Enhanced Practical Photosynthetic CO_2 Mitigation

David J. Bayless[1], Greg Kremer[1], Morgan Vis-Chiasson[2], Benjamin J. Stuart[3], Michael Prudich[3], Keith E. Cooksey[4], and Jeff Muhs[5]

1. Department of Mechanical Engineering
2. Department of Environmental and Plant Biology
3. Department of Chemical Engineering
Ohio Coal Research Center
Ohio University
Athens, OH 45701-2979
United States of America
bayless@ohio.edu

4. Department of Microbiology, LW-113B
Montana State University
Bozeman, MT 59717-0326

5. Photonics and Fiber Optic Systems
Oak Ridge National Laboratory
P.O. Box 2009, MS-8058
Oak Ridge, TN 32831

Abstract

Mitigation of greenhouse gas emissions by photosynthetic processes offers many advantages for small- and medium-sized fossil-based generating stations, including the potential for lower capital cost and lower heat rate penalty. Besides being the natural process to recycle carbon, photosynthesis produces a byproduct, biomass, which has beneficial uses, including as a potential source of H_2. It may also be used to accelerate sequestration in terrestrial systems. Despite the large body of research in photosynthesis, little work has been done to create a ***practical*** photosynthetic system for greenhouse gas control for use with both new and existing power plants. Current systems, such as a raceway cultivator (or microbial pond) often ignore land availability limitations and numerous problems of flue gas sparging. The work presented in this paper describes the design and development of a potentially cost-effective engineered photosynthesis system for CO_2 recycling. The project, directed by Ohio University, incorporates thermophilic organism research at Montana State University and design work the Oak Ridge National Laboratory to better utilize full-spectrum solar energy. Research has focused on study of viable thermophilic organisms, design of the growth surfaces within the bioreactor to reduce overall system size, photon collection and delivery via fiber optics to optimize growth and reduce system footprint, and sustainable harvesting schemes to facilitate maximum growth rates. Research has also been directed to the application of translating slug flow technology to enhance concentrations of soluble carbon species to increase organism growth rates and to reduce flue gas temperatures to sustainable levels. This paper describes the progress of this work towards creation of a "pilot-scale" bioreactor to demonstrate the integration of these efforts.

Introduction

It is generally believed that a portfolio of options will be needed to address the complexities of greenhouse gas emission control. Engineered photosynthetic systems offer advantages as a viable near-to-intermediate term solution for reduced carbon emissions in the energy sector (Hanagata et al., 1992; Maeda, et al., 1995; Benemann, 1997). Such systems could minimize capital and operating costs, complexity, and energy required to transport CO_2 that challenge sequestration. The potential for low cost control could be critical for smaller units, where capital cost per megawatt could be substantial for CO_2 control. For coal to remain competitive, especially in the rapidly emerging distributed generation market and to ensure future fuel diversification, low cost marginal control systems, such as photosynthetic systems, must be developed.

Despite the large body of research in the area of photosynthesis for carbon sequestration, little work has been done to create a practical system, one that could be used with both new and existing fossil generating units. For example, use of raceway cultivators ignores land availability limitations at existing fossil generation plants. Few existing smaller generation units could find 200+ acres of suitable land for siting a microbial pond much less build and maintain one throughout a midwestern winter. Additionally, how would the CO_2 be introduced to the photosynthetic agents? Would such a system need expensively separated CO_2 (not direct flue gas) for sparging, thus vastly increasing the system cost? Would local stack emissions restriction prevent dispersion of flue gas at ground level? In addition, questions exist about supply and distribution of light. For example, in a pond, only organisms near the surface would receive sufficient photons for photosynthesis due to the high degree of reflection and attenuation caused by the water. If organisms had to exist at the surface (and outside), would cold weather have a negative impact on their performance? Further, to keep any such system operating at maximum carbon uptake rate, mature and dead organisms would need to be harvested. How would that be accomplished and at what rate? Finally, although numerous post-harvesting uses exist, what would be the optimal use with respect to the specific application and host site? These questions must be addressed before deploying a practical photosynthetic system.

The concept behind engineered photosynthesis systems is straightforward. Even though CO_2 is a fairly stable molecule, it is the basis for the formation of complex sugars (food) by green plants through photosynthesis. The relatively high content of CO_2 in flue gas (approximately 14% compared to the 360 ppm in ambient air) has been shown to significantly increase growth rates of certain species of microalgae. Therefore, application is ideal for contained systems, engineered to use specially selected (but currently existing) strains of microalgae to maximize CO_2 conversion to biomass, absorbing greenhouse gases (Brock, 1978; Ohtaguchi et al., 1997). In this case, the microalgal biomass represents a natural sink for carbon.

As shown in Figure 1, if the composition of "typical" microalgae (normalized with respect to carbon) is $CH_{1.8}N_{0.17}O_{0.56}$, then one mole of CO_2 is required for the growth of one mole of microalgae. Based on the relative molar weights, the carbon from 1 kg of CO_2 could produce increased microalgal mass of 25/44 kg, with 32/44 kg of O_2 released in the process, assuming O_2 is released in a one-to-one molar ratio with absorption of CO_2. Therefore, a photosynthetic system provides critical oxygen renewal along with the recycling of carbon into potentially beneficial biomass.

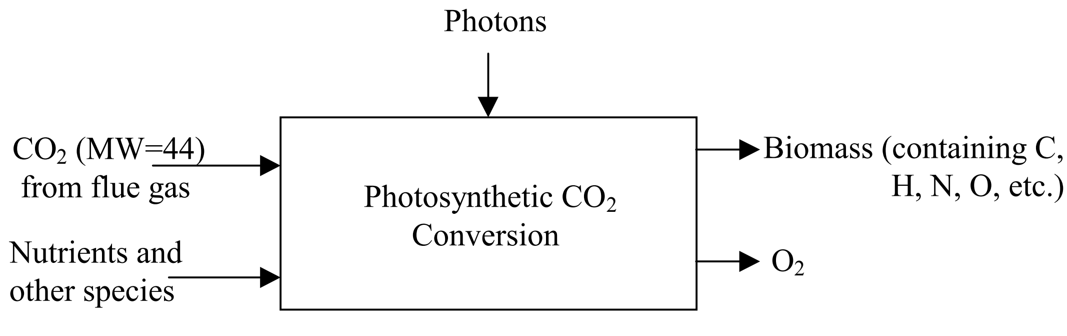

Figure 1. Photosynthetic conversion of CO_2 to biomass and oxygen

Enhanced natural sinks could be among the most economically competitive and environmentally safe carbon sequestration options because they do not require pure CO_2 and they do not incur the costs of separation, capture, and compression of CO_2 gas (Kajiwara et al., 1997; Hirata, et al., 1996). Among the options for enhanced natural sinks, the use of existing organisms in an optimal way in an engineered photosynthesis system is lower risk, lower cost, and benign to the environment. This contrasts the use of ocean-based sinks, which could present problems (Bacastow and Dewey, 1996). Large amounts of iron must be added to the ocean to promote additional CO_2 fixation. As a result, there may be little control over resulting growth. "Weed" plankton, the most likely organisms to grow, would not provide sufficient nutrients for the food webs, generating a high probability of negative environmental impact (Cooksey et al., 1995).

An engineered photosynthesis system could be placed at the source of the emissions to allow measurement and verification of the system effects, rather than being far removed from the emissions source, as is the case with forest-based and ocean-based natural sinks. The power source is natural and abundant. And the energy is converted to byproducts –biomass– that could be used as a fuel, fertilizer, feedstock, or source of hydrogen (Fisher, 1961). And even though some carbon is eventually released from biomass through decomposition, bioconversion is the fastest and safest method to add carbon to natural terrestrial sinks. Further, the process described in this paper also requires relatively small amounts of space, estimated to be $1/25^{th}$ of a comparable raceway cultivator design. Because the organisms are grown on membrane substrates arranged much like plates in an electrostatic precipitator, there is little pressure drop. The system described here could be used at virtually any power plant with the incorporation of translating slug flow technology to create favorable conditions, such as reduced temperatures and enhanced soluble carbon concentration. Finally, engineered photosynthesis systems will likely benefit from current research into enhancing the process of photosynthesis, either genetically or via photocatalytic reactions.

Objectives

The effort described in this paper focuses on the development of a pilot-scale photobioreactor to demonstrate that engineered photosynthetic systems are a practical alternative for greenhouse gas control. The work described here has focused on selection and study of viable thermophilic organisms, design of the growth surfaces within the bioreactor to reduce overall system size, photon collection and delivery via fiber optics to optimize growth and reduce system footprint, and harvesting schemes to facilitate maximum growth rates. Research has also been directed to the application of translating slug flow technology to reduce flue gas temperatures and to enhance concentrations of soluble carbon species to increase organism growth rates. The ultimate goal is to complete pilot scale system testing to demonstrate process viability.

Project Description

The conceptualized process, shown in Figure 2, begins after the flue gas has passed through suitable particulate control device(s) so that the gas will be substantially free of solid impurities. Then the flue gas must be cooled. In our concept, translating slug flow is used for both cooling the flue gas and generating soluble carbon species to "feed" the bioreactor. The water used in the process must also be cooled (using a cooling tower) due to solubility limitations of carbon dioxide in water. The cooled flue gas, and separately the soluble carbon from the slug flow reactor, pass through the bioreactor, which houses vertically suspended growth membranes growing thermophilic organisms, arranged to minimize pressure drop of the flue gas throughout the reactor. The growth substrate, which is a woven fibrous membrane, must be resistant to wear in the harsh environment of the flue gas and corrosive potential of the growth media and, because of the vertical position, offer a high degree of adhesion with the microalgae. However, the degree of adhesion can be too high, becoming problematic for harvesting.

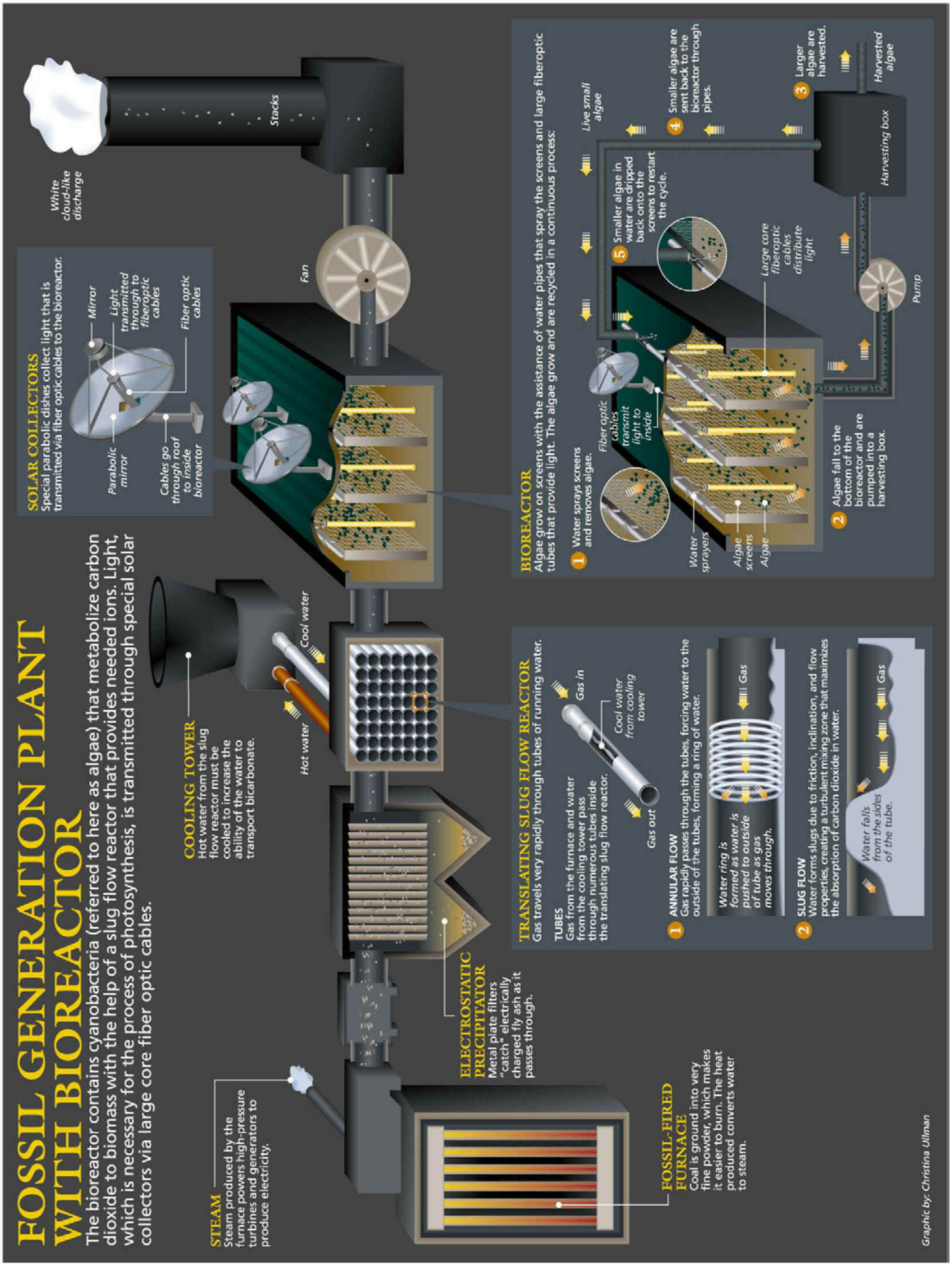

Figure 2. Artist's concept of the bioremediation process

Pilot Scale Bioreactor Test Facility

The pilot-scale photobioreactor, also known as the Carbon Recycling Facility (CRF), is shown schematically in Figure 3. The CRF is designed to simulate the flue gas emission from fossil-fired power plants. It has four subsystems in addition to the bioreactor: the flue gas circulation system, the growth media transport (circulation) system, light delivery system, and the harvesting system.

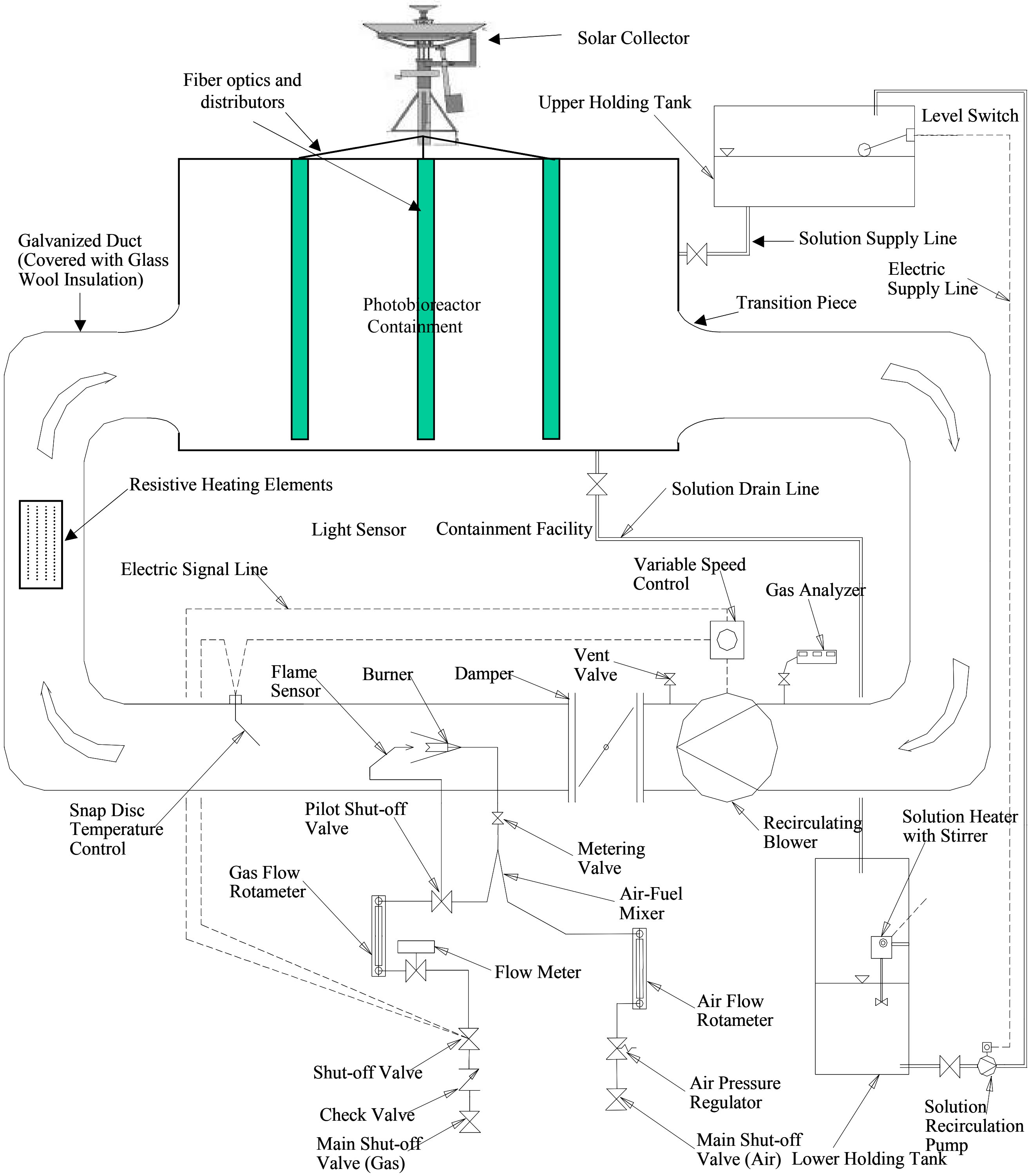

Figure 3. Schematic flow diagram of Carbon Recycling Facility

Flue gas is generated by a premixed air-natural gas burner with metered flow. The temperature of the flue gas may be maintained using this burner, or when no additional CO_2 is needed, using resistive electrical heating elements. The flue gas is continuously analyzed for CO, CO_2 and O_2 content using a Nova Analytical Systems Inc., model 375WP analyzer. The temperature of the flue gas is analyzed by inserting the thermocouple wire into the flue gas stream in the containment. The simulated flue is circulated through the bioreactor and ductwork using a fan.

Growth Media Transport System

The growth media transport system consists of two distinct parts – a circulating fluid system and liquid distribution system. The circulating fluid system is a closed looped, pump and gravity fed transmission system where water containing defined levels of nutrients and soluble carbon (or void of soluble carbon) is delivered to the membrane support for the organisms. The water then flows through distribution headers and then into the fibers by gravity assisted capillary action. A view of the capillary transport of water on a populated substrate is seen in Figure 4.

One of the more significant engineering challenges of this project is nutrient enhancement and delivery to the photobioreactor. Microalgae often more easily fix carbon and inorganic nitrogen in soluble form. Translating slug flow technology, developed at Ohio University's Institute for Corrosion and Multiphase Processes, not only increases concentrations of nutrients in the aqueous phase by directly removing them from the flue gas, but also lowers flue gas temperatures (Jepson, et al., 1993). Slugs create zones of greatly enhanced gas-liquid mass transfer, putting CO_2 and NO_x into soluble form for the microalgae. Such transfer would greatly speed up the natural process of photosynthesis, which in large-scale bioreactors, may be limited by the rate of diffusion of the carbon through the organism membranes.

Figure 4. Populated substrates showing capillary transport of water

Photon Collection and Delivery

Solar photons are the energy source of the system and one of the primary factors determining system efficiency. In order to utilize solar photons at maximum efficiency, the light delivery subsystem must deliver a sufficient quantity and quality of photosynthetic photons deep within the bioreactor and minimize the light loss due to reflection and adsorption. Direct, filtered sunlight is collected and delivered into the bioreactor, via collection optics and large-core optical fibers. As seen in Figure 3, the collector will mount outside the bioreactor, preferably on top of the reactor. The actual installed collector for the pilot-scale reactor is shown in Figure 5.

Figure 5. Solar Collector Mounted Above Pilot-Scale Bioreactor

The visible light from the sun reflected from collector dish and secondary optics is launched into an array of optical fibers. These large core fiber optic cables then supply photons necessary to support photosynthesis, using special distributors located between the vertical growth membranes, shown in Figures 6 and 7.

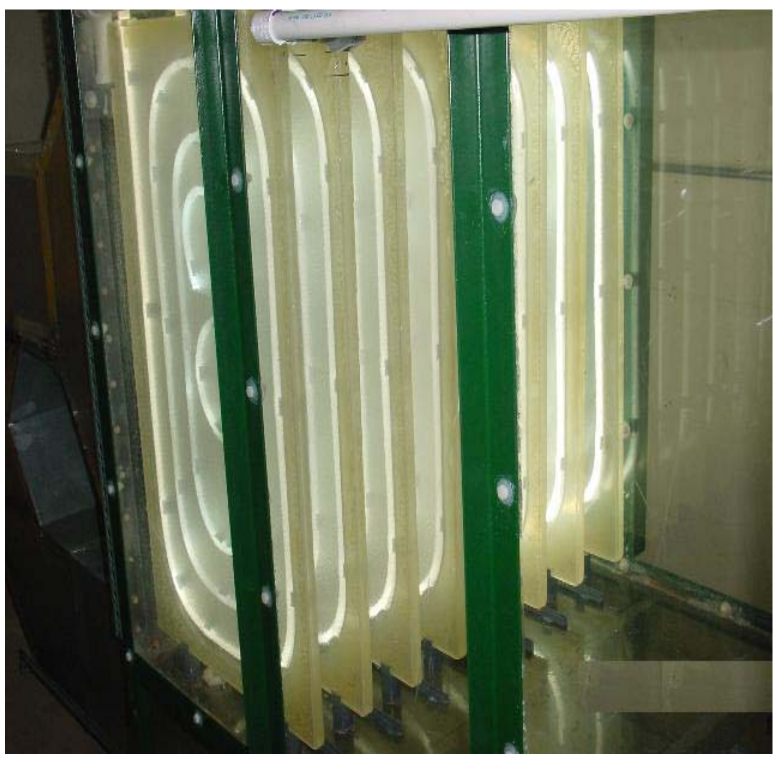

Figure 6. Lighting panels viewed from direction of gas flow

Figure 7. Lighting panels with fiber optic leads

By controlling attenuation through the fiber optic cables and using specially designed distributor plates made from similar materials, a uniform distribution of photons may be supplied, typically at a rate between 60-100 μmols m^{-2} s^{-1}. This distribution is a key element in reactor design. The sunlight, originally collected by tracking mirrors (optimizing solar collection) will provide over 2000 μmols m^{-2} s^{-1} of suitable photons throughout the day. However, at that rate, most photons would be wasted, as photosynthesis in thermophiles occurs at much lower levels of light.

A further point of interest is that sunlight contains wide spectra of energy; some is useless to the photosynthetic organisms, such as infrared, and some is harmful, such as certain ultraviolet spectra. Filters on the entrance to the fiber optic cables remove unwanted portions of the solar spectra and allow it to be used for photovoltaic production of electricity needed to power the auxiliary components of the system.

Organism Harvesting and Repopulation

The harvesting system provides a way to remove mature organisms and repopulate the membranes with developing organisms, thus maximizing carbon uptake. Preliminary tests indicate that microalgae, removed in "clumps" from the growth strata, are easily agitated into a diffuse state. Mature or dead microalgae (organisms with a low potential for carbon utilization) can be removed and microalgae that are maturing, (organisms with a high potential for carbon utilization), can be repopulated on the growth strata. The harvesting process is also necessary to promote cell division and to reap the benefits of post-processed biomass.

The harvesting for the experimental bioreactor is done using the water distribution system to minimize needs for additional components. By increasing the water pressure to the distribution header, a great flow of water per unit area of membrane is achieved, creating a gentile washing effect. This gentle washing is critical, so as not to shock the organisms and delay continued growth. Further, the gentle washing process is generally 30-40% effective (on a mass basis) in removing organisms from the membrane substrate, which is needed to maintain cell density to sustain continued cell division. Illustrations of the membranes before and after washing are shown in Figures 8 and 9.

Figure 8. Membrane populated with microalgae

Figure 9. Membrane washed with the harvesting system

Potential Benefits

Several benefits, in addition to CO_2 mitigation, could result from this novel method of photosynthetic carbon conversion. Obviously, one advantage would be the generation of O_2 as a byproduct of photosynthesis. Another potential benefit would be electrical power generation. By using filters capable of separating the infrared region of the spectrum coupled to the solar photon collection and delivery system, the infrared portion of the spectrum could be directed to photovoltaics, which use the heat to generate direct-current electricity.

Another anticipated benefit would be reduction of additional gaseous pollutants including NH_3 (that slips through selective catalytic reduction for NOx control) and NOx (nitrogen oxides) that form from the combustion process. Work by Nagase et al. (2001) demonstrated considerable nitrogen assimilation from NOx species bubbled through a bioreactor and it is well established that NH_3 is an excellent source of nitrogen for many photosynthetic organisms.

Finally, the resulting biomass has numerous beneficial uses. In addition to being a potential fuel, microalgae have been used as soil stabilizers, fertilizers, in the generation of biofuels, such as biodiesel and ethanol, and to produce H_2 for fuel cells. In recent tests, it also has shown several positive ignition characteristics for cofiring with coal in pulverized coal-fired generation units.

Expected Cost of Deployment

In this section, the costs of biological control of CO_2 are examined, and various assumptions of process efficiency and subsystem costs are studied for a power plant with a gross capacity of 200 MW, a capacity factor of 65% operating as a load-following unit (peaking during the day when solar photons are available), with a heat rate of 9000 BTU/kW-hr, burning a coal containing 70% carbon by mass and a higher heating value (HHV) of 12,000 BTU/lbm. The bioreactor for this economic case study is assumed to remove 50% of all CO_2 during daylight hours (during peak CO_2 production), and the incident photon flux on the solar collectors as delivered to the bioreactor is 1200 μmols m^{-2} s^{-1}. This value assumes that the only significant decrease in photon flux is not solar angle (overcome by mirror positioning), but cloud cover.

It should be noted that the key cost parameter is the cost of the solar collectors. It is estimated that the collectors, built by hand, would cost $90,000 a piece to install. Without mass production and economies of scale, $90,000 per collector would translate to $6,000 per ton of CO_2 removed from the flue gas. However, commercialization and mass manufacture of the solar collector technology is likely. The design team, headed by Oak Ridge National Laboratories, has received an addition grant from DOE to further their hybrid lighting work. This technology is focused on use as a lighting system in commercial buildings.

In order to examine the effect of photon conversion efficiency at a collector cost of $2000 per unit, Figure 10 was generated. Using the previously stated assumptions, the minimum cost for collection of one ton of CO_2 over the lifetime of the bioreactor, assuming continuous use, would be $44. Assuming an optimistic 30% conversion efficiency, the more likely cost is $146 per ton.

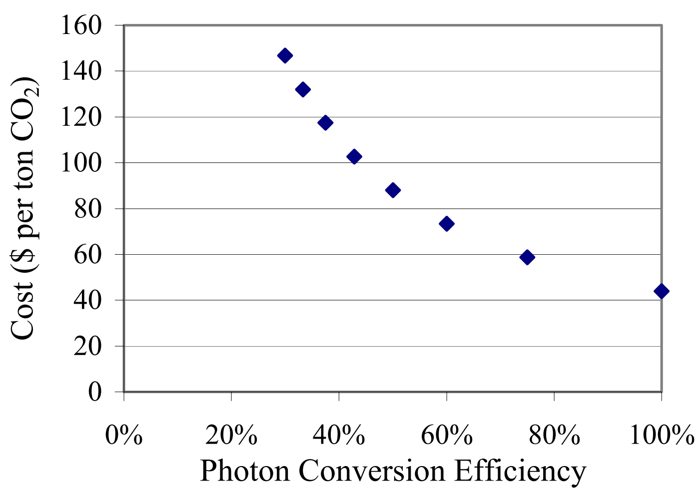

Figure 10. Cost of one ton of CO_2 removed as a function of photon conversion efficiency for a collector price of $2000 per unit.

At $500 per collector, the costs are more reasonable, as shown in Figure 11 Using the same assumptions, except for the $500 per collector cost, the cost of removing one ton of CO_2 over the life of the bioreactor falls to a minimum of $11 and a more likely value of $37 per ton.

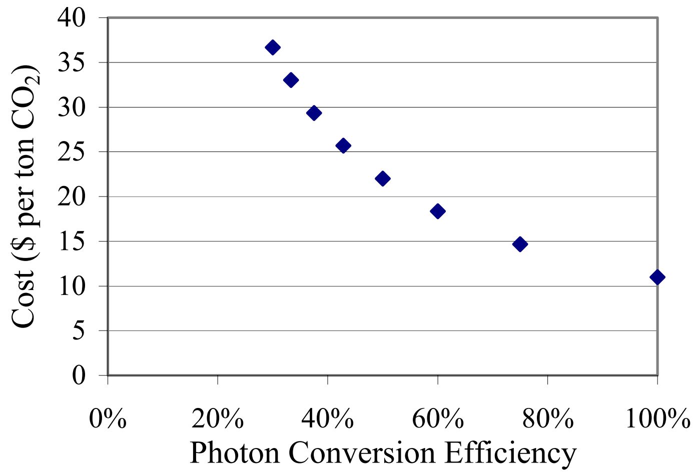

Figure 11 Cost of one ton of CO_2 removed as a function of photon conversion efficiency for a collector price of $500 per unit.

If photon attenuation is reduced and deployment of such a unit occurs in a "sunnier" location, the incident photon level could increase to approximately 1500 μmols m^{-2} s^{-1}, the cost of CO_2 removal (per ton) for a conversion efficiency of 30% would become $29.

While not all the analysis done on economics is presented here, it is clear that current system design, even if deployed in "sunny" locations, will require highly efficient organisms or processed to carry out photosynthesis. It is important to note that the target economics, $8-$10 per ton, would require 45% conversion efficiency and a collector cost of $250 per unit. These will be difficult to achieve, however, any revenue generated from the sale of harvested biomass could offset the need for such targets.

Conclusions

Because this is a work-in-progress, few significant conclusions can be drawn. However, the subsystem research has progressed to the point that a viable pilot-scale bioreactor is being constructed to test long term, sustainable and continuous conversion of CO_2 to biomass using collected solar photons. Further, this photobioreactor offers numerous possibilities for not only greenhouse gas mitigation, but also to control a wide variety of pollutants, notably NOx and ammonia slip, while producing a product that could have sustainable economic value.

Finally, it is clear that the economics of implementation are a significant hurdle to commercialization. Particularly, the cost of the solar collectors and photo distribution systems will be key to providing low-cost greenhouse gas emission remediation.

Bibliography

Bacastow R., and Dewey, R. (1996) *Energy Conversion and Management*, **37**(6-8),1079-1086.

Benemann J.(1997) *Energy Conversion and Management*, **38**(Supplemental Issue), 475-479.

Brock, T.D. (1978) *Thermophilic Microorganisms and Life at High Temperatures*, Springer-Verlag, New York, USA.

Cooksey, K.E. and Wigglesworth-Cooksey, B.(1995) *Aquatic Microbial Ecol.*, **9,** 87-96.

Fisher, A., (1961) *Solar Energy Research*, University of Wisconsin Press, Madison, WI, USA., 185-189.

Hanagata, N., Takeuchi, T., Fukuju, Y., Barnes, D., Karube, I. (1992) *Phytochemistry*, **31**(10), 3345-3348.

Hirata, S., Hayashitani, M., Taya, M., and Tone, S. (1996) *Journal of Fermentation and Bioengineering* **81,** 470-472.

Jepson, W.P. and Taylor, R.E., (1993) *Int. J. Multiphase Flow* **19** (3) 411-420.

Kajiwara, S., Yamada, H., Ohkuni, N., and Ohtaguchi, K. (1997) *Energy Conversion and Management* **38**(Supplemental Issue), 529-532.

Kaplan, A., Schwarz, R., Lieman-Hurwitz, J., and Reinhold, L. (1997) *Plant Physiology.* **97,** 851-855.

Maeda, K., Owada, M., Kimura, N., Omata, K., Karube, I (1995) *Energy Conversion and Management* **36**(6-9), 717-720.

Nagase H, Yoshihara K. (2001) *Biochemical Engineering Journal* **7,** 241-246.

Ohtaguchi, K., Kajiwara, S., Mustaqim, D., Takahashi, N., (1997) *Energy Conversion and Management* **38**(Supplemental Issue), 523-528.

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