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Utilization of flue gas for cultivation of microalgae (*Chlorella* sp.) in an outdoor open thin-layer photobioreactor

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Abstract

Flue gas generated by combustion of natural gas in a boiler was used for outdoor cultivation of *Chlorella* sp. in a 55 m^2 culture area photobioreactor. A 6 mm thick layer of algal suspension continuously running down the inclined lanes of the bioreactor at 50 cm s^{-1} was exposed to sunlight. Flue gas containing 6–8% by volume of CO_2 substituted for more costly pure CO_2 as a source of carbon for autotrophic growth of algae. The degree of CO_2 mitigation (flue gas decarbonization) in the algal suspension was 10–50% and decreased with increasing flue gas injection rate into the culture. A dissolved CO_2 partial pressure (pCO_2) higher than 0.1 kPa was maintained in the suspension at the end of the 50 m long culture area in order to prevent limitation of algal growth by CO_2. NO_X and CO gases (up to 45 mg m^{-3} NO_X and 3 mg m^{-3} CO in flue gas) had no negative influence on the growth of the alga. On summer days the following daily net productivities of algae [g (dry weight) m^{-2}] were attained in comparative parallel cultures: flue gas = 19.4–22.8; pure CO_2 = 19.1–22.6. Net utilization (η) of the photosynthetically active radiant (PAR) energy was: flue gas = 5.58–6.94%; pure CO_2 = 5.49–6.88%. The mass balance of CO_2 obtained for the flue gas stream and for the algal suspension was included in a mathematical model, which permitted the calculation of optimum flue gas injection rate into the photobioreactor, dependent on the time course of irradiance and culture temperature. It was estimated that about 50% of flue gas decarbonization can be attained in the photobioreactor and 4.4 kg of CO_2 is needed for production of 1 kg (dry weight) algal biomass. A scheme of a combined process of farm unit size is proposed; this includes anaerobic digestion of organic agricultural wastes, production and combustion of biogas, and utilization of flue gas for production of microalgal biomass, which could be used in animal feeds. A preliminary quantitative assessment of the microalgae production is presented.

Introduction

Technologies for microalgal cultivation have been studied over the past decade in the context of greenhouse gas mitigation, specifically in Japan and the USA. Biological CO_2 fixation by microalgae grown outdoors is considered to be the best way of fixing CO_2 because solar energy utilization is much higher than in terrestrial plants which attain maximum photosynthetic capacity only for short period of the cultivation season. It has been shown (Tapie & Bernard, 1988) that the cost of CO_2 in large-scale algal cultures is of prime importance to the total economics. In terms of amount, carbon is the dominant nutrient (45–50% of the dry algal mass); so, theoretically, 1.65–1.83 g CO_2 is needed for the biosynthesis of 1 g (DW) of algal biomass. Utilization of CO_2 in flue gas by means of microalgae alleviates impact of CO_2 on the environment (greenhouse effect) and makes production of algal biomass cheaper.

Several studies have been published elsewhere concerning the use of flue gas as a carbon source for growth of microalgae. Balloni et al. (1983) suggested a scheme where biogas generated by anaerobic digestion of organic wastes is combusted and flue gas is used as

carbon source for culturing microalgae and where the algal biomass, after separation, is returned to the anaerobic digestion process. Negoro et al. (1992) introduced flue gas containing 5 and 15% by volume of CO_2 into a pond (depth of suspension 10–20 cm) where CO_2 was fixed by algae (*Nannochloropsis* sp., *Phaeodactylum tricornutum*). It was found that sulphur and nitrogen oxides (SO_x, NO_x), which were present in flue gases from power plant boilers, inhibited algal growth (Negoro et al., 1991). Later, they reported (Negoro et al., 1993) that the productivity of algae using flue gas approached that from pure CO_2 and growth was barely influenced by the content of SO_x and NO_x. Similarly, Hauck et al. (1996) found the low levels of NO_x, typically present in scrubbed flue gas did not inhibit the growth of *Chlorella*. Traviesco et al. (1993) bubbled biogas from an anaerobic digester into a deep algal pond. The CO_2 content was reduced from 44–48 to 2.5–11 vol.% and the gas leaving the pond had 88–97% by volume of methane. However, it is difficult to imagine the collection of enriched methane gas from a large algal pond. Straka et al. (2000, 2002, 2003) proposed a combined process, in which agricultural wastes are anaerobically digested, and the biogas produced is combusted in a boiler and flue gases are decarbonized by microalgae.

Preliminary tests demonstrated that flue gas could be used as a carbon source for the production of microalgae (*Chlorella* sp.) without harmful effects using an open, solar, thin-layer photobioreactor. The construction of the bioreactor permits cultivation of microalgae in a layer only a few mm thick (Doucha et al., 1993; Doucha & Lívanský, 1995) up to harvesting densities higher than 30 g (DW) L^{-1} (Doucha & Lívanský, 1998, 1999, 2003). Because the concentration of CO_2 in flue gas is comparatively low, it can be expected that the efficiency of CO_2 transfer from gas stream into algal suspension will be lower than it is for pure CO_2. The thin layer dense suspension on the culture area of the bioreactor may have a lower capacity for dissolved free CO_2 to cover its consumption and escape from the algal culture into the atmosphere, than do deep-layer ponds (Weissman et al., 1988). The problem of ensuring sufficient concentration of CO_2 for microalgae growth in a very thin layer at the constraint of minimum CO_2 loss into atmosphere (alleviation of CO_2 emissions) is resolved in this work.

Further aims of this study were: (i) to optimise flue gas supply into the open thin-layer photobioreactor; (ii) to compare the productivity and utilization of photosynthetic active radiation by algae cultured with flue gas on with pure CO_2 as a carbon source; (iii) to propose a combined biotechnological scheme for processing agricultural wastes, production of biogas and utilization of flue gas for production of microalgae.

Materials and methods

Strain and culture medium

Chlorella sp., strain P12 (from the collection in our laboratory) was used in the experiments. Nutrients were supplied twice a day in a fed-batch regime. Their amounts per 1 kg (dry weight) of produced biomass were: macronutrients (technical grade) – urea = 182 g; KH_2PO_4 = 39.5 g; $MgSO_4 \cdot 7H_2O$ = 29 g; $FeSO_4 \cdot 7H_2O$ = 5 g; micronutrients (analytical grade) – H_3BO_3 = 137 mg; $CuSO_4 \cdot 5H_2O$ = 158 mg; $CoSO_4 \cdot 7H_2O$ = 100 mg; $MnSO_4 \cdot 4H_2O$ = 608; $(NH_4)_6Mo_7O_{24} \cdot 4H_2O$ = 29 mg; $ZnSO_4 \cdot 7H_2O$ = 440 mg; NH_4VO_3 = 2.3 mg. Tap water was used for preparation of the medium.

Outdoor culture system

A scheme of the pilot plant photobioreactor is given in Figure 1. Algal suspension was delivered from the retention tank (3) by a pump (4) to the upper rim of the culture area of the photobioreactor. The area was constructed from polypropylene sheets forming eight inclined lanes (1) (inclination 1.6%) arranged in a meandering way. Each lane was 5.7 m long and 1.16 m wide. The lanes were connected by troughs, with a total culture area of 55 m^2. The mean velocity of the suspension on the culture area was about 50 cm s^{-1}, the thickness of suspension layer was 6 mm, giving a Reynold's number of about $Re = 3,000$. The total volume of the suspension in the bioreactor was 0.4 m^3, the volume of the suspension on the irradiated culture area was 55 m^2 × 0.006 m = 0.33 m^3, and the surface–volume ratio of the algal suspension on culture area of the bioreactor was 55 m^2/0.33 m^3 = 166 m^{-1}. We found in preliminary tests that CO_2, CO and NO_X content in the flue gas from combustion of both biomass and natural gas was practically the same. Because the use of natural gas was simpler, we used natural gas instead of biogas in our experiments. Natural gas was combusted in a gas boiler (6), and the heat energy was dissipated by means of a water circuit in an air cooler (18). Gas blowers (15) took away flue gas from the chimney (7) via a Venturi gas cooler (8) and scrubber (9) and delivered the gas to the saturation system. Gas flow rate was measured

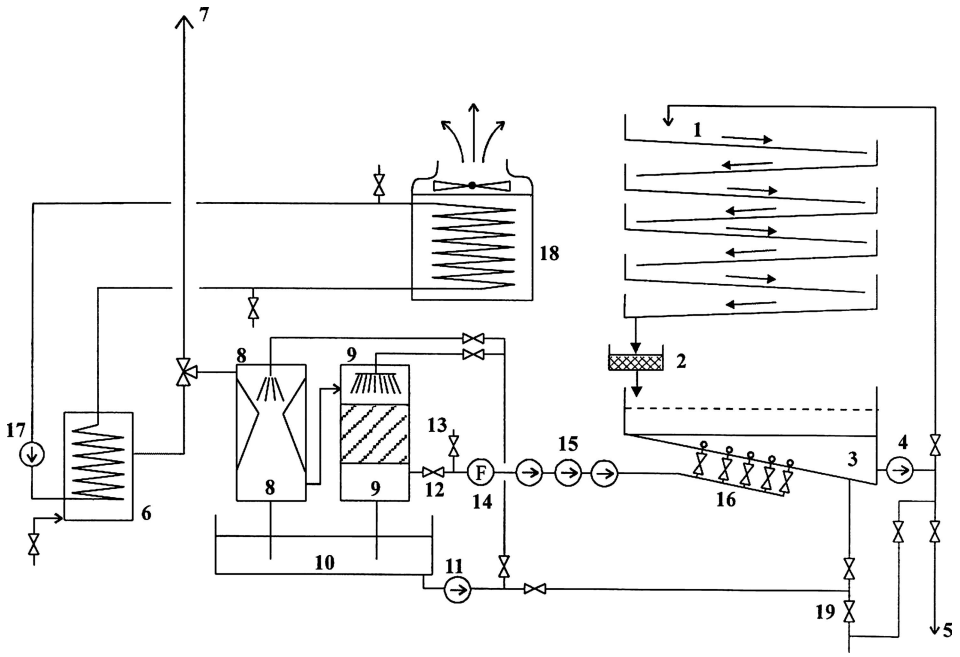

Figure 1. Schematic diagram of an experimental photobioreactor for cultivation of microalgae using flue gas. (1) cultivation lanes; (2) sieve filter; (3) retention tank; (4) circulation pump; (5) harvesting of algae; (6) gas boiler; (7) chimney; (8) flue gas cooler; (9) flue gas scrubber; (10) cooling water tank; (11) water circulation pump; (12) flue gas valve; (13) air valve; (14) gas flow meter; (15) gas blower set; (16) saturation/aeration system; (17) hot water pump; (18) air cooler; (19) water in/out.

with a flowmeter (14). Saturation of the suspension by carbon dioxide from flue gas was achieved by means of porous ethylpropylenedimer (EPDM) membrane tubes of the saturation system (16) placed at the bottom of the retention tank (3). At night the suspension was kept in a retention tank and was aerated by means of an aeration system (16).

The bioreactor was operated in a fed-batch mode. Nutrients were supplemented twice a day (at the beginning of daily cultivation and at noon) in quantities dependent on the measured concentrations of nitrogen and phosphorus (as phosphate) in the medium. After stopping cultivation in the evening, the remaining algal cells were washed from the culture surface into the retention tank.

To minimize losses of dissolved CO_2 in the algal suspension into the atmosphere, pCO_2 at the end of the culture area was maintained at a minimum pCO_2 of 0.1–0.2 kPa, which is necessary for non-limited algal growth (Lívanský & Doucha, 1998; Weissman et al., 1988).

Analytical methods

The partial pressure of dissolved CO_2 was measured by means of a pCO_2 ion selective electrode (type OP 9353, RADELKIS, Budapest) connected to a portable pH-meter. The concentration of dissolved oxygen was measured using an oximeter (model 330, WTW Weilheim, Germany). Culture pH was measured with a pH-meter (model 320, WTW Weilheim, Germany). PAR was measured with an instrument developed in our laboratory and produced by DETEGO (Třeboň, Czech Republic).The PAR energy incident on 1 m^2 area was measured by an integrator (DETEGO). Cell concentration (DW) was determined gravimetrically by centrifugation (10,000 g, 3 min) of 2 mL of algal suspension in an Eppendorf tube, then drying at 105 °C for at least 8 h. The determination was made in triplicate for each sample. Net daily (per 24 h) algae productivity derived from 1 m^2 of culture area was calculated from the differences between each morning total algal mass in the bioreactor. Net efficiency of utilization of PAR energy, η (%), was calculated from the net productivity of algae (g (DW) m^{-2}) × conversion factor 6.4 W h PAR g $(DW)^{-1}$ – (Kubín et al., 1983; Simmer, 1979; Morita et al., 2001) × 100 and divided by the reading of the PAR integrator (W h PAR m^{-2} day^{-1}). Chemical gas analyses of the flue gas streams were done before and after saturation of algal suspensions using the following instruments: CO_2–IR gas analyzer, Junkalor Infralyt 4 and Geotechnical instrument GA

94; CO–IR gas analyzer Hartmann–Braun URAS 3G; NO_X–IR gas analyzer Hartmann–Braun RADAS IG; O_2–polarometric analyzer Geotechnical Instruments GA 94. All gas analyzers were calibrated using standard gas mixtures every 6 h of operation.

Results

The composition of flue gas before and after saturation of algal suspension is given in Table 1. Concentrations of the flue gas constituents diminished after passing through the suspension, whereas dissolved oxygen was desorbed from the suspension into the gas stream. Corresponding cultivation parameters are given in Table 2.

Rate of CO_2 supply ($g\,h^{-1}$) in flue gas can be expressed as:

$$M = \frac{Q_g \rho_{CO_2} C_{g,in}}{100} \quad (1)$$

where Q_g is volumetric flow rate of flue gas ($m^3\,h^{-1}$), ρ_{CO_2} is CO_2 density ($g\,m^{-3}$), $C_{g,in}$ is CO_2 content (vol.%) in flue gas before passing through the suspension. CO_2 absorbed in the suspension was partially utilized by photosynthesizing algal cells and partially lost due to its escape into the atmosphere. The rate of CO_2 supply related to a unit of culture area A is:

$$\frac{M}{A} = \frac{R_{CO_2} + K_{L,CO_2} K_H (p_{mean} - p^+)}{(Dec/100)} \quad (2)$$

where R_{CO_2} is the rate of consumption of carbon dioxide by algae (g $CO_2\,m^{-2}\,h^{-1}$) within a unit of culture area, K_{L,CO_2} is the liquid phase mass transfer coefficient ($m\,h^{-1}$) for CO_2 transport from the suspension into the atmosphere, K_H is Henry's constant (g $CO_2\,m^{-3}\,kPa^{-1}$) for CO_2, p_{mean} is the mean partial pressure (kPa) of CO_2 in algal suspension, p^+ is the partial pressure of CO_2 (kPa) in an ambient atmosphere, Dec is degree (%) of flue gas decarbonization after passing the gas stream through the suspension. To keep the left side of Eq. (2) at a minimum (optimization criterion), p_{mean} must be such that pCO_2 (partial pressure of dissolved CO_2) in the suspension leaving the culture area should be held at a minimum value (pCO_2 = 0.1–0.2 kPa), not yet limiting algal photosynthesis by CO_2 shortage. In this manner the CO_2 loss from the suspension into the atmosphere should be minimized. On the other hand, the degree of flue gas decarbonization, Dec, should be as high as possible to keep the left side of Eq. (2) at a minimum. Some quantities on the right side of Eq. (2) should be influenced by light intensity or culture temperature. The R_{CO_2} was related to the rate of oxygen evolution by algal cells as follows: $R_{CO_2} = Y_{CO_2/O_2} R_{O_2}$, where Y_{CO_2/O_2} (g $CO_2\,g^{-1}$ O_2) represents the amount (g) of CO_2 which must be consumed by algal cells to evolve 1 g of oxygen by photosynthesis and R_{O_2} is the rate of oxygen evolution (g $O_2\,m^{-2}\,h^{-1}$) by algae related to a unit of culture area. The $R_{O_2}$was dependent on PAR irradiance (Figure 2). The mass transfer coefficient for CO_2 was estimated from the formula: $K_{L,CO_2} = K_{L,O_2}(D_{CO_2}/D_{O_2})^{1/2}$ (Talbot et al., 1991), where K_{L,O_2} ($m\,h^{-1}$) is the mass transfer coefficient for transfer of dissolved oxygen from the suspension into the atmosphere, D_{CO_2} and D_{O_2} are diffusion coefficients ($m^2\,h^{-1}$) for CO_2 and O_2 in the suspension. The partial pressure of dissolved carbon dioxide decreased exponentially from the beginning p_0 to the end p_L of the culture area. Therefore, the following formula was used for calculating the mean pCO_2 in the suspension on culture area:

$$p_{mean} = \frac{p_0 - p_L}{\ln(p_0/p_L)} \quad (3)$$

Table 1. Flue gas composition before (inlet) and after (outlet) saturation of algal suspension.

Time	Flue gas flow rate ($m^3\,h^{-1}$)	CO_2 (vol.%)		O_2 (vol.%)		NO_X ($mg\,m^{-3}$)		CO ($mg\,m^{-3}$)	
		Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
10:45	27.2	5.46	4.40	8.24	8.39	30.0	28.1	3.45	2.80
13:30	9.1	7.50	3.60	8.12	8.36	29.1	25.0	1.66	0.26
14:15	34.9	6.05	5.70	8.07	8.12	32.3	32.0	3.61	3.12
15:05	16.8	6.55	3.90	9.47	9.68	22.4	22.1	1.01	0.17
15:25	14.6	6.80	4.50	8.68	8.80	20.4	17.9	1.61	1.75
17:05	13.2	7.13	3.90	8.58	8.95	28.1	24.5	1.12	0.11

Table 2. Cultivation parameters of algal suspension saturated with flue gas.

Time	PAR irradiance ($W\,m^{-2}$)	Culture temperature (°C)	pCO_2 (kPa)		pH		DO (mg $O_2\,L^{-1}$)	
			Inlet ($x = 0$ m)	Outlet ($x = 50$ m)	Inlet ($x = 0$ m)	Outlet ($x = 50$ m)	Inlet ($x = 0$ m)	Outlet ($x = 50$ m)
10:45	308	31.2	1.73	0.49	6.95	7.88	5.60	19.02
13:30	377	32.3	0.66	0.21	7.55	7.96	6.36	18.64
14:15	383	32.4	2.85	0.11	6.61	8.09	3.97	25.35
15:05	323	33.2	1.45	0.28	7.23	7.92	5.69	18.99
15:25	334	31.9	2.30	0.07	6.85	8.05	4.58	22.20
17:05	188	31.7	1.53	0.32	7.02	7.87	5.99	16.30

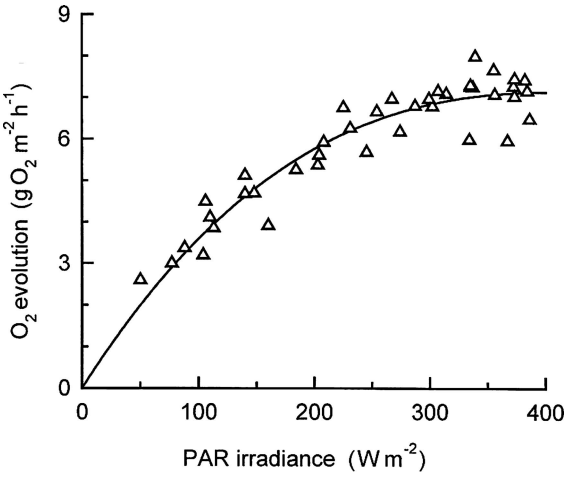

Figure 2. Influence of PAR irradiance on the rate of oxygen evolution by algae on culture area.

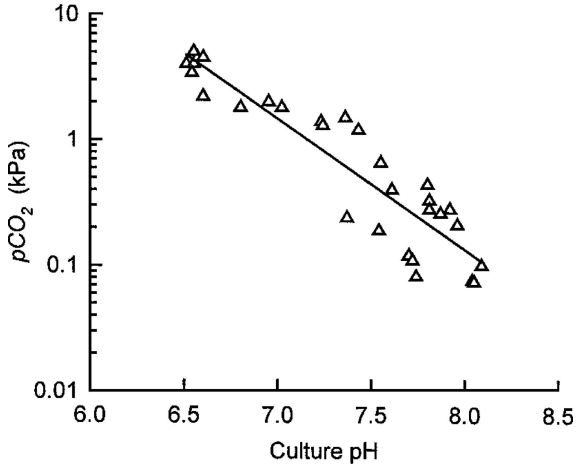

Figure 3. Relationship between partial pressure of dissolved carbon dioxide and algal culture pH. Line-fitted in accord with Eq. (4).

It was found that $\log pCO_2$ decreased linearly with increasing suspension pH (Figure 3):

$$\log\ p = a - b\,\mathrm{pH} \tag{4}$$

where a, b are empirical coefficients; (experimentally found: $a = 8.434$; $b = 1.201$; $r = 0.922$).

The degree of flue gas decarbonization was calculated from the content of carbon dioxide in the flue gas stream:

$$\mathrm{Dec} = 100\left(1 - \frac{C_{g,\mathrm{out}}}{C_{g,\mathrm{in}}}\right) \tag{5}$$

where $C_{g,\mathrm{out}}$ is the CO_2 content (vol.%) in the flue gas after passing through the suspension. As apparent from Figure 4a, the degree of decarbonization decreased with increasing flow rate of the flue gas into the suspension and the mass transfer coefficient for CO_2 absorption into the suspension decreased with the flue gas flow rate (Figure 4b). This phenomenon may be caused by coalescence of bubbles. Non-linear regression of experimental data gave:

$$\mathrm{Dec} = 100\left(1 - 0.282\ Q_g^{0.336}\right) \tag{6}$$

The mass balance of dissolved carbon dioxide in the algal suspension on the culture area can be written as:

$$Q_s(C_{\Sigma,0} - C_{\Sigma,\mathrm{L}}) = R_{CO_2}A + K_{\mathrm{L},CO_2}AK_{\mathrm{H}}(p_{\mathrm{mean}} - p^+) \tag{7}$$

where Q_s is volumetric flow of suspension ($m^3\,h^{-1}$), $C_{\Sigma,0}, C_{\Sigma,\mathrm{L}}$ are total concentrations ($g\,m^{-3}$) (free + chemically bound) of CO_2 at the beginning and at the end of the culture area. Assuming that free CO_2 and

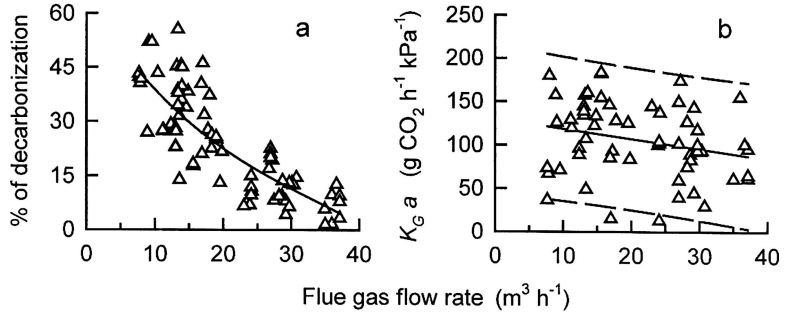

Figure 4. Influence of flue gas flow rate on the degree of CO_2 decarbonization (a) and on mass transfer coefficient of CO_2 absorption (b) into algal suspension.

CO_2 bound as bicarbonate ions were the predominant forms of carbon dioxide in the suspension, the total dissolved carbon dioxide concentrations at the beginning and at the end of culture area can be expressed as:

$$C_{\Sigma,0} = K_{\mathrm{H}} p_0 \left(1 + \frac{K_1}{H_0}\right) \tag{8a}$$

$$C_{\Sigma,L} = K_{\mathrm{H}} p_{\mathrm{L}} \left(1 + a_1 \frac{K_1}{H_{\mathrm{L}}}\right) \tag{8b}$$

where H_0 and H_{L} are molar concentrations of hydrogen ions in the algal suspension at the beginning and at the end of culture area, a_1 is an empirical coefficient introduced here in order to take into account the fact (Lívanský & Doucha, 1999) that the concentration of free carbon dioxide in the suspension at the end of the culture area is lower than the carbon dioxide concentration which would be in equilibrium with bicarbonate ions in the hours of intensive algal photosynthesis, and K_1 is the first apparent dissociation constant of carbonic acid. From Eqs. (7), (8a) and (8b) we obtain:

$$p_0 = \frac{M/(Q_{\mathrm{s}} K_{\mathrm{H}}) + p_{\mathrm{L}}\left(1 + a_1 \frac{K_1}{H_{\mathrm{L}}}\right)}{1 + \frac{K_1}{H_0}} \tag{9}$$

For $Q_{\mathrm{s}} = 13.6\,\mathrm{m^3\,h^{-1}}$ and taking into account the temperature dependence of Henry's constant K_{H} (Buhr and Miller, 1983) and that $pK_1 = -\log K_1$ (Kern, 1960), Eq. (9) applied to the experimental data gave the value $a_1 = 1.103$. Figure 5 shows a comparison of estimated and experimental p_0 values. The optimum daily course of the rate of flue gas supply into the $55\,\mathrm{m^2}$ culture unit was computed from Eqs. (1) and (2) for the daily course of irradiance and culture temperature shown in Figure 6 (the data were approximated by second order polynomials as a function of daily hours), taking into account the values given in Table 3. Utilization φ (%) of CO_2 by the algae in relation to CO_2 supplied with

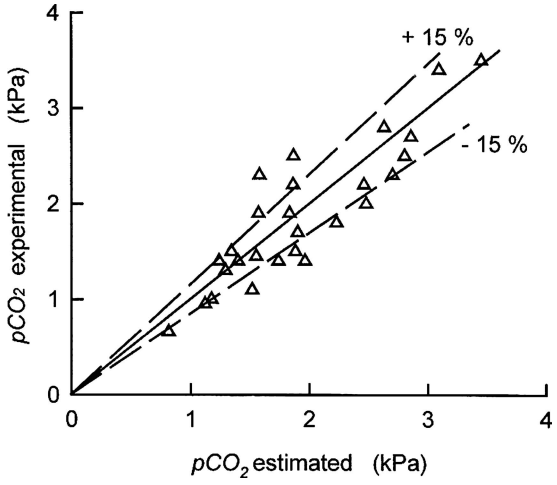

Figure 5. Comparison of experimental and estimated (Eq. (9)) values of partial pressure of CO_2 dissolved in algal suspension.

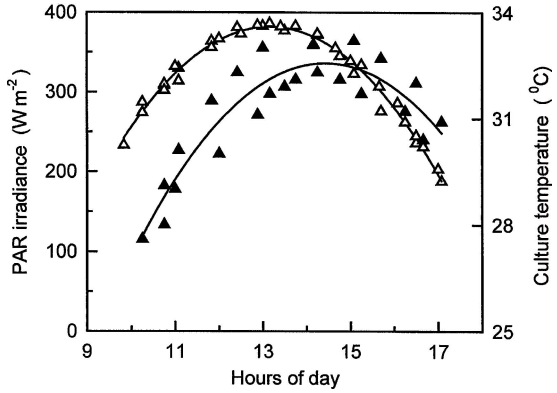

Figure 6. Daily course of PAR irradiance (△) and culture temperature (▲) for clear summer days (August 14–16).

Table 3. Values of parameters used in computations.

$A = 55\,m^2$	Size of culture area
$K_{L,O_2} = 0.24\,m\,h^{-1}$	Lívansky and Doucha (2003)
$K_{L,CO_2} = K_{L,O_2} \cdot (D_{CO_2}/D_{O_2})^{1/2} = 0.21\,m\,h^{-1}$	Talbot et al. (1991)
$p_L = 0.2\,kPa$	
$p^+ = 0.04\,kPa$	
$Q_s = 13.58\,m^3\,h^{-1}$	
$Y_{CO_2/O_2} = 1.115\,g\,CO_2\,g\,O_2{}^{-1}$	Lívansky and Doucha (unpublished results)

flue gas can be defined as:

$$\varphi = \frac{R_{CO_2} A}{M} \tag{10}$$

The computed optimum courses for the content $C_{g,in} = 8\%$ volume of CO_2 in flue gas are plotted in Figure 7.

Algal productivity in cultures saturated with flue gas and cultures saturated with pure CO_2 was approximately the same (Table 4). Theoretically, at the assumed mean content of 47% of carbon in algal dry biomass, about 1.72 kg CO_2 per 1 kg biomass is required. If 49% of CO_2 mass contained in flue gas can be absorbed in the algal suspension, then 4.4 kg CO_2 is required for the production of 1 kg of algal biomass (Figure 8).

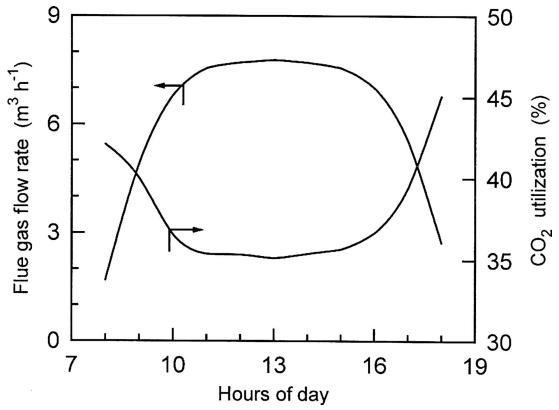

Figure 7. Optimum flue gas flow rate and CO_2 utilization by algae in a 55 m^2 photobioreactor during daylight hours of cultivation. Values are computed for 8% volume of CO_2 in flue gas and for the PAR irradiance and culture temperature courses plotted in Figure 6.

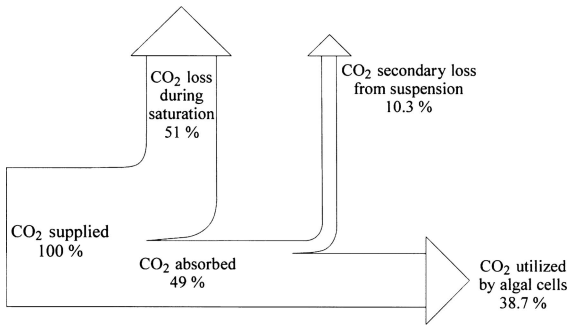

Figure 8. Scheme of CO_2 mass balance for a photobioreactor in which flue gas containing 8% volume of CO_2 is injected into algal culture.

Discussion

To date almost all bioreactors used for outdoor commercial production of *Chlorella*, *Dunaliella* and *Arthrospira* (*Spirulina*) are based on circular or raceway ponds in which a deep layer of algal culture is mixed by paddlewheels. Nevertheless, experience gathered over the years indicates a number of limitations of such culture systems (Torzillo et al., 1993; Pushparaj et al., 1997). On the other hand, the second generation of thin-layer culture technology developed in this laboratory for open large-scale cultivation of unicellular microalgae (Doucha et al., 1993; Kajan et al., 1994; Doucha and Lívanský, 1995, 1998, 1999, 2003), characterized by very high culture densities in a several millimeters thick layer of well-mixed microalgae, results in higher production rates and lower operational costs.

We found that the presence of NO_X in flue gas did not inhibit the growth of microalgae, in accord with the findings of Hauck et al. (1996) and Matsumoto et al. (1997). Inlet NO_X and CO content in flue gas was relatively low (Table 1) due to good operational conditions of the gas boiler producing the flue gas. The degree of denitrification of the flue gas, estimated from NO_X absorption in the suspension, was about 10% of the NO_X content in the inlet gas stream.

A commercial microalgae production plant in Hawaii is already using flue gas from a small power plant as a source of CO_2 for the production of algal biomass (Pedroni et al., 2001). However, the ultimate objective of microalgal biofixation of CO_2 is to operate large-scale systems that are able to convert a significant fraction of CO_2 outputs from a power plant into biomass. Grobbelaar et al. (2000) calculated that biofixation of CO_2 from a 300 MW thermo-electric coal-fired

Table 4. Productivity and utilization of PAR in outdoor open microalgal cultures saturated with flue or CO_2 gas.

Date	Daily PAR energy input ($W\,h\,m^{-2}$)	Flue gas[a]		CO_2 gas[b]	
		Daily net productivity ($g\,m^{-2}\,24\,h^{-1}$)	Utilization of PAR energy (%)	Daily net productivity ($g\,m^{-2}\,24\,h^{-1}$)	Utilization of PAR energy (%)
14–16 August	$2\,615 \pm 98$	22.8 ± 5.3	5.58 ± 1.28	22.6 ± 3.9	5.49 ± 0.89
27–29 August	$1\,787 \pm 323$	19.4 ± 4.8	6.94 ± 1.71	19.1 ± 9.8	6.88 ± 2.94

[a]Culture unit 55 m^2.
[b]Culture unit 224 m^2.

power plant would require an algal culture area of about 100 km^2. They concluded that conventional mass cultures of microalgae are not economically feasible to bind substantial amounts of CO_2 emitted from point sources.

Based on our results, it is possible to operate medium-size culture systems (e.g. in combination of biomethanation of agricultural wastes with production of microalgae), where the lowest emissions of greenhouse effect causing gases becomes a really achievable solution. An example of such a combined biotechnological process on a small farm-size unit is given in Figure 9. In this scheme, the carbon cycles terminate in two directions – via recycling of organic carbon containing solid residues from anaerobic fermentation to the fields as fertilizer, and via algal biomass to the

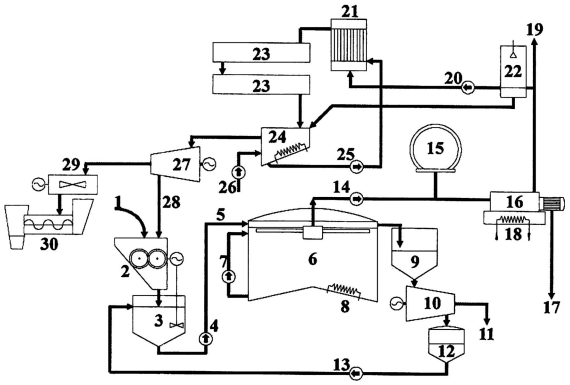

Figure 9. Farm unit flow sheet for production of biogas from organic agricultural wastes and for production of microalgae using flue gas. (1) waste inlet; (2) crusher; (3) homogenizer; (4) slurry pump; (5) feeding slurry; (6) anaerobic digestor; (7) mixing pump; (8) heating coil; (9) spent slurry; (10) centrifuge; (11) residue to composting; (12) waste water tank; (13) water pump; (14) biogas blower;(15) gas holder; (16) gas engine; (17) electricity; (18) waste heat exchanger; (19) flue gas outlet; (20) flue gas blower; (21) saturator; (22) quencher; (23) photobioreactor for algae cultivation; (24) retention tank; (25) pump for circulation of algal suspension; (26) aerating blower; (27) separator for algae; (28) waste water; (29) disintegrator; (30) animal food mixer.

Table 5. Specific emissions of CO_2 during production of electric power from various sources.

Energy source	Specific CO_2 emission ($kg\,CO_2\,MW\,h_{el}^{-1}$)	Power technology
Lignite	1850	Thermal power plant
Natural gas	662	Gas engine
Biogas	1067	Gas engine

livestock farming in the form of fodder supplements. Biogas generated in a 500 m^3 anaerobic digester can be utilized in a cogeneration unit producing about 40 kW of electricity. At the lower heating value of biogas, 22.225 $MJ\,m^{-3}$, about 21.6 $m^3\,h^{-1}$ of biogas must be supplied to the engine. This volume of combusted biogas corresponds to the production of about 1025 kg CO_2 day^{-1} in flue gases. Assuming that algae are grown, on average, 11 h daily, then $(11/24) \times 1025 =$ 470 kg CO_2 day^{-1} remains to be injected into the algal culture in the bioreactor. At a content of 47% carbon in algal biomass (DW), about 1.72 kg CO_2 is needed for biosynthesis of 1 kg (DW) of algal biomass. It can be seen in Figure 8 that 38.7% of CO_2 contained in flue gas was utilized for the biosynthesis of biomass so that about 4.4 kg of CO_2 in the flue gas was required for production of 1 kg dry algal mass. Therefore, 470 kg CO_2 in flue gas is sufficient to produce about 106 kg (DW) of biomass day^{-1}. At a mean net algae productivity of 20 g (DW) m^{-2} day^{-1}, the required size of the culture area is 5300 m^2. Thus, about 16 t (DW) of algal biomass can be produced in a culture season under mid-European climatic conditions, lasting approximately 150 days.

In another variant of the above scheme, the flue gas from a cogeneration unit is accumulated in a gas holder in the night when the bioreactor is not operated. The gas from the engine and from the gas holder is injected into the algal culture only during the daylight hours of cultivation. From the above values it can be calculated that the culture area for growing algae must be enlarged to 11650 m^2, yielding about 35 t (DW) of algal biomass over a culture season lasting 150 days.

Table 6. Specific emissions of CO_2 during production of electric power (gas engine) from biogas with various methods of CO_2 mitigation in algal culture.

	Specific emission (kg CO_2 MW h_{el}^{-1})	Decrease of CO_2 emissions (%)	Remarks
Biogas	1067	0.0	Without flue gas utilization
Biogas + algae without flue gas accumulation	878	17.7	Emissions in cult. season
	989	7.3	Annual mean value (cult. season 150 days)
Biogas + algae with flue gas accumulation	654	38.7	Emissions in cult. season
	897	15.9	Annual mean value (cult. season 150 days)

In this system, anaerobically generated CH_4, which is a greenhouse gas more potent than CO_2, is converted into utilizable energy and CO_2. Optimum flue gas injection into algal culture may be regulated by means of an infrared-analyzer measuring the bypass concentration of CO_2 in the gas phase, which is continuously equilibrated with carbon dioxide dissolved in the algal suspension. Specific emissions of CO_2 during production of electric power from various sources are compared in Table 5. Specific emissions of CO_2 during the production of electric power (gas engine) from biogas with various methods of CO_2 mitigation in algal culture are given in Table 6.

The impacts of flue gas utilization for the production of microalgae are as follows: partial decarbonization of the flue gas diminishes production of greenhouse CO_2; production costs of algal biomass could be about 15% lower (price of CO_2); due to high harvesting algal density, the algal biomass can be used fresh (without separation and drying – Kajan et al., 1991; Doucha and Lívanský, 1995, or dried – Kotrbáček et al., 1996; Kotrbáček and Doucha, 2000), as an additive to feed mixtures for animals.

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