(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
28 July 2005 (28.07.2005)

PCT

(10) International Publication Number
WO 2005/068605 A1

(51) International Patent Classification[7]: C12M 1/00

(21) International Application Number:
PCT/NL2005/000025

(22) International Filing Date: 14 January 2005 (14.01.2005)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
04075110.9 16 January 2004 (16.01.2004) EP

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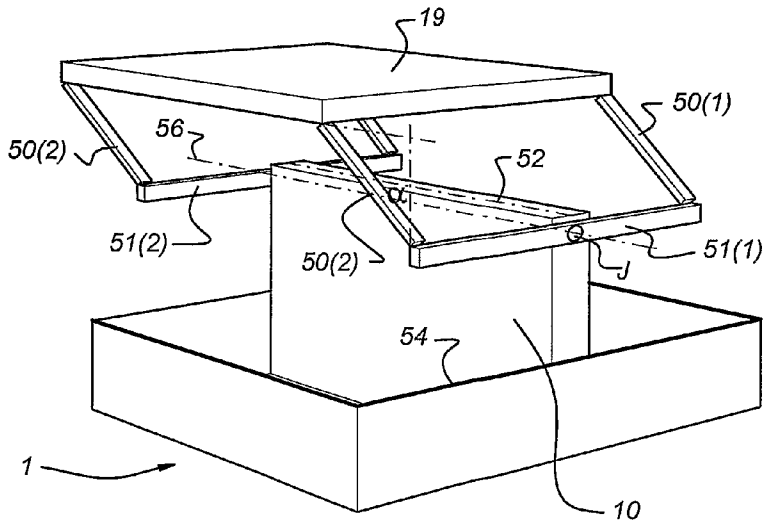
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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, MC, NL, PL, PT, RO,

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(54) Title: REACTOR AND PROCESS FOR THE CULTIVATION OF PHOTOTROPHIC MICRO ORGANISMS



(57) Abstract: This invention describes a reactor for cultivating phototrophic micro organisms, wherein the sunlight is introduced in compartment walls (10) by using one or more moveable collimators (19). The compartment walls (10) are transparent and from there light is distributed into the reactor. Such a reactor has an improved collection of radiation and an improved distribution of the radiation into the reactor, thereby providing a more efficient reactor and a more efficient cultivation of phototrophic micro organisms.

WO 2005/068605 A1

SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report*

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

Reactor and process for the cultivation of phototrophic micro organisms

Field of invention

The present invention is related to a reactor and a process for the cultivation of phototrophic micro organisms.

Prior art

Algae, belonging to the class of phototrophic micro organisms, are organisms that can efficiently convert sunlight into biomass. Most of the systems used to cultivate micro-algae are shallow ponds. In these ponds, micro-algae can be cultivated with an efficiency of about 2% of sunlight in the PAR region only. PAR is the photosynthetic active region, i.e. sunlight with a wavelength between 400 and 700 nm. The energy content of sunlight in the PAR region is about 43% of the total energy content of sunlight. Algae can theoretically convert about 20% of the collected radiation (within PAR) into biomass. However, in most cases, this efficiency is lower because light is absorbed in a much higher rate than the rate in which photons can be converted into biomass.

Most of the, for the micro-alga, lost energy is dissipated as heat. The efficiency of systems in which micro-algae convert radiation of the sun into biomass can be increased by using flat-plate glass reactors. Such reactors are for example known from Singh et al., Journal of Applied Phycology 12: 269-275, 2000, from Usui, Energy Convers. Mgmt, vol. 38, Aupple., pages 487-492, 1997. The photochemical efficiency of photobioreactor systems, especially of the flat-plate glass reactor, can reach about 16%, which is much higher than those of micro-algae in ponds. However, the flat plate glass reactors known from the state of the art have still some disadvantages, for example that not all radiation of the sun is converted into biomass efficiently, or that the energy within the system is not used economically. A reactor for a photosynthetic culture is also known from Kondo et al., US6287852. A disadvantage of this reactor is the use of fixed collectors, which means that during most of the time, radiation of the sun is not collected efficiently.

Summary of the invention

It is an object of the invention to provide an improved reactor for the cultivation of phototrophic micro organisms such that sunlight is converted more efficiently into biomass. In a further aspect of the invention, it is an object to provide a process for the cultivation of phototrophic micro organisms in which sunlight is more efficiently converted into biomass.

According to the invention, there is provided a reactor for the cultivation of phototrophic micro organisms comprising:

one or more compartments suitable for containing a liquid comprising an phototrophic micro organism culture,

an inlet for supplying a CO_2 comprising gas flow to the one or more compartments,

an outlet for removing gas from the one or more compartments,

a means for regulating the temperature of the phototrophic micro organism culture, and

one or more irradiance collector assemblies for collecting radiation and distributing at least part of the radiation to the one or more compartments, wherein the one or more irradiance collector assemblies provide radiation into one or more compartment walls of the one or more compartments, and wherein the one or more compartment walls are transparent for the radiation, and wherein the irradiance collector assembly comprises

a lens;

a means for rotating the lens around a first axis which is substantially parallel to the top surface of the compartment wall; and

a means for moving the lens in a direction parallel to the top surface of the wall.

Collimators may comprise (spherical) mirrors, (Fresnel) lenses or both. Collimators may be fixed or adjustable over one or more axes. In an embodiment, the invention is directed to a reactor wherein the one ore more irradiance collector assemblies are adjustable to track the incoming radiation, thereby providing an optimised amount of radiation to the one or more compartments wall present in the reactor. Further, the reactor may be a reactor wherein the reactor comprises a means for rotating the reactor

to track the incoming radiation. For example, the reactor or a combination of more reactors may be equipped with means for rotating over a horizontal axis.

Hence, in an embodiment there is provided a reactor wherein the irradiance collector assembly comprises one or more base members and one or more side members connecting the one or more base members and the one or more lenses. This assembly may be pivotable around rotation points present on the first axis (virtual axis). These rotation points may be connection to the one or both sides of a wall, wherein these sides are the substantially vertical edges. In this way, the assembly may be rotated to a position over the wall, or to a position offset from the wall, to one of the sides of the wall directed to the liquid. The rotation angle that can be provided may be between about 90° (lens(es) substantially parallel to one of the surfaces of the wall directed to the liquid) and -90° (lens(es) substantially parallel to the other surface of the wall directed to the liquid). Preferably, the rotation angle is at least between about 45 and 0°, more preferably between at least about 80° and 0°, even more preferably between at least about -45 and 45°, and yet more preferably between at least about -80° and 80°. The selection of the rotation freedom may be dependent upon the degree of latitude where the reactor is used. The first axis is preferably a substantially horizontal axis, parallel to the top surface of the wall (in the length direction).

In yet a further embodiment, there is provided a reactor wherein the length of the one or more side members as mentioned above is chosen such that a distance of the lens(es) to the top of the wall is provided substantially equal to the focal length of the lens(es). For example, there is provided a reactor wherein the length of the one or more side members is chosen substantially equal to the focal length of the one or more focal lenses for radiation parallel to the one or more side members. Preferably, the length of the one or more side members as mentioned above is chosen substantially equal to the focal length of the one or more focal lenses for radiation parallel to the one or more side members, wherein the radiation is radiation having a wavelength in the range of 400 to 700 nm. This results in an efficient coupling of the radiation into the wall. The distance between the lens, or plurality of lenses, and the top of the wall can be varied maintaining the focal line on the top of the wall. Alternatively, the focal length of the

lenses may be varied, thereby compensating differences in distance between the lens and the top of the wall.

The assembly also provides the function of moving the lens in a direction parallel to the top surface of the wall. To this end, the one or more side members may be connected by a hinge or a means for hinging to the base member and to the lens or plurality of lenses. In this way, an efficient tracking of the sun can be provided by a rotation movement and by a translation movement. The translation angle between side member and substantial vertical edge of wall 10 may be between about 90° and -90°, preferably between at least about -45° to 45°, more preferably between at least about -80° and 80°, thereby enabling a tracking from sunrise to sunset.

Such a reactor has an improved collection of radiation and an improved distribution of radiation into the reactor, thereby providing a more efficient reactor and a more efficient cultivation method for phototrophic micro organisms. Next to collection by irradiance collector assemblies, radiation may also directly enter the reactor through reactor walls.

Phototropic micro organisms comprise micro algae, but also other species that can convert radiation of the sun into biomass like for example photosynthetic purper bacteria. In this invention, phototropic micro organisms comprise at least the cyanobacteria, the Rhodophyta (red algae), the Chlorophyta (green algae), Dinophyta, Chrysophyta (golden-brown algae), Prymnesiophyta (haptophyta), Bacillariophyta (diatoms), Xanthophyta, Eustigatophya, Rhaphidophyta, Phaeophyta (brown algae) and photosynthetic purper bacteria. However, phototropic micro organisms according to this invention may also comprise cell cultures of other organisms like e.g. micro algae, genetically modified micro algae, genetically improved micro algae, etc..

Radiation to the compartment walls can be provided with one or more irradiance collector assemblies. Here, an irradiance collector assembly comprises collimators, hence, each of the one or more irradiance collector assemblies may comprise a collimator. A collimator is a mirror, which can be curved, or a positive Fresnel lens, which can be used to concentrate light in a beam, or focus the light in a focus point or

focus line. The radiation will be introduced in the compartment walls by using on ore more fixed or moveable collimators. In general, radiation will be collected from sunlight. Hence, radiation comprises sunlight or part of the radiation of the sunlight; and the irradiance collector assemblies will therefore usually be solar irradiance collector assemblies. Therefore, the invention is directed to a reactor, wherein an irradiance collector assembly comprise a collimator. This may be a reactor comprising collimators, wherein collimators comprise flat or curved mirrors or wherein collimators comprise cylindrical lenses or cylindrical Fresnel lenses.

In an embodiment, the invention is directed to a reactor wherein one or more compartment walls comprise a Fresnel pattern, the Fresnel pattern directing the light from the compartment walls into the one or more compartments. In this way, the phototrophic micro organism culture in the liquid is efficiently irradiated by radiation in a radiation zone along the transparent compartment walls. A compartment will usually comprise at least two transparent compartment walls, which may be shared with other compartments. The Fresnel patterns may be configured in such a way, that light is only transmitted to the liquid phase and not to the gas phase (above the liquid phase in the compartment), employing the difference in index of refraction of the media.

In a specific embodiment, the invention is further directed to a reactor wherein the one or more irradiance collector assemblies and/or the one or more compartment walls comprise a means for converting at least part of the radiation to radiation with a predefined wavelength range. This means may be provided on the irradiance collector assembly, e.g. on the collimators. This means may also be provided on the compartment walls, or in the compartment walls. The person skilled in the art may choose one or more items of the reactor for providing the means for converting at least part of the radiation. The means for converting at least part of the radiation to radiation with a predefined wavelength range may comprise a coating, a particle layer, one ore more layers of foil, a fiber, etc. The means comprises luminescent materials like down or up converters or both. Such luminescent materials may absorb e.g. IR radiation, and convert this to visible radiation (up conversion), that can be absorbed by the phototrophic micro organisms. The luminescent materials may also absorb UV radiation and convert this radiation to visible radiation (down conversion). Depending

on the properties of the materials like absorption, reflection, conversion properties, they can convert IR or UV or both to visible radiation, or to radiation that is more efficiently converted by phototrophic micro organisms (e.g. PAR) and less radiation is dissipated as thermal energy. Such means may comprise organic compounds and/or doped inorganic matrices with the required luminescent properties.

In another embodiment, the invention is directed to a reactor wherein the means for regulating the temperature of the phototrophic micro organism culture comprises a channel in contact with the one or more compartments, means for providing a second liquid at a predetermined temperature to the channel and means for cooling and/or heating the second liquid. Such a means can be used to control the temperature of the compartments of the reactor, of liquid comprising the phototrophic micro organism culture, or both, at the optimum cultivation temperature of the phototropic micro organisms, which is typical about 20-35 °C, depending on the type of phototropic micro organisms (like algae), in special cases even up to about 65 °C and higher, but can also be used for dissipation of excess heat (not al photons are converted into biomass, leading to some excess heat).

In a specific embodiment of the invention, the invention is directed to a reactor wherein the inlet for supplying a CO_2 comprising gas flow further comprises one or more movable baffles comprising one or more channels, wherein the baffles may be parallel or substantially parallel to the compartment walls. One or more channels for the distributors for the CO_2 comprising gas may be integrated in the baffles. When the distributors for the CO_2 comprising gas are located at the correct location in respect to the baffles, it has the effect of an airlift pump. Liquid is sucked from under the baffle, mixed with gas, leaving from the distributor and the liquid and gas mixture move upwards. At the top of the baffle, the mixture separates and subsequently liquid returns in the compartment (to the other side of the baffle) in a continuous or semi continuous process. In this way, the residence time of the phototrophic micro organisms in the light zone, located in the vicinity of the one or more illuminated compartment walls can be controlled. This can further be controlled by varying the flow rate of the CO_2 comprising gas and or by varying the position of the distributors and or by varying the distance between the baffle and the compartment wall. This distance is indicated as first

distance, and is the shortest horizontal (parallel to the surface of the liquid) distance between the baffle and compartment wall providing the closest radiation zone.

Further, the reactor may comprise inlets for electrodes (CO_2, T, turbidity sensor, dissolved oxygen, etc.) which can be used by a controller to regulate the light entrapment, temperature control, pH control, an inlet for supplying a phototrophic micro organism culture to the one or more compartments, and so on, and thereby providing optimised conditions for the reactor.

Distributors (and or baffles) may move or may be moved such that this distance (distance between the baffle and the compartment wall; first distance) varies, however, distributors and or baffles may also be movable in height (movement parallel to one or more compartment walls). For example, this may be achieved by providing the baffles with drifting means, whereby the height of the baffles is adapted to the height of the liquid. The distributor may comprise one or more porous or perforated channels, permeable for CO_2, but substantially not permeable for the liquid of the compartment.

In a further embodiment, the invention is directed to a reactor, further comprising a Stirling motor. For example, this may be a reactor wherein the Stirling motor is arranged to provide at least part of the mechanical energy for direction of the CO_2 comprising gas flow to the one or more compartments. The Stirling pump may also be used to provide energy for other (liquid or fluid) flows or generate electricity. The Stirling pump is actuated by the temperature difference between the cold and warm liquid in the buffer. In an integrated buffer, cold and warm liquid are kept separated by an insulating membrane. The cold liquid, e.g. water is stored above the warm liquid (also e.g. water). The Stirling pump can be mounted in this membrane. The Stirling pump may use part of the thermal energy collected by the reactor, and energy may be saved in this way. Hence, the invention is also directed to a reactor comprising a Stirling pump, wherein the Stirling motor is arranged to provide at least part of the mechanical energy for cooling down or heating up the reactor. The Stirling pump may also be used for other purposes or for both above-mentioned purposes.

In another embodiment, the invention is directed to a reactor further comprising an outlet for collecting at least part of the phototrophic micro organism culture from the reactor. Harvesting of the phototropic micro organisms can be done by sedimentation of phototrophic micro organisms, extraction of phototrophic micro organisms, electro-flotation of phototrophic micro organisms, electrophoresis of phototrophic micro organisms, centrifugation, sonification, flocculation, use of ultrasound and micro filtration of phototrophic micro organisms. The phototropic micro organisms can be dried and can than be used as biomass.

In a specific embodiment, the invention is directed to a reactor wherein the one or more compartments are manufactured from a transparent material, like a transparent plastic. For example, this may be a reactor wherein the one or more compartments are manufactured from polycarbonate or polymethylacrylate. Using plastics has the advantage that the reactor can be relatively cheap and light. The reactor may partly or completely be obtained by an extrusion process of such plastics. Compartment walls, reactor walls, irradiance collector assemblies, covers, baffles, or other parts of the reactor may be obtained in this way. Also the compartment walls comprising a Fresnel pattern may be obtained via extrusion and may be of a plastic. For example, in one embodiment, the invention is directed to a reactor, wherein the compartments, compartment walls and reactor walls are integrated as single reactor structure. In another embodiment, the invention is directed to a reactor wherein the compartments, compartment walls and irradiance collector assemblies are integrated as single reactor structure. Such a reactor can e.g. be obtained by an extrusion process. After extrusion, inlets and outlets can be provided.

Advantageously, the invention provides a reactor wherein the liquid comprises 1-50 gram/l algal culture. Concentrations of 5 up to 50 gram/l, or possibly even higher, may be obtained, whereas reactors for the cultivation of phototrophic micro organisms of the state of the art may comprise liquids containing 2-3 gram/l algal culture. The reactor according to the invention comprises at least 2 compartments. In this way, the reactor volume is better utilised than it is the case for reactors in the state of the art.

In a further aspect of the invention, there is provided a process for the cultivation of phototrophic micro organisms, comprising:
providing a reactor according to the invention with one or more compartments suitable for containing a liquid comprising phototrophic micro organism culture,
supplying phototrophic micro organism culture to the one or more compartments of the reactor,
supplying a CO_2 comprising gas flow to the one or more compartments of the reactor,
removing gas from the one or more compartments of the reactor,
regulating the temperature of the of the phototrophic micro organism culture, and
collecting radiation with one or more irradiance collector assemblies, the irradiance collector assemblies for collecting radiation and distributing at least part of the radiation to the one or more compartments, wherein the one or more irradiance collector assemblies provide radiation into one or more compartment walls of the one or more compartments, and wherein the one or more compartment walls are transparent for the radiation, such that the phototrophic micro organisms in the liquid comprising a phototrophic micro organism culture are illuminated.

In this process, the reactor according to the invention may be used. The process provides an improved collection of radiation and an improved distribution of the radiation into a reactor, thereby providing a more efficient conversion and a more efficient cultivation of phototrophic micro organisms. Further, by using the reactor according to the invention, the process advantageously provides the option of adjusting the collector assembly depending upon conditions of the radiation of the sun, in order to optimize radiation input in the wall or walls of the reactor.

The phototrophic micro organisms are illuminated a certain time (light/dark cycle) as cells move from the radiation zone close to the compartment walls to dark zones in the reactor. This time is also called light/dark circulation time. In a further embodiment, the invention is directed to a process wherein the circulation time is controlled. For example, this may be a process wherein the circulation time is controlled such that the phototrophic micro organisms in the radiation zone receive a constant radiation intensity. The radiation zone is about at least 0.2 mm to about 5 cm distance from the

wall directed to the liquid (distance calculated perpendicular to this wall), e.g. 0.5-4 cm. By controlling the circulation time, it is possible to use high algal concentrations and by that obtain a high photosynthetic efficiency. An advantage of using higher algal concentrations is that also the efficiency of the reactor is increased with respect to prior art bioreactors. Hence, a more efficient conversion and also a more cost efficient process is obtained. Controlling the light/dark circulation time can be done by controlling the input of energy (flow in compartment of liquid comprising phototrophic micro organisms, which is e.g. induced by the introduction of CO_2 and or air). The circulation time is e.g. between about 20 ms - 6 seconds, i.e. on average, each 20 ms to 6 seconds the micro organisms enter the radiation zone. Hence, in an embodiment the light/dark circulation time is controlled by controlling a flow of gas into the liquid, preferably the flow of the CO_2 comprising gas to the liquid in the one or more compartments. Preferably, the circulation time is smaller than about 2 seconds.

In another embodiment, the invention is directed to a process further comprising providing in one or more compartments one or more movable baffles, a baffle comprising one or more channels, the baffle having a horizontal distance to a compartment wall, and wherein one controls the circulation time by one or more of a) regulating the flow of one or more of the CO_2 comprising gas through the movable baffle and the flow of air and b) by regulating the horizontal distance of the movable baffle to said compartment wall. Herein the horizontal distance is the above-mentioned first distance. As mentioned above, in this way the efficiency of the conversion of radiation into biomass can be increased. Phototrophic micro organisms are grown at elevated CO_2 concentrations. The system is maintained just above the atmospheric pressure. The pH in the system can be controlled with CO_2. As a result, the reactor is sparged with a mixture of air and CO_2. Light is absorbed by the phototrophic micro organisms. Due to light absorption the light intensity near the illuminated surface of the reactor will be high and further away from that surface it will be low. Usually a photobioreactor contains dark regions. The total superficial gas flow velocity in the system will usually be between 0.0001 - 0.1 m/s. e.g. about 0.005 - 0.1, like about 0.02 m/s.

Due to the gas flow, phototrophic micro organisms like algae will circulate and move from illuminated zones in the reactor (near the illuminated surface) to dark zones. At high superficial gas flows the light/dark cycle in the reactor will be short. The light dark cycle that phototrophic micro organisms observe during circulation should be as short as possible (in the order of milliseconds) in order to maximise the photosynthetic efficiency. Shorter light/dark cycles can be obtained by increasing the superficial gas flow velocity. The higher the photosynthetic efficiency the higher the biomass concentration in the photobioreactor. The temperatures at which the reactor will be operated will in general be between 20 and 35 °C. However, it is also possible to work under more extreme conditions (up to 65 °C).

In a further embodiment, the invention is directed to a process wherein the flow of the CO_2 comprising gas is at least partly realised by a Stirling pump. The advantage of using a Stirling pump is that part of the thermal energy collected by the reactor can be used in a Stirling pump and at least partly converted into mechanical energy. This mechanical energy can at least partly be used to control one or more flows in the system, for example the flow of the CO_2 comprising gas. For instance, in a specific embodiment the invention is directed to a process, wherein one provides at least part of thermal energy collected by the reactor to a Stirling pump. In yet another embodiment, the invention is directed to a process, wherein the Stirling motor is arranged to provide at least part of the mechanical energy for cooling down or heating up the reactor.

Harvesting can be done according to a number of techniques. In an embodiment, the invention is directed to a process wherein one harvests phototrophic micro organisms by one or more selected from sedimentation of phototrophic micro organisms, extraction of phototrophic micro organisms, electroflotation of phototrophic micro organisms, electrophoresis of phototrophic micro organisms, centrifugation, sonification, flocculation, use of ultrasound and micro filtration of phototrophic micro organisms.

The reactor for the cultivation of phototrophic micro organisms according to the invention can be used in different ways positioned on any surface. Depending on the local conditions and the latitude, the reactor can be equipped for 0, 1 or 2 axis solar

tracking mode. For example the reactor can be used on roofs or green houses, in the field as floating means on water in lakes or in oceans, etc. Reactors may be coupled to each other, and can e.g. also be positioned in a terrace like structure. Hence, in another aspect of the invention, the invention is directed to the use on any surface in or on a roof, in or on a floating means (on water), on the ground, in the air, and in or on a greenhouse. The reactors can for example be coupled to each other, thereby increasing the effective surface. Coupling can for example be done by snap-on means, attached or integrated in reactor walls.

In the context of the invention "transparent" means that about 50% or more, e.g. 70% or more, of the radiation is transmitted to the compartments through the compartment walls (without taking into account possible effects induced by means for converting at least part of the radiation to radiation with a predefined wavelength range, which may reduce the transmission).

In the invention, the "liquid comprising a phototrophic micro organism culture" will usually be water comprising such culture, but this may also be a mixed water/organic solvent culture. With phototrophic micro organism culture are not only meant green algae, but all photosynthetic micro organisms, i.e. the cyanobacteria, the Rhodophyta (red algae), the Chlorophyta (green algae), Dinophyta, Chrysophyta (golden-brown algae), Prymnesiophyta (haptophyta), Bacillariophyta (diatoms), Xanthophyta, Eustigmatophya, Rhaphidophyta, Phaeophyta (brown algae) and photosynthetic purper bacteria. Suitable algae are known to the person skilled in the art. For example, Dunaliella salina, Haematococcus pluvialis, Nannochloropsis sp., Chlorella sp., Chlamydomonas rheinhardtii, Arthrospira sp., Nostoc sp, Scenedesmus, Porphyridium, Tetraselmis etc. can be used.

"CO_2 comprising" gas means a gas comprising CO_2, like air, a CO_2 enriched air flow or pure CO_2 gas, etc. A second liquid for cooling and/or heating, means a liquid that, can be used to heat or to cool the reactor, compartments and liquid comprising algae, when necessary. This second liquid may be water. "Movable baffles" may be sheets or walls, e.g. from a plastic, like polycarbonate. These baffles may comprise channels or distributors for providing the CO_2 comprising gas. They may e.g. be movable in guides.

Further, in the context of the invention the "means for converting at least part of the radiation to radiation with a predefined wavelength range" indicates that part of the radiation, that is radiation of a certain wavelength (or wavelengths) and/or certain wavelength range (or wavelength ranges) is converted to radiation with another wavelength (or wavelengths) and/or another wavelength range (or wavelength ranges). The means will usually convert only a part of the radiation at a certain wavelength, since usually not all radiation is absorbed by the means and/or not all radiation absorbed is usually completely converted.

Brief description of the drawings

Figures 1a-d schematically depict a number of embodiments of the reactor of the invention;

Figure 2 schematically shows a side view of a reactor according to an embodiment of the invention;

Figures 3a-c schematically depict a number of embodiments of the collector assembly of the invention;

Figure 4 schematically depicts the use of a Stirling motor according to an embodiment of the invention;

Figures 5a-d schematically depict a number of embodiments of the reactor and collector assembly of the invention.

The invention will further be described by way of non-limiting embodiments.

Description of embodiments

Embodiment 1: Reactor for the cultivation of algae

Figure 1 schematically depicts an embodiment of the reactor for the cultivation of algae according to the invention. Figure 1a, 1b and 1c shows a cross section of the reactor of the invention in different arrangements. In figure 1a, 1b, 1c and 1d, reactor 1 is depicted with 4 compartments 2. These compartments 2 comprise a liquid containing an algae culture. Irradiance collector assemblies 3 are present at the part of the reactor exposed to radiation (e.g. of the sun).

In figure 1a and 1d reactor 1 is depicted with an irradiance collector assembly 3 of the type depicted in figure 3a (type 3'). In figure 1b reactor 1 is depicted with irradiance collector assembly 3 of the type depicted in figure 3b (type 3").

In figure 1c reactor 1 is depicted with irradiance collector assembly of the type depicted in figure 3c (type 3'").

Irradiance collector assemblies type 3' and 3'" enable one axis solar tracking. Reactors equipped with collector assembly type 3' and 3'", enable two axis solar tracking by rotation of the reactor assembly. Collector assembly type 3" enable single axis solar tracking by rotation of the reactor.

Actuation of the variable angle collector assemblies type 3' and 3'" may be performed by mechanical means such as a rack-and pinion drive, actuated by electromagnetic, pneumatic or hydraulic force. A single drive may be attached to an array of coupled irradiance collector assemblies, e.g. a number of irradiance collector assemblies on one compartment wall or on a number of compartment walls.

Further a cover 4 may be installed to protect these collector assemblies 3. For all types of collector assemblies 3a, 3b and 3c, cover 4 may comprise a Fresnel pattern for collimation of the incoming radiation.

Above the compartments 2, and under irradiance collector assemblies 3, space 5 is available, which can be used to collect gas. Under compartments 2, channels 6 are present to provide a CO_2 comprising gas. These channels 6 (CO_2 distributors) may have porous walls in order to provide the CO_2 comprising gas to compartments 2. In figure 1a, 1b and 1c, channels 6 are present under the compartments 2, however, they may also be present at other positions in reactor 1 for instance integrated in baffle 11 such as shown in fig 1d. In this arrangement, an airlift pump 12 is established.

Further, channels 7 are present for providing a liquid for cooling or heating the compartments 2 of reactor 1. Reflective foil 8 (reflective for radiation of the sun and/or reflective for visible radiation) may be present, which improves the efficiency of the

reactor 1. In figure 1, this reflective foil 8 is present below channels 7, but reflective foils may be present also at other places in the reactor 1 and at all kind of angles. For isolation, an isolated layer 9 may be present as bottom of reactor 1. Such an isolated layer may for example comprise isolated foam.

As shown in figure 1, reactor 1 comprises a number of compartments 2 which are separated by compartment walls 10. Irradiance collector assemblies 3 provide radiation to compartment walls 10. Compartment walls 10 may comprise a number of collector assemblies 3 per compartment wall (not shown in figure 1). Compartment walls 10 may comprise a number of openings through which the cultures in different compartments 2 are in contact and mixing of the algae culture can occur between compartments. The height of reactor 1, especially the height of the compartments 2, is chosen such that, depending on the kind of phototrophic micro organisms and depending on the expected intensity of the radiation of the sun where the reactor 1 is applied, the efficiency of reactor 1 is high. This height may be varied in the reactor design. For example, a reactor may have compartments with compartment walls of about 200 mm height and compartments (or channels) 2 of about 50 mm width. When the compartments or channels 2 have a length of about 5-10 m, e.g. a reactor 1 comprising 40 compartments 2, will have a surface of cover 4 of about 10-20 m^2.

Figure 2 shows a side view of the reactor of the invention. In the description of figure 2 below is referred to elements shown in figure 1, which are not depicted in figure 2 (not visible in the side view). In figure 2, the reactor comprises reactor end walls 21, which will also function as compartment walls of compartments 2. Reactor walls 21 comprise a number of inlets and outlets: inlet 22 can be used to introduce a liquid comprising an phototrophic micro organism culture, like algae (algal culture), into compartments 2 of reactor 1 (separate compartments are not shown; collector assemblies are also not shown in this figure), inlet 23 can be used to introduce a liquid for regulating the temperature (of the liquid with the phototrophic micro organism culture in channels 2 of reactor 1) into channels 7, inlet 24 can be used to introduce the CO_2 comprising gas into compartments 2 of reactor 1, outlet 26 can be used for collecting liquid from channels 7, outlet 25 can be used for collecting liquid comprising an phototrophic micro organism culture, and outlet 27 can be used to provide an outlet for gas or to

collect gas from reactor 1. Also inlets to measure the temperature, a turbidity sensor, DO_2 (dissolved oxygen) sensors and a pH sensor can be introduced.

Reactor end walls 21, as well as the inlets and the outlets, may be designed in such a way that reactors may easily be connected to each other, e.g. by snap–on/snap-off means.

Embodiment 2: Irradiance collector assembly

Figures 3a ,3b and 3c schematically depict the three extreme variants of the irradiance collector assemblies according to an embodiment of the invention. Within these extremes, multiple variants are possible. For example, also, cover 4 can be fitted with a Fresnel pattern.

Collector assembly type 3', as depicted in figure 3a, features a curved collimator mirror 15 (which is in this case a curved mirror) and another variable curved collimator mirror 20, adjustable over one or more axes. Reference symbol 14 and 16 describes the rotation axis and rotation drive of collimator mirror 20, respectively, and reference symbol 13, with the arrows, the rotation range thereof. The radiation reception area is indicated with reference symbol 17. Incoming radiation to the radiation reception area 17 and transferred to one of more compartment walls 10.

Collector assembly type 3", as depicted in figure 3b, features a fixed collimator, with radiation reception area 17 and mirror 15 (in this case a flat mirror). Irradiance collector assembly 3b comprises a positive cylindrical Fresnel lens collimator, incorporated in cover 4 and collection mirrors 15. These mirrors 15 may be curved or flat (see also fig. 3a). Radiation is reflected to the radiation reception area 17. The radiation reception area 17 is formed in such a way that incoming radiation strikes the radiation reception area at an angle greater than the angle of total internal reflection so that the radiation is retained and transferred to one of more compartment walls 10.

Collector assembly type 3"', as depicted in figure 3c, features a variable angle positive Fresnel lens 19, adjustable over one or more axes. Reference symbol 14 and 16 describes the rotation axis and rotation drive of collector assembly type 3"', respectively, and reference symbol 13, with the arrows, the rotation range of the

assembly. The radiation reception area is indicated with reference symbol 17. The Fresnel lens 19 is automatically positioned to focus the incoming radiation to the radiation reception area 17 and transferred to one of more compartment walls 10. In a variation on this embodiment irradiance collector assembly 3''' may be position on an elevation 28 (which may be part of a compartment wall 10), such that the rotation drive 13 is enlarged. This is shown in figure 3c for the irradiance collector assembly 3''' at the right hand.

Adjustment of the collector assemblies 3' and 3''', e.g. by adjustment of mirrors 15, mirrors 20 and Fresnel lenses 19 may be controlled by a radiation intensity sensor (not shown). An array of a number of collector assemblies 3' of figure 3a and of the collector assemblies 3''' of figure 3c may be actuated similarly.

The mirrors 15 may for example be foil or a deposited layer with reflecting properties. To enhance the efficiency, the surface of radiation reception area 17 may consist of layers with varying refractive indices, and/or doped with fluorescent dyes. Such means are known in the art.

Mirrors 15, elevation 28, cover 4 and radiation reception areas 17 are designed in such a way that at least part of the radiation is transmitted into compartment walls 10. Compartment wall 10 in figure 3 may comprise a Fresnel pattern, which realises reflection of at least part of the radiation from compartment wall 10 to compartments 2 (not shown in this figure).

The focal length of lenses may e.g. be about 2-10 cm, like e.g. about 6 cm. In case cylindrical fresnel lenses are used, the maximum width of the lens may be about 2-10 cm, e.g. about 6 cm.

Embodiment 3: Reactor comprising moveable baffles

Figure 1d schematically depicts a variation on the embodiment shown in figure 1a-1c. Here, compartments 2 comprise one or more baffles 11, which may be moveable in horizontal and/or vertical directions. Thereby one may control the residence time of the phototrophic micro organisms in the radiation zone close to the compartment walls 2. Further, the baffle may comprise perforated or porous channels 6 (distributors) for

providing the CO_2 comprising gas. Baffle 11 may also comprise floating means (not shown in figure 1d), which can be used to adapt the height of baffle 11 with the height of the fluid comprising algae. At the injection of the CO_2 comprising gas from channels 6, a mixture of gas/liquid is formed instating an airlift 12. This mixture moves upward between the compartment wall and the baffle 11. At the top of baffle 11, liquid separates and flows back to the compartment. The use of baffles, as shown in figure 1d, is also applicable for the embodiments shown in figures 1b and 1c, or variations thereon.

Embodiment 4: Use of a Stirling motor and temperature control

Figure 4 schematically depicts such arrangement comprising a reactor 1 and a Stirling motor 40. The Stirling motor is mounted between a cold water buffer 41 and a warm water buffer 42, which are separated from each other by an isolating membrane. The Stirling motor produces mechanical power to e.g. partly or completely drive ventilator 33 for the circulation of CO_2 comprising gas 32, but which can also be used for other means (for example to pump liquid in and out of the reactor). Gas from the reactor can escape by flow 31, of which part 34 can be purged and of which part can be reused via ventilator 33 and flow 32. CO_2 comprising gas can be introduced via flow 30. Additional pumps like pump 39 can be present. Flow 35 is a flow of a phototrophic micro organisms comprising liquid, which is e.g. extracted to harvest phototrophic micro organisms. This flow 35 is transported to a concentrator 36 providing product 37.

The temperature in reactor 1 is controlled by cooler 46, and by buffers 42 and 41. At daytime, irradiated heat is collected in warm flow 38 and is stored in warm water buffer 42. Cold flow 43 is returned to the reactor 1. During daytime, the hot water buffer heats, the heat is transferred to the cold water buffer through the Stirling motor 40. When required, preferably at night time the cold water buffer is cooled by circulating flow 44 and 45, respectively through cooler 46. At daybreak, the reactor is heated with warm flow 47. Flow 43 and flow 47 can be transported to reactor 1.

Other positions of Stirling pump 40 are also possible, for instance when separate buffers are installed. The Stirling pump 40 may be used to directly drive ventilator 33 and other pumps such as pump 39 or be attached to a generator, to drive the above items.

Embodiment 5: Use of means for converting at least part of the radiation

Compartment walls 10 and/or cover 4 may comprise a thin layer of a means for converting at least part of the radiation. For example, part of the UV may be converted to visible light by phosphors known in the art that convert UV to e.g. blue or green, like a number of (divalent) europium containing aluminates which are used in commercial lighting applications, (doped) zinc sulphides, dyes etc..

Embodiment 6: Focusing direct sunlight in the top of a sheet with a cylindrical lens

This embodiment describes focusing of direct sunlight in the top of a sheet like wall 10, e.g. a plastic sheet, using a lens or a number of lenses like e.g. a number of cylindrical (fresnel) lenses.

This embodiment is schematically depicted in figure 5. Figure 5a and 5b show a side view of a reactor 1 wherein a wall 10 is provided. This wall may be higher than the top edge 54 of tank 1. As mentioned above, wall 10 may comprise a fresnel lens. Wall 10 may further comprise an envelope, cladding or shaft 55, which may be used to arrange the lens construction or collector assembly. Alternatively, the lens construction or collector assembly may be arranged on wall 10, e.g. in the absence of such envelope 55, or, yet in another alternative on top edge 54 of tank 1. Different constructions or combination of constructions will be possible for arranging the collector assembly to tank 1 and wall 10, as will be clear to the person skilled in the art. The lens construction comprises means to rotate a lens or a number of lenses 19 around a journal or pivot, indicated with J, at one or both sides of wall 10 (on a (virtual) axis 56, as shown in figures 5c and 5d), and to move the lens in a sideways direction around points R which form the hinges between base member 51 (rotator) and side members or side members 50(1) and 50(2), respectively, and which form the hinges between side members 50(1) and 50(2), respectively, and lens or number of lenses 19.

To this end, this embodiment provides a base member 51, this rotator further comprising one or more side members, indicated with reference numbers 50(1) and 50(2), which on their turn bear or support a lens or plurality of lenses 19. In this way, a kind of parallelogram may be obtained with rotation points R (see side/front view in figures 5c and 5d). Different positions may be obtained, of which two are depicted in

figure 5a and 5b, from a (substantial) horizontal lens 19 as depicted in figure 5a, with a rotation angle θ of 0, to a substantial vertical position as depicted in figure 5b, with a rotation angle θ of 90 (or -90). In these figures 5a and 5b, the collector assembly rotates around point J, at one or both sides of wall 10.

Cylindrical lenses may focus direct sunlight in one dimension of the focal plane. The radiation of the sun may be focused in a line, when the lens is positioned well. In the side view of figure 5a, this line is indicated with reference number 52. Preferably, radiation is focused on the top horizontal surface of a fixed plastic sheet like wall 10, which stands substantially vertical in the reactor. In order to keep the light of the sun (which moves along the horizon) focused, the cylindrical lens must follow the sun during the day.

The altitude and azimuth of the sun changes during the day and between days, so the lenses have to be able to move in all directions, while the position of the line of focused light has to be maintained in the top of the plastic sheet.

The lens can rotate around the sheet or wall 10; the lens can rotate to a vertical position on both sides of wall 10 . A further mode of freedom is the movement of side members 50(1) and 50(2) in a direction parallel to the top of wall 10, thereby varying angle α (also indicated with the dotted position in fig. 5d). Angle α can be changed to point the lens(es) to the sun so that the side members50(1) and 50(2) are parallel to the direction of the rays of incoming direct sunlight. This feature guarantees the focusing of direct sunlight during the entire day. The length l of the side members 50(1) and 50(2) is preferably chosen such that lens 19 can focus radiation of the sun in focal line 52, i.e. preferably equal to the focal length of the cylindrical (fresnel) lens 19 resulting in the focusing of the sunlight on the top of the wall 10. The focal length may e.g. be about 2-10 cm, like e.g. about 6 cm. In case cylindrical Fresnel lenses are used, the maximum width of the lens may be about 2-10 cm, e.g. about 6 cm. The width of the lens refers in an embodiment to the width of the lens between side members 50(1) and 50(2), i.e. the width of lens 19 in the direction perpendicular to focal line 52. The length of lens 19, i.e. the length in the direction parallel to wall 10 may vary upon the dimensions of the reactor (length of wall 10). Fresnel lenses, cylindrical Fresnel lenses and the way the

focus are known to the person skilled in the art. Focal line 52 is usually a central line, in the middle with respect to both sides of wall 10 which are directed to the liquid in reactor 1 and on the top surface of wall 10, as indicated in e.g. figure 5c.

The translation angle α that can be provided may be between about 90 and -90°. Preferably, the translation angle α is at least between about 45 and -45°, more preferably between about 80 and -80°. Angle α, indicating the translation movement, and the rotation θ of base member 51 may be chosen and adapted such that during the day, sunlight is substantially focussed in focal line 52, thereby providing maximum radiation into wall 10 of reactor 1. Good results can be obtained with translation angle α is at least between about 40 and -40° and rotation angle θ between about 40 and -40°. The lenses 19, as well as reactors 1 (and thereby walls 10), can be positioned in all orientations; the favourable position depends on the degree of latitude. Two aspects have to be taken in to account, when determining the optimal orientation; mutual shading of lenses that are placed next to each other and reflection of the surface of the lens and surface of the sheet. Both aspects have the largest influence at low heights of the sun. The optimal orientation depends on the path of the sun along the horizon; the hours of sunlight and the azimuth and height of the sun during the day.

Figures 5c and 5d schematically show a front view of a reactor 1, divided by a wall 10 in two compartments, the wall 10 being higher than the top edge of reactor 10. On wall 10, the lens construction is arranged, comprising rotators 51 and a number of side members 50(1) and 50(2). This construction comprises a number of lenses 19, which may focus the radiation of the sun to the centre of the top edge of wall 10 (i.e. focal line 52). Reactor 1 may have a number of walls 10, wherein one or more of these wall further comprise the lens construction according to this embodiment.

The collimator assembly with lens 19 may be provided to reactors 1 as depicted in figures 1a-1c, 1d, 2, 3c and 4 (instead of the assemblies depicted in these figures) (see embodiments above). Preferably, the light/dark circulation time is controlled by controlling the flow a gas to the liquid in the reactor (sparging), e.g. of the CO_2 comprising gas to the liquid in the one or more compartments, which can be done as described above via channel 6 and or via baffles 11 with channels 6.

Further, radiation detectors like photovoltaic cells, etc., known to the person skilled in the art, on the reactor (e.g. on top of wall 10), in the reactor (on the bottom of wall 10) or in the vicinity of the reactor, of which the output may be used to optimize the rotation angle α and translation angle θ, thereby optimizing the coupling of radiation into the wall. Rotation and translation may be provided by (electro)motors, known to the person skilled in the art, which may be triggered by the signal of the radiation detector or a computer (reading the signal of the radiation detectors or having a program which provides the values for e.g. rotation angle α and translation angle θ for a number of times during the day (e.g. each minute)). Hence, there may also be provided a computer program product comprising computer executable instructions which, when loaded on a computer which interfaces with a reactor according to the invention, and with e.g. above mentioned detectors and motors, provides the combination of computer and reactor with the functionality of the process according to the invention.

While specific embodiments of the invention have been described above, it will be appreciated that the invention may be practiced otherwise than as described. The description is not intended to limit the invention. Further, the drawings usually only comprise the important elements and features that are necessary to understand the invention. Beyond that, the drawings are schematically and not on scale. The invention is not limited to those elements, shown in the schematic drawings. For example, an assembly may have a different configuration than with the base and side members as described above, but providing equivalent rotation and translation of lenses for tracking the sun.

Claims

1. Reactor for the cultivation of phototrophic micro organisms comprising:
one or more compartments suitable for containing a liquid comprising an phototrophic micro organism culture,
an inlet for supplying a CO_2 comprising gas flow to the one or more compartments,
an outlet for removing gas from the one or more compartments,
a means for regulating the temperature of the phototrophic micro organism culture, and
one or more irradiance collector assemblies for collecting radiation and distributing at least part of the radiation to the one or more compartments, wherein the one or more irradiance collector assemblies provide radiation into one or more compartment walls of the one or more compartments, wherein the one or more compartment walls are transparent for the radiation, and wherein the irradiance collector assembly comprises
a lens;
a means for rotating the lens around a first axis which is substantially parallel to the top surface of the compartment wall; and
a means for moving the lens in a direction parallel to the top surface of the wall

2. Reactor according to claim 1, wherein the irradiance collector assembly comprises one or more base members and one or more side members connecting the one or more base members and the one or more lenses.

3. Reactor according to claim 2, wherein the length of the one or more side members is chosen equal to the focal length of the one or more focal lenses for radiation parallel to the one or more side members.

4. Reactor according to one of the preceding claims, wherein the reactor comprises a means for rotating the reactor to track the incoming radiation.

5. Reactor according to one of claims 2-4, wherein collimators comprise cylindrical lenses or cylindrical Fresnel lenses.

6. Reactor according to one of the preceding claims, wherein the one or more irradiance collector assemblies comprise covers, wherein the covers comprises a Fresnel pattern, the Fresnel pattern collimating incoming radiation.

7. Reactor according to one of the preceding claims, wherein one or more compartment walls comprise a Fresnel pattern, the Fresnel pattern directing the light from the compartment walls into the one or more compartments.

8. Reactor according to one of the preceding claims, wherein the one or more irradiance collector assemblies and/or the one or more compartment walls comprise a means for converting at least part of the radiation to radiation with a predefined wavelength range.

9. Reactor according to one of the preceding claims, wherein the means for regulating the temperature of the phototrophic micro organism culture comprises a channel in contact with the one or more compartments, means for providing a second liquid at a predetermined temperature to the channel and means for cooling and/or heating the second liquid.

10. Reactor according to one of the preceding claims, wherein the inlet for supplying a CO_2 comprising gas flow further comprises one or more movable baffles comprising one or more channels or distributors for gas.

11. Reactor according to one of the preceding claims, further comprising a Stirling motor, wherein the Stirling motor is arranged to provide one or more of a) at least part of the mechanical energy for direction of the CO_2 comprising gas flow to the one or more compartments and b) at least part of the mechanical energy for cooling down or heating up the reactor.

12. Reactor according to one of the preceding claims wherein the one or more compartments are manufactured from polycarbonate or polymethylacrylate.

13. Reactor according to one of the preceding claims, wherein the compartments, compartment walls and reactor walls are integrated as single reactor structure.

14. Process for the cultivation of phototrophic micro organisms, comprising:
providing a reactor according to one of claims 1-13, with one or more compartments suitable for containing a liquid comprising phototrophic micro organism culture,
supplying phototrophic micro organism culture to the one or more compartments of the reactor,
supplying a CO_2 comprising gas flow to the one or more compartments of the reactor, removing gas from the one or more compartments of the reactor,
regulating the temperature of the of the phototrophic micro organism culture, and
collecting radiation with one or more irradiance collector assemblies, the irradiance collector assemblies for collecting radiation and distributing at least part of the radiation to the one or more compartments, wherein the one or more irradiance collector assemblies provide radiation into one or more compartment walls of the one or more compartments, and wherein the one or more compartment walls are transparent for the radiation, such that the phototrophic micro organisms in the liquid comprising a phototrophic micro organism culture are illuminated.

15. Process according to claim 14, wherein a light/dark circulation time of the phototrophic micro organism culture is controlled.

16. Process according to claim 15, wherein the light/dark circulation time is controlled by controlling the flow of the CO_2 comprising gas to the liquid in the one or more compartments.

Fig 1a

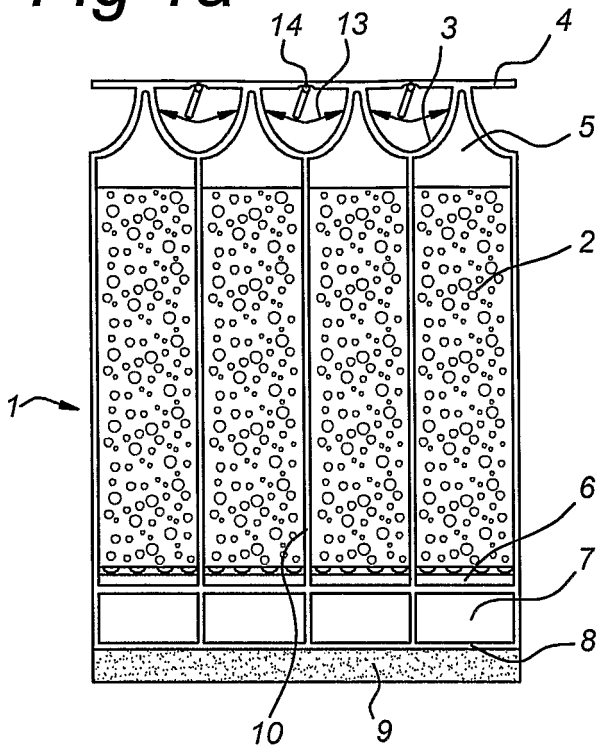


Fig 1b

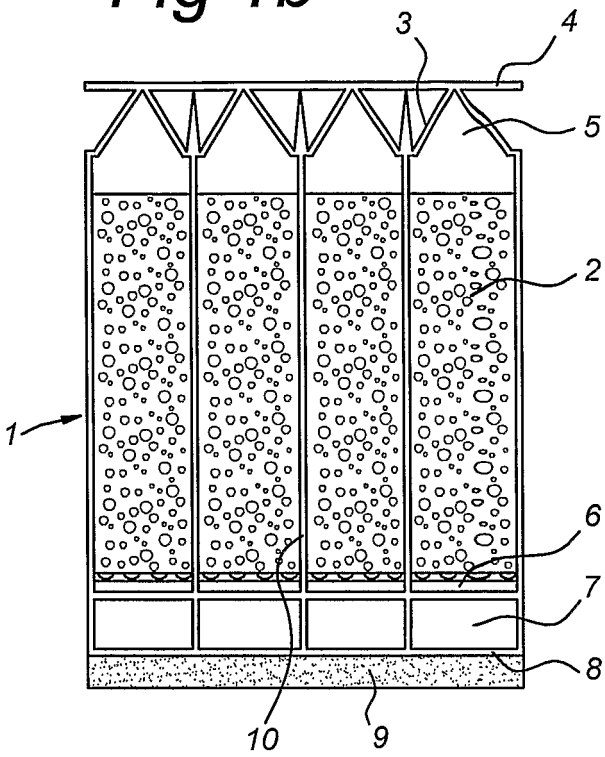


Fig 1c

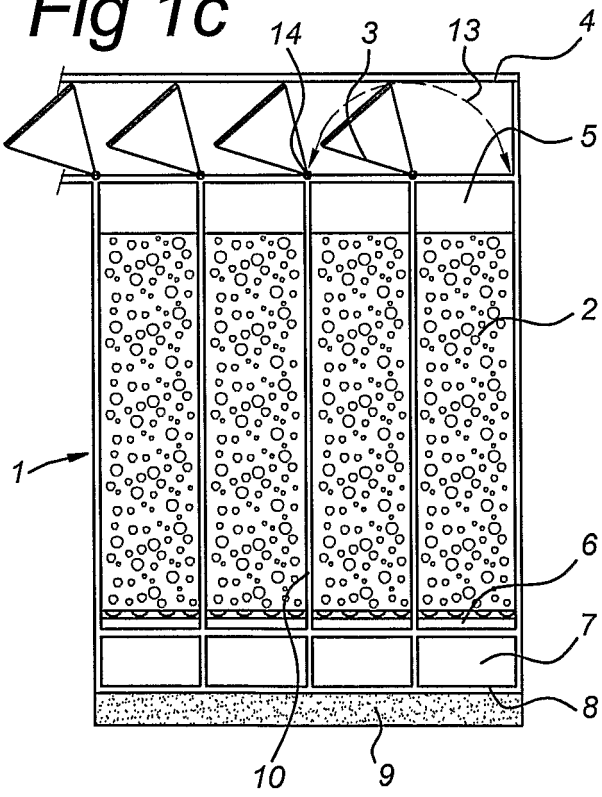


Fig 1d

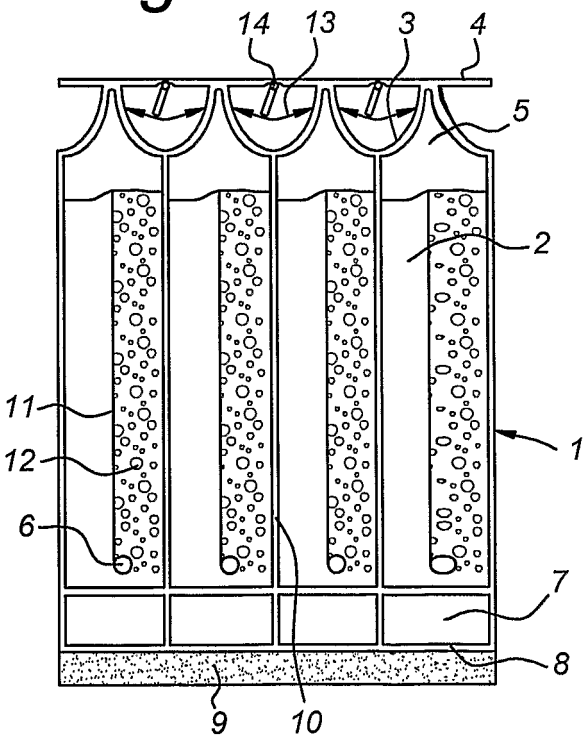


Fig 2

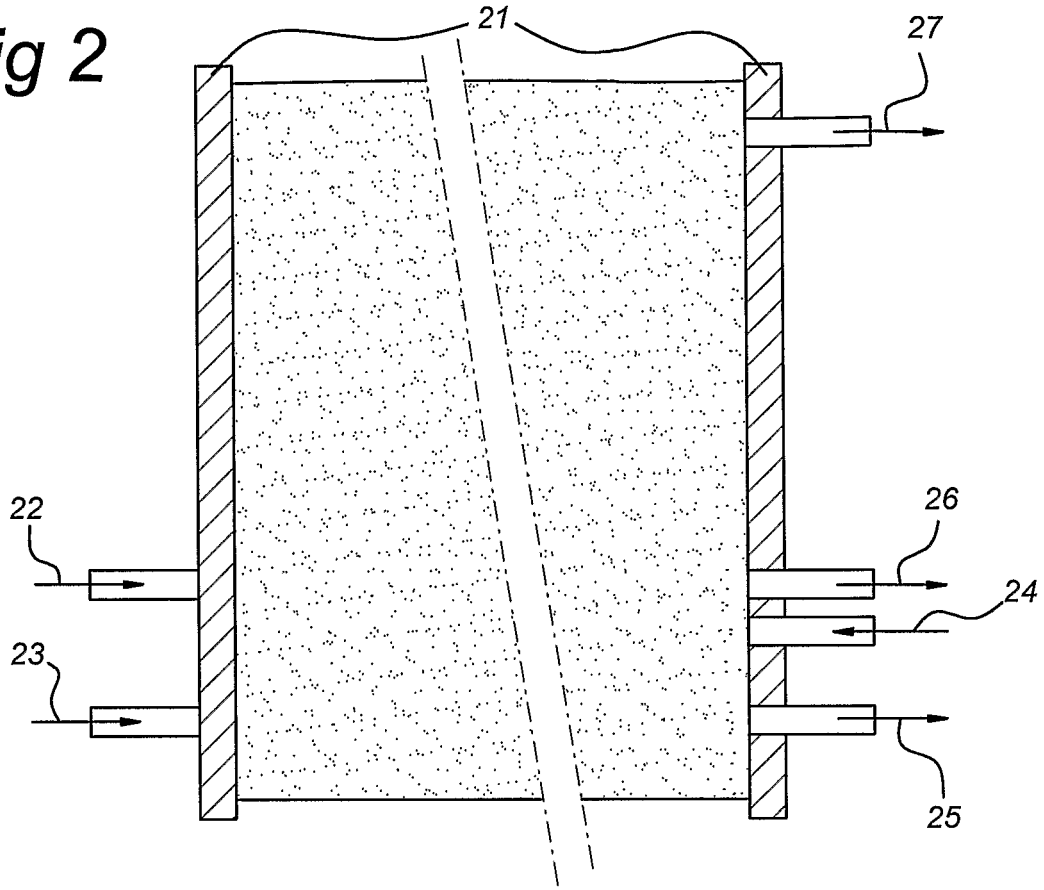


Fig 3a

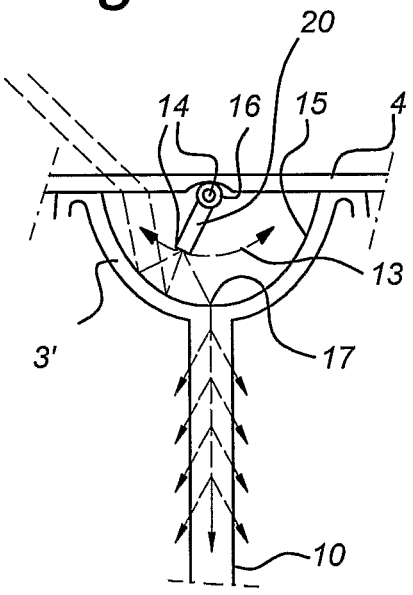


Fig 3b

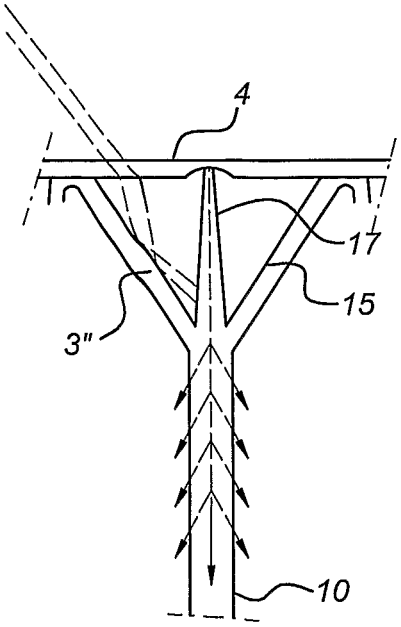


Fig 3c

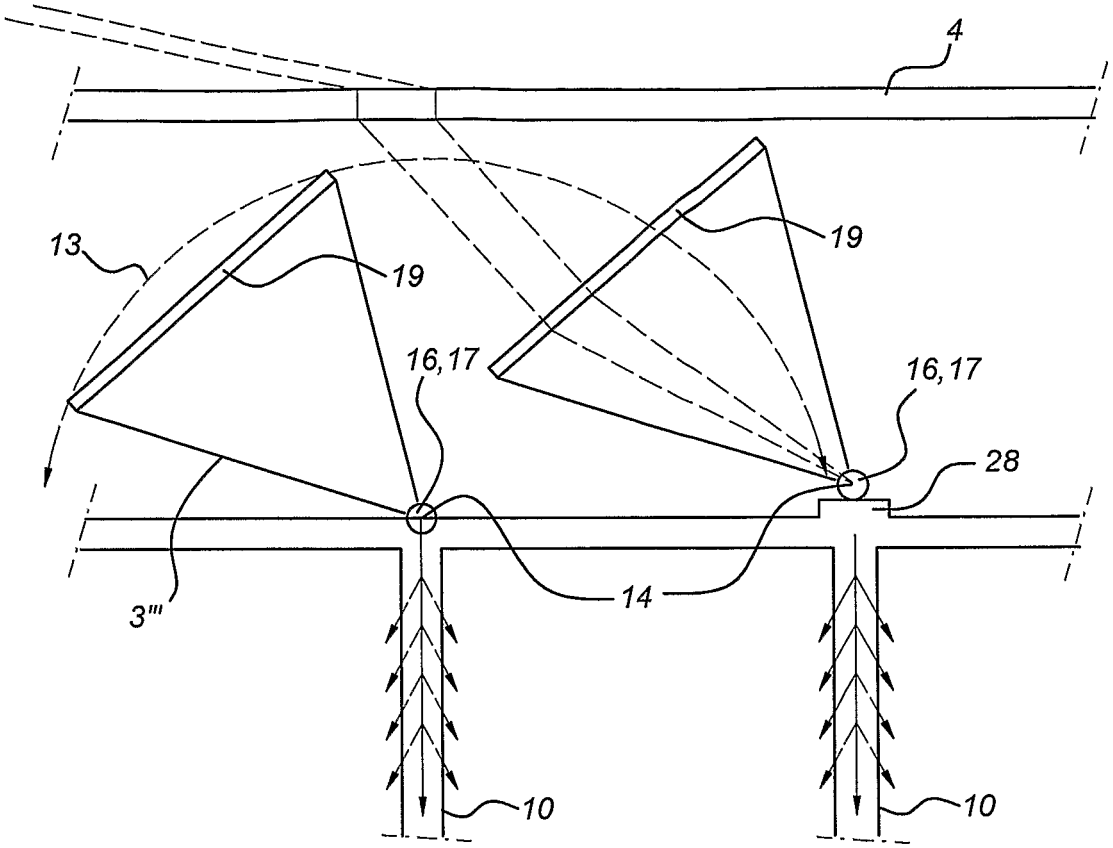

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Fig 4

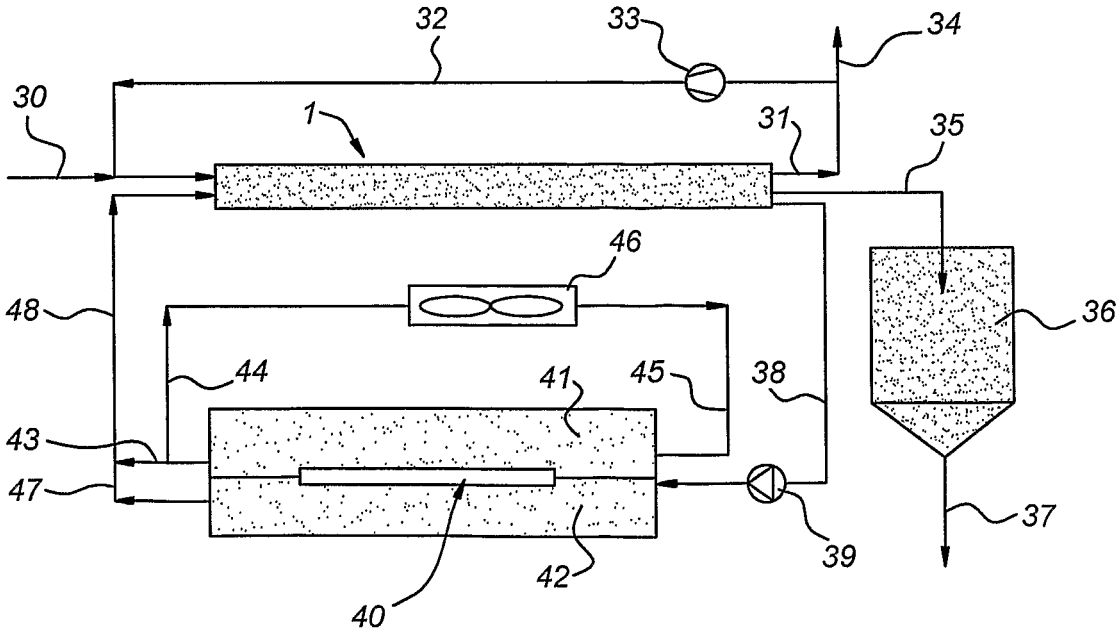

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Fig 5a

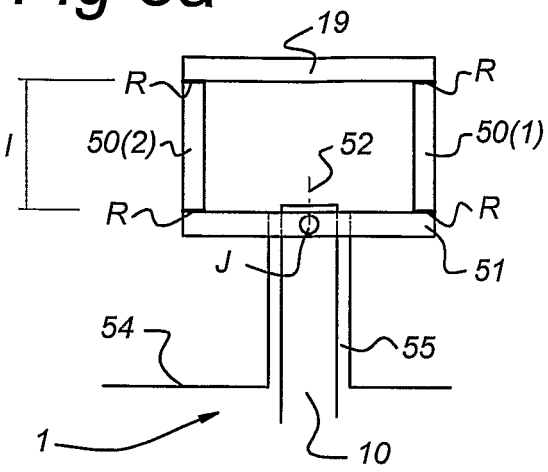


Fig 5b

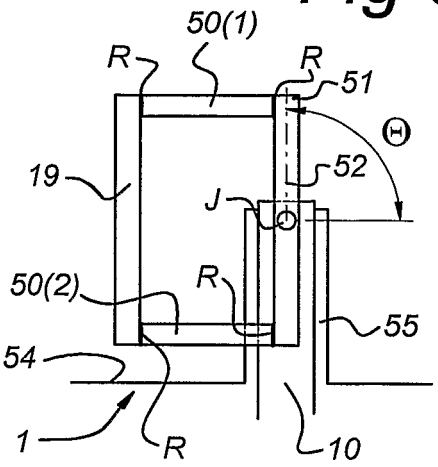


Fig 5c

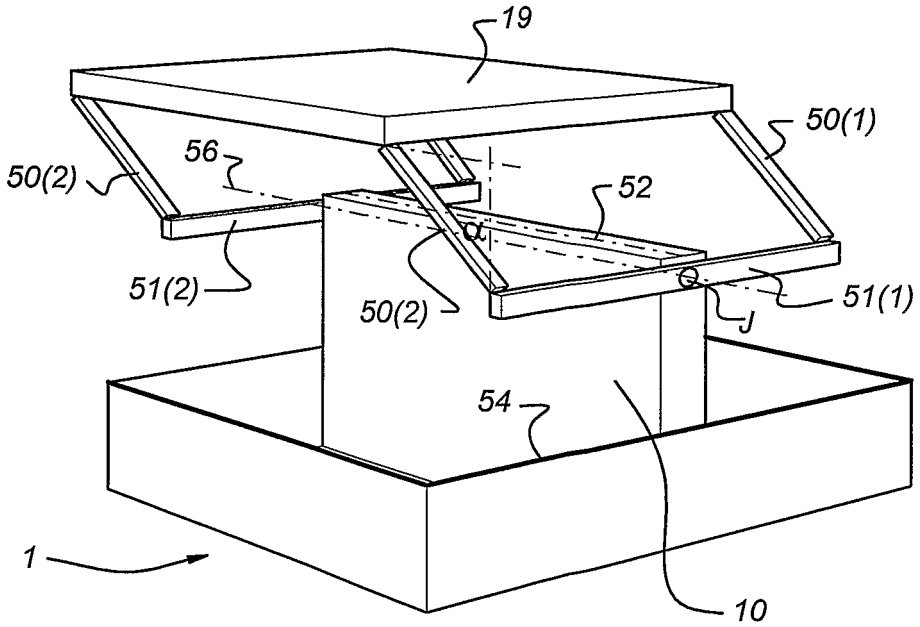


Fig 5d

