

GEOTHERMAL CO₂ BIO-MITIGATION TECHNIQUES BY UTILIZING MICROALGAE AT THE BLUE LAGOON, ICELAND

Indra Suryata^{1,2}, Halldor G. Svavarsson^{1,2}, Sigurbjörn Einarsson¹,
Ása Brynjólfssdóttir¹ and Grzegorz Maliga³

1. Blue Lagoon R&D, Grindavik, Iceland
2. Reykjavik University, Reykjavik, Iceland
3. Wroclaw University of Technology, Wroclaw, Poland
e-mail: indra08@ru.is

ABSTRACT

This paper describes the techniques used to sequester the CO₂ from geothermal power plant's flue gas by means of photosynthetic microalgae. Some fundamental parameters of microalgae growth (pH-level, CO₂ feed rate, temperature and illumination conditions) were analyzed in the process of optimizing its growth. A unique microalgae species that thrives in the geothermal area of the Blue Lagoon at the Reykjanes peninsula was investigated. The preliminary results published here provide additional alternatives for managing CO₂ greenhouse gas emission from geothermal power plant and also provide additional value for the microalgae biomass production. It is demonstrated that geothermal flue gas can be efficiently used as a feedstock for microalgae cultivation.

INTRODUCTION

Compared to conventional power plants, burning fossil fuel, geothermal energy is generally considered to be a benign energy source in regard to environmental impact. Geothermal power plants does, however, release considerable amount of the greenhouse gas, CO₂, to the atmosphere. The geothermal power plant HS Orka Ltd. in Svartsengi (Figure 1), which is currently producing 75 MW of electricity and 150 MW of thermal water, emits approximately 181 g CO₂/kWh (power production only) to the atmosphere [Armannsson, 2003]. For the last few years, extensive research and experiments has been conducted and shown the feasibility to reduce the CO₂ gas emission by utilizing the concept of microalgae CO₂ sequestration.

The geothermal area

The high-temperature geothermal areas in Iceland are found inside the spreading zone of the two tectonic plates which Iceland straddles, the American and the Eurasian plate, closely associated with the country's

active volcanic systems. Cold ingresses fluid geothermal seawater, a mixture of sea water and ground water, comes into contact with cooling magmatic intrusions at great depth, is rapidly heated and ascends towards the surface. The HS Orka power plant in Svartsengi, located at the Reykjanes peninsula in south western of Iceland, extracts the geothermal reservoir fluid from wells drilled into the reservoir. The wells are as deep as 2,000 meters and the fluid attains temperature of 240°C. This geothermal fluid is then used to heat freshwater for central heating purposes and to produce electricity. After dissipating most of its heat away, a part of the geothermal reservoir fluid is led directly to the surrounding lava where it creates the lagoon, Blue Lagoon.



Figure 1. The geothermal power plant of HS Orka in Svartsengi, Iceland.

The lagoon is a dynamic ecosystem, which is mainly characterized by two organisms: firstly, the photoautotrophic *Cyanobacterium* (blue-green microalgae), which represents the primary producers, using light as the energy source, gradually dominating the ecosystem as the brightness increases during the summer and creating organic matter for the consumers. Secondly, *S. lacuscaerulensis* [Petursdottir et. al., 2009], the heterotrophic alphaproteobacterium, which is dominant during

autumn and winter and represents the main heterotroph of the ecosystem. The Blue Lagoon company has been cultivating microalgae biomass from the lagoon under controlled conditions since 1992 for application as an ingredient in skin care products [Grether-Beck, et al., 2008].

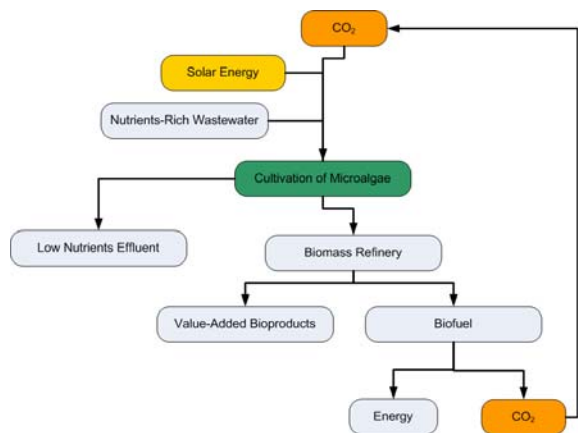


Figure 2. A conceptual flowchart for the complete "recycling" of CO₂ for solar energy capturing.

Microalgae

Microalgae are a unicellular species which exist individually in nature or in chains or groups. Different species has different size which can range from just a few micrometers to a few hundreds of micrometers and they do not have roots, stems and leaves like higher plants do. Like other plants, microalgae are capable of photosynthesizing. This process by microalgae is important for life on earth as they produce approximately half of the atmospheric oxygen and use simultaneously the greenhouse gas carbon dioxide to grow photoautotrophically (utilizing energy from light). The chemical composition of microalgae is not intrinsic constant factor but varies over a wide range, both depending on species and on cultivation conditions.

CO₂ biomitigation by microalgae cultivation

In view of CO₂ mitigation by microalgae, the strategy offers numerous advantages. Microalgae have much higher growth rates and CO₂ fixation abilities as compared to conventional forestry, agricultural and aquatic plants. It also offer the possibility to recycle carbon dioxide completely because carbon is converted to chemical energy through photosynthesis process, which can be converted to fuels using existing technologies, such as transesterification process (Figure 2).

CO₂ biomitigation using microalgae could be made profitable from the production of biofuels and other novel bioproducts, as compared to the chemical reaction-based strategy which is considered energy consuming and costly process. The possibility of

global carbon trading also favors the economical aspect. Finally, the biological carbon mitigation by utilizing microalgae could be further made economical and environmentally sustainable, by combining it with wastewater treatment and other related processes. The advantages would include the following: (1) microalgae have been shown to be effective in nitrogen and phosphorus removal, as well as in metal ion depletion, and combination of microalgae with wastewater treatment will significantly enhance the environmental benefit of this strategy, and (2) it will lead to savings in the consumption of nutrients for microalgae growing process and (3) it will results in savings of the precious freshwater resources.

Other methods of CO₂ sequestration such as the chemical reaction-based carbon mitigation strategy often suffers from disposal problems because both the captured CO₂ and the wasted absorbents need to be disposed of.

Microalgae are able to fix CO₂ from different sources, such as: (i) from atmosphere; (ii) from industrial flue gases and (iii) from soluble carbonates (NaHCO₃ or Na₂CO₃). These sources of carbon dioxide are used as a supply for open ponds, which are aerated to provide capturing CO₂ by microalgae cells. Generally atmosphere contains only 0.03 to 0.06% volumetric of carbon dioxide [Wang, et al., 2008]. Because of relatively low carbon dioxide content in atmospheric air, it is expected that growth of cell is limited and could be slow. Industrial flue gas, on the other hand, contains from 10 to 20% of CO₂ [Wang, et al., 2008]. The contribution of flue gas in total world emissions of CO₂, is about 7%. From above reasons it would be beneficial if microalgae were able to fix carbon dioxide from flue gases. The tolerance of microalgae to relatively high temperature is very important in reducing cooling costs of the feeding flue gases released from industrial facilities at high temperature.

For most microalgae species the optimum temperature lies in the range of 20-30°C. Only few thermo tolerant species of microalgae have been observed, like for example several unicellular green algal, which are identified as species of *Chlorella*, which can grow at temperature up to 42°C and supplied by air with more than 40% CO₂ [Wang, et al., 2008]. The optimal CO₂ level in the flue gas, however, is about 6-10% for most species. *Scenedesmus obliquus* and *Spirulina* have good CO₂ fixation rate when they are cultivated at 30°C and for *Spirulina* the maximum biomass productivity was 0.22 g•l⁻¹ per day at 6 - 12% of CO₂ in the feeding gas [Wang, et al., 2008].

Many microalgae species are able to utilize carbonates such as Na₂CO₃ and NaHCO₃ for cell

growth [Wang, et al., 2008]. This way of absorbing carbonate by microalgae has some advantages: a) carbon dioxide released in nighttime from industrial facilities could be converted to carbonate salts and stored for conversion in daytime; b) because of limited number of microalgae species, which can exist in high concentration of carbonate salt, it is not difficult to control the types of species which breed in the solution; and c) most of these species have high pH optima (pH 9 -11).

From the two main organisms, which grow naturally in the lagoon as previously mentioned, the Blue Lagoon CO₂ bio-mitigation project currently uses microalgae species of coccoid algae strain (Blue Lagoon coccoid algae) derived from the Blue Lagoon [Grether-Beck, et al., 2008].

INSTRUMENTAL

In the pilot scale set-up, the Blue Lagoon CO₂ bio-mitigation project is currently utilizing so-called tubular photobioreactor with total volume of 1,400 liters and artificial illumination in replace of sunlight (Figure 3) from Varicon Aqua Solutions Ltd., UK.

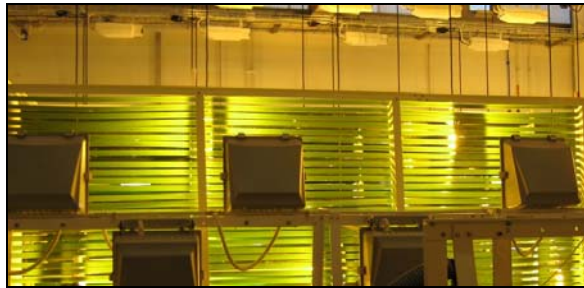


Figure 3. Pilot scale photobioreactors used at Blue Lagoon R&D lab.

A tubular photobioreactors usually consist of an array of straight transparent tubes that are normally made of plastic or Plexiglas®. The diameter of the tubes is limited to a certain size because light will not penetrate too deep in the case of dense microalgae culture, which is necessary to ensure a high level of biomass productivity. The culturing liquid consists of geothermal brine enriched with 2.25 % Walne medium [Walne, 1970]. Microalgae culture is circulated from a reservoir tank to the solar collector and back to the reservoir tank, continuously (Figure 4).

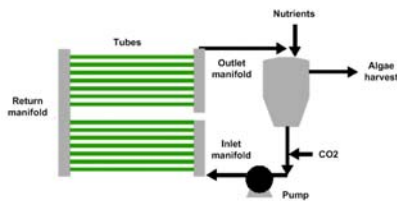


Figure 4. Main equipment of the photobioreactors system.

Some of the most important growth parameters are temperature, salinity, pH-value and level of illumination. These parameters were varied systematically in a laboratory scale photobioreactors with total volume 10 liters and the results are then applied to grow the microalgae in the large scale photobioreactors. The lab-scale reactor consists of four 2.5 liters glass (roux) bottles placed in water bath, as illustrated in Figure 5 below.

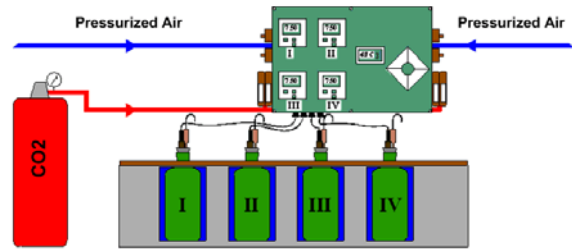


Figure 5. Lab-scale reactors at the Blue Lagoon R&D lab.

EXPERIMENTAL

Optimization of pH value.

The level of pH depends on the amount of carbon dioxide dissolved in the medium. The experiment to assess the pH variation was carried out at 43°C, salinity 2% vol. and average photoactive radiation level of 180 μE/m²sek. The measurements are visualized in Figure 6.

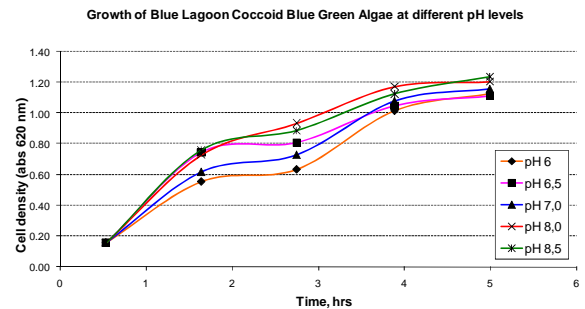


Figure 6. Growth characteristics dependent on pH level.

Optimization of temperature

As stated in many technical publications, the optimum temperature for microalgae growth is highly dependent on the species being used. For most microalgae species it is recommended that the media temperature be kept near 28°C. In the case of blue-green microalgae, which adapted to geothermal environment, some have optimum temperature up to approximately 50 °C. As natural respiration of the microalgae is not able to maintain the temperature near this level, an additional heat source is used. A heating element is thus used to increase the medium temperature, in combination with temperature regulator. The experiment was carried out at pH level

of 7.5 with salinity about 2% vol. and photoactive radiation level of 140 $\mu\text{E}/\text{m}^2\text{sek}$. The results are shown in Figure 7 below.

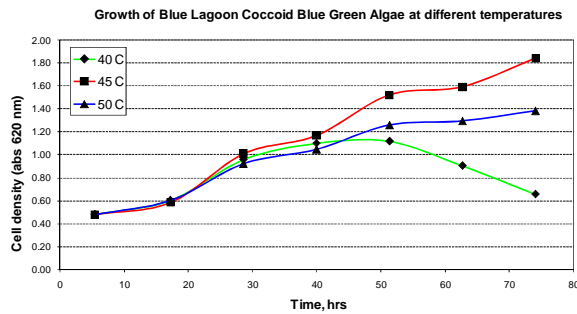


Figure 7. Growth characteristics dependent on temperature.

Salinity optimized

In many cases, fresh and brackish water from lakes, rivers and aquifers can be used as the growth media. Thus, in general, the growth media are generally inexpensive. For the Blue Lagoon blue-green microalgae, the natural environment is geothermal water with content 70% vol. of seawater and 30% vol. of freshwater. Since a close relative of the Blue Lagoon blue-green microalgae have been registered in marine environment [Petursdottir et. al., 2009], one could expect that the optimal salinity of media for that kind of algae should be close to the level of seawater with additional nutrients of nitrogen phosphorous and sulfur. The result as shown in Figure 8 below is based on experiment for salinity effect which was carried out at temperature 45°C, pH 7.5 and irradiation level of about 140 $\mu\text{E}/\text{m}^2\text{sek}$.

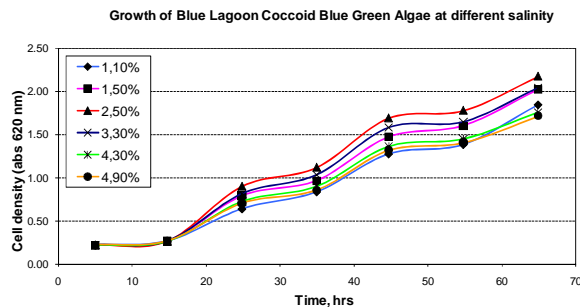


Figure 8. Growth characteristics dependent on salinity level.

Illumination level optimized

Based on previous experiments the optimization of irradiation level was carried out at temperature 45°C, pH = 7.5 and salinity level 2.5% vol. The result is shown in Figure 9 below.

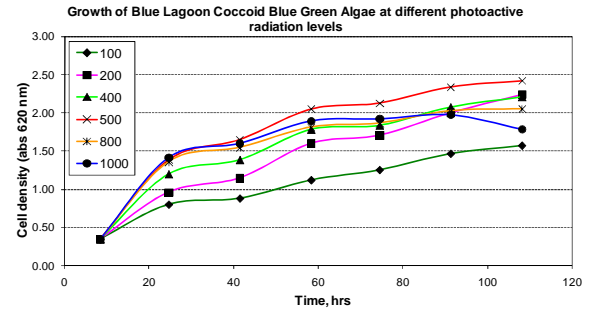


Figure 9. Growth characteristics dependent on irradiance level, $\mu\text{E}/\text{m}^2\text{sek}$.

Comparison of two different CO₂ sources

Two types of gases sources were used for the microalgae growth: a gas from the geothermal power plant in Svartsengi and a pure CO₂ gas (commercial) as a reference (Figure 10). Effect of supplying geothermal carbon dioxide was investigated on Blue Lagoon blue-green microalgae. The CO₂ was collected into a 200 liters gas container after initial preparation process. The flue gas, which is released as non-condensable gas from the condenser, contains approximately 2% vol. of H₂S.

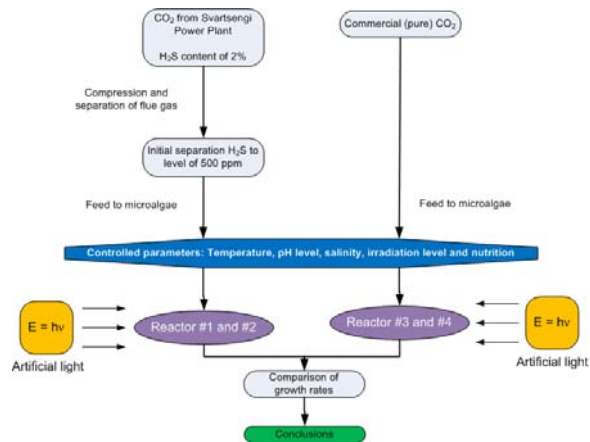


Figure 10. Schematic flow chart of geothermal biomitigation experiment by utilizing Blue Lagoon blue-green microalgae.

The gas collection set up is shown in Figure 11 below. A metal pipe is connected to power plant's non-condensable exhaust gas line. The pipe is then passing through a condenser, which is a helical metal pipe inside a bucket of cold water (4 - 8°C). The condensed gases/steam is then separated in a separator tank before it is connected to a compressor and a gas container. The H₂S content and other toxic gases are monitored during these steps.

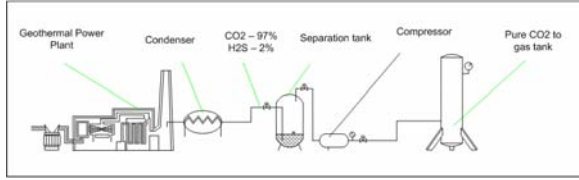


Figure 11. General setup for CO₂ collection process.

After the gas collection stage, a volume of condensed water from crude gas was measured. In order to fill up the 200 liters gas container to 8 bars, about 1.5 liters of condensed water was collected. The pH value of the collected water was 4.5. This value, however, does not give direct information about H₂S content because the amount of dissolved carbon dioxide, which also affects the acidity, was unknown. Chemical analyses (with Dräger-Tubes®) of the gas after the gas tank indicated a concentration H₂S of 2 – 6 ppm. The reason for this dramatic drop in the H₂S content (from 2% to few ppm) is not clear but it may be attributed to chemical reactions between the gas and the iron interior of the gas container. However, the specific analysis of this occurrence will not be discussed further in this report. The storage time of the gas, prior to use, varied from 1-3 days and one might conclude that a longer time would be needed to finish such chemical reaction.

The cell density was monitored two times per day in two ways, by means of spectrophotometer and dry weight.



Figure 12. Lab scale reactors in the experiment.

In the spectrophotometer measurement, light absorbance of 620 nm wavelength was used. This method is based on light absorption law (Beer–Lambert law), where some components absorb only selected length of light spectrum wave and the absorbance value of pick gives an equivalent of cell density.

Absorbance transmissivity is considered following Figure 13 and Equation 1.

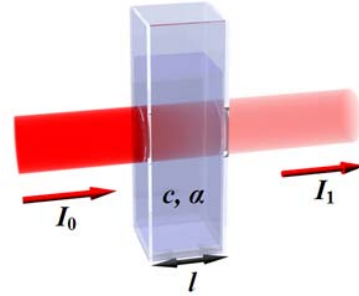


Figure 13. Diagram of Beer–Lambert absorption of a beam of light as it travels through a cuvette of width l [Crouch, et al., 1988].

The transmission (or transmissivity) is expressed in terms of an absorbance which for liquids is defined as

$$A = -\log_{10} \frac{I}{I_0} \quad (\text{Eq. 1})$$

where I_0 and I are the intensity (or power) of the incident light and the transmitted light, respectively.

The growth rate comparison (measured by using spectrophotometer) of blue-green microalgae fed by geothermal CO₂ gas and pure commercial CO₂ gas is shown in Figure 14 below.

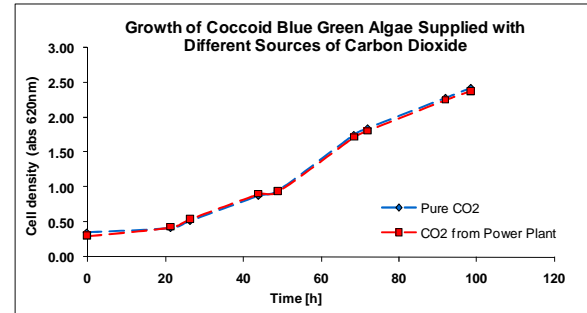


Figure 14. Growth comparison curve with different CO₂ sources.

During exponential growth the rate of increase in cells per unit time is proportional to the number of cells present in the beginning of any unit time and population growth follows first order kinetic as shown by Equation 2:

$$\frac{dN}{dt} = rN \quad (\text{Eq. 2})$$

where N is the population size at time t and r is the rate constant. This equation is then easily solved as

$$N_t = N_0 e^{rt} \quad (\text{Eq. 3})$$

where N_0 and N_t are the population at the beginning and at time t , respectively.

When the Equation 3 is solved for r , it has the structure:

$$r = \frac{\ln\left(\frac{N_t}{N_0}\right)}{\Delta t} = \frac{\ln N_t - \ln N_0}{\Delta t} \quad (\text{Eq. 4})$$

where Δt is the length of the time interval.

Under favorable conditions, a growing unicellular microbial population doubles at regular interval, because each of the two daughter cells produced by a division has the same potential for growth as the parent cell.

The time required for a doubling of mass or number is known as the doubling time (T_d). If a population doubles in size (that is, increases by a factor of 2), the ratio N_t / N_0 would be exactly 2. Thus, the doubling time can be derived by dividing the natural logarithm of 2 by the percentage of growth (r) as shown in Eq. 5 and 6 below.

$$T_d = \frac{\ln(2)}{r} = \frac{\ln(2)}{\frac{\ln N_t - \ln N_0}{\Delta t}} \quad (\text{Eq. 5})$$

$$T_d = (t_2 - t_1) \times \frac{\ln(2)}{\ln N_t - \ln N_0} \quad (\text{Eq. 6})$$

The optimized values of the growth parameters (pH, salinity, temperature and irradiation level) were used in the experiment to calculate its doubling time as shown in Figure 15 below by taking two consecutive data points with the highest net increase in cell density.

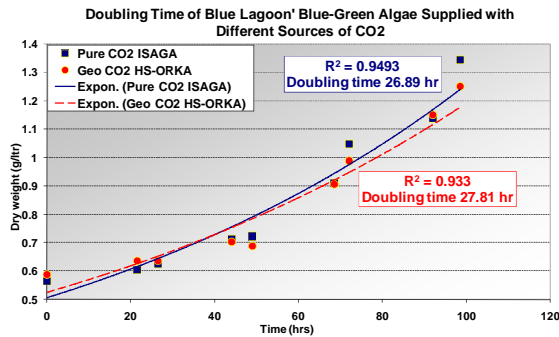


Figure 15. Doubling time of Blue Lagoon blue-green microalgae growth rate with different sources of CO_2 .

CO_2 fixation rate

From an economical point of view, it is fundamental to know how efficient the microalgae absorb the supplied carbon dioxide gas.

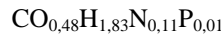
Carbon dioxide fixed through photosynthesis is converted to different organic cell components including carbohydrates, lipids, proteins, and nucleic acids (*Spolaore P*). Although the cell carbon content varies with microalgae strains, media, and cultivation conditions, it changes in a relatively small range, and the law of material conservation allows us to calculate CO_2 fixation rate from biomass productivity at a given cell carbon content.

In Table 1, such calculations were conducted using a reported biomass molecular formula, $\text{CO}_{0.48}\text{H}_{1.83}\text{N}_{0.11}\text{P}_{0.01}$ [Chisty, 2007], when direct data on CO_2 fixation rate was not available, based on the assumption that CO_2 fixed in the form of extracellular products was negligible. The detailed calculation is presented as follow:

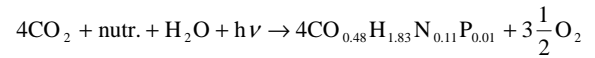
Table 1. Some microalgae strains studied for CO_2 biomitigation from Wang, et al., 2008. The result from Blue Lagoon blue-green microalgae is also shown in the list as comparison.

| Microalgae species | CO_2 % | T deg-C | P, g/l per day | P, CO_2 g/l per day |
|-------------------------------------|-----------------|-----------|----------------|------------------------------|
| <i>Chlorococcum littorale</i> | 40 | 30 | N/A | 1 |
| <i>Chlorella kessleri</i> | 18 | 30 | 0.087 | 0.163 |
| <i>Chlorella sp. UK001</i> | 15 | 35 | N/A | >1 |
| <i>Chlorella vulgaris</i> | 15 | | N/A | 0.624 |
| <i>Chlorella vulgaris</i> | air | 25 | 0.04 | 0.075 |
| <i>Chlorella vulgaris</i> | air | 25 | 0.024 | 0.045 |
| <i>Chlorella sp.</i> | 40 | 42 | N/A | 1 |
| <i>Dunaliella</i> | 3 | 27 | 0.17 | 0.313 |
| <i>Haematococcus pluvialis</i> | 16-34 | 20 | 0.076 | 0.143 |
| <i>Senedesmus obliquus</i> | air | - | 0.009 | 0.016 |
| <i>Senedesmus obliquus</i> | air | - | 0.016 | 0.031 |
| <i>Botryococcus braunii</i> | - | 25-30 | 1.1 | >1.0 |
| <i>Senedesmus obliquus</i> | 18 | 30 | 0.14 | 0.26 |
| <i>Spirulina sp.</i> | 12 | 30 | 0.22 | 0.413 |
| Blue Lagoon blue-green algae | 98 | 45 | 0.069 | 0.128 |

Biomass molecular formula:



$$M_{\text{biomass}} = 23.2 \text{ gr/mol}$$



$$M_{\text{CO}_2} = 44 \text{ gr/mol}, \quad M_{\text{biomass}} = 23.2 \text{ gr/mol}$$

The CO_2 fixation rate constant K is then defined as the ratio $M_{\text{CO}_2}/M_{\text{biomass}} = 44/23.2 = 1.89$.

Hence the total fixation is given by $K \times$ biomass productivity

Table 2. Results from CO₂ fixation rate experiments of Blue Lagoon blue-green microalgae.

| Time | Time | Dry biomass | Dry biomass | CO ₂ | Efficiency | Cell density |
|------|------|-------------|-------------|-----------------|------------|--------------|
| hr | day | gr | gr (total) | gr (total) | % | abs (620 nm) |
| 0 | 0.00 | | | 1.72 | | 2.259 |
| 19 | 0.79 | | | 2.00 | | 2.273 |
| 26 | 1.06 | | | 2.10 | | 2.269 |
| 44 | 1.83 | | | 2.26 | | 2.253 |
| 51 | 2.13 | | | 2.26 | | 2.226 |
| 67 | 2.79 | 72 | 235 | 2.26 | 19 | 2.079 |
| 139 | 5.79 | | | 3.22 | | 1.045 |
| 142 | 5.92 | | | 3.32 | | |
| 150 | 6.23 | 94 | 329 | 3.5 | 18 | |

RESULTS

As revealed by the graph in Figure 6, the highest growth rate for Blue Lagoon blue-green microalgae was obtained at pH level between 7 and 8.

Based on the experiments visualized in Figure 7, it can be concluded that the temperature, which provides the optimum growth rate was around 45°C, which is relatively high temperature as compared to other common microalgae.

Results presented in Figure 8 show that the highest growth rate for the blue green microalgae occurred at 2.5% vol. of salt content, which is a lower salinity as compared to its relative that has optimal salinity of sea water. The conductivity of 2.5% vol. salt solution is about 50 mS/cm.

The data from irradiation experimental indicate that 500 µE/m²sek gives the optimal level of microalgae in respect to growth rate (Figure 9). However, the optimal irradiation level would however be closer to 200 µE/m²sek when the cost of electricity is considered [Einarsson, 2009]. It can also be deduced from the graph that the cell density reaches a plateau after certain period of time. The growth rate is constant for a certain time in the beginning but gradually slow down as the microalgae density increases. This occurs due to a blockage of light.

A comparison between growth rate of blue-green microalgae fed by geothermal CO₂ gas and pure commercial CO₂ gas (Figure 14) demonstrated only 2.41% difference, which is insignificant. Similarly, the difference of doubling time for microalgae fed with pure CO₂ gas and geothermal CO₂ was insignificant, with values of 26.89 hours and 27.81 hours, respectively.

Referring to the biomass molecular formula, carbon dioxide flow rate measurement and continuous microalgae biomass dry weight monitoring, the approximate carbon dioxide fixation rate for Blue Lagoon blue-green microalgae is approximately **18%** vol. (18% vol. of the supplied CO₂ is absorbed by

microalgae, while the remaining CO₂ gas has escaped from the system) as shown in Table 2.

CONCLUSIONS

CO₂ fixation by using fast-growing blue green microalgae species of the Blue Lagoon, Iceland proved to be a very promising alternative for mitigation of CO₂. The primary merit of this strategy lays in the fact that, via the cultivation of microalgae, CO₂ mitigation and valuable biomass production could be combined in an economically feasible and environmentally sustainable manner. The feasibility of this strategy is further enhanced by fixing CO₂ from industrial exhaust gases such as geothermal power plant's flue gases.

Results regarding the effect of sulfide from the flue gas were inconclusive since its concentration had dropped to such low level before use. The reason for this large drop is currently unknown but it has been speculated that it may be due to chemical reactions between the sulfide and its metal container during storage.

Acknowledgements

The project was a part of collaboration between the Blue Lagoon Ltd., The Reykjavik University and HS Orka Ltd. Special thanks to Albert Albertsson of HS Orka Ltd. and his colleagues at the power plant in Svartsengi. The project is funded by the Blue Lagoon Ltd. and the National Energy Fund of Iceland.

REFERENCES

- Armannsson, Halldor. "CO₂ emissions from Geothermal Plants." International Geothermal Conference (2003). Reykjavik.
- Chisty, Y. "Biodiesel from microalgae." Biotechnol Adv (2007): 25:294–306.
- Crouch, J. D. J. Ingle and S. R. "Spectrochemical Analysis." New Jersey: Prentice Hall, 1988.
- Einarsson, S. Personal interview. Blue Lagoon R&D. 16 November 2009.
- Grether-Beck, S., Muhlberg, K., Brenden, H., Felsner, I., Brynjolfsdottir, A., Einarsson, S. and Jean Krutmann. "Bioactive molecules from the Blue Lagoon: in vitro and in vivo assessment of silica mud and microalgae extracts for their effects on skin barrier function and prevention of skin ageing." Journal of Experimental Dermatology (2008). Germany.
- Petursdottir, S.K., Bjornsdottir, S., H., Hreggvidsson, G., O., Hjorleifsdottir, S. and Jakob K. K. "Analysis of the unique geothermal microbial ecosystem of the Blue Lagoon." FEMS Microbiol Ecol 70 (2009) 425–432.
- Walne, P.R., "Studies on food value of nineteen genera of algae to juvenile bivalves of the genera *Ostrea*, *Crassostrea*, *mersenaria* and *Mytilu*" Fish.

Invest. Lond. Ser. (1970) 2.26(5): 1-62.

Wang, B., Li, Y., Wu, N. and Christopher Q. Lan.
"CO₂ bio-mitigation using microalgae." Applied
Microbiol Biotechnol (2008): 79:707–718.