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A new tubular reactor for mass production of microalgae outdoors

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Abstract

A novel reactor for outdoor production of microalgae is described. Air-lift is used for circulation of the culture in transparent tubes lying on the ground and interconnected by a manifold. Dissolved O_2 is removed through a gas-separator placed 2.0 m above the tubes and water-spray is used for cooling. The manifold permits short-run durations between leaving the gas separator and re-entering it, preventing thereby damaging accumulation of dissolved oxygen. Day temperature control in summer is attained using water-spray. In winter, temperature in the tubes rises rapidly in the morning, as compared to an open raceway even if placed in a greenhouse. The number of hours along which optimal temperature prevails in the culture throughout the year increased significantly. Very high daily productivity computed on a volumetric basis (e.g. 550 mg dry wt l^{-1} culture) was obtained and preliminary observations indicate that a significantly higher output, e.g. 1500 mg dry wt l^{-1} d^{-1}, is attainable. Much more research is required to assess the year-round, sustained productivity attainable in this reactor.

Introduction

Industrial reactors for mass cultivation of microalgae are at present nearly without exception all designed as open raceways. Essentially, these raceways are shallow ponds (water level ca. 15 cm high) covering each an area of 1000 to 5000 m^2 and constructed as a loop in which the culture is circulated by a paddle-wheel. This production mode has many disadvantages which relate to the factors governing outdoor productivity of photoautotrophic microorganisms (Richmond, 1991).

A major weakness of the open raceway is the relatively long light-path (ca. 15 cm, corresponding to the pond-depth) which mandates maintenance of relatively dilute cultures, e.g. cell densities at the range of 400 to 700 mg dry wt l^{-1}. Such dilute cultures pose difficulties in harvesting the algal biomass and in addition become rather easily contaminated. Adding to the relatively large running costs involved in maintaining a large volume of water with a low concentration of cells, water temperature cannot be readily controlled. This feature alone limits the usage of open raceways in many parts of the world.

The limitations of the open raceways result in an overall low annual productivity prompting the development of enclosed photobioreactors, i.e. reactors made of transparent tubes or containers, in which the culture may be circulated by various devices and the temperature is better controlled. The possibility for mass production of photosynthetic microorganisms in tubular systems rather than in the common open raceway has been pioneered by John Pirt and co-workers (1983), who proposed the theory and design for tubular photobioreactors. Gudin and Chaumont (1983) were the first to develop a tubular system expanding 100 m^2 for the cultivation of *Porphyridium* spp., and Florenzano and Materassi together with their coworkers pioneered the development of a tubular photobioreactor for the outdoor production of *Spirulina platensis* (Torzillo *et al.*, 1986). A very important advantage of the tubular photobioreactor over the open raceway is that temperature in the photobioreactor may be readily controlled: The optimal temperature for the microalgal species is reached early in the day by direct gain of solar heat and is thereafter maintained at the optimal level by water spray. At evening, the relatively low volume cools down quickly to the ambient night temperature, resulting in lower respiratory losses, as compared to the large volumes involved in the open raceway which cool slowly. Also, the diameter of the tubes, which must yet be optimized, corresponds to only a fraction of the height of the water column in an open raceway and the ratio of culture volume to illuminated area is therefore greatly improved. The pump to circulate the culture represents an integral part of any photobioreactor, and special attention should be given to ascertain that circulating the culture volume is carried out with minimal shearing forces. One difficulty in this respect concerning a screw-pump has been well documented recently (Gudin & Chaumont, 1991), and there is evidence that an air-lift which is used for our photobioreactor is superior to centrifugal or rotary displacement pump in supporting maximal growth rates in *Chlorella* (Pirt *et al.*, 1983).

In this report, we describe a novel tubular reactor for outdoor production of microalgae, the biological potential of which having been tested by monitoring the growth and productivity of *Spirulina* and *Anabaena* cultures.

Materials and methods

Strains and culture conditions

Spirulina platensis was grown in a modified Zarouk's medium (Vonshak, 1986) and the nitrogen-fixing rice field isolate cyanobacterium *Anabaena siamensis* in a medium described previously (Thomas *et al.*, 1992). The inoculum for the photobioreactor was grown in small open raceway ponds, as described by Boussibat *et al.* (1988). Following an initial two week period of growth in the reactor, cell concentration was maintained constant by daily harvesting of the biomass, using a 350-mesh screen for *Spirulina* cultures or diluting with fresh medium the *Anabaena* cultures. All nutritional requirements were supplied in excess in order to prevent nutrient limitation.

Productivity was estimated by daily measurement of biomass concentration. Dry weight of samples drawn out of the culture before and after harvest were determined according to Vonshak (1986). Chlorophyll content was determined according to Bennet and Bogorad (1973).

Photon flux was measured with a Li-Cor 185 photometer and a quantum sensor. O_2 concentration and temperature were measured in the culture using an Oxi-meter model 86, WTW, Germany.

Results and discussion

A. The reactor

The reactor features three main components: (a) an airlift pump, (b) gas-separator and (c) transparent reactor tubings running in parallel and connected by manifolds (Fig. 1). It thus represents an enclosed system in which the algal culture is circulated by an airlift.

An airlift is a low pressure, high volume water pump. Its maximal pressure differential is linearly proportional to the height of the riser (Fig. 1) and in efficient systems $\Delta P = 0.17\Delta H$; where

ΔP = pressure differential of airlift in cm H_2O or mb.

ΔH = vertical length (in cm), of the airlift riser, from the air injection point to the connection point of the degassing separator chamber (Fig. 1).

In a tubular reactor, the linear velocity of the culture circulated in the tubes has to be sufficient to ensure turbulent flow to prevent settling of algal cells and ensure a favorable light regime, condu-

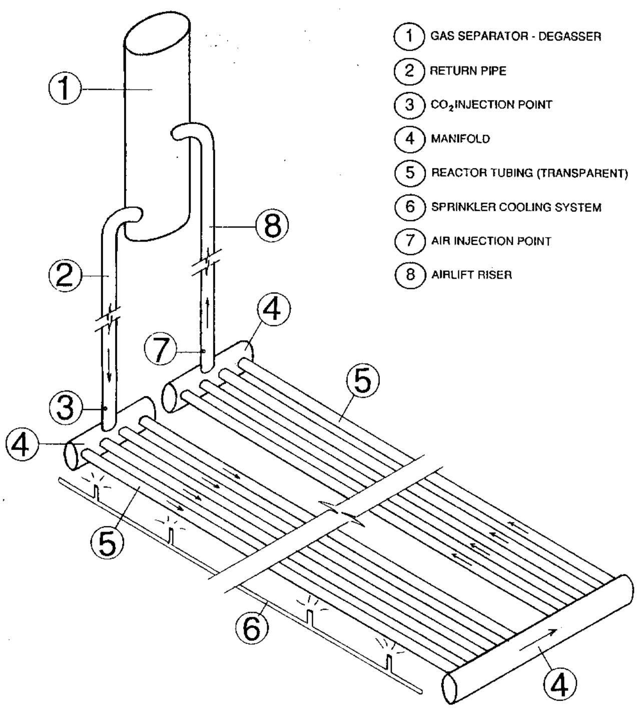

Fig. 1. Schematic diagram of the reactor (not to scale).

cive to intensive photosynthesis. At the same time the gas exchange requirements of the culture must be treated. Two related factors thus need attention: (1) The Reihnold Number (N_R) in the reactor; (2) The run duration (in seconds) between aeration stages.

The N_R manifests itself as a specific linear velocity of the culture for any reactor configuration and viscosity. The run duration is dependant on the linear velocity and the distance between aeration stages. Run duration rather than the run distance is chosen because CO_2 depletion and O_2 formation are time dependent under given environmental conditions. The product of the linear velocity and run-duration dictates in turn the maximum length of reactor tubing between aeration points. Cost considerations concerning the reactor design indicate that it is advantageous to maximize this length, but any increase in length in a single loop system requires a linear proportional increase in pressure differential, i.e. the height of the airlift tower and a corresponding increase in the supplied air pressure. For example, for a 5-m high airlift system, the expected attainable pressure differential is 85 mb. Assuming that the minimum required linear velocity is 35 cm s^{-1} then for a 30 mm inner diameter tube and using the Hazen Williams equation (Albertson & Simons, 1964), the pressure drop is 5.4 mb per 1000 cm tube length. The total length of the loop should therefore not exceed 160 m, as follows:

$$\frac{85 \text{ mb}}{5.4 \text{ mb}} \cdot 1000 \text{ cm} = \sim 160 \text{ m}.$$

Local pressure losses of 10% will require a further reduction of the workable length to ca. 145 m. In addition, the rise in the viscosity of the culture as the algal population density increases, accompanied by increased production of gas and formation of bubbles, requires that the hydraulic resistance calculated for water will be raised by 30 to 50% to accommodate algal cultures. Clearly, the velocity of the culture medium decreases with the increase in cell concentration and the designed velocity should thus be further increased by 15 to 20%. The sum total of all these considerations reduce the desirable length of a single loop to about 100 m.

The duration of the run at a linear velocity of 35 cm s^{-1} for one 100-m loop is about 5 min. This may be too long because of O_2 concentration buildup. Considering the design cost, longer loops and higher velocities would be advantageous, but longer loops require higher airlift devices and, due to higher required air pressure, a switch over from the more efficient rotary (air) blower to the more costly and less suitable piston air compressors.

To reduce this constraint, a Parallel Flow Tubular Reactor (PFTR) that uses manifolds to connect several loops in parallel, has been devised. The model (Fig. 1) has an airlift pipe (5.0 cm O.D, 4.6 cm I.D) which is 2.22 m long between the point of air injection and the out flow to the gas-separator. The latter is 20 cm in diameter (18 cm ID) and 80 cm high with a 20 l capacity. The reactor pipes are thin walled tubing extruded of transparent polycarbonate (3.2 cm O.D, 3.0 cm I.D), coextruded with U.V resistant outer coating (Polygal – Ramat Hashofet, Israel). Four such pipes, each 20 m long, were connected in parallel to a manifold made of 63 mm (O.D) black polyethylene irrigation tubing and standard saddle connectors.

The culture flows down from the separator via one 50 mm pipe (Fig. 1, 2) to the manifold (Fig. 1, 4) which distributes the culture among four, 32 mm in diameter, pipes, 20 m long, with 3 cm space between pipes (Fig. 1, 5). At the far end these pipes connect to a similar manifold with 8 openings: 4 for incoming pipes and 4 for the outgoing pipes which run back for another 20 m (parallel to the outgoing pipes) to the airlift riser and gas-separator.

This system was tested for hydraulic characteristics and robustness. Linear velocity of water could be elevated up to 50 cm s^{-1}. Only small differences in flow rates were measured in the parallel tubes and all gas bubbles entering the reactor were removed by the flow.

The flow characteristics changed when the microalgal culture became dense (e.g. 1.5 to 2.0 g dry wt l^{-1}). Trapped gas bubbles lower the attainable velocity and increased the variations in flow velocity between parallel tubes. These changes were thought to be due to increased viscosity in the culture and accumulation of O_2 bubbles. Gas trapped in the tubes indicates the system is not adequately optimized – either the viscosity should be reduced by diluting the culture or the flow rate accelerated.

An important advantage of the parallel flow tubular reactor is recognized at the scale-up stage; each major component of the reactor (airlift station, gas-separator, reactor tubes) may be sized up separately. One large separator can serve several high capacity airlift devices, each one combining several loops connected in parallel. One central air blower can easily serve several systems, each one consisting of tens or hundreds of airlift installations.

B. Biological performance of the system

Algal cultures

The growth performance of two species of cyanobacteria, *Spirulina platensis* and *Anabaena siamensis*, were tested in the new reactor. Both species are filamentous and mesophilic, having a similar optimal temperature for growth (37 °C and 42 °C for *Spirulina* and *Anabaena*, respectively). These were inoculated at an initial concentration of ca. 100–200 mg dry cell mass per liter, and the increase of biomass was assessed by daily monitoring the chlorophyll concentration, the turbidity and the dry weight (dw). When biomass concentration reached 2 g l^{-1} (end of ~ logarithmic phase), the culture was maintained at a semicontinuous mode by daily dilutions of 30 to 40% of culture volume, replacing it by the same volume of fresh culture medium.

Oxygen removal

The accumulation of dissolved oxygen represents one of the major obstacles for growing algae in closed photobioreactors. Supersaturated oxygen concentrations may be readily reduced in an open pond through diffusion to the atmosphere, accelerated by the action of the paddle wheel. In the closed photobioreactor, O_2 does not escape except in the degasser and there is a tendency for a quick O_2 buildup, particularly when photosynthetic rates are higher. The high O_2 concentration may in turn impose a severe impediment to productivity, causing inhibition to photosynthesis. In extreme conditions photooxidative death may take place. Using an air-lift device seems to provide not only an efficient way of inducing convective mixing in the reactor but also a simple and efficient means for removal of super saturated oxygen via the degasser. Typically, O_2 concentration measured at the inlet to the air-lift system was found to have reached a concentration of 18 mg l^{-1}, whereas at the outlet the concentration was only 10.5. These measurements were carried out at noon time, when O_2 concentration reached peak values.

Temperature control

The optimal day temperature of the culture was readily maintained in the tubular reactor. Typically in the summer, the temperature was kept at its optimal range (35 to 37 °C for *Spirulina*) from 1000 to 1800, i.e. during most of the light period. In contrast, temperature in the open raceways never reached under our conditions the optimum for *Spirulina*. In open raceways placed in a greenhouse the temperature did reach the optimal but prevailed only between 1400 and 1600 (Fig. 2) i.e. for only two hours during day light. The most pronounced effect in the rate of heating took place in the morning: while the rate of increase in temperature was ca. 2 °C per hour in the open raceway and 3 °C in the green house, in the tubular reactor the cultures were heated at the rate of 6.5 to 7.0 °C h^{-1}, i.e. twice as fast.

The effect of the temperature difference between the open raceway and the tubular reactor was particularly evident in *Anabaena siamensis* cultures, with an optimal temperature of 42 °C. Such a high temperature was never reached in the open raceway, and even in warm summer days, the typical temperature difference between that maintained in the enclosed reactor and the temperature in open raceway was often as high as 10 °C at noon. The potential of the tubular reactor for the production of high-yielding thermophiles (Sorokin, 1959) is clearly evident.

Evaluating productivity

Comparing the productivity in terms of dry biomass per volume of *Anabaena siamensis* in different culturing methods, the advantage of the tubular system over open raceways becomes ever so evident: whereas in the open raceways outdoors the daily output rate averaged 86 mg of dry wt l^{-1} culture (Reactor I, Fig. 3), it was some six times higher (550 mg dry wt l^{-1}) in the tubular reactor of the smallest diameter experimented with (Reactor V, Fig. 3).

As expected in a light-dependent system, the smaller the tube diameter the higher the productivity on per volume basis. Indeed, optimization of the tube diameter represents an essential target for future research, to determine the tube diameter which yields the best results year round: first, as tube diameter decreases and cell number per volume increases, the viscosity of the culture together with density effects not related to mutual shading exert new limitations on growth in addition to the limitation imposed by light. Secondly, each algal species may respond differently to tube diameter. In preliminary experiments with *Isochrysis galbana*, a species adaptable to relatively high population densities, output rates as high as 1500 mg dry wt l^{-1} d^{-1} were obtained in a tu-

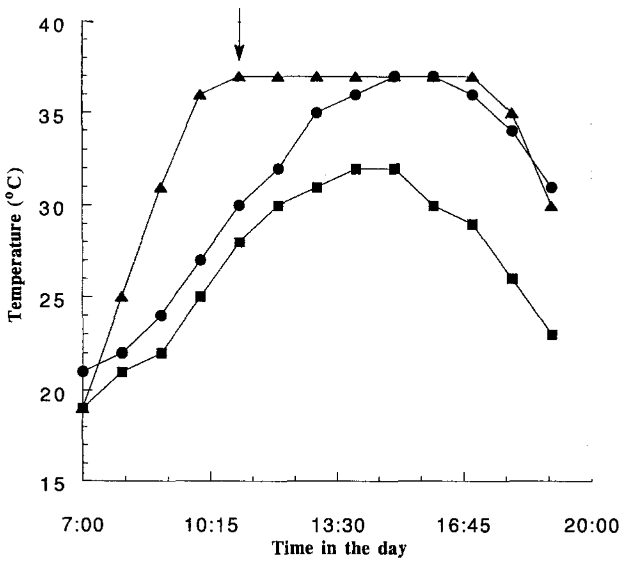

Fig. 2. Daily changes in temperature of *Spirulina* cultures grown outdoors in: ■ open raceway; ●open raceway in greenhouse; ▲ the tubular reactor.

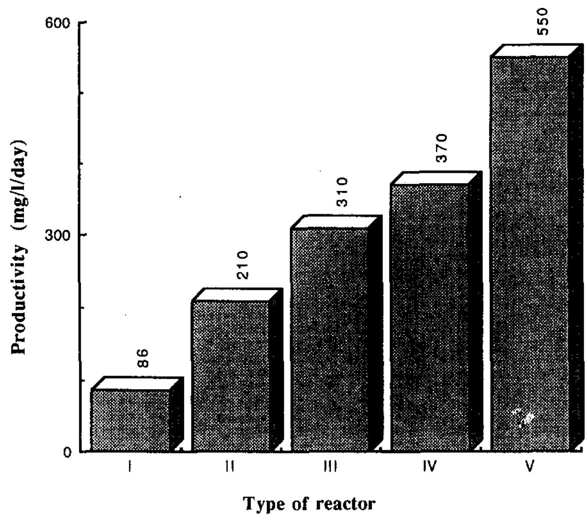

Fig. 3. Productivity obtained in several reactor types:

I. Open raceway, 300 l capacity, 15 cm high.
II. Open raceway, covered with polyethylene.
III. Tubular reactor, 5.0 cm diameter.
IV. Tubular reactor, 3.2 cm diameter.
V. Tubular reactor, 2.8 cm diameter.

bular reactor made of glass tubes 28 mm inner diameter.

Although the productivity attained with tubular reactors represents a breakthrough when computed on volume basis, it should be born in mind that when productivity of the various production modes is compared on areal basis, i.e. the illuminated area, the production range is rather similar for all reactor types, falling within the limits of 15 to 30 mg dry wt m^{-2} d^{-1}.

Comparing culture performance of the new tubular reactor with the well established open raceways, it should be born in mind that the overall sophistication reflected in the protocols employed for maintaining open systems has been acquired through many years of optimization studies. Much more research must be carried out with tubular reactors before the maximal, year-round productivity potential may be accurately assessed.

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