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Light energy supply in plate-type and light diffusing optical fiber bioreactors

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Abstract

The light distribution profiles of plate-type photobioreactors were investigated. Light reaching individual channels of a plate module is dependent on the orientation of the module to the sun, the position of the channel within a plate and the position of the plate. The highest incident radiation was measured at the south oriented side of the first channel of the front plate. The light intensity decreased from top to ground channels. Different types of light diffusing optical fibers (LDOF) were characterized with respect to their applicability in photobioreactor systems.

Introduction

The most widespread industrial microalgal cultivation system currently in use is the open raceway pond (Becker, 1981; Weissman *et al.*, 1987). Its low volumetric productivity of about 0.08 g L^{-1} d^{-1} (Pulz, 1992b) is due to the rapidly decreasing light supply with increasing culture depth and density, which can be counteracted to a certain degree by effective mixing though this is technically and economically difficult. Moreover, open systems are open to contamination by biological and non-biological materials. The specific disadvantages of open reactor systems led to the development of closed photobioreactors (Lee, 1986).

If light energy is to be available continuously to the cells, a lamination of the reactor directed to the light source seems to be the best solution. This basic principle of the laminar concept for photobioreactors is practiced by plants. On the basis of these considerations the development of tubular photobioreactors (Gudin & Chaumont, 1991; Tredici & Materassi, 1992) and plate-type photobioreactors (Tredici *et al.*, 1991; Pulz, 1992a) have been reported. Compared with plate-type systems, tubular systems seem to have identical configuration potential and high surface to volume ratio, but some disadvantages in respect to compactness (turnings of 180 degrees, wall thickness).

Recently, a concept of supplying light to dense algal cultures by light diffusing elements was introduced (Mori, 1985; Matsunaga, 1991). The aim of this paper is to provide some results on light penetration and distribution in plate-type reactors oriented vertically and using light diffusing optical fibers.

Materials and methods

Plate-type photobioreactors (PBR)

For investigating outdoor plate-type photobioreactors, 500- and 6000-liter devices consisting of plate modules and made from polyacrylic polymers (Fig. 1) were used. A plate module consisted of two parallel transparent plastic plates 25 mm apart and leakproof from all sides. Internal structures formed horizontal channels which caused the fluid to move on an alternating path through the module. The 500-L device was oriented from east to west and the temperature was adjusted to 25 °C, while the 6000-L plant was orientated from north to south at ambient temperature. The equipment was situated near Potsdam, Germany, and exposed to

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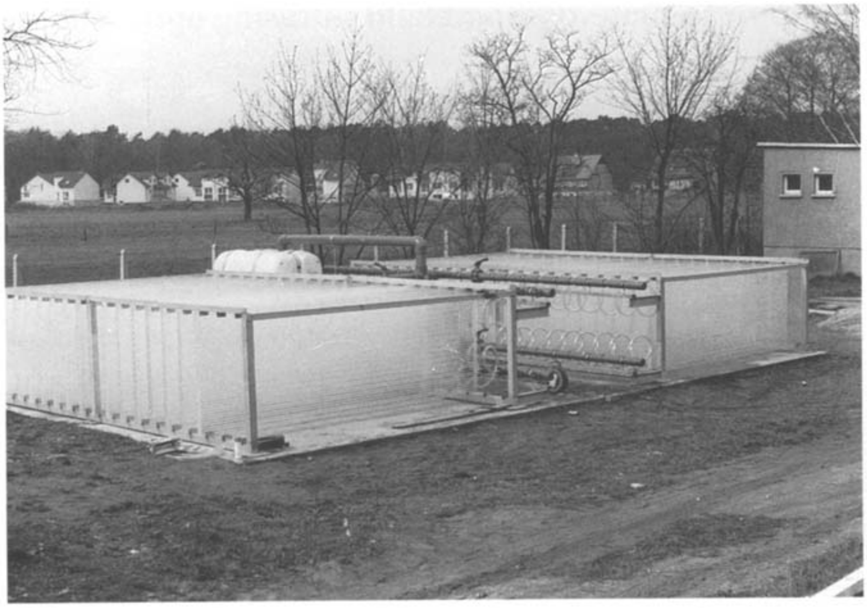

Fig. 1A.

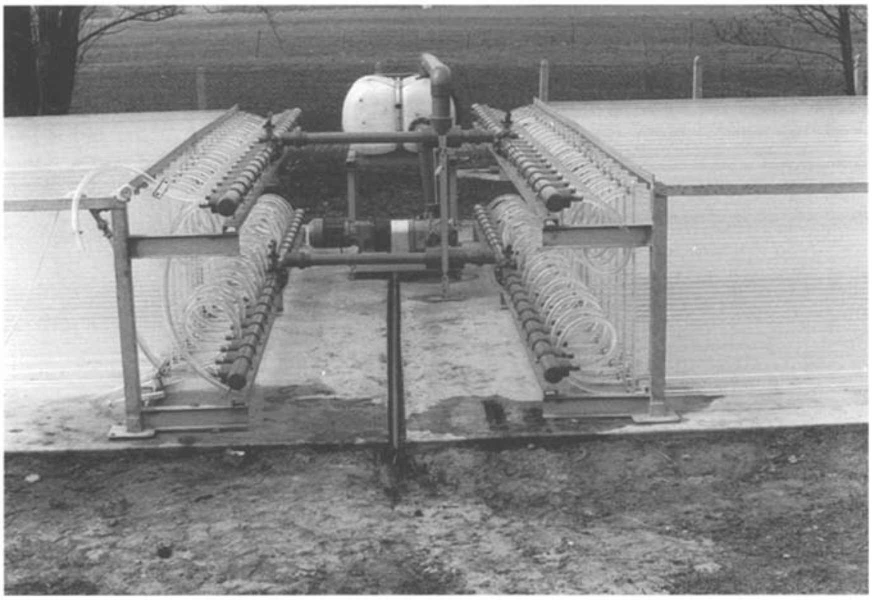

Fig. 1B. Fig. 1. Plate type photobioreactor PBR 6000.

the prevailing climatic conditions. Photon irradiance was measured at the plate surfaces.

Light measurements for PBR

For the determination of the incident light intensity, a LICOR LI 189 quantum meter (with a LI-190SZ or a LI-192SA quantum sensor) and a WPI SD 1000 fiber optic spectrometer calibrated for measuring photon irradiances were used. The devices integrated the photosynthetically active radiation between 400 and 700 nm.

If not stated explicitly, all measurements were made perpendicular to the reactor plane and fiber axis, respectively.

Light diffusing optical fibers (LDOF)

Two basic types of light diffusing optical fibers were used. Type A was made of a combination of synthetic materials, coated with polyfluorated polymer. It was available in two diameters of 5 and 10 mm. The fibers were stable up to 200 °C and autoclavable. Type B of light diffusing optical fiber was made of polymethylmethacrylate (PMMA) and unsuited to thermal sterilization. The fiber had a diameter of 0.7 mm. To cause light emittance, type B fiber had to be roughened with emery paper.

Light measurements for LDOF

To determine at which angles the light was emitted from a point on the type A LDOF, a fiber optic sensor was used. The fiber optic sensor registered radiation only from a small area around it. The detection sensor was positioned at 4 cm from the LDOF with the projection of its middle axis directed to the point to be characterized. The angle of the sensor to the LDOF was then changed within the plane of the LDOF (angle α) while keeping the distance of the sensor constant. The following definition was applied: $\alpha = 0$ °: detection fiber oriented parallel to the light propagation direction in LDOF, $\alpha = 180$ °: detection fiber oriented in opposite direction.

Light sources

The plate-type reactors were exposed to natural sunlight. The optical fibers were lighted by an Osram 400 W (24 LL) metal vapour lamp using a projector.

Results

Plate-type photobioreactors

Natural sunlight profiles at the surface of PBR 500 are depicted in Fig. 2, which represents the incident irradiance at the sun-oriented side of the four plates at noon of a cloudy day providing diffuse illumination. The position on the respective plate is indicated by the channel number with channel 1 being at the top of the plate module and channel 38 at the bottom.

The most interesting finding is the sharp decrease of incident light measured at the surface of the shadowed plates (plate 2–4) which were situated behind the front plate. To reduce such sharp gradients at noon, the PBR 6000 was placed at north to south orientation. The effect of the change in orientation of the bioreactor is presented in Fig. 3 which shows the ratio between

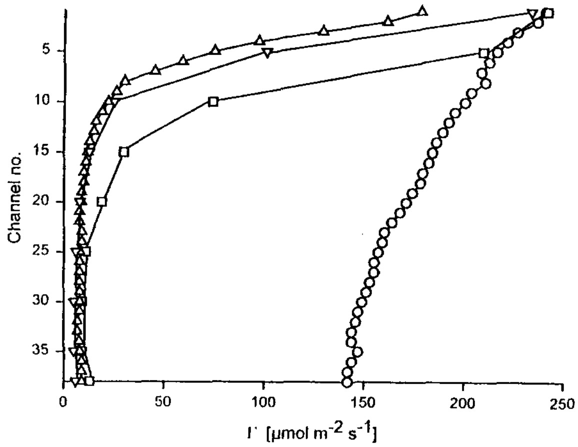

Fig. 2. Diffuse irradiance (Γ) incident on front side of photobioreactor PBR 500 plate modules related to the channel position (channel 1: top, channel 38: bottom of the module). Plate 1, ○; Plate 2, □; Plate 3, △; Plate 4, ▽.

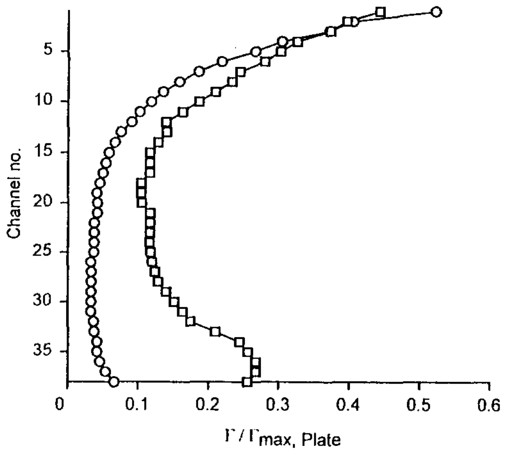

Fig. 3. A plot of irradiance (Γ) of the rear sides of the first plate of PBR 500 (○) and PBR 6000 (□), normalized to maximum irradiance of the respective front side ($\Gamma_{maxplate}$) related to channel position. PBR 500 plate axe was placed east-west whereas PBR 6000 plate axe was oriented north-south.

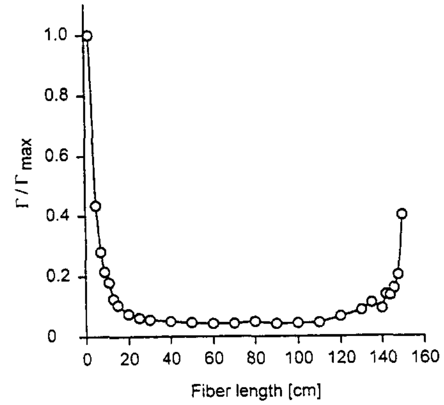

Fig. 4. A plot of photon irradiance (Γ) normalized to maximum photon irradiance (Γ_{max}) against fiber length of a type A fiber measured in air at the fiber surface.

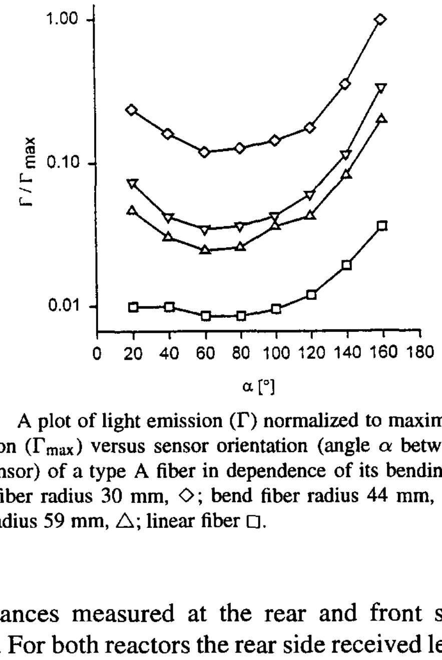

Fig. 5. A plot of light emission (Γ) normalized to maximum light emission (Γ_{max}) versus sensor orientation (angle α between fiber and sensor) of a type A fiber in dependence of its bending radius. Bend fiber radius 30 mm, ◇; bend fiber radius 44 mm, ▽; bend fiber radius 59 mm, △; linear fiber □.

irradiances measured at the rear and front sides at noon. For both reactors the rear side received less than 50% of the front irradiance. The decrease in irradiance from top to bottom channels was however smaller for PBR 6000 than for PBR 500, due to the reduced self shadowing of PBR 6000 plates in north/south orientation. The establishment of a reflecting ground layer in the case of PBR 6000 led to an additional increase in irradiance for the bottom channels.

Light diffusing optical fibers

Figure 4 shows the normalized irradiance versus fiber length (z) of a 10 mm type A fiber measured in air at the fiber surface. The irradiance decreased rapidly over the first 25 cm. This was followed by a sector of constant emittance. At the end of the fiber the irradiance increased again.

The total irradiance was derived from measurements at various angles to the fiber axis. It was especially noticed that the irradiance was not isotropic but showed a maximum at $\alpha = 160$ °. By numerical integration of the measurements at different angles, a photon irradiance of 12 μmol m^{-2} s^{-1} for a single linear 10 mm type A fiber at $z = 70$ cm was estimated. The emitted light could be enhanced by bending the fibers (Fig. 5). The change from a linear to a bent configuration with type A fiber caused considerable increase in total emitted photon irradiance.

For type B fiber the emission also depended on the roughness of the surface. The average photon irradiance measured at the fiber surface was about 60 μmol m^{-2} s^{-1}.

Discussion

At high algal cell density light is attenuated to an extent that even suspension layers of few centimeters can be light limited. The only way to avoid such limitation is to reduce the suspension layer as far as practically possible. One method to realize this principle is the use of plate-type photobioreactors with suspension layers in the range of a few centimeters. As was shown by light intensity measurements, the reactors received sufficient light even under the rather unfavourable climatic conditions in Germany, leading to a biomass productivity of about 1.3 g L^{-1} d^{-1} (Pulz, 1993). This value is considerably higher than that obtainable with raceway ponds (0.08 g L^{-1} d^{-1}) or conventional tubular reactors (0.26 g L^{-1} d^{-1}) (Gitelson, 1990; Tredici *et al.*, 1991).

The light reaching individual channels of a plate module depends on the orientation of the module to the sun, the position of the channel within a plate and the position of the plate. The highest incident radiation was measured at the south oriented side of the first channel of the front plate. The light intensity decreased from top to ground channels. The decrease in light intensity was nearly linear for the first plate but decreased exponentially for plates located behind the first one. This was caused by shadowing of the plates. The north/south orientation of the plates in PBR 6000 resulted in an increase in diffuse and reflected light. Diffuse and reflected light reaches all plates and is therefore much more important than direct light incident mainly on outer plates. Correspondingly algal cultures in PBR 6000 grew better than in PBR 500, although PBR 6000 was not operated at optimum temperature (data not presented).

However, both tubular and plate-type PBR have two major disadvantages: they cannot be sterilized and are incompatible to generally available industrial fermentation equipment.

A promising approach to overcome these obstacles is the use of light-diffusing optical fibers. LDOF can transmit light into compact culture systems. This investigation has shown that the selection of fiber type/material as well as the geometric design are crucial for the success of this approach. Measurements of light emission along fiber length revealed that for the first 25 cm, light, especially longer wavelengths, left the fiber. For the middle part of the fiber length, an equilibrium was established, where the emittance was constant and low. To the end of the fiber, emittance increased again, probably caused by back reflection of light from the end which was not perfect planar. The fact that the light emission can be enhanced considerably by bending the fibers provides a tool for technical applications. The search for an appropriate fiber configuration is going on.

So far the major disadvantage of type A fibers is their large diameter, thus occupying large cultivation space. Type B fibers have to be roughened at the surface in order to reach sufficient light emittance. Furthermore, type B fibers cannot be thermally sterilized and tend to attract algal growth on the roughened surface. These fibers led to rather disappointing results in growth experiments.

These studies on LDOF are still in the beginning; there are many parameters to be optimized, such as the coupling of light source and LDOF and the improvement of the LDOF themselves. In respect to the latter a very promising new generation of quartz-glass based LDOF is currently under investigation. It is reasonable to expect that medium and long term LDOF studies will provide a new generation of photobioreactors, allowing economical processes for the production of high-value algal products.

Acknowledgments

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