept. 2014.

5. Gaffron, H. Rubin, J. *Journal of General Physiology (1942):*26, 219.

6. "Hydrogen Energy." *Hydrogen Power and Fuel Cells*. N.p., n.d. Web. 25 Sept. 2014.

7. "A Better Way to Get Hydrogen from Water | MIT Technology Review." *MIT Technology Review*. N.p., n.d. Web. 26 Sept. 2014.

8. "Friendly Mutant Algae Could Churn Out Sustainable Hydrogen On Your Desktop." *CleanTechnica*. N.p., n.d. Web. 26 Sept. 2014.

9. "Photobiological Hydrogen Production from Cyanobacteria Anaebena Variabilis." *Photobiological Hydrogen Production from Cyanobacteria Anaebena Variabilis*. N.p., n.d. Web. 26 Sept. 2014.