Conceptual Design of a Zero CO₂ Emissions Fossil Fuel Power Plant

V. Mahalec, A. Nadim

McMaster University, Hamilton, Ontario, Canada

Abstract

In this paper we examine a promising pathway involving the elimination of CO₂ emissions by growing oil-containing algae which naturally absorb solar energy during the growth phase. The dry algae or algal oil can be used as a fuel in the power plant boilers or to make bio-diesel. The remaining biomass can also be used for producing thermal energy.

If we use dry algae or algae oil as a fuel in the power plant boiler, then in the extreme one can envision the following process:

1. Use enough fossil fuel to produce sufficient amount of CO₂ to produce as much algae oil as needed for electricity production and for algae processing.
2. Use algae oil as fuel in the boilers and grow again algae from CO₂ in the flue gas.
3. Etc. (repeat from 2).

Theoretically, if there is 100% capture of CO₂ via algae and if there is efficient capture of solar energy in the growth of algae, we could continue production of electricity without consuming any fossil fuel (other than the initial “charge”). We present a preliminary process design for 1,000 MW plant using algae oil as fuel.

Keywords

Zero CO₂ emissions, power plant, algae

Introduction

We present a design for a 1,000 MW power plant that uses algae as fuel. Our assumption is that the climate is temperate throughout a year, thereby enabling algae to grow without being sheltered within buildings. Advantage of using algae over other forms of sources of biofuels are: most algae can grow in saline water and do not have to compete for fresh water, productivity per unit area of land is much higher, and the overall uses of water is much less than growing oilseeds.

Our goal is to capture all CO₂ emissions from a power plant. Hence, we can not use open ponds to grow algae.

Flue gases from the power plant boilers contain 13-14% CO₂ which is absorbed in H₂O in a pressurized absorption column. CO₂ absorbed in water is a feed to photo-bioreactors to grow algae. Algae in the reactor effluent is separated by centrifuging, dried and then either used as a fuel in the power plant boiler or to produce algal oil. Algal oil can be used again as a fuel or to produce bio-diesel.

Choice of alternative uses for algae depends on the price of different forms of energy (e.g. power plant fuel vs. biodiesel) and on the efficiency of boilers that burn different forms of fuel. If we can use a biomass boiler that has the same efficiency as boilers for conventional fuels (e.g. natural gas or powdered coal), then the most energy efficient alternative is to burn dried algae in the boilers, thereby displacing fossil fuels.

Once-through process captures all CO₂ from the flue produced by burning fossil fuel, converts it to algae and burns the algae in the boilers. Assuming 50% algae oil

content and 80% biomass boiler efficiency, such process produces net 250 MW from the algae. Therefore, to produce 1,000 MW entirely from algae, i.e. without using any fossil fuel, one would need to process 4 times larger amount of CO₂. This would require a modification of the combustion subsystem in the power plant in order to handle 4 times larger amounts of flue gases.

Process Structure

Simplified process flowsheet is shown in Fig. 1. Flue gas from the power plant has to be compressed in order to absorb all of CO₂. Prior to entering the absorption section, the compressed flue gas is used to dry algae that was separated from the reactor effluent. The absorbers operate

Figure 1. Algae Growth from Flue Gas

at a pressure sufficiently high to absorb all CO₂ from the flue gas. Following the absorption section is a holding tank which operates at a pressure sufficiently high to keep all of the absorbed CO₂ in the liquid phase. Photobioreactors are horizontal tubes made of transparent plastic (plexiglass). Effluent of the photobioreactors is divided into a recycle (which brings the required seed concentration of algae to the reactor inlet) and the product stream which is sent to a bank of centrifuges to separate algae from water. Dryers pass hot flue gas above the centrifuged algae until the water content is reduced sufficiently to send the algae to spray dryers.

Dry algae can be used either as a fuel in the boilers or it can be processed further to extract the oil from it.

CO₂ Capture by Absorption in Water

In order to absorb the entire CO₂ present in the flue gas, the design uses 10 absorption columns operating under an elevated pressure. From the absorption column, the solution is pumped to a holding tank which is kept at 3 atm in order to retain all CO₂ in the liquid phase.

Selection of Algae and Photobioreactor Design

Production of algae occurs in the presence of sunlight as described by Eq. (1):

Various strains of algae have been studied (Chisti, 2007) with respect to their oil content and the conditions optimal for their growth. For instance, *Chlorella* have 28-32% of algae oil, while *Schizochytrium* and *Nannochloropsis* can have more than 50% of oil. The oil content of *Chlorella* sp. can reach 46% dry weight under stress conditions (Hu et al, 2008). It was found that *chlorella* is tolerant to CO₂ concentrations of up to 40% by volume (Hanagata et al, 1992). Similar results reported that maximum growth occurred at a concentration of 10% and found that the strain could grow under various combinations of the trace elements NO_x and SO₂ in flue gas (Maeda et al, 1995). Finally, *chlorella* was found to grow in conditions of up to 40 degrees Celsius (Sung et al, 1998). *Chlorella* doubles every 8 hours on average. All of these characteristics may *Chlorella* a suitable algae for the proposed design.

In order to initiate the growth of algae, there must be some amount of algae at the reactor inlet. The initial concentration, rate of algae growth, fraction of the reactor effluent that is recycled, and the reactor residence time are design parameters that determine the length of the reactor.

Figure 2. Recycle Enables Control of Algae Concentration at the Reactor Inlet

Reactor diameter is limited by the requirement that the sun light must penetrate through the liquid in order to enable the growth of algae. It has been found (Edwards, 2008) that the reactor diameter can be up to 0.6m , with maximum productivity per ground surface area occurring at diameter of approx. 0.3m.

Reactor residence times from 2hr to 24hrs and the recycle fractions from 0.8 to 0.12 respectively, have been evaluated. Concentration of algae in the reactor effluent has been kept at 1kg/m³ in all cases. For 0.3m reactor diameter, the length of the reactors is 2.2 to 26km. Residence time of 8 hrs requires a reactor length of 8,600m with total number of reactors being 1,722 for 1,000 MW plant.

Oxygen produced during the growth of algae impedes algae growth. Hence, the reactor design needs to accommodate removal of oxygen. Molina and Chisti (2007) have determined that the liquid velocities of 0.3-0.5 m/s are required to have a steady growth and for the culture not to collapse in the tubular reactor. Moreover, they determined that the oxygen concentration should not exceed 300% of the saturation in order not to impede the growth of algae. This study uses 0.3 m/s velocity which results in the requirement that the oxygen be removed approximately every 60m of reactor length.

Algae Harvesting and Drying

The least costly but also the least efficient method to harvest algae is through filtration. This method is not very efficient since the large flow rates associated with harvesting can create clogging and backwash (Boersma, 1978). Centrifugation and chemical flocculation are more expensive than filtration but they are also more effective ways to harvest algae. Chemical flocculation has the main disadvantage of introducing chemicals to our process, which can be costly, but more importantly it can affect the quality of the biomass produced. Flocculation can add toxins to the biomass which would be a disadvantage in the case of using the biomass as feed or fertilizer. Benemann (1996) tested various ways of harvesting algae that included centrifugation, chemical flocculation, filtering, and sedimentation. He has found that harvesting using

centrifugation is the most efficient as it concentrates the paste to about 20% solids compared to

Figure 3. *CO₂ Capture via Absorption and Growing Algae for Fuel or Algae Oil*

less than 10% for all the other methods that he has evaluated. For our proposed design, a solid ejecting nozzle separator centrifuge will be used that has a maximum capacity throughout of 200m³/hr. Therefore we will require approx. 220 centrifuges to be used to centrifuge the entire production per hour for the absorption at 15 atm.

Drying of the algae is to be accomplished in two stages: countercurrent flow of flue gas against the slurry containing algae. Since the compression of the flue gas is a employs multistage centrifugal compressors, flue gas after each stage is passed through a dryer with the target exit temperature of the flue gas being sufficiently low that it can enter the absorption columns. The amount of energy available from the flue gas provides only about 2/3 of the energy required to dry the algae. Following energy recovery section is a set of spray dryers which reduce the moisture content in the algae to 5%.

Process Flowsheet

Simplified process flowsheet is shown in Fig. 3. Due to a large volume of flue gas, it is required to have 10 parallel three stage compression trains. After each compression stage there is an inter-stage heat recovery through algae dryers. The absorption section consists of 10 parallel absorption columns due to the large volume of flue gas.

Economics

Absorption at increased pressures enables the entire CO₂ to be removed from the flue gas. Moreover, the higher the pressure, the less water is needed to absorb CO₂. However, as the CO₂ concentration increases so does the required pressure in the reactors in order to keep the CO₂ in the liquid phase. Higher reactor pressures require thicker reactor walls, thereby increasing the capital cost of the reactors.

The proposed design has been evaluated at a range of pressures (from 2 to 30 atm). Shown in Fig 4. Is the total capital cost per kg of algae produced. The optimum absorption pressure is approx. 15 atm.

Figure 4. Capital Cost as a Function of Absorption Pressure

Algae biomass can be burnt as fuel in the boilers (current biomass boiler efficiency is 35%), or one can extract oil and then burn the oil in 80% efficient boiler or one can produce biodiesel. Table 1. Summarizes net energy produced by these options, including a case where algae contains 50% oil and it is burnt in an 80% efficient boiler. Such boiler design should not be out of reach, since pulverized coal boilers have roughly the same efficiency.

Power MW	Combust algae biomass	Combust algal oil & biomass by-product	Biodiesel & combust biomass by-product
<u>30% algae oil, 35% boiler eff.</u>			
Consumed	149	165	165
Produced	133	155	117
Net	-16	-10	-48
<u>50% algae oil, 35% boiler eff.</u>			
Consumed	149	165	165
Produced	177	238	176
Net	28	73	11
<u>30% algae oil, 80% boiler eff.</u>			
Consumed	149	165	165
Produced	303	232	194
Net	154	67	29
<u>50% algae oil, 80% boiler eff.</u>			
Consumed	149	165	165
Produced	404	318	256
Net	255	153	91

Table 1. Comparison of Algae Usage Options

Zero CO₂ Emissions Plant

Our best case scenario is to use algae with 50% oil content and 80% biomass boiler efficiency. Both of these assumptions are within reach and should be attainable with more research effort. In order to produce 1,000 MW we need to process 4 times as much CO₂ as the amount of CO₂ from the 1,000 MW plant that burns natural gas (see Fig. 5). This enables us to operate a closed system that recirculates all of CO₂. Cost of producing electricity

incurred by using the algae is approx. \$0.04/kWh. To this price one needs to add the amortization of the traditional power plant equipment. There is no cost for purchasing fossil fuel (e.g. natural gas) since all required energy is produced from algae.

Figure 5. 1,000 MW Power Plant with CO₂ Recirculation

References

- Benemann, J.; Oswald, P.I.: Systems and Economic Analysis of Microalgae Ponds for Conversion of CO₂ to Biomass. Department of Energy Pittsburgh Energy Technology Center, 1996
- Boersma, L., "Management of swine manure for the recovery of protein and biogas: final report", Corvallis, Or.: Agricultural Experiment Station, Oregon State University 1978
- Chisti, Y. (2007) "Biodiesel from microalgae". Biotechnol. Adv. 25, 294–306
- Hanagata, N., Takeuchi, T., Fukuju, Y., Barnes, D. J., Karube, I. (1992) "Tolerance of microalgae to high CO₂ and high temperature". Phytochemistry 31(10), 3345–3348.
- Hu, Q. et al., 2008. "Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances". The Plant Journal, 54, 621–639.
- Maeda, K., Owada, M., Kimura, N., Omata, K., Karube, I. 1995. "CO₂ fixation from the flue gas on coal-fired thermal power plant by microalgae". Energy convers. Mgmt 36, 717–720
- Molina, E.M and Chisti, Y, Scale-up of tubular photo bioreactors, *J. Appl. Phycol.* **12** (2000), pp. 355–368