# D610: RECOVERY OF $CO_2$ FROM INDUSTRIAL LOW PRESSURE VENT AND FLUE GASES USING ALGAE CULTIVATION PROCESSES

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# 1. INTRODUCTION

The purpose of this study is to find information of algae processes, which could be utilized in carbon capture from CO2-containing gases. Based on this information, a concept method is developed for a pilot scale process.

Industrial vent gases can contain plenty of CO2. The removal of CO2 could be best performed after desulfurization of industrial gases. This sulphur-free gas could be further treated in algae process where algae utilize CO2 containing gas to growing biomass.

At first we would need to estimate different types of algae cultivation methods and figure out which type of method would be optimal for our pilot scale purpose. Then we examined different downstream methods to collect biomass and biomass containing lipids. Finally we tried to find out and choose the best solutions for CO2 feeding and dissolving in algae cultivations.

## LITERATURE PHASE

# 2. PRODUCTION OF ALGAE BIOMASS

Algae growth is based on photosynthesis: Algae use solar light to combine CO2, water and nutrients into organics substances (like cell constituents and lipids), and excrete oxygen (autotrophic growth). The optimal availability of sunlight is essential to photosynthesis. The most suitable algae cultivation regions can be found by using optimal temperature areas: The annual average temperature should be > 15 °C. (Benemann, 2009) The optimal overnight temperature should be 4 - 10 °C and during daytime temperature should be 10 – 22 °C which usually produce higher lipid content and reduce contaminations. Light availability will be optimized in production technology to maximize CO2 absorption to algae cells. Photosynthetic activity vs. productivity is presented according to Ben-Amotz (Ben-Amotz, 2008) in table 1:

Table 1: Photosynthetic activity vs. productivity.

| **Photosynthetic Limitation of Long Term Algal Productivity Max Theoretical Algal Productivity 25 g/m$^2$/day Environment Factor** | **Reduction** | **(%)** |
|---|---|---|
| Solar light | ------ | 100 |
| Scattering and reflecting properties of surface | 10% | 90 |
| *Absorption spectrum (depth of culture)* | 50% | 45 |
| Photosynthetic efficiency (25%) | 75% | 11.3 |
| Light saturation (7-95%) | 60% | 4.5 |
| Respiration, photo-respiration, excretion | 5% | 4.3 |
| Photo-inhibition | 10% | 3.8 |
| Temperature | 20% | 3.1 |
| ========== | ========== | |
| Productivity | | |
| Mean daily solar intensity | 4,000 kcal/m2/day | |
| Energy productivity at 3% efficiency | 120 kcal/m2/day | |
| Algal biomass productivity (5 kcal/g) | 25 g/m2/day | |
| Higher Plants Max (sugar cane, corn, wheat, etc.) | 5 g/m2/day | |

Microalgae biomass contains approximately 50 % carbon, which will be supplied as CO2 into cultivation. Other essential nutrients for algae are nitrogen (nitrates), phosphorus (P), iron (Fe) and in some cases silicon (Chisti, 2007) Algae cell biomass is processed to yield products like fatty acids and carotenoids or it is used as such to produce other products like biogas and fertilizers. (Molina, 2003)

Basically there are three type systems which are used in cultivation of microalgae: controlled or non-controlled open ponds, and closed bioreactors. Usually the most suitable types of algae cultivators are raceway pond and tubular photobioreactors. However, many other type reactors are studied and developed too.

## 2.1 Large open ponds

There are different sizes of cultivation ponds globally in use. The cultivation ponds have different shapes, materials of construction, method of mixing and the slope of pond can also differ between cultivation ponds. The most used algae species are *Dunaliella, Spirulina* and *Chlorella*

in large cultivations. These algae species succeed best in various outside circumstances. (Moheimani, 2005)

### 2.1.1 Uncontrolled ponds

Usually the size of uncontrolled pond varies from 1 to 100 hectares. The depth of pond is approximately 0,5 m. The uncontrolled pond does not contain any mechanical mixer or additional CO2 feeding. The selecting of suitable algae species is essential for this type of cultivation: e.g. *Spirulina* grows well in high alkalinity media and *Dunaliella* grows well in high salt concentration. This type of algae species characteristic makes possible to keep cultivation almost monoculture. (Benemann, 2005)

### 2.1.2 Controlled ponds

Controlled ponds are usually in ring or raceway form. The ponds are shallow; less than 0,3 m and area can vary between 0,2 - 0,6 hectares. In raceway pond mixing and circulation are produced by a paddlewheel in simple channel system (Figure 1.) or pond can have several flow channels (Figure 2.) The circulation prevents to forming thick algae layer in cultivation pond and algae can grow more effectively.

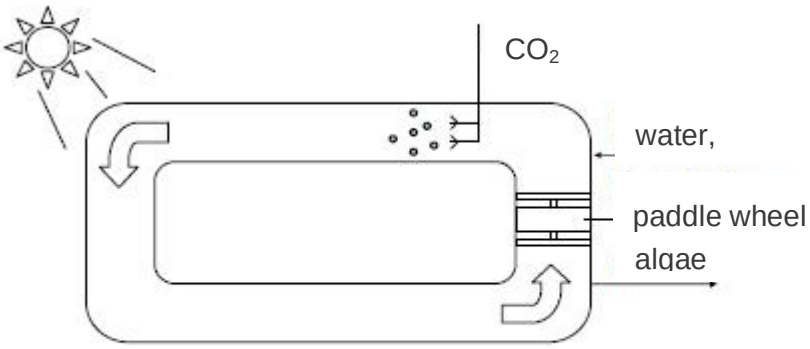



Figure 1: Simple ring raceway pond.

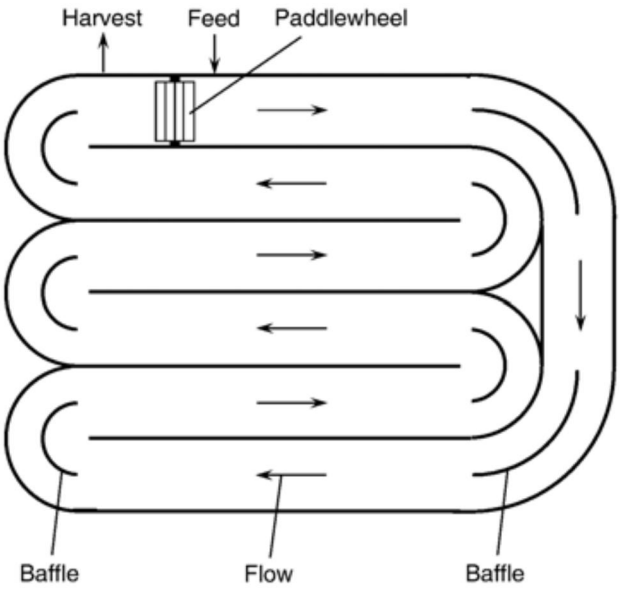



Figure 2. Raceway pond, many flow channels. (Chisti 2007)

CO2 and nutrients are constantly fed in the daytime just after the paddle wheel and algae biomass is harvested other side of paddlewheel. Cultivation broth is diluted in order to maintain optimal conditions for algae growth. Productivity is much higher compared to open uncontrolled systems. (Chisti, 2007) Usually algae ponds have plastic lining to getting stronger light reflection and cleaning is also much easier to perform.

### 2.1.3 Algae harvesting

Algae cell mass can be separated from water with sedimentation, flotation or various filtration methods. Selection of method depends on algae species and cultivation conditions. After harvesting the algae cell mass is collected for further processing and water and nutrients are recycled back to the pond. Algae cell mass is dewatered mechanically with e.g. pressure filtration to maximize dry substance content which is normally less than 30 %. However, very high lipid content can bring the dry substance content up to 50 % or even more. The rest of moisture is removed by drying. The residual moisture in dried cell powder is approximately 5 %. The dried algae powder can be e.g. pressed into tablets depending on desired product properties.

## 2.2 Closed photobioreactors (PBR)

There are different types of photobioreactors in use: Tubular, panel, bag and tank model reactors. (Moheimani, 2005) In large scale applications tubular and panel type reactors have been used. However, floating bag reactors are also interested in their very large size application. Photobioreactors have been designed to maximize exposure to light in order to maximize algae productivity. The idea is that circulated algae layer is as thin as possible inside photobioreactor tubes. (Roselllo Sastre, 2007) Photobioreactor technology is still under developing phase. There are still numerous technical problems e.g. algae growth on surfaces which reduces light exposure. The most important factors in photobioreactor design are light absorption, flow dynamics in the systems and mass transfer and metabolism of the algae.

### 2.2.1 Tubular photobioreactor

Tubular photobioreactor is composed of lightless recycling tank for gas exchange and cooling and transparent tube bundle in which light is absorbed into algae culture. The tubes are mostly manufactured of transparent plastic and the diameter is limited (≤ 10 cm) to ensure good light

penetration. The length of tubes varies from 10 meters to 100 meters. The ground under the tube bundle is often painted white or covered with plastic for good light reflection. In figure 3 algae culture is recycled between tubular solar collectors and the recycling tank. Fresh algae suspension, nutrients and CO2 is fed to system and matured cell mass suspension is collected continuously from system. In order to keep the inside surfaces of the tubes clean, a sufficient flowrate must be maintained by pumping. (Chisti, 2007) The cultivation bioreactor must be regularly cleaned and disinfected. The oxygen must be removed from the system since it reduces the rate of photosynthesis. The temperature of the cultivation tank is kept close to optimum by cooling the recycling tank.

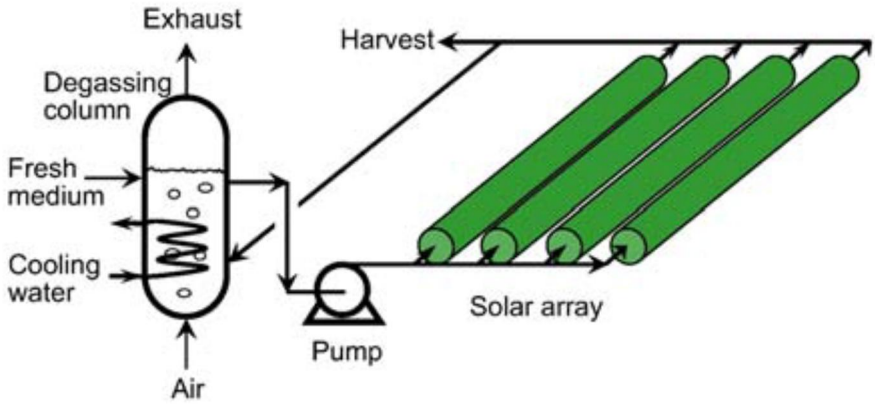



Figure 3. A tubular photobioreactor with parallel run horizontal tubes.

### 2.2.2 Flat panel photobioreactor

Flat panel photobioreactor has a transparent, rectangular tank (panel) which thickness is between 0,01 and 0,05 m. (Figure 4.) Liquid flow is generated by injecting air (CO2) into the bottom of the reactor. The temperature is controlled with a heat exchanger and the place /position/direction of reactor is selected according to sunlight. This type of reactor needs less energy for liquid flow and mixing than tubular reactors. (Kadam, 2001)

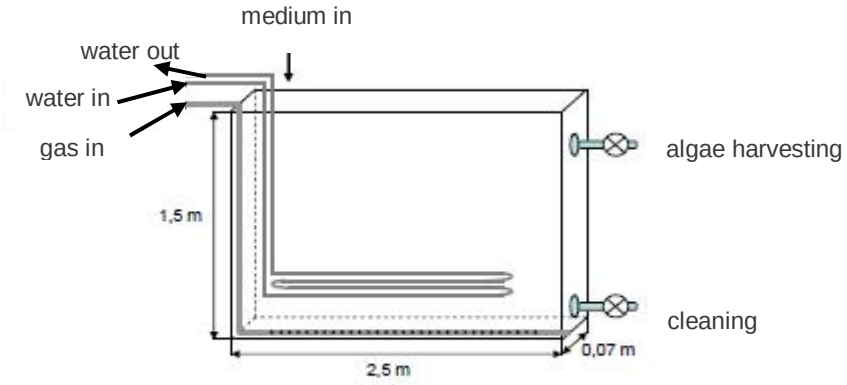



Figure 4. Flat panel photobioreactor (Sierra et al.

### 2.2.3 Other types of photobioreactor

Stirred tank photobioreactors are mainly used for algae species maintenance and growing for large scale cultivations. These reactors are used for feed production in fish farming. Light can be supplied to these reactors from outside by using fiber optics. The maintenance for these reactor is easy but scaling up is difficult. (Moheimani, 2005)

Bag PBR:s are mainly used for fish feed production. The bag volume is normally 2 -30 m3. Bag PBR:s usually supported by frame and mixing is generated by injecting air into the bottom. (Moheimani, 2005) The Solix-system consists of bag PBR in water basin which gives the mechanical support as well as temperature control. A large scale demo plant is built in Coyote Gulch, USA. In research small bag PBR are often used indoors with electric lightning. The bag PBR is easy to use and construction materials are not expensive.

## 2.3 Comparison between open raceway pond and photobioreactor

A comparison between open raceway pond and photobioreactor is needed when suitable method is estimated for pilot scale solution. In the table 2 there are figures which describe both

open raceway pond and photobioreactor method when annual production amount is 100 tons of algae biomass. These figures are based on experience and applied to large production size.

Table 2. Comparison: photobioreactor vs. open raceway pond (Chisti 2007 & Kadam 2001).

| | Tubular PBR | Open raceway pond |
|---|---|---|
| Biomass produced [t dry substance/a] | 100 | 100 |
| Productivity [kg / m3 / d] | 1,535 | 0,117 |
| Biomass concentration in cultivation broth [kg / m3] | 4,00 | 0,14 |
| Cultivation surface area needed [ha] | 0,5681 | 0,7828 |
| Oil yield [m3 / ha]<br>- 70 % oil in d.s.<br>- 30 % oil in d.s. | 136,9<br>58,7 | 99,4<br>42,6 |
| CO2 consumption [t/a] | 183 | 183 |
| System geometry | 132 parallel tubes/unit<br>Tube length 80 m<br>Tube diameter 0,06 m | Surface area 978 m2/pond<br>Pond length 82 m<br>Pond width 12 m<br>Pond depth 0,3 m |
| Number of units | 6 | 8 |

As seen in table 2, PBR is remarkably more efficient in algae biomass production. In this comparison it gives 13-fold amount of biomass.

According to Chisti, concentration of biomass is almost 30-fold compared to open raceway pond. The concentration in open pond looks very low. According to Benemann, Ben Amotz and others, 1 kg/m3 can realistically be achieved in open ponds with added CO2. 5 kg/m3 is achieved in PBR:s. However, in a continuous cultivation the growth rate must be kept high,

which is possible only with sufficient dilution. Safe and realistic figures for biomass concentration may look as follows:

- 0,5 – 0,7 kg/m3 in continuous open pond cultivation with added CO2-gas
- 0,2 – 0,4 kg/m3 in continuous open pond cultivation with air only
- 2,5 – 4 kg/m3 in continuous PBR cultivation with added CO2-gas
- 1,5 – 3 kg/m3 in continuous PBR cultivation with added air

Consumption of CO2 is presumed similar in this comparison, but in reality a considerable portion of CO2 escapes in the atmosphere from open raceway ponds. Due to closed constructions, PBR:s utilize CO2 much more effectively. An open pond is always subject to contamination, so the medium must be very specific to the algae species. (Chisti, 2007)

Contamination risk in a closed PBR is much smaller, at least when it is new and clean. For continuous cultivation in a PBR, good cleaning becomes critical to keep it aseptic enough. However, monoculture is possible to run for a reasonable time. High investment and operating costs are the major challenge of closed tubular PBR:s. E.g. pumping energy must be optimized to productivity and a need for cleaning disinfection adds operating costs. (Moheimani, 2005) Temperature control is not very accurate due to complexity of the equipment; however, this is not a problem to most algae. Scale up does not reduce unit investment cost remarkably, since the diameter of reactor tubes must be kept same.

Nowadays the most large scale algae plants have open ponds. Correspondingly, most practical experience is gained in these plants.

## 3. UTILIZATION OF INDUSTRIAL CO2 EMISSIONS IN ALGAE CULTIVATION

Microalgae biomass contains about 50 % carbon of dry substance. Algae need carbon and the easiest way to get it is to process CO2 from air. According to Chisti (2007), about 183 tons of CO2 is needed to produce 100 tons of algae biomass (dry substance). CO2 shall be fed into cultivation continuously during daytime when light is available. CO2 emissions from power plants

using fossil fuels can be used in algae cultivation. This has been studied in various locations. (Kadam, 2001)

According to Kadam (2001), 1000 hectares of algae pond could process about 250 000 tons of CO2 annually. If 50 MW coal fired power plant produces 414 000 tons of CO2 emissions, algae pond system could utilize 60 % of these CO2 emissions. Main components of power plant exhaust gas are N2, CO2, O2 and water (vapor). The composition of exhaust gas depends on type of fuel and burning technique. (Mäki, 2004) Algae growth depends on CO2 content of the exhaust gas, but on other components, too. E.g. SO2 is toxic to most algae, so it should be stripped off before feeding into cultivation. In some cases enrichment of CO2 in the exhaust gas is useful. Algae biomass could be used as fuel, too. Since it is too wet as such (d.s. 30 – 50 %) it should either be dried, or used as co-feed with other fuels.

It is technically possible to reduce CO2 emissions with algae by several tens of percent, but the price of CO2 emission license (6 €/ton, 2014) is too low. The price should go up to 30 – 40 €/ton at minimum to make it feasible.

## 4. FEEDING OF CO2 INTO ALGAE CULTIVATION

Productivity in autotrophic algae cultivation is about 3 g/m2/day in an open pond, when all CO2 is taken from the ambient air. When CO2 or CO2 containing gas is fed directly into the cultivation, the productivity can increase even 10-fold, about 30 g/m2/day. (Benemann, 2013)

Aerators designed for waste water treatment plants can be used to feed CO2 to algae cultivation (figures 5 and 6). These aerators are composed of nozzles or membranes, which disperse the gas efficiently. Waste water ponds are usually 2-5 meters deep.

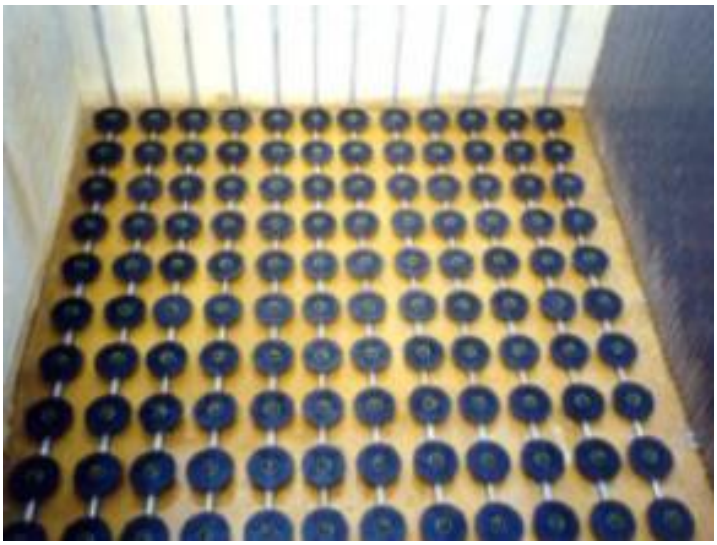


Figure 5. Membrane disc diffusers in wastewater treatment plant.

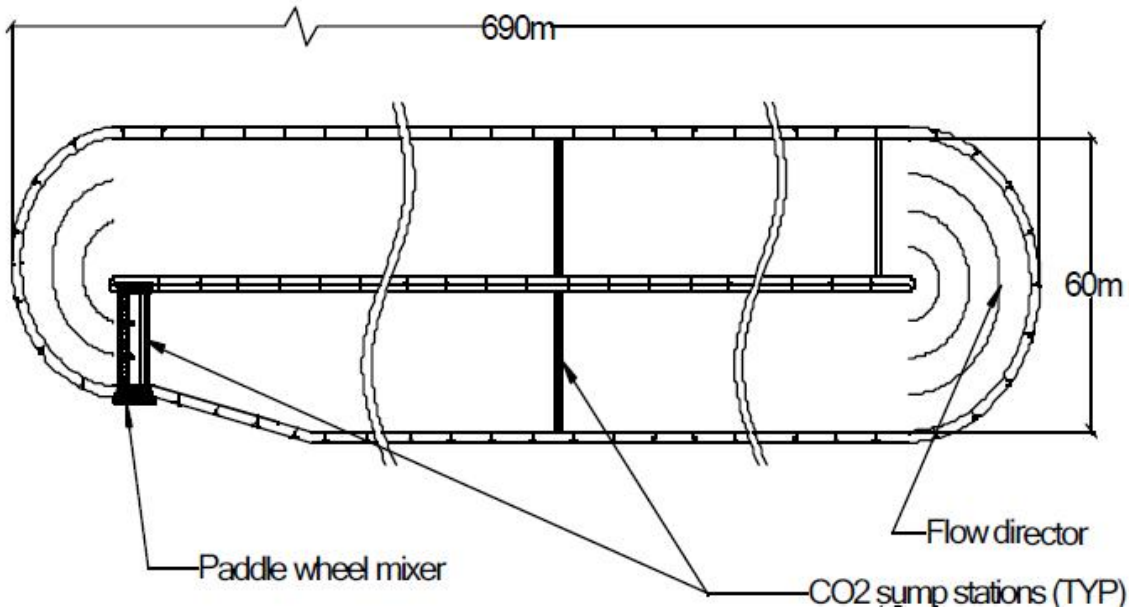
Figure 6. Membrane diffusers in wastewater treatment plant.

Membrane systems described above fit better in closed PBR:s, since there is more time for CO2 to dissolve. Gas dissolving in PBR is usually done in a separate mixing tank, which can be several meters deep. About 70 – 80 % of CO2 fed can be utilized in a closed PBR. Open algae ponds are usually less than 0,3 meters deep, and this is challenging for gas dissolving. Only

about 1 – 10 % of CO2 dissolves, the rest escapes in the air. One way to compensate the low depth problem is to make gasification pits or sumps in the pond (Figure 7.). This helps to dissolve CO2 due to higher hydrostatic pressure, but it will make cleaning of the pond more difficult, as well as increase investment cost. (Benemann, 2013) The feeding point of CO2 in an open pond is located usually after the paddle wheel mixer. If CO2 distribution is wanted to make more effective there should be more than just one feeding point in the pond.

In closed PBR-system CO2 is fed into a mixing tank, in which both gas dissolving and medium cooling takes place. CO2 can be fed directly into the solar reactor tubes (more expensive system). A more efficient distribution and better dissolving is gained with several feeding points. The amount of CO2 fed depends on intensity of light in the reactor tubes, mass transfer in the reactors and flowrate of the cultivation.

Figure 7. CO2 feeding sumps in open raceway pond.



## 4.1 Dissolving of CO2 into algae cultivation

CO2 acts as source of carbon and pH lowering/buffering factor in algae cultivation. Increasing pH in cultivation will improve CO2 solubility in water/medium. pH should be at least 8 to make CO2 dissolving optimal, however, this depends on the algae species. (Weissman, 1989) Lowering cultivation temperature will improve CO2 dissolving too (Figure 8.). This would increase operating cost especially in warm climate, since a large volume of medium must be cooled. Increasing pressure will improve CO2 dissolving, but this is possible only in a closed system. Investment cost is likely to rise remarkably.

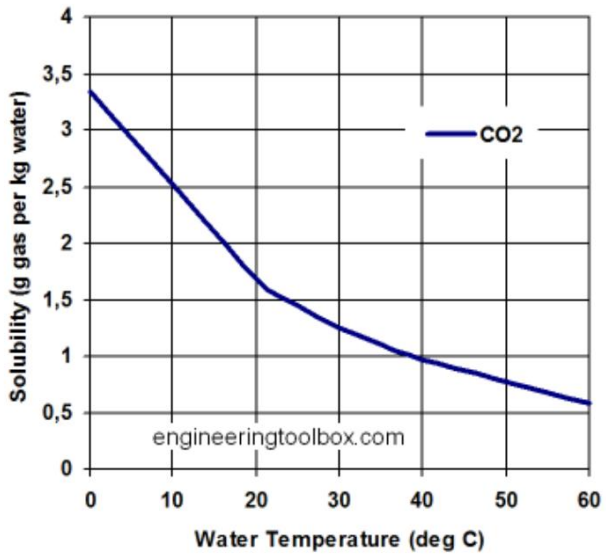



Figure 8. Solubility of CO2 in water.

## 4.2 CO2 concentration in algae cultivation

Optimal concentration of CO2 depends on the algae species to be cultivated. CO2 concentration in cultivation should be 50 µmol – 5 000 µmol /L. E.g. Chlorella Vulgaris: optimal

CO2 concentration is 60 µmol/L. CO2 concentration is difficult to control in open cultivation systems. In closed systems it is controlled and CO2 is fed according to measured concentrations.

## 5. CULTIVATION OF ALGAE IN OPEN POND

According to Neste Jacob´s background information, own experience and general knowledge open pond system is much easier and less expensive to build and easier and cheaper to operate. Neste Jacobs selected this type of cultivation method to design model in our pilot scale case.

### 5.1 General issues

Autotrophic algae cultivation in open ponds is described in this design part of this study. This method applies to photosynthetic algae generally, not to any specific species. The physiological properties of different algae shall be taken into account separately in each applied case. Dimensions and parameters for algae cultivation are chosen according to Algae Parc presentation.

Downstream process concept has been designed according to Neste Jacob´s process technical expertise and experience. Methods, equipment and parameters have been selected according to properties of algae cell mass learned in several development projects with our customers. The process describes here is mostly hypothetical, since production scale algae cultivations are still quite few and experience with real algae material is limited. Algae biomass as such as beta-carotene is produced in large scale. Algae lipids for fuel have not reached production scale yet.

## 5.2 General presumptions

The algae to be cultivated are autotrophic and photosynthetic and it can be cultivated either in continuously or batch method. The maximum algae concentration is estimated to be 1 g dry substance /liter in batch cultivation. Typical productivity is 20 g/m2/day in continuous cultivation which must be checked for each specific alga separately. In continuous cultivation 50 % /day dilution is presumed. The maximum algae concentration is 0,5 – 0,7 g dry substance /liter depending on dilution and growth rate of alga. This depends on properties of alga in case, climate and conditions on cultivation site. Optimal cell concentration and dilution shall be optimized for each alga to be cultivated.

CO2 containing gas (e.g. flue gas) is added to provide more carbon than what is available in the atmosphere. Nutrients including N- and P-salts are added and dosed according to cell growth. The salts are not specified here, but shall be selected according to availability and price on each cultivation site. Nutrients shall be recovered in downstream process and recycled to maximal extent. Waste waters may be used as nutrient source too, depending on their quality and the algae species in case. The effluent from algae production plant is presumed to be clean, but somewhat saltier than sea water, since algae absorb practically all nutrients, when dosed up to cell growth. Natural algae species are not harmful to environment. In most cases they are selected from the same area and climate in which they are cultivated.

Algae inoculum is prepared in laboratory, and following series of inoculum ponds. Each following pond is 10 x the size of the previous one. A separate “starvation” step is provided to boost production of intracellular lipids. Starvation is provided by limiting the dose of N and P. Starvation is preferably done in a separate production pond. All production ponds can be used both for cultivation and starvation. Sea water containing 3,5 % of salt is used as process water. Salt concentration will rise to about 4 % due to evaporation during cultivation. pH in algae cultivation is usually close to neutral. It shall be taken into account when selecting nutrient salts. pH measurement and control is recommended in algae cultivation. Cooling is provided through evaporation during cultivation. No separate cooling or temperature control is used. The cultivation is in open air, and thus not aseptic. The inoculum is grown aseptically in the laboratory. A close to aseptic surrounding is provided in the smallest ponds. A good competitive algae growth is provided by controlled dosing of nutrient salts and physical conditions. Lipid

content in algae biomass is usually 30 % or less. Higher lipid contents have been reported in literature, but repeating these results seems to be difficult.

## 5.3 Open pond structure and equipment

The open pond used in algae cultivation is a raceway type ring channel pond. Circular flow is created with horizontal paddle wheel mixers. The ponds are built on a levelled ground. Concrete can be used to build the pond walls and floor in bench and pilot scale. In production scale the walls and bottom are typically built of soil. Good levelling of the pond bottom is challenging and critical due to very shallow water level. Plastic lining is recommended on the pond bottom to ease cleaning. However, according to John Benemann this is too expensive.

A horizontal paddle wheel mixer is placed in the beginning of a straight line part of the pond. One paddle wheel should be enough for a 100 m long pond. The paddle wheel mixers shall be simple in construction and easily removable for cleaning and maintenance. CO2 gas dissolving can be improved with dedicated dissolving device (e.g. static mixer) to minimize escaping of CO2 in the atmosphere. This device shall be simple in construction to ease cleaning, and quickly removable and replaceable. Several units can be used depending on the length of the pond and growth rate of the alga.

In continuous cultivation a separate gas dissolving column can be used to saturate recycled process water with CO2. Flow guides can be placed in the curves of the ponds to line up the flow. In small ponds they are normally not needed. Although temperature is not controlled, measurement and recording of it may be useful. Cell density can be measured by turbidity, and more accurately in the laboratory. pH measurement and control is also recommended.

## 5.4 Algae pond dimensions

A production size cultivation pond may look as follows: length 510 m, width 28 m, depth 0,2 m. This gives liquid volume of 2850 m3 and surface area of 14 300 m2. A pond of this large size needs several paddle wheels and feeding points for CO2-gas. In pilot plant size a 50 m long and 3 to 5 m wide pond is sufficient.

## 5.5 Algae pond operation

### 5.5.1 Cultivation of inoculum

In inoculum cultivation asepsis is reduced as pond size increases. Pure cultures can be produced in laboratory, but as soon as they are transported to open ponds, the culture will face other organisms. Inoculum cultivation is normally run as batch culture.

Ways to maximize the proportion of desired organisms in inoculum are as follows:

- Choose algae species and strains, which are competitive and suitable to the climate and environment on site. The species may be necessary to change according to the time of the year.
- Provide N- and P-nutrients in optimal selection and feed rate to the species in case. This leaves as little nutrients to other organisms as possible.
- Sterilized process water can be used in the smallest units, followed by pasteurization and finally only sand filtration in the last units.
- Give sterile CO2 containing gas to cultivations to speed up growth.
- Control temperature in smaller units, pH in all units.
- Use 10 x expansion principle in inoculum line dimensioning.

### 5.5.2 Production scale cultivation

Production scale cultivation is preferably run continuous. The flow of algae culture to harvesting is very large. Living algae cannot wait for harvesting too long, since unwanted changes in cell composition may occur. However, this depends on the production organism properties. Algae shall be harvested in optimal phase of growth, since growth slows down as the cell concentration approaches 1 g dry substance/l. This means that harvesting shall be designed according to 0,6

– 0,8 g dry substance/l concentration. Cell growth rate and outflow to harvesting shall be in optimal balance to keep cell concentration constant.

CO2 containing gas is added into cultivation preferably through a dedicated dissolving device to make the dissolving more efficient. Gas dissolving conditions are not very good in the pond: liquid layer is very thin, only about 0,2 m, and the temperature is quite high, usually 25 – 40 °C. pH should be measured and controlled, when necessary. This depends on the algae species in case. Temperature can be measured, but is not controlled during cultivation. Evaporation of water cools the cultivation down to some extent depending on the climate on site.

# 6. DOWNSTREAM PROCESSING

## 6.1 Harvesting

Since cell concentration in cultivation is very low and the volume is large, only very low cost unit operations are possible in cell mass harvesting. Flocculation, flotation and sedimentation are possible, direct centrifugation is not sensible. However, in pilot plants centrifugation is often used for quick harvesting.

## 6.2 Dewatering

Harvested cell mass has still very low dry substance content, typically about 5 %. This should be further increased e.g. by pressure filtration in order to reduce thermal drying. Since the cells are full of water, usually less than 30 % dry substance is achieved. However, some exceptions exist: high lipid content molds have been pressed up to 50 % dry substance.

## 6.3 Lipid recovery

Algae produce lipids inside the cells to serve as energy reserve. This is a natural reason, why the cells do not give lipids away easily. Two process routes have been studied: wet extraction and dry extraction. Algae which grow and produce lipids well – e.g. Nannochloropsis and Chlorella - usually have a strong cell wall, which is expensive to break. On the other hand algae like Dunaliella break easily, because they have no cell wall. Unfortunately their growth rate and lipids production is relatively low.

### 6.3.1 Wet extraction

In wet extraction lipids are extracted directly from wet cells. A suitable solvent penetrates through the cell walls and brings the lipids out. So far test results have not been very good. Extraction yield is poor, and rough processing conditions needed in extraction spoil the feed value of residual biomass. However, wet extraction could avoid expensive drying of biomass, so it is worth trying.

### 6.3.2 Dry extraction

In dry extraction solvent is applied on dried and ground biomass. Grinding breaks the dried cells, which makes extraction of lipids relatively easy. Operating cost is a major disadvantage of dry extraction. In most cases algae biomass has less than 30 % dry substance prior to drying, so a substantial amount of water must be removed by heat. Following grinding, extracting and filtering of remaining solids add both operating and investment cost.

### 6.3.3 Processing of residual biomass

Residual biomass production is 2 to 3 fold compared to lipid production, so it should be sold as good value products to make the business feasible. Animal feed, especially fish feed is a well-known application of algae protein. Combining algae protein to algae lipids production has faced problems. The solvents with high temperature, which work well in lipid extraction, tend to spoil the feed value of the algae biomass. If only algae biomass is produced, this problem does not

exist. For reasonable transportation, algae biomass must be dried. This is a high energy cost as described above. For maximum yield in feed value, flash drying with hot air is preferred to contact drying methods.

# 7. CO2 DISSOLVING

## 7.1 Description of challenge

Algae can be cultivated in open raceway ponds to produce algae cell mass, b-carotene and some other chemicals. A more recent interest is to produce lipids for biofuels, and to use algae cultivation as CO2 sequestration method. When algae are cultivated in partly controlled open raceway pond it needs additional feeding of CO2 to maximizing algae cell mass titer. In open pond cultivation only 1 g/l cell dry mass concentration can be obtained and without additional CO2-feeding concentration is less than 50 % of it.

The structure of raceway pond for CO2 feeding is very challenging. Obtaining optimal algae concentration in cultivation step the depth of pond should be only about 20 cm. In usual CO2 feeding methods the CO2 containing gas is supplied from bottom of pond and the most part of gas escapes into the atmosphere. The contact time of CO2 containing gas in water is too short. In order to prolonging CO2 gas contact time in water the cultivation pond can be easily modified by adding deep sumps (2-3 m) to cultivation pond. However this is not a cost-effective way to prolong contact time because submerging gas distribution nozzles to 2 -3 m depth cause high pressure drop, very expensive blower and high operation costs. For example, in case of 550 MW power plant, this submersion increases OPEX about 3,5 M€ yearly with 10 – 40 % reduced carbon capture efficiency. Our target was to find alternative cost-effective solutions to improve CO2 dissolving in water in algae pond cultivation.

## 7.2 CO2 dissolving system

The aim was to propose a more effective CO2 dissolving system. Currently this proposal has been redeemed by Neste Oyj with exclusive rights for their further considerations.

## 8. EXPERIMENTAL CALCULATIONS FOR CO2 FEEDING IN ALGAE CULTIVATION

During our design phase study we also figured out how much algae can produce CO2 containing gas in production scale facility. At the same time we were also interested in to see how large oil and other products quantities can be produced in the same production facility. For that purpose we created a calculation model for open pond cultivation system which gives theoretical figures for oil and algae cell mass production and it calculates solvent, water and energy consumption as well. Illustrated case is based on ONGC Hazira example where vent gas from sulfur recovery unit is used. The volume flow 50 000 Nm3/h is for full industrial scale. For pilot the capacity will naturally be downscaled. The suggestions in this report were intended to be used as future pilot concept but ONGC withdrew from the program. Illustration is shown in Figure 9:

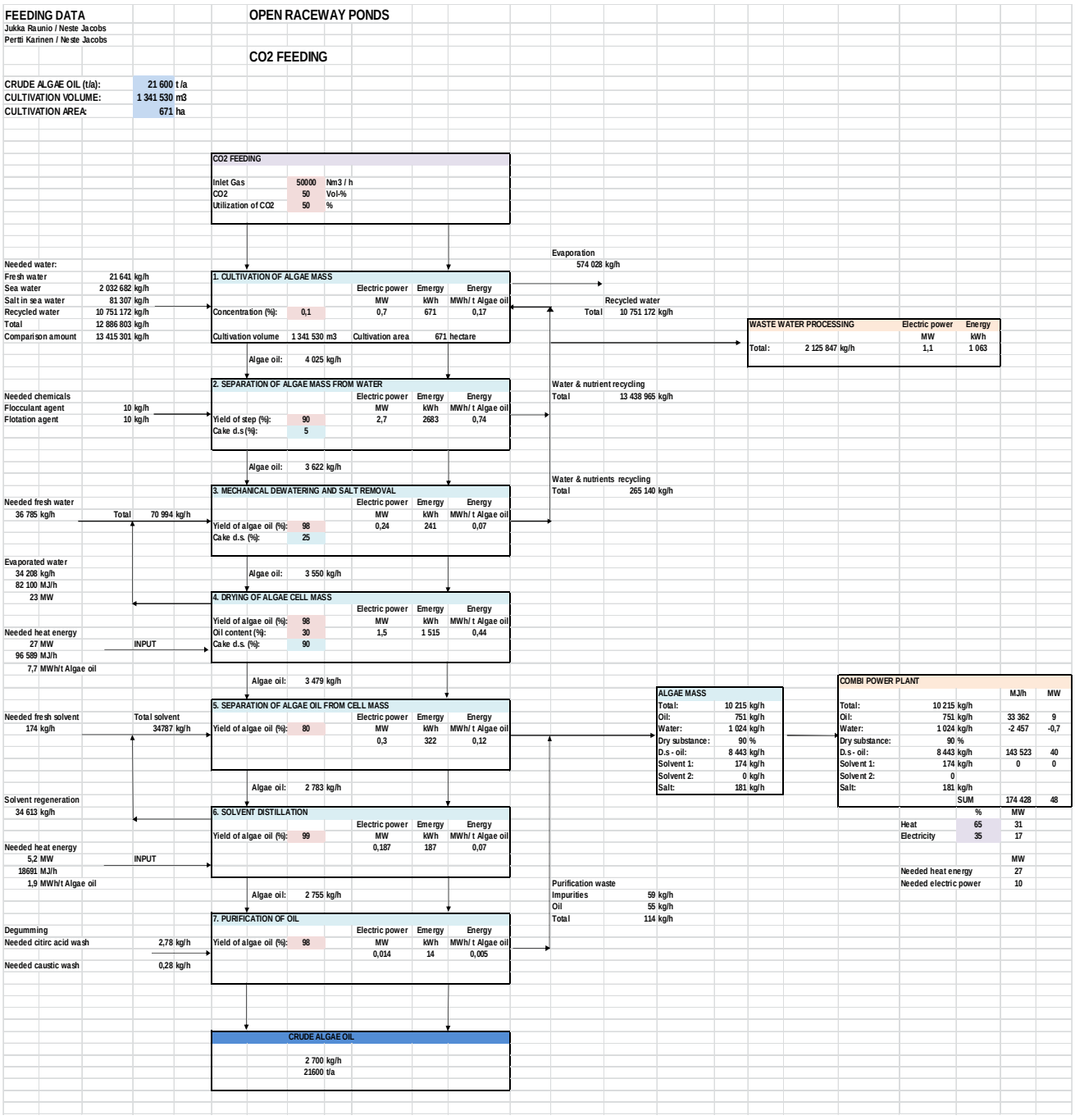



Figure 9: Excel program compilation sheet calculating mass balances, operation costs and area requirements of algae cultivation in open pond producing algae oil.

A similar workbook was also made for PBR cultivation process. At first the input figures of all process steps have been supplied into calculation table. These information have been got from literature, laboratory and benchmarked tests and some information was educated guess. In our experiment we used CO2 containing gas which contain 50 % of pure CO2 and gas flow was 50 000 Nm3/h into system. We estimated that algae cultivation can utilize 50 % of this inlet gas. When algae production titer was 1 g/l and oil content in algae was 30 %, the algae cultivation produced 4025 kg/h algae oil theoretically. In next step the yield of separation of algae mass from water was 90 % and algae oil volume was 3622 kg/h. The mechanical dewatering and salt removal step (yield 98 %) dropped algae oil volume to 3550 kg/h. After drying step algae volume was 3479 kg/h with 98 % yield. Solvent extraction of algae cell mass decreased oil volume to 2783 kg/h with 80 % yield. Finally after solvent distillation and oil degumming steps (yields 99 % and 98 %) crude algae oil volume was 2700 kg/h. Annual (8000 h cultivation time) crude algae oil production volume was 21600 tons. When algae cell mass had been separated from algae oil, it can be collected and utilized to energy production. In our experiment downstream process produced algae cell mass 10 215 kg/h which consist of dry algae substance, algae oil, water, solvent and salts. These components can be utilized in power plant where residual material is produced to heat and electricity.

Algae cultivation needed a huge amount of water (media) and land area. According to our calculations the continuous cultivation needed more than 1,3 millions of cubic meters of cultivation media with 1,0 % outflow of cultivation. When this volume was divided to 0,2 m depth open ponds the algae cultivation needed 671 hectares land area and this was just the area for production ponds. In addition different size pre-cultivation ponds, different downstream process steps and laboratory buildings etc. need a lot of area.

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