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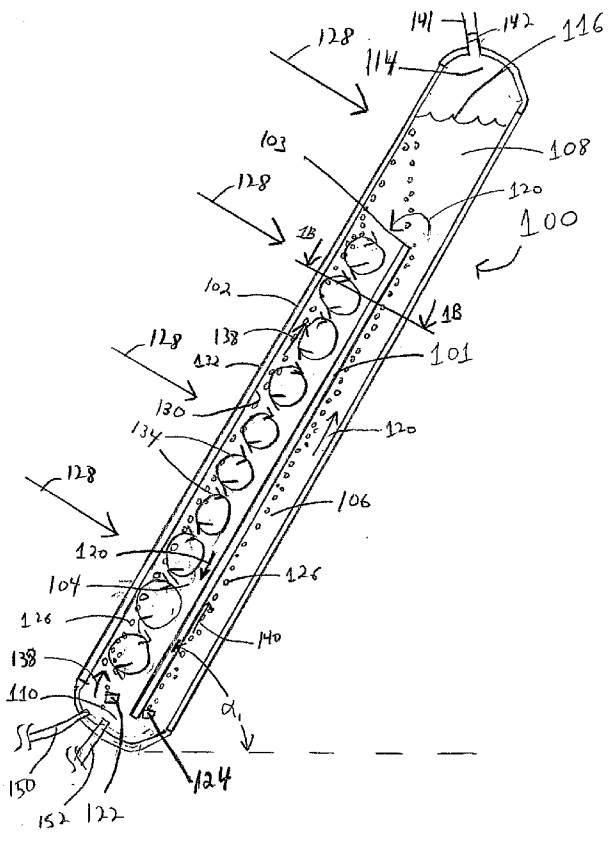
(54) **Title:** PHOTOBIOREACTOR AND PROCESS FOR BIOMASS PRODUCTION AND MITIGATION OF POLLUTANTS IN FLUE GASES



(57) **Abstract:** Certain embodiments and aspects of the present invention relate to photobioreactor apparatus to contain a liquid medium comprising at least one species of photosynthetic organism therein, and to methods of using the photobioreactor apparatus as part of fuel generation system and/or a gas-treatment process or system able to at least partially remove certain undesirable pollutants from a gas stream.

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PHOTOBIOREACTOR AND PROCESS FOR BIOMASS PRODUCTION AND MITIGATION OF POLLUTANTS IN FLUE GASES

Field of Invention

The invention relates generally to photobioreactors and processes to operate and use photobioreactors for the treatment of gases, such as flue gases, and for production of biomass.

BACKGROUND OF THE INVENTION

In the United States alone, there are 400 coal burning power plants representing 1,600 generating units and another 10,000 fossil fuel plants. Although coal plants are the dirtiest of the fossil fuel users, oil and gas plants also produce flue gas (combustion gases) that may include CO_2, NO_x, SO_x, mercury, mercury-containing compounds, particulates and other pollutant materials.

Photosynthesis is the carbon recycling mechanism of the biosphere. In this process, photosynthetic organisms, such as plants, synthesize carbohydrates and other cellular materials by CO_2 fixation. One of the most efficient converters of CO_2 and solar energy to biomass are microalgae, often referred to herein simply as "algae," the fastest growing photoautotrophic organism on earth and one of nature's simplest microorganisms. In fact, over 90% of CO_2 fed to algae can be absorbed, mostly through the production of cell mass. (Sheehan John, Dunahay Terri, Benemann John R., Roessler Paul, "A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae," 1998, NERL/TP-580-24190; hereinafter "Sheehan et al. 1998"). In addition, algae are capable of growing in saline waters that are unsuitable for agriculture.

Using algal biotechnology, CO_2 bio-regeneration can be advantageous due to the production of useful, high-value products from waste CO_2. Production of algal biomass during combustion gas treatment for CO_2 reduction is an attractive concept because dry algae has a heating value roughly equivalent to coal. Algal biomass can also be turned into a high quality liquid fuel which is similar to crude oil or diesel fuel ("biodiesel") through thermochemical conversion by known technologies. Algal biomass can also be used for gasification to produce highly flammable organic fuel gases suitable for use in

gas-burning power plants. (e.g., see Reed T. B. and Gaur S. "A Survey of Biomass Gasification" NREL, 2001; hereinafter "Reed and Gaur 2001").

Approximately 40 kilocalories (167 kJ) of free energy are stored in plant biomass for every mole of CO_2 fixed during photosynthesis. Algae are responsible for about one-third of the net photosynthetic activity worldwide. Photosynthesis can be simply represented by the equation:

$$CO_2 + H_2O + \text{light} \rightarrow (CH_2O) + O_2$$

where (CH_2O) represents a generalized chemical formula for carbonaceous biomass.

Although photosynthesis is fundamental to the conversion of solar radiation into stored biomass, efficiencies can be limited by the limited wavelength range of light energy capable of driving photosynthesis (400-700 nm, which is only about half of the total solar energy). Other factors, such as respiration requirements (during dark periods), efficiency of absorbing, sunlight and other growth conditions, can affect photosynthetic efficiencies in algal bioreactors. The net result is an overall photosynthetic efficiency that can range from 6% in the field (for open pond-type reactors) to 24% in the most efficient lab scale photobioreactors.

Algal cultures also can be used for biological NO_x removal from combustion gases. (Nagase Hiroyasu, Ken-Ichi Yoshihara, Kaoru Eguchi, Yoshiko Yokota, Rie Matsui, Kazumasa Hirata and Kazuhisa Miyamoto, "Characteristics of Biological NO_X Removal from Flue Gas in a *Dunaliella tertiolecta* Culture System," Journal of Fermentation and Bioengineering, 83, 1997; hereinafter "Hiroyasu et al. 1997"). Some algae species can remove NO_x at a wide range of NO_x concentrations and combustion gas flow rates. Nitrous oxide (NO), a major NO_x component, is dissolved in the aqueous phase, after which it is oxidized to NO_2 and assimilated by the algal cell. The following equation describes the reaction of dissolved NO with dissolved O_2:

$$4NO + O_2 + 2H_2O \rightarrow 4NO_2^- + 4H^+$$

The dissolved NO_2 is then used by the algal as a nitrogen source and is partially converted into gaseous N_2. The dissolution of NO in the aqueous phase is believed to be the rate-limiting step in this NO_x removal process. This process can be described by the following equation, when k is a temperature-dependent rate constant:

$$-d[NO]/dt = 4k[NO]^2[O_2]$$

For example, NO_x removal using the algae species *Dunaliella* can occur under both light and dark conditions, with an efficiency of NO_x removal of over 96% (under light conditions).

Creating fuels from algal biotechnology has also been proposed. Over an 18-year period, the U.S. Department of Energy (DOE) funded an extensive series of studies to develop renewable transportation fuels from algae (Sheehan et al. 1998). In Japan, government organizations (MITI), in conjunction with private companies, have invested over $250 million into algal biotechnology. Each program took a different approach, but because of various problems addressed by certain embodiments of the present invention, none has been commercially successful to date.

A major obstacle for feasible algal bio-regeneration and pollution abatement has been an efficient, yet cost-effective, growth system. DOE's research focused on growing algae in massive open ponds as big as 4 km^2. The ponds require low capital input; however, algae grown in open and uncontrolled environments result in low algal productivity. The open pond technology made growing and harvesting the algae prohibitively expensive, since massive amounts of dilute algal waters required very large agitators, pumps and centrifuges. Furthermore, with low algal productivity and large flatland requirements, this approach could, in the best-case scenario, be applicable to only 1% of U.S. power plants. (Sheehan et al. 1998). On the other hand, the MITI approach, with stricter land constraints, focused on very expensive closed algal photobioreactors utilizing fiber optics for light transmission. In these controlled environments, much higher algal productivity was achieved, but the algal growth rates were not high enough to offset the capital costs of the expensive systems utilized.

Typical conventional photobioreactors have taken several forms, such as cylindrical or tubular bioreactors, for example as taught by Yogev et al. in U.S. Patent No. 5,958,761. These bioreactors, when oriented horizontally, typically require additional energy to provide mixing (e.g., pumps), thus adding significant capital and operational expense. In this orientation, the O_2 produced by photosynthesis can become trapped in the system, thus causing a reduction in algal proliferation. Other known photobioreactors are oriented vertically and agitated pneumatically. Many such photobioreactors operate as "bubble columns," as discussed below. Some known photobioreactor designs rely on artificial lighting, e.g. fluorescent lamps, (such as

described by Kodo et al. in U.S. Patent No. 6,083,740). Photobioreactors that do not utilize solar energy but instead rely solely on artificial light sources can require enormous energy input.

Many conventional photobioreactors comprise cylindrical algal photobioreactors that can be categorized as either "bubble columns" or "air lift reactors." Bubble columns are typically translucent large diameter containers filled with algae suspended in liquid medium, in which gases are bubbled at the bottom of the container. Since no precisely defined flow lines are reproducibly formed, it can be difficult to control the mixing properties of the system which can lead to low mass transfer coefficients, poor photomodulation, and low productivity. Air lift reactors typically consist of vertically oriented concentric tubular containers, in which the gases are bubbled at the bottom of the inner tube. The pressure gradient created at the bottom of this tube creates an annular liquid flow (upwards through the inner tube and downwards between the tubes). The external tube is made out of translucent material, while the inner tube is usually opaque. Therefore, the algae are exposed to light while passing between the tubes, and to darkness while passing in the inner tube. The light-dark cycle is determined by the geometrical design of the reactor (height, tube diameters) and by operational parameters (e.g., gas flow rate). Air lift reactors can have higher mass transfer coefficients and algal productivity when compared to bubble columns. However, control over the flow patterns within an air lift reactor to achieve a desired level of mixing and photomodulation can still be difficult or impractical. In addition, because of geometric design constraints, during large-scale, outdoor algal production, both types of cylindrical-photobioreactors can suffer from low productivity, due to factors related to light reflection and auto-shading effects (in which one column is shading the other).

SUMMARY OF THE INVENTION

Certain embodiments and aspects of the present invention relate to photobioreactor apparatus, gas-treatment systems and methods employing photobioreactors, methods and systems for controlling and operating photobioreactors and photobioreactor systems, and integrated combustion/gas-treatment/carbon fuel recycling methods and systems.

In a first embodiment of the invention, a photobioreactor apparatus comprises a conduit having a generally longitudinal partition that is constructed and arranged to divide the conduit into at least a first and a second fluidically interconnected channels contained within the conduit, at least one of which has at least one surface that is at least partially transparent to light of a wavelength capable of driving photosynthesis, the channels together providing at least a portion of a flow loop enabling a liquid medium contained within the photobioreactor to flow sequentially from a region of origin within the flow loop through the first and second channels and back to the region of origin, the conduit forming an angle, with respect to the horizontal, having an absolute value of less than 90 degrees.

In another embodiment of the invention, a photobioreactor apparatus comprises at least a first and a second fluidically interconnected channels that are substantially parallel to each other, at least one of which has at least one surface that is at least partially transparent to light of a wavelength capable of driving photosynthesis, the channels together providing at least a portion of a flow loop enabling a liquid medium contained within the photobioreactor to flow sequentially from a region of origin within the flow loop through the first and second flow channels and back to the region of origin, each channel forming an angle, with respect to the horizontal, of greater than 10 degrees and less than 90 degrees. The photobioreactor apparatus further comprises a first gas sparger configured and positioned to introduce a gas stream into the first channel, a second gas sparger configured and positioned to introduce a gas stream into the second channel, and at least one outlet configured to release gas from the photobioreactor.

In a further embodiment of the invention, a photobioreactor system comprises a photobioreactor comprising at least a first and a second fluidically interconnected channels that are substantially parallel to each other, at least one of which has at least one surface that is at least partially transparent to light of a wavelength capable of driving

photosynthesis, the channels together providing at least a portion of a flow loop enabling a liquid medium contained within the photobioreactor to flow sequentially from a region of origin within the flow loop through the first and second channels and back to the region of origin, each channel forming an angle, with respect to the horizontal, having an absolute value less than 90 degrees. The photobioreactor system further comprises a controller configured to control the flow of the liquid medium to yield a desired level of photomodulation within the photobioreactor.

In yet another embodiment of the invention, a photobioreactor apparatus comprises a conduit having a surface that is at least partially transparent to light of a wavelength capable of driving photosynthesis, the conduit forming an angle, with respect to the horizontal, of greater than 10 degrees and less than or equal to 90 degrees. The photobioreactor apparatus further comprises a first gas sparger configured and positioned to introduce a gas stream into the conduit at a first height, a second gas sparger configured and positioned to introduce a gas stream into the conduit at a second height, different from the first height, and at least one outlet configured to release gas from the photobioreactor.

In a further embodiment of the invention, a photobioreactor apparatus comprises a conduit having a surface that is at least partially transparent to light of a wavelength capable of driving photosynthesis, the conduit having a smallest internal cross-sectional dimension that is at least 1 meter.

In another embodiment of the invention, a method comprises acts of producing CO_2 gas with a biological process, passing the CO_2 to an inlet of an enclosed photobioreactor containing a liquid medium therein comprising at least one species of photosynthetic organisms and exposed to the sun as a source of light driving photosynthesis, and at least partially removing the CO_2 from the biological process gas with the photosynthetic organisms, the CO_2 being utilized by the organisms for growth and reproduction.

In a further embodiment of the invention, a method of treating a source of gas derived from a fermentation process with a photobioreactor comprises acts of receiving a gas from a fermentation process, passing the gas through a photobioreactor, and at least partially removing at least one substance from the gas in the photobioreactor.

BRIEF DESCRIPTION OF THE DRAWINGS

Other advantages, novel features, and uses of the invention will become more apparent from the following detailed description of non-limiting embodiments of the invention when considered in conjunction with the accompanying drawings, which are schematic and which are not intended to be drawn to scale. In the figures, each identical, or substantially similar component that is illustrated in various figures is typically represented by a single numeral or notation. For purposes of clarity, not every component is labeled in every figure, nor is every component of each embodiment of the invention shown where illustration is not necessary to allow those of ordinary skill in the art to understand the invention.

In the drawings:

FIG. 1A is a cross-sectional side view of a tubular photobioreactor according to one embodiment of the invention;

FIG. 1B is a cross-sectional top view taken along line 1B-1B of the tubular photobioreactor of FIG 1A;

FIG. 1C is a cross-sectional side view of a tubular photobioreactor according to one embodiment of the invention including multiple spargers in each channel positioned at different heights within the photobioreactor conduit;

FIG. 2A is a plan view of a gas sparger assembly according to one embodiment of the invention;

FIG 2B is a side view of a dual gas sparger assembly positioned within a photobioreactor according to one embodiment of the invention;

FIG. 3A is a side view of an array of photobioreactors at a first inclination angle according to one embodiment of the invention;

FIG. 3B is a side view of an array of photobioreactors at a second inclination angle according to one embodiment of the invention;

FIG. 3C is a rear elevation view of an array of photobioreactors according to one embodiment of the invention;

FIG. 3D is an elevation view of an array of photobioreactors according to one embodiment of the invention;

FIG. 4 is a schematic block diagram of a photobioreactor system according to one embodiment of the invention;

FIGs. 5A-5E are schematic, cross-sectional views of a variety of photobioreactor configurations;

FIG. 6A is a side view of a photobioreactor apparatus according to one embodiment of the invention;

FIG. 6B is a rear elevation view of the photobioreactor apparatus shown in FIG. 5A;

FIG. 7A is a schematic diagram of a photobioreactor system employing the photobioreactor of FIG. 1A and including a computer-implemented control system, according to one embodiment of the invention;

FIG 7B is a graph illustrating an algae growth curve.

FIG. 8A is an cross-sectional side view of a heat exchange element positioned within a photobioreactor according to one embodiment of the invention;

FIG. 8B is a cross-sectional top view, taken along line 7B-7B of FIG. 7A, of a heat exchange element positioned within a photobioreactor according to one embodiment of the invention;

FIG. 8C is a plan view of the heat exchange element of the photobioreactor of FIG 7A;

FIG. 9A is a block flow diagram illustrating one embodiment of a method for operating the computer-implemented control system of the photobioreactor system of FIG. 7A;

FIG. 9B is a block flow diagram illustrating another embodiment of a method for operating the computer-implemented control system of the photobioreactor system of FIG. 7A;

FIG. 10 is a schematic process flow diagram of one embodiment of an integrated combustion method, according to one embodiment of the invention; and

FIG. 11 is a process flow diagram of one embodiment of an integrated wastewater treatment method, according to one embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

Certain embodiments and aspects of the present invention relate to photobioreactor apparatus designed to contain a liquid medium comprising at least one species of photosynthetic organism therein, and to methods of using the photobioreactor

apparatus as part of a gas-treatment process and system able to at least partially remove certain undesirable pollutants from a gas stream. In certain embodiments, the disclosed photobioreactor apparatus, methods of using such apparatus, and/or gas treatment systems and methods provided herein can be utilized as part of an integrated method and system for treating waste gasses produced by industrial processes, wherein photosynthetic organisms utilized within the photobioreactor are at least partially remove certain pollutant compounds contained within effluent gases, e.g. CO_2 and/or NO_x, and are subsequently harvested from the photobioreactor, processed, and utilized as a fuel source for a combustion device (e.g. an electric power plant generator, industrial furnace, and/or incinerator). Such uses of certain embodiments of the invention can provide an efficient means for recycling carbon contained within a combustion fuel (i.e. by converting CO_2 in a combustion gas to biomass in a photobioreactor), thereby reducing both CO_2 emissions and fossil fuel requirements. The integrated industrial system may include a combustion system, or industrial systems such as fermenters, agricultural waste digestors, catalytic cracking system or pyrolysis/gasification/liquifaction system (e.g. as may be present in many chemical manufacturing facilities, such as oil refineries) or wastewater treatment plants. In certain embodiments, a photobioreactor apparatus can be combined with a supplemental gas treatment apparatus to effect removal of other typical gas contaminants, e.g. as may be present in combustion/flue gas, such as SO_x, mercury, mercury-containing compounds, fly ash, heavy metals, ammonia, VOCs, and/or phosphate ash.

In certain embodiments, the photosynthetic organisms that are harvested from a photobioreactor system may be used as a food source for fish or other animals. In certain closed system embodiments, harvested photosynthetic organisms may be used for pharmaceutical purposes.

In certain embodiments a control system and methodology is utilized in the operation of a photobioreactor, which is configured to enable automatic, real-time, optimization and/or adjustment of operating parameters to achieve desired or optimal photomodulation and/or growth rates for a particular environmental operating conditions.

Certain aspects of the invention are directed to photobioreactor designs and to methods and systems utilizing photobioreactors. A "photobioreactor," or "photobioreactor apparatus" as used herein, refers to an apparatus containing, or

configured to contain, a liquid medium comprising at least one species of photosynthetic organism and having either a source of light capable of driving photosynthesis associated therewith, or having at least one surface at least a portion of which is partially transparent to light of a wavelength capable of driving photosynthesis (i.e. light of a wavelength between about 400-700 nm). Certain photobioreactors for use herein comprise an enclosed bioreactor system, as contrasted with an open bioreactor, such as a pond or other open body of water, open tanks, open channels, etc.

The term "photosynthetic organism" or "biomass," as used herein, includes all organisms capable of photosynthetic growth, such as plant cells and micro-organisms (including algae and euglena) in unicellular or multi-cellular form that are capable of growth in a liquid phase (except that the term "biomass," when appearing in the titles of documents referred to herein or in such references that are incorporated by reference, may be used to more generically to refer to a wider variety of plant and/or animal-derived organic matter). These terms may also include organisms modified artificially or by gene manipulation. While certain photobioreactors disclosed in the context of the present invention are particularly suited for the cultivation of algae, or photosynthetic bacteria, and while in the discussion below, the features and capabilities of certain embodiments that the inventions are discussed in the context of the utilization of algae as the photosynthetic organisms, it should be understood that, in other embodiments, other photosynthetic organisms may be utilized in place of or in addition to algae. For an embodiment utilizing one or more species of algae, algae of various types, (for example *Chlorella, Chlamdomonas, Chaetoceros, Spirolina, Dunaliella, Porphyridum*, etc) may be cultivated, alone or in various combinations, in the photobioreactor.

The phrases of "at least partially transparent to light" and "configured to transmit light," when used in the context of certain surfaces or components of a photobioreactor, refers to such surface or component being able to allow enough light energy to pass through, for at least some levels of incident light energy exposure, to drive photosynthesis within a photosynthetic organism.

FIGs. 1A and 1B illustrate one exemplary embodiment of a tubular photobioreactor apparatus 100, according to one aspect of the invention. Photobioreactor 100 comprises a conduit 102 that includes a partition 101 which separates conduit 102 into two fluidically interconnected channels 104, 106. In certain embodiments, the

partition is substantially continuous and impermeable to liquid along its entire length and width. In certain embodiments, the partition has a length that is at least 20% of the conduit length, in certain embodiments the partition has a length that is at least 85% of the conduit length. In certain embodiments, the partition has a length that is at least less than 85% of the conduit length. In certain embodiments, the partition has a length that is between 80% and 85% of the conduit length. The interconnected channels together provide a flow loop enabling the liquid medium 108 contained with the photobioreactor to flow sequentially from a region of origin (e.g., header 110) within the flow loop, through the two channels, and back to the region of origin. Liquid medium 108 is shown as flowing in a counterclockwise direction in the direction of arrows 120. As discussed in more detail below, liquid medium 108 may, alternatively, flow in a clockwise direction, or be controlled to be substantially stagnant, i.e. not have a bulk flow for any desirable period of time. While in the illustrated embodiment the tubular photobioreactor includes two channels 104 and 106, in other embodiments, the photobioreactor can include multiple partitions and/or conduits providing three or more channels and/or can be arranged having a geometry other than a single straight conduit as illustrated in FIGs. 1A and 1B (e.g. two parallel, fluidically interconnected conduits, such as illustrated in FIG. 5E). Also, while in the illustrated embodiment, the volume of the channel 104 is different from the volume of the channel 106, in other embodiments, the partition may essentially bisect the conduit along the length of the partition to form a first channel and a second channel, such that the first channel and the second channel have essentially equal volumes.

The term "fluidically interconnected", when used in the context of conduits, channels, chambers, or other structures provided according to the invention that are able to contain and/or transport gas and/or liquid, refers to such conduits, channels, containers, or other structures being of unitary construction or connected together, either directly or indirectly, so as to provide a continuous coherent flow path from one conduit or channel, etc. to the other(s) to which they are fluidically interconnected. In this context, two conduits or channels, etc. can be "fluidically interconnected" if there is, or can be established, liquid and/or gas flow through and between the conduits and/or channels (i.e. two conduits/channels are "fluidically interconnected" even if there exists a

valve between the two conduits/channels that can be closed, when desired, to impede fluid flow therebetween).

A "channel" as used herein, refers to a passage or lumen through which a liquid or other fluid can flow. A channel may comprise, in certain embodiments, fluid impermeable wall(s) for completely surrounding a fluid passing through the channel along its direction of flow. In other embodiments, wall(s) of a channel may only partially surround a fluid passing through the channel along its direction of flow and/or the wall(s) may have some degree of permeability with respect to a fluid flowing in the channel, so long as the wall(s) sufficiently surround the fluid and are fluid impermeable to a sufficient extent so as to be able to establish and maintain a bulk flow direction of fluid generally along a trajectory parallel to a longitudinal axis or curve defining the geometric center of the channel along its length. In some cases, a channel may comprise the lumen of a conduit. In other cases, the lumen of a conduit may include therein one or more partitions dividing the lumen into two or more channels. A "conduit" as used herein refers to a pipe, tube, duct, or the like having a lumen through which a liquid or other fluid can flow, which pipe, tube, duct, or the like comprises a structure that is physically distinct from other conduits, in that more than a single wall thickness separates fluid contained in the conduit from the fluid contained in any other conduit. As mentioned above, in certain cases, the lumen of a conduit may comprise a single channel. In other cases, the lumen of a conduit may comprise one or more partitions therein which divide it into two or more channels.

As discussed in greater detail below, the liquid medium contained within the photobioreactor during operation typically comprises water or a saline solution (e.g. sea water or brackish water) containing sufficient nutrients to facilitate viability and growth of algae and/or other photosynthetic organisms contained within the liquid medium. As discussed below, it is often advantageous to utilize a liquid medium comprising brackish water, sea water, or other non-portable water obtained from a locality in which the photobioreactor will be operated and from which the algae contained therein was derived or is adapted to. Particular liquid medium compositions, nutrients, etc. required or suitable for use in maintaining a growing algae or other photosynthetic organism culture are well known in the art. Potentially, a wide variety of liquid media can be utilized in various forms for various embodiments of the present invention, as would be understood

by those of ordinary skill in the art. Potentially appropriate liquid medium components and nutrients are, for example, discussed in detail in: Rogers, L.J. and Gallon J.R. "Biochemistry of the Algae and Cyanobacteria," Clarendon Press Oxford, 1988; Burlew, John S. "Algal Culture: From Laboratory to Pilot Plant." Carnegie Institution of Washington Publication 600. Washington, D.C., 1961 (hereinafter "Burlew 1961"); and Round, F.E. The Biology of the Algae. St Martin's Press, New York, 1965; each incorporated herein by reference).

Photobioreactor 100, during operation, is filled with enough liquid medium 108 so that the fill level 116 is above a top 103 of partition 101, so as to permit a recirculating loop flow of liquid medium (e.g., in the direction of arrows 120) during operation. In some embodiments, some portion, e.g. approximately 20%, of the volume of photobioreactor 100 is left unfilled with liquid medium. As is explained in more detail below, in certain embodiments, liquid flow inducing elements may be used to control the liquid flow direction and/or stop or reverse the liquid flow direction from the counterclockwise direction illustrated. In certain embodiments, the liquid flow inducing elements may also inject gas into the channels. In the illustrated embodiment, as described in more detail below, photobioreactor 100 employs a feed gas introducing mechanism and liquid medium flow-inducing mechanism comprising two gas spargers 122 and 124, which are configured to create a plurality of bubbles 126 rising up and through channels 104 and 106, thereby inducing liquid flow.

In certain embodiments, photobioreactor apparatus 100, is configured to be used in conjunction with a source of natural light, e.g. sunlight 128. In such an embodiment, at least one of channels 104 and 106 should be at least partially transparent to light of a wavelength capable of driving photosynthesis. In the illustrated embodiment, conduit 102 comprises a "solar panel" surface 132 that is at least partially transparent to sunlight 128. The partial transparency of conduit 102 may permit sunlight 128 to penetrate a distance into conduit 102, but leave portions of conduit substantially unilluminated, thereby providing "dark tubes" or dark regions within a tube. In certain embodiments, partition 101 is not transparent, resulting in channel 106 being a dark tube.

Conduit 102 may be constructed from a wide variety of transparent or translucent materials that are suitable for use in constructing a bioreactor. Some examples include, but are not limited to, a variety of transparent or translucent polymeric materials, such as

polyethylenes, polypropylenes, polyethylene terephthalates, polyacrylates, polyvinylchlorides, polystyrenes, polycarbonates, etc. Alternatively, conduit 102 can be formed from glass or resin-supported fiberglass. Preferably, conduit 102, is sufficiently rigid to be self-supporting and to withstand typical expected forces experienced during operation without collapse or substantial deformation. Portions of conduit may be non-transparent in certain embodiments, and such portions can be made out of similar materials as described above for the at least partially transparent portions of conduit 102, except that, when they are desired to be non-transparent, such materials should be opaque or coated with a light-blocking material. For example, the rear portion of conduit 102 that forms channel 106 may be constructed from an opaque material, along with partition 101, while the front portion of conduit 102 that forms channel 104 may be constructed from a transparent material. As will be explained in more detail below, an important consideration in designing certain photobioreactors according to the invention is to provide a desirable level of photomodulation (i.e. temporal pattern of alternating periods of exposure of the photosynthetic organisms to light at an intensity sufficient to drive photosynthesis and to dark or light at an intensity insufficient to drive photosynthesis) within the photobioreactor. By using materials which do not allow light to penetrate the entire conduit 102, or by making at least a portion of at least one of the conduits non-transparent, dark intervals may be built into the flow loop and can help establish a desirable ratio of light/dark exposure of the algae in the photobioreactor leading to improved growth and performance.

While conduit 102 and channels 104 and 106 as illustrated, comprise straight, linear segments, in alternative embodiments, one or more of the conduit and/or channels may be arcuate, serpentine, or otherwise non-linear, if desired. While, in certain embodiments, tubular conduit 102 and/or channels 104, 106 may have a wide variety of cross-sectional shapes, for example, square, rectangular, oval, triangular, etc., as described below with reference to FIGs. 5A-5E, as illustrated, conduit 102 comprises a length of tubing having an essentially circular cross-sectional shape and channels 104 and 106 have a semi-circular cross-sectional shape.

Partition 101 is illustrated in FIG. 1B to be as wide as conduit 102 in a plane of partition 101. In certain embodiments, partition 101 may be less wide than conduit 102

in a plane of the partition. For example, in certain embodiments, partition 101 may be at least 50%, 75%, 90% or 95% of the conduit width.

Additionally, if desired, one or more of channels 104 and 106 (and especially channel 104 which is exposed to more sunlight than channel 106) can have a variety of flow-disrupting and/or mixing-enhancing features therein to increase turbulence and/or gas-liquid interfacial mixing within the channel. This can, for example, lead to improved short-duration "flashing light" photomodulation, as explained in more detail below, and/or to improved diffusional uptake of gas within the liquid medium for embodiments wherein the gas to be treated is injected directly into the photobioreactor (e.g. as illustrated in FIGs. 1A and 1B). Such flow enhancements can comprise, but are not limited to, fins, baffles, or other flow directing elements within channels 104 and/or 106, and/or can comprise providing conduit 102 with a helical twist along its length, etc.

For certain embodiments, especially for embodiments wherein the gas to be treated, such as combustion gas, flue gas, gas from a biological process, etc., gas is injected directly into the photobioreactor at the base of a light-transparent channel (e.g., within header 100 below channel 104), performance of the photobioreactor can, in certain situations, be improved by providing certain geometric and structural relationships, as described below.

As illustrated, gas sparger 122 is configured and positioned within channel 104 to introduce a gas to be treated into a lower end of conduit 102, so as to create a plurality of gas bubbles 126 that rise up and through liquid medium 108 contained within channel 104 along a portion 130 of the inner surface of the conduit that is directly adjacent to that portion 132 of the outer surface of the conduit that most directly faces sunlight 128. This arrangement, in combination with providing certain angles α_1 between channels 104 and/or 106 and the horizontal plane can enable sparger 122 to introduce the gas stream into the lower end of channel 104 such that a plurality of bubbles rises up and through the liquid medium inducing a liquid flow within channel 104 characterized by a plurality of recirculation vortices 134 and/or turbulent eddies positioned along the length of channel 104. These recirculation vortices and/or eddies both can increase mixing and/or the residence time of contact between the bubbles and the liquid within channel 104, as well as provide circulation of the algae from light regions near inner surface 130 of conduit 102 to darker regions positioned closer to inner surface 136 of conduit 102,

thereby providing a "flashing light" relatively high frequency photomodulation effect that can be very beneficial for the growth and productivity, (i.e. in converting CO_2 to biomass). This effect, and inventive means to control and utilize it, is explained in greater detail below in the context of FIGs. 7A, 9A, and 9B. It is believed that a reason why recirculation vortices 134 and/or turbulent eddies can facilitate enhanced photomodulation is that as the as algae grows within the photobioreactor, the optical density of the liquid medium increases, thereby decreasing the effective light penetration depth within the liquid medium, such that regions within channel 104 positioned sufficiently far away from inner surface 130 will be in regions of the tube where the light intensity is insufficient to drive photosynthesis.

Only a schematic representation of spargers 122, 124 is shown in FIG. 1A. One embodiment of an arrangement for positioning spargers 122, 124 in photobioreactor 100 and supplying gas to the spargers is shown in FIGs. 2A and 2B, described in more detail below.

Other advantages of the illustrated arrangement wherein gas sparger 122 and conduit 102 are arranged such that gas bubbles 126 rise along the region of the conduit upon which the light is most directly incident include improved cleaning and thermal buffering. For example, as bubbles 126 rise up and along the inner surface 130 of channel 104 of conduit 102, they serve to effectively scour or scrub the inner surface, thereby reducing build up of algae on the surface and/or removing any algae adhered to the surface. In addition, because the bubbles can also be effective at reflecting at least a portion of the light incident upon conduit 102, the bubbles can act to effect a degree of thermal buffering of the liquid medium in the photobioreactor. In some embodiments, to enhance the scrubbing and/or thermal buffering effect of the bubbles, a plurality of neutrally buoyant, optionally transparent or translucent, microspheres (e.g. having a diameter of between 0.5 to about 3 mm) could also be utilized. Such buoyant particles would be carried with the liquid flow within conduit 102, thereby creating an additional scrubbing and/or thermal buffering effect, and/or an additional "flashing light" photomodulation effect.

The term "recirculation vortices" as used herein, refers to relatively stable liquid recirculation patterns (i.e. vortices 134) that are superimposed upon the bulk liquid flow direction (e.g. 120). Such recirculation vortices are distinguishable from typical

turbulent eddies characterizing fully developed turbulent flow, in that recirculation vortices potentially can be present even where the flow in the conduit is not fully turbulent. In addition, turbulent eddies are typically relatively randomly positioned and chaotically formed and of, for a particular eddy, short-term duration. As will be explained below, the selection of geometries and liquid and/or gas flow rates within the photobioreactors to create such recirculation vortices and/or turbulent eddies can be determined using routine fluid dynamic calculations and simulations available to those of ordinary skill in the art.

In certain other embodiments, as illustrated, the inventive photobioreactor includes multiple gas spargers, e.g. two gas spargers 122 and 124, each of which may be configured and positioned within the photobioreactor to inject gas bubbles at the base of an upwardly-directed channel, such as channel 104 and channel 106. In certain embodiments using direct gas injection into the photobioreactor, a single gas sparger or diffuser (e.g., sparger 122) can be utilized. As will be appreciated by those skilled in the art, the gas bubble stream released from sparger 122 and rising through channel 104 and the gas bubble stream released from sparger 124 and rising through channel 106 (in the direction of arrows 138 and 140, respectively), each provide a driving force having a tendency to create a direction of liquid flow around the flow loop that is oppositely directed from that created by the other. Accordingly, by controlling the overall flow rate of a gas to be treated by the photobioreactor and the relative ratio or distribution of the overall flow rate that is directed to sparger 122 and to sparger 124, it is possible to induce a wide variety of pressure differentials within the photobioreactor, which are governed by differences in gas holdups in channel 104 and channel 106, so as to drive a bulk flow of the liquid medium either counterclockwise, clockwise, or, with the proper balance between the relative gas injection rates, to induce no bulk liquid flow whatsoever around the flow loop.

In short, the liquid medium fluid dynamics are governed by the ratio of gas flow rates injected into spargers 122 and 124. For example, if all of the gas flow injected into the photobioreactor were injected into one of the spargers, this would create a maximal overall liquid flow rate around the flow loop. On the other hand, there is a certain ratio of distribution that, as mentioned above, would result in a stagnant liquid phase. Thus, the relative bulk liquid flow, the gas-liquid residence time in each of channels 104 and

106, as well as the establishment of particular liquid flow patterns within the photobioreactor (e.g., recirculation vortices) can be reproducibly controlled via control of the combination of the overall gas flow rate and the relative ratio of the overall gas flow rate injected into each of spargers 122 and 124.

This arrangement can provide a much greater range of flexibility in controlling overall liquid flow rates and liquid flow patterns for a given overall gas flow rate and can enable changes in liquid flow rates and flow patterns within the photobioreactor to be effected without, necessarily, a need to change the overall gas flow rate into the photobioreactor.

Accordingly, as discussed in more detail below in FIG. 7A, control of the gas injection rates into the spargers of such a two-sparger photobioreactor, as illustrated, can facilitate control and management of fluid dynamics within the photobioreactor on two levels, without the need for supplemental liquid recirculation means, such as pumps, etc., thereby enabling control and optimization of photomodulation (i.e. maintaining maximal continuous algae proliferation and growth via controlled light/dark cycling). These two levels of fluid dynamic control enabling photomodulation control comprise: (1) control of the overall liquid flow rate around the flow loop, which controls the relative duration and frequency that the algae is exposed to light in channel 104 and dark in channel 106; and (2) creation and control of rotational vortices and/or turbulent eddies in solar panel channel 104, in which the algae are subjected to higher frequency variations of light-dark exposure creating, for example, a "flashing light" effect. The liquid flow rate within such a photobioreactor can be adjusted to give a wide range of retention time of the algae within each channel 104 and 106 (e.g., in a range of seconds to minutes).

An additional advantage of the two-sparger gas injection embodiment illustrated, is that in one of the channels in which gas is injected, the relative direction of the gas flow with respect to the direction of bulk liquid flow will be opposite that in the other channel into which gas is injected. In other words, as illustrated in FIG. 1, gas flow direction 140 in channel 106 is co-current with the direction of liquid flow 120, while gas flow direction 138 in channel 104 is counter-current to bulk liquid flow direction 120. Importantly, by providing at least one conduit in which the direction of gas flow is counter-current to the direction of liquid flow, it may be possible to substantially increase

the effective rate of mass transfer between the pollutant components of the gas to be injected, (e.g., CO_2, NO_x), and the liquid medium.

This can be especially important in the context of NO_x removal in the photobioreactor. It has been shown that in bubble column and airlift photobioreactors utilized for NO_x removal, a counter-flow-type airlift reactor can have as much as a three times higher NO_x removal ability than a reactor in which gas and liquid flow are co-current (Nagase, Hiroyasu, Kaoru Eguchi, Ken-Ichi Yoshihara, Kazumasa Hirata, and Kazuhisa Miyamoto. "Improvement of Microalgal NO_x Removal in Bubble Column and Airlift Reactors." Journal of Fermentation and Bioengineering, Vol. 86, No. 4, 421-423. 1998; hereinafter "Hiroyasu et al. 1998"). Because this effect is expected to be more important in the context of NO_x removal, where, as mentioned in the background, the rate of uptake and removal is diffusion limited, and since algae can process NO_x under both light and dark conditions (i.e. during both photosynthesis and respiration), it may be possible to obtain a similar advantage in NO_x removal with the photobioreactor even for a situation wherein the direction of liquid flow 120 is opposite to that illustrated in FIG. 1, i.e. such that the gas and liquid flow in channel 104 is co-current and the gas and liquid flow in channel 106 is counter-current. The chemical formula "NO_x", as used herein, refers throughout the present specification to any gaseous compound comprising at least one nitrogen oxide selected from the group consisting of: NO and NO_2.

The term "gas sparger" or "sparger," as used herein, refers to any suitable device or mechanism configured to introduce a plurality of small bubbles into a liquid. In certain embodiments, the spargers comprise gas diffusers configured to deliver fine gas bubbles, on the order of about 0.3 mm mean bubble diameter or less so as to provide maximal gas-to-liquid interfacial area of contact. A variety of suitable gas spargers and diffusers are commercially available and are known to those of ordinary skill in the art, including gas spargers that provide bubbles with uncontrolled diameters.

In the embodiment illustrated in FIGs. 1A-1B, gas to be treated that is injected into photobioreactor 100 through spargers 122 and 124 makes a single pass through the photobioreactor and is released from the photobioreactor through gas outlet 141. In certain embodiments, a filter 142, such as a hydrophobic filter, having a mean pore diameter less than the average diameter of the algae can be provided to prevent algae from being carried out of the bioreactor through gas outlet 141. In this or alternative

embodiments, other well known means for reducing foaming within a header 114 and loss of algae through the gas outlet may be employed, as would be apparent to those skilled in the art.

In certain embodiments, a photobioreactor apparatus of the invention can include multiple spargers within each of one or more channels positioned at different positions along the length of the conduit(s) forming the photobioreactor. For example, a photobioreactor could include a first gas sparger configured and positioned to introduce a gas stream into the conduit at a first longitudinal position (height when inclined) along its length, a second gas sparger configured and positioned to introduce a gas stream into the conduit at a second height, different from the first height. Such an arrangement may be advantageous at reducing gas flow pressure drop and improving liquid recirculation flow rates for very long photobioreactor conduits. Such a configuration is illustrated schematically in FIG. 1C, which shows an embodiment of photobioreactor 100 comprising a conduit 102 in which channel 104 includes three spargers 122, 122′, and 122″ therein, and in which channel 106, similarly, includes three spargers 124, 124′, and 124″ therein.

As would be apparent to those skilled in the art, particular configurations of the various conduits and components of the photobioreactor, as well as the particular gas injection rates, liquid recirculation rates, etc. will depend upon the particular use to which the photobioreactor is employed and the composition and quantity of the gas to be treated. Given the guidance provided herein and the knowledge and information available to those skilled in the arts of chemical engineering, biochemical engineering, and bioreactor design, can readily select certain operating parameters appropriate for a particular application, utilizing no more than a level of routine engineering and experimentation entailing no undue burden.

Moreover, as discussed below in the description of FIGs. 3A-3D, and as would be apparent to those skilled in the art, in certain embodiments, photobioreactor 100 can comprise one of a plurality of identical or similar photobioreactors interconnected in parallel, in series, or in a combination of parallel and series configurations so as to, for example, increase the capacity of the system (e.g., for a parallel configuration of multiple photobioreactors) and/or increase the degree of removal of particular components of the gas stream (e.g., for configurations having gas outlets of a photobioreactor in series with

the gas inlet of the same and/or a subsequent photobioreactor). In one such embodiment, a photobioreactor system is designed to separate algae species that are efficient in utilizing NO_x from species efficient in utilizing CO_2. For example, a nitrogen-efficient algae is placed in a first photobioreactor(s) and carbon-efficient algae is placed in a second photobioreactor(s) in series with the first photobioreactor(s). The flue gas enters the first photobioreactor(s) and is scrubbed of nitrogen (from NO_x), then flows through the second photobioreactor(s) and is scrubbed of carbon (from CO_2). All such configurations and arrangements of the inventive photobioreactor apparatus provided herein are within the scope of the present invention.

Although photobioreactor 100 was described as being utilized with natural sunlight 128, in alternative embodiments, an artificial light source providing light at a wavelength able to drive photosynthesis may be utilized instead of or in supplement to natural sunlight. For example, a photobioreactor utilizing both sunlight and an artificial light source may be configured to utilize sunlight during the daylight hours and artificial light in the night hours, so as to increase the total amount of time during the day in which the photobioreactor can convert CO_2 to biomass through photosynthesis.

Since different types of algae can require different light exposure conditions for optimal growth and proliferation, in certain embodiments, especially those where sensitive algal species are employed, light modification apparatus or devices may be utilized in the construction of the photobioreactors according to the invention. Some algae species either grow much more slowly or die when exposed to ultraviolet light. If the specific algae species being utilized in the photobioreactor is sensitive to ultraviolet light, then, for example, certain portions of external surface 132 of conduit 102, or alternatively, the entire conduit outer and/or inner surface, could be covered with one or more light filters that can reduce transmission of the undesired radiation. Such a light filter can readily be designed to permit entry into the photobioreactor of wavelengths of the light spectrum that the algae need for growth while barring or reducing entry of the harmful portions of the light spectrum. Such optical filter technology is already commercially available for other purposes (e.g., for coatings on car and home windows). A suitable optical filter for this purpose could comprise a transparent polymer film optical filter such as SOLUS™ (manufactured by Corporate Energy, Conshohocken, PA). A wide variety of other optical filters and light blocking/filtering mechanisms

suitable for use in the above context will be readily apparent to those of ordinary skill in the art. In certain embodiments, especially for photobioreactors utilized in hot climates, as part of a temperature control mechanism (which temperature control strategies and mechanisms are described in much more detail below in the context of FIG. 7A and FIGs. 8A-8C), a light filter comprising an infrared filter could be utilized to reduce heat input into the photobioreactor system, thereby reducing the temperature rise in the liquid medium.

As discussed above, particular configurations and operating parameters yielding desirable or optimal photobioreactor performance will depend on the particular application for which the photobioreactor is utilized and the particular environmental and operating conditions to which it is subjected. While those of ordinary skill in the art can readily, utilizing the teachings in the present specification, the routine level of knowledge and skill in the art, and readily available information, and utilizing no more than a level of routine experimentation that requires no undue burden, select functional configurations, flow rates, materials, etc. for a particular application, certain exemplary and/or preferred parameters are given below and, more specifically, in the examples at the end of the written description of the application, for illustrative, non-limiting purposes.

In certain embodiments, in order to more readily facilitate the formation of recirculation vortices and/or desirable liquid flow patterns, bubble trajectories, etc., a photobioreactor, such as photobioreactor 100 illustrated in FIGs. 1A and 1B, can be configured so that the angle of channel 104 relative to the horizontal differs from the angle of channel 106 relative to the horizontal, e.g. by forming each channel as an independently positionable conduit. In certain embodiments, at least one of the channels forms an angle with respect to the horizontal having an absolute value of less than 90 degrees, in certain embodiments less than or equal to 85 degrees, in certain embodiments less than or equal to 65 degrees. In certain embodiments, at least one of the channels forms an angle with respect to the horizontal having an absolute value of greater than 10 degrees, in certain embodiments at least about 35 degrees. In certain embodiments, at least one of the channels forms an angle with respect to the horizontal having an absolute value of between 10 degrees and less than 90 degrees, between 20 degrees and 85 degrees inclusive, between 35 and 65 degrees inclusive, or in certain embodiments about

45 degrees. In certain embodiments, the angle that falls within the above-mentioned ranges and values comprises the angle between the horizontal and a channel that is transparent to light and in which photosynthesis takes place, (e.g. angle α_1 between the horizontal and channel 104).

In certain embodiments, because outer surface 132 of conduit 102 acts as the primary "solar panel" of the photobioreactor, the photobioreactor is positioned, with respect to the position of incident solar radiation 128, such that sunlight is most directly incident upon surface 132, thereby increasing solar uptake and efficiency. As described below with reference to FIGs. 3A-3D, to maintain a desired angle of sunlight incidence, photobioreactor 100 may be used within a system that changes the angle between conduit 102 and the horizontal and/or rotates and/or revolves conduit 102 about an axis of revolution or rotation, e.g. a vertical axis.

The lengths of gas-sparged channels 104 and 106 are selected to be sufficient, for a given desired liquid medium circulation rate, to provide sufficient gas-liquid contact time to provide a desired level of mass transfer between the gas and the liquid medium. Optimal contact time depends upon a variety of factors, especially the algal growth rate and carbon and nitrogen uptake rate as well as feed gas composition and flow rate and liquid medium flow rate. The length of channel 106 should be long enough, when channel 106 is used a dark channel, to provide a desired quantity of dark, rest time for the algae. In certain embodiments, conduit 102 is between about 1.5 ft (~0.5 m) and about 24 ft (~7.3 m) inclusive in length, and in certain embodiments conduit 102 is between about 6 ft (1.8 m) and 12 ft (3.7 m) inclusive in length, although shorter or longer conduit lengths may be used.

The internal diameter or minimum internal cross-sectional dimension of conduit 102 and channels 104 and 106 will depend on a wide variety of desired operating conditions and parameters and should be selected based upon the needs of a particular application. In general, an appropriate inner diameter *D* (see FIG. 1B) of conduit 102 can depend upon, for example, desired volumetric or production capacity, total gas injection flow rate through spargers 122 and 124, bubble size, dimensions of the gas diffuser, etc. If an inner dimension of channel 104 is too small, bubbles from sparger 122 might coalesce into larger bubbles resulting in a decreased level of mass transfer of

CO_2, NO_x, etc. from the gas into the liquid phase, resulting in decreased efficiency in removing pollutants and/or a decreased level or rate of biomass production.

The inner cross-sectional area and dimensions of channel 106 can depend upon the liquid medium flow rate and desired light-dark exposure intervals. Typically, the cross-sectional area should be chosen so that it is not so large to result in an unduly long residence time of the liquid and algae in conduit 106 such that the algae spends too much time during a given flow loop cycle not exposed to light, thereby leading to a reduction in the solar efficiency of the photobioreactor.

Regarding the cross-sectional sizes of the cross-sectional areas of channels 104 and 106 relative to one another, a wide variety of operating conditions may be involved in choosing appropriate relative sizes, for example, the intensity of solar radiation 128, algal concentration and optical density of the liquid medium, gas flow rate, and the desired mixing and flow pattern properties of the liquid medium within the channels during operation. In certain embodiments, the cross-sectional area of channel 104 may be between approximately 10% and 90% of the total cross-sectional area of channels 104 and 106 combined. In certain preferred embodiments, the cross-sectional area of channel 104 may be 50% or more, 60% or more, or 70% or more of the total cross-sectional area of channels 104 and 106 combined. In certain embodiments, the volumes of each channel 104, 106 may be essentially equal to one another. The cross-sectional area of a conduit refers to the area within the internal walls defining the outer perimeter of lumen of the conduit taken along a cross-section that is substantially perpendicular to the longitudinal direction of the conduit. The cross-sectional area of a channel refers to the cross-sectional area of the lumen within the bounding walls of the channel (e.g., circumscribed by a partition wall and an internal conduit wall as is the case for conduits 104 and 106 as illustrated).

As a specific example, one photobioreactor includes a tubular bioreactor as illustrated in FIGs. 1A and 1B, wherein the conduit has a circular cross-sectional shape and includes a partition 101 running along a substantial length of the conduit. The exemplary bioreactor may be oriented at an angle α_1 between about 20 and 85 degrees. Conduit 102, in this example, is approximately 12 ft (3.7 m) in length and approximately 12 inches (0.3 m) in diameter. The total volume of liquid medium in the bioreactor is about two hundred liters, and the mean bubble size from the spargers is about 0.3 mm.

Concentration of algae (for example, one or more species of the genera *Dunaliella* or *Chaetoceros*) is maintained at about 0.5 – 1.5 g (dried weight)/L of liquid medium.

According to one embodiment of the invention, a photobioreactor having a substantially larger diameter than conventionally employed may be used. For example, conduit 102 of photobioreactor 100 may have a diameter of at least 100 cm such that significantly larger quantities of liquid medium may be used within a single photobioreactor 100. With a larger quantity of liquid medium, such a photobioreactor may be better able to maintain conditions favorable for the survival of algae within the photobioreactor when system or process disruptions occur. For example, if heat exchange capabilities were to be lost, the much larger volume of liquid medium could buffer the effects of heat creation. In addition, larger volume photobioreactors may be able to be operated to provide increased biomass production capacity and/or productivity when compared to smaller volume photobioreactors.

Harvesting algae, adjusting algal concentration, and introducing additional liquid medium can be facilitated via liquid medium inlet/outlet lines 150, 152 as explained in more detail below in the context of the inventive control system for operating the photobioreactor illustrated in FIG. 7A. Control of the concentration of algae is important both from the standpoint of maintaining a desirable level of algal growth and proliferation as well as providing desirable levels of photomodulation within conduit 102. As explained below, algae is harvested periodically or continuously to maintain the desired concentration range during operation. According to a preferred method, harvesting takes place in a semi-continuous fashion, meaning that only a portion of the algae is removed from the photobioreactor at a given time. To harvest the algae, sparging is discontinued and the algae are permitted to settle within header 110. Since algae that is denser than the liquid medium will drop to the bottom of the header, gravity can be utilized to harvest the algae; however, flocculants, chemicals that cause algae to clump and settle, may be used, in certain embodiments, to assist in the harvest. Some useful flocculants include clay (e.g. with particle size $< 2\mu m$), aluminum sulfate or polyacrylamide. After settling, algae-rich liquid medium may be withdrawn through one or both of lines 150 and 152. In certain embodiments, fresh, algae-free liquid medium may be injected into one of lines 150 and 152, with the other line open, thereby flushing algae-rich medium out of the photobioreactor while simultaneously replenishing

the photobioreactor with fresh medium. In certain embodiments, a volume of algae-free fresh liquid medium that is substantially equal to the volume of algae-rich medium withdrawn is added to the photobioreactor before gas sparging is recommenced. As explained below in FIG. 10, the water and nutrients contained in the harvested algae can be extracted and recycled to the liquid medium supply of the photobioreactor. This step may reduce waste and water use of the photobioreactor and the overall system, thereby lowering environmental impact and operational cost.

Certain species of algae tend to float in water. For embodiments of the photobioreactor which use such algae species, the algal harvesting process described above may be modified so that after gas sparging is turned off, a sufficient time is permitted to allow algae to float to the top of the photobioreactor and into header 114. In such an embodiment, a liquid medium outlet/inlet line (not shown) could be provided in header 114 to facilitate removal of the algae-rich liquid medium for harvesting.

In certain embodiments of a photobioreactor apparatus provided according to the invention, fouling of the inner surface of the conduit by algal adherence may be reduced or eliminated and cleaning and regeneration of the inner surfaces of the photobioreactor may be facilitated by coating at least the portion of the inner surfaces with a layer of a biocompatible substance that is a solid at temperatures of normal operation and that has a melting temperature that is less than the melting temperature of the surface onto which it is coated. Such substances may be transparent or translucent such that they do not unduly reduce the transparency of the surface onto which they are coated. Examples of suitable substances can include a variety of waxes and agars. In one variation of such embodiments, a manual or automatic steam sterilization/cleaning procedure may be applied to the photobioreactor after use and prior to a subsequent use. Such a procedure may involve melting and removing the above described coating layer, thereby dislodging any algal residue that adhered thereto. Prior to use, a new coating layer may be applied. This procedure may allow the light transmitting portions of the photobioreactor to remain clean and translucent over an extended period of use and re-use.

One embodiment of a gas sparger assembly which may be used to inject gas into photobioreactor 100 is shown in FIGs. 2A and 2B. A sparging elements 168 and 174 are positioned toward the bottom of photobioreactor 100 in channels 104 and 106, respectively, in an orientation that is generally perpendicular to the longitudinal axis of

the photobioreactor and generally parallel to the plane of partition 101. Gas inlets 170 and 176 extend into the photobioreactor from a position at or near the top of photobioreactor 100, where gas inlets 170 and 176 are connected to a gas supply header 202 (see FIGs. 3A-3C) to receive a supply of gas via gas flow distribution control valves 205 and 207, respectively, which can be independently adjusted and/or controlled to provide a desired gas flow to each of spargers 168 and 174. Support legs 172 are attached to the gas inlet that is positioned within channel 104 so that gas inlet 170 and gas sparger 168 are supported on partition 101. Support legs are optional and gas inlets 170, 176 may be constructed of materials and/or shaped such that they are supported only at the entrance to the photobioreactor. In some embodiments, the gas inlets may be supported external to the photobioreactor and the photobioreactor entrance.

Of course, more than two sparging elements may be used with photobioreactor 100. In some embodiments, only one sparger is used. Additionally, one or both of gas inlets 170, 176 may enter photobioreactor 100 at location other than the top of the photobioreactor, for example, one or both of the gas inlets may be positioned to enter at or near the bottom of photobioreactor 100. In certain embodiments, rather that each sparger being supplied via a common gas supply header 202 via an adjustable/controllable valve, each sparger is provided with its own separate, flow controlled gas supply line feeding the photobioreactor.

Reference is now made to FIGs. 2A-2D. FIGs. 2A-2D illustrate an embodiment comprising a plurality of photobioreactors 100i–100ix arranged in parallel to form a photobioreactor array 200. Parallel array 200 illustrates a distinct advantage of the tubular photobioreactor apparatus provided according to embodiments of the invention, namely that the capacity of the photobioreactor system may be scaled linearly with the number of identical, similar, or differently sized photobioreactor units used. In the embodiment shown in FIGs. 2A-2D, array 200 includes photobioreactors of various sizes, but array 200 may include photobioreactors of only similar or identical sizes, in which case the capacity of the photobioreactor system would scale in direct proportion with the number of photobioreactor unit used.

Photobioreactor array 200, comprising nine photobioreactor units 100i – 100ix, may share a common gas supply header 202 (not shown in FIG. 3D) and a common liquid medium header 206 (not shown in FIG. 3C). Gas sparger header 202 may be

connected to each sparger(s) of each photobioreactor, e.g. two spargers may be used, one for each of the solar channels 104 of each photobioreactor and one for each of the dark channels 106 for each of the photobioreactors. As described above, to facilitate the ability to independently control the gas flow to each of the spargers, flow control valves 205, 207 may be used. Liquid medium header 206 may be connected to each photobioreactor with flexible tubing 207 and may include a valve (not shown) which allows for flow control. Alternatively, in some embodiments, liquid medium header 206 may not comprise a simple conduit-like header, as illustrated, but, rather, may comprise a solid structure providing a plurality of cavities located at the points where the various conduits of the photobioreactors connect to the headers, which cavities facilitate fluid communication between the channels of the individual photobioreactor units, while preventing liquid fluid communication between adjacent photobioreactors.

As illustrated in FIGs. 3C and 3D, individual photobioreactor units may have various diameters/cross-sectional areas, for example, a 10 inch (25.4 cm) diameter, a 12 inch (30.5 cm) diameter, or a 14 inch (35.6 cm) diameter. As discussed above, the lengths of individual photobioreactor units may be chosen based on various performance requirements and/or operating conditions. In the illustrated embodiment, the photobioreactor units 100iv-100ix are approximately nine and a half feet in length and made from a single, extruded conduit, which may be made with a polymeric material (e.g. a polyacrylic material, such as PMMA). Conduits of the photobioreactors may, however, be formed by joining two or more shorter conduit segments together with a connection collar 208, as shown in photobioreactors 100i – 100iii of FIGs. 3C and 3D.

In certain embodiments, as illustrated, photobioreactor array 200 optionally may be supported by a support platform 210. Support platform 210 may be configured to rotate or revolve about a vertical axis (not shown) and/or translate from one location to another such that photobioreactor array 200 can be oriented/positioned toward the sun as it crosses the sky throughout the day. In some embodiments, individual photobioreactor units may be configured to rotate independently from one another.

Support arms 212, 214 are shown in FIG. 3C supporting braces 216 which in turn support the photobioreactor array 200. Support arms 212, 214 may be manually or hydraulically operated telescoping arms in some embodiments with pivot joints 216, 218 at either end of the arms to facilitate changing the angle of the photobioreactor units. In

some embodiments, bottom ends of the support arms may be movable relative to support platform 210 to facilitate changing the angle of the photobioreactors relative to horizontal. Changing the angle of the photobioreactors may be performed manually or automatically according to a set of instructions and/or calculations and/or in response to values from various sensors (e.g., temperature sensors or light intensity sensors). Real-time control of the positioning of the photobioreactors may be facilitated as part of the computer-implemented control strategy discussed below in the context of FIG. 7A.

Referring now to FIG. 4, an exemplary schematic block diagram of a photobioreactor system including various components external to the photobioreactor array 200 is illustrated. A blower 302 is used to feed gas to the gas spargers or other gas feed mechanisms in the photobioreactor tubes. A medium mixing tank 304 is fluidically interconnected to the photobioreactor tubes to replace medium that is removed during algae harvesting from the tubes. Additional tanks of course may be used as buffer tanks or mixing tanks within the system. A chiller 306 cools a heat exchange fluid, such as water, ethylene glycol solutions, etc., which is pumped through heat exchange elements within the photobioreactors to remove heat from the photobioreactors in some embodiments. Further description of one embodiment of a heat exchange system is provided below with reference to FIGs. 8A-8C.

Regarding algae harvesting operations, a centrifuge 308 may be used to remove water from the liquid medium that is removed from the photobioreactors. The removed liquid, and nutrients contained therein, may optionally be mixed with fresh liquid medium (for example, in medium mixing tank 304) so as to be reused in the photobioreactors. Alternatively, the removed may be processed to isolate therefrom various desirable substances produced by the algae. A dryer (e.g. an oven) 310 may be used to further dry the algae depending on the planned use of the algae. A controller, e.g. computer-implemented system 312, may be used to monitor and control the operation of the various components, including valves, sensors, etc. In addition to automating operation of aspects of the photobioreactor system, use of computer-implemented system 312 may facilitate optimizing or improving the efficiency of the system by determining suitable values for various control parameters.

FIGs. 5A-5E illustrate a variety of alternative shapes and configurations for alternative embodiments of photobioreactor 100. FIG. 5A illustrates a conduit 402

having rectangular configuration, which can have, in an exemplary embodiment, one solar panel channel 404 and one dark channel 406 divided by a partition 405. FIG. 5B illustrates a conduit 407 having an ovoid configuration. In an exemplary embodiment channel 408 may be configured as a solar panel channel which is separated from a dark channel 410 by a partition 409. FIG. 5C illustrates a conduit 411 having a triangular configuration. In this embodiment, a partition 413 forms a solar panel channel 412 and a dark channel 414.

FIG. 5D illustrates a conduit 415 including a tubular partition 417 forming a separate channel 418 within conduit 415 such that an annular channel 416, which would comprise a solar panel channel, is also formed. In some embodiments, instead of entirely enclosing the perimeter of dark channel 418, partition 417 may form a substantially but less than complete perimeter around liquid flowing in dark channel 418.

FIG. 5E illustrates two parallel channels 420 and 422, each of which is formed with a separate conduit 419 and 421. In the illustrated embodiment, channel 420 is a solar panel channel and is slightly larger in diameter than channel 422, which is a dark channel. Channel 422 may be formed with the same or different materials as channel 420. The shape and or size of conduits 419, 421 may be varied and the two conduits (or more) need not have the same shape.

In certain embodiments, the conduit(s) of a photobioreactor may have an inner wall perimeter that remains substantially constant in size along the length of the conduit length. In certain embodiments, the conduit(s) of a photobioreactor may have an inner wall perimeter that remains substantially constant in shape along the length of the conduit length.

In an alternative embodiment which is similar to the embodiment illustrated in FIG. 5E, the two channels 420 and 422 may be formed by coextruding conduits 419 and 421 such that they are formed of one conduit having two channels that share an internal, dividing wall.

As should be evident to one of skill in the art, while many of the partitions illustrated herein are substantially planar, arcuate partitions (such as partition 417) or otherwise non-planar partitions, e.g. a partition which is helically twisted along the length of the conduit, may be used to form channels of a variety of geometric forms in various conduits.

FIGs. 6A and 6B illustrate an alternative embodiment of a photobioreactor apparatus 500, which, when used as part of a photobioreactor system similar to those described above in the context of FIGs. 1A-3 can have similar performance characteristics as previously described for tubular photobioreactor 100 and provide the increased gas scrubbing capacity of parallel photobioreactor array 200, while being constructed as a unitary, integral structure. Photobioreactor apparatus 500 comprises an elongated box-like structure 502 including a solar panel surface 532 that is at least partially transparent to light of a wavelength capable of driving photosynthesis. Photobioreactor apparatus 500 also includes an elongated partition 501 within and spanning the entire or some substantial portion of the width of elongated box-like structure 502. The partition splits elongated box structure 502 into two flow channels 504, 506 which enable recirculating flow of liquid medium 108 within photobioreactor 500, similar to the flow arrangements described above in the context of FIGs. 1A and 1B.

Circulation of liquid medium around the flow loop of photobioreactor apparatus 500 can be facilitated by at least one gas sparger configured to introduce a gas stream into the flow loop of the container. In the illustrated embodiment, gas is introduced into channels 504 and 506 by elongated tubular gas spargers 521 and 523, which extend along the bottom width of bioreactor 500. Similar to the embodiment illustrated in FIGs. 3A-3D, one or more support arms 512 may be used to support apparatus 500 at an angle relative to the horizontal. The dimensions of photobioreactor 500 can be chosen to provide a desired total gas treatment capacity and are typically limited only by the topography/geometry of the site in which the units 500 are to be located and/or limitations in manufacturing, operation and transportation of the units.

In other aspects, the invention provides systems and methods for treating a gas with a photobioreactor including methods for monitoring and controlling liquid flow rates and flow patterns within the photobioreactor to create desired or optimal exposure of the photosynthetic organisms to successive and alternating periods of light and dark exposure to provide a desired or optimal level of photomodulation during operation. It is known that excessive exposure time of algae to light can cause a viability and growth limiting phenomena known as photoinhibition, and that, algal growth and productivity is improved when the algae cells are exposed to both light and dark periods during their growth (i.e. photomodulation). (Burlew 1961; Wu X. and Merchuk J.C. "A model

integrating fluid dynamics in photosynthesis and photoinhibition processes," *Chem. Eng. Sci.* 56:3527-3538, 2001 (hereinafter "Wu and Merchuk, 2001," incorporated herein by reference); Merchuk J.C., et al. "Light-dark cycles in the growth of the red microalga *Porphyridium sp.*," *Biotechnology and Bioengineering*, 59:705-713, 1998; Marra, J. "Phytoplankton Photosynthetic Response to Vertical Movement in A Mixed Layer." *Mar. Biol.* 46:203, 1978). As illustrated in FIG. 7A, certain aspects of the present invention provide gas treatment systems comprising one or more photobioreactors and further comprising a control system for controlling and/or monitoring various environmental and performance conditions and/or operating parameters of the photobioreactor, as well as implementing the methods for inducing and controlling photomodulation.

Referring to FIG. 7A, a gas treatment system 600 is shown that includes a photobioreactor 100, a plurality of monitoring and control devices, described in more detail below, and a control system comprising a computer-implemented system 602 that is configured to control various operating parameters as well as to control flow within the photobioreactor to provide desired or optimal levels of light/dark exposure intervals and frequency to yield desired or optimal levels of photomodulation. In certain embodiments, computer-implemented system 602 may be the same as, or a component of, control system 312 described previously in the context of FIG. 4.

In certain embodiments, as discussed in more detail below in the context of the FIGs. 9A and 9B, the computer-implemented system 602 is configured to control photomodulation by: performing a simulation of liquid flow patterns within the photobioreactor; and, from the simulation, to calculate exposure intervals of the photosynthetic organisms to light at an intensity sufficient to drive photosynthesis and to dark or light at an intensity insufficient to drive photosynthesis; and to control the flow of the liquid medium within the photobioreactor so as to yield desired or optimal exposure intervals providing a desired or optimal level of photomodulation. Also, as explained in more detail below, desirable or optimal light/dark exposure intervals are, in certain embodiments, also determined by the computer-implemented system utilizing a mathematical model, described in more detail below, of algal growth rate as a function of light/dark exposure intervals.

As used in the above context, an "exposure interval" of a photosynthetic organism to light or dark refers to both length and frequency of exposure to such conditions over a given time period of interest (e.g. a time period required for liquid medium in a tubular flow loop photobioreactor to flow around the entire flow loop). Specifically, as discussed in more detail below, computer-implemented system 602, in certain preferred embodiments in calculating "exposure intervals" determines the duration of exposure of the algae, on average, to light intensities both above and below the threshold required to drive photosynthesis as well as the frequency of exposure of the algae to light and dark periods as the algae in the liquid medium is carried around the flow loop of the photobioreactor.

It should be understood that even though this aspect of the present invention is illustrated utilizing photobioreactor 100 for illustrative purposes, in other embodiments, the photomodulation control methodology and control systems described herein could be utilized with other photobioreactors described herein or other conventional photobioreactors. In certain embodiments, photobioreactors of a design similar to photobioreactor 100 are preferred because of the above-described ability of the photobioreactor to create liquid flow in a solar panel channel, such as channel 104, characterized by recirculating vortices 134 and/or turbulent eddies, which can be effective in subjecting the algae within the channel 104 relatively high frequency cycling between areas of the tube in which light intensity will be sufficient to drive photosynthesis (e.g. near surface 132) and other areas of the channel further away from the surface where light intensity may be insufficient to drive photosynthesis.

For example, depending on the relative velocities of the liquid medium flow and gas bubble flow within channel 104, photomodulation frequency (i.e. light to dark interval transition) of greater than 100 cycles per second to less than one cycle per second may be provided. Such a high frequency "flashing light" effect during photosynthetic activity has been found to be very beneficial for growth and productivity of many species of algae (see, Burlew 1961). Moreover, various portions of channel 104 and/or 106, in certain embodiments, may be made either entirely or partially non-transparent to provide additional, more extended exposure of the algae to dark, rest periods, which may be beneficial for productivity as well.

Before describing the photomodulation control methodology and control system of the photobioreactor system 600, various sensors and controls that can be provided in the photobioreactor system will be explained. Control of certain of the physico-chemical conditions within the photobioreactor can be achieved using conventional hardware or software-implemented computer and/or electronic control systems together with a variety of electronic sensors.

For example, it can be important to control liquid medium temperature within photobioreactor 100 during operation to maintain liquid medium temperature within a range suitable or optimal for productivity. These specific, desirable temperature ranges for operation will, of course, depend upon the characteristics of the algae species used within the photobioreactor systems. Typically, it is desirable to maintain the temperature of the liquid medium between about 5 degrees C and about 45 degrees C, more typically between about 15 degrees C and about 37 degrees C, and most typically between about 15 degrees C and about 30 degrees C. For example, a desirable temperature operating condition for a photobioreactor utilizing *Chlorella* algae may have a liquid medium temperature controlled at about 30 degrees C during the daytime and about 20 degrees C during nighttime.

Gas treatment system 600 may control the liquid medium temperature, in certain embodiments, in one or more ways. For example, the temperature of the liquid medium may be controlled via control of the inlet temperature of the gas to be treated fed to spargers 122 and 124 and/or via supplemental cooling systems for directly cooling photobioreactor 100. An exemplary supplemental cooling system is described below with reference to FIGs. 8A-8C. Liquid medium temperature can be monitored in one or more places throughout photobioreactor 100 for example by temperature sensors 604 and 606. Feed gas from gas source 608 fed to sparger 122 and sparger 124 can be temperature monitored via one or more temperature sensors 612. In certain embodiments, feed gas from gas source 608 is passed through a heat exchanger, for example algal drier 912 illustrated in FIG. 10 prior to injection into photobioreactor 100. Depending on the temperature of the liquid medium detected by temperature sensor 604 and 606, the computer-implemented control system 602 can, in certain embodiments, control such a heat exchange system so as to increase or decrease the temperature of the gas fed to spargers 122 and 124 to raise or lower the temperature of the liquid medium.

One exemplary embodiment of a heat exchange element 650 which may be used as part of a heat exchange system is shown in FIGs. 8A-8C. Heat exchange element 650 includes an inlet 652, an inlet manifold 654, a number of heat exchange tubes 656, an outlet manifold 658, and an outlet 660. Inlet 652 and outlet 660 are fluidically interconnected with a source of cooling water or other coolant, e.g. chiller 306 illustrated in FIG. 4. These components may be constructed of any suitable material such as thin-walled stainless steel tubing. Inlet 652 and outlet 660 may enter photobioreactor tube 100 at the top of the conduit 102, as shown in FIGs. 8A and 8B. Inlet 652 and outlet 660 connect to heat exchange tubes 656 which are located within dark channel 106 in the present exemplary embodiment, although, in alternative embodiments, the heat exchange element may be located in solar channel 104 or both channels 104 and 106. Heat exchange element 650 may be supported within conduit 102 by, for example, support legs 662.

As will be evident to one of skill in the art, any suitable heat exchange element or heat exchange system may be used in conjunction with the photobioreactor systems and methods described herein. In some embodiments, no supplemental heat exchange system is required to be present within photobioreactor tubes 100.

As mentioned above, and as explained in more detail below, the demand for cooling and/or heating of the photobioreactor system can be lessened by using an algal strain which has an optimal productivity at temperatures close to actual temperatures to which the algae will be exposed at the operating site. In addition to controlling the liquid medium temperature via modifying the temperature of the feed gas with a heat exchange device, and/or with a supplemental heat exchange element(s) located within the photobioreactor as illustrated in FIGs. 8A-8C and as described above, in other embodiments, especially for embodiments wherein the photobioreactor apparatus is operated in a hot climate, infrared optical filters can be utilized to keep heat energy out of the photobioreactor and/or a supplemental external cooling system, such as a set of external water sprinklers spraying water on the outside of the photobioreactor, could be utilized to lower temperature.

Liquid medium pH can be monitored via pH probe 614. pH can be controlled at desirable levels for a particular species of algae by, for example, providing one or more injection ports, for example in fluid communication with liquid medium inlet/outlet 150,

into which pH adjusting chemicals, such as hydrochloric acid and sodium hydroxide, could be controllably injected.

System 600 can also provide various probes and monitors for measuring the pressure of the feed gas fed to the spargers (e.g., one or more pressure monitors 616), as well as one or more flow meters 620, 622 for measuring gas flow rates, and one or more flow meters 624 for measuring bulk liquid flow rate within the photobioreactor flow loop. Gas and liquid flow rates can be controlled, as explained in more detail below, at least in part, to facilitate desired or optimal levels of photomodulation by inducing desirable liquid flow patterns within the photobioreactor. A second control factor dictating the overall flow of gas fed to photobioreactor 100 can be the desired level of removal of pollutants such as CO_2 and/or NO_x by the photobioreactor. For example, as illustrated, system 600 includes appropriate gas composition monitoring devices 626 and 628 for monitoring the concentration of various gases, such as CO_2, NO_x, O_2, etc. in the feed gas and treated gas, respectively. Gas inlet flow rate and/or distribution to the spargers can be adjusted and controlled to yield a desirable level of pollutant removal by the photobioreactor system.

As mentioned above, periodically, in order to keep the concentration of algae within the photobioreactor within a range suitable for long term operation and productivity, at least a portion of the algae may be harvested and the photobioreactor may be supplemented with fresh, algae-free medium (or previously harvested medium having a low algae concentration) to adjust concentration of algae within the photobioreactor. As illustrated in FIG. 7B, under growth conditions, algae concentration (y-axis) will increase exponentially with time (the log growth phase) up to a certain point 629, after which the concentration will tend to level off and proliferation and growth will decrease. In certain preferred embodiments, the concentration of algae within the photobioreactor is maintained within an operating range 630 that is near the upper end of the concentration in which the algae is still in the log growth regime. As would be understood by those by those skilled in the art, the particular growth curve characterizing a given species of algae will be different from species to species and, even within a given a species of algae, may be different depending on differences in operating and environmental factors, (e.g., liquid medium composition, growth temperature, gas feed composition, etc.). In certain embodiments the invention teaches the use of

photobioreactor systems using pre-conditioned or pre-adapted algae optimized for growth at the particular operating conditions expected within the photobioreactor gas treatment systems as described in more detail in commonly-owned U.S. Patent Application Publication No. 2005/0064577 A1, incorporated herein by reference. In any case, the appropriate algae concentration range within which photobioreactor control system 602 may be configured to maintain the photobioreactor may be determined for a particular application by routine testing and optimization. Such routine testing and optimization may take place in a pilot-scale photobioreactor system or in an automated cell culture management system, as are described in more detail below.

Once a desired algae concentration range has been determined, as described above, control system 602 can be configured to control the algal concentration within this range by detecting the algae concentration within the liquid medium, harvesting the algae, and supplementing the system with fresh liquid medium. To determine the concentration of algae within the photobioreactor, a turbidity meter and/or spectrophotometer 632 (or other appropriate optical density or light absorbance measuring device) can be provided. For example, a spectrophotometer could be used to continuously measure the optical density of the liquid medium and evaluate the algal concentration from the optical density according to standard methods, such as described in Hiroyasu et al. 1998. Of course other methods of determining algae concentration may be used, for example, a cell counter or a measurement of TOC (total organic carbon) may be used.

In general, chemicals for nutrient level maintenance and pH control and other factors may be added automatically directly into the liquid phase within the photobioreactor, if desired. Computer control system 602 can also be configured to control the liquid phase temperature in the photobioreactor by either or both of controlling a heat exchange system or heat control system within or connected with the photobioreactor, or, in alternative embodiments removing liquid medium from the photobioreactor and passing through a heat exchanger in, for example, a temperature controlled water bath (not shown).

As mentioned above, certain preferred embodiments of photobioreactor gas treatment system 600 include a computer-implemented control system 602 configured for controlling liquid flow patterns within photobioreactor 100 so as to provide desired

photomodulation characteristics to provide a desired average algae growth rate, for example a maximum average growth rate achievable. In certain embodiments, the photomodulation control system and methodology utilizes two mathematical models to determine optimal or desired liquid flow patterns for optimizing photomodulation. The first mathematical model involves simulating the growth rate of the algae as a function of sequential and alternating exposure to intervals of light and dark, and the second mathematical model involves a simulation of liquid flow patterns within the photobioreactor as a function of system configuration and geometry and flow rates of liquid medium, (and for systems involving gas injection-driven liquid flow, gas injection rates into the photobioreactor). FIGs. 9A and 9B outline two of the many possible strategies for implementing the above-described photomodulation control scheme with computer-implemented control system 602.

Regarding the above-described mathematical models that can be utilized by control system 602 in optimizing photomodulation, the first mathematical model for correlating light/dark exposure intervals (photomodulation) to average growth rate can, in certain embodiments, be based upon a mathematical model proposed in the literature (see Wu and Merchuk, 2001). The model is based upon the hypothesis that the photosynthetic process in algal cells has three basic modes: (1) activated, (2) resting, and (3) photoinhibited. The fraction of an algal population in each of the three above modes can be represented by x_1, x_2, and x_3 respectively (where $x_1 + x_2 + x_3 = 1$).

The model proposes that under normal conditions, an active algal culture reaches photosaturation, becomes photoinhibited and must rest at regular intervals for optimal productivity. In the photoinhibition and resting modes, the culture is unable to use light for carbon fixation. Thus, light exposure during periods of photoinhibition or rest is essentially wasted because it is not available for photosynthesis and carbon fixation and can actually be detrimental to the viability of the culture. The proposed model provides a series of differential, time-dependent equations describing the dynamic process by which the algal culture shifts between the activated, resting, and photoinhibited modes:

$$\frac{dx_1}{dt} = -\alpha I\, x_1 + \gamma x_2 + \delta\, x_3 \qquad \text{Eq.1}$$

$$\frac{dx_2}{dt} = \alpha I\, x_1 - \gamma x_2 - \beta I\, x_2 \qquad \text{Eq.2}$$

$$\frac{dx_3}{dt} = \beta I\, x_2 - \delta x_3 \qquad \text{Eq.3}$$

while, $x_1 + x_2 + x_3 = 1$ Eq.4

and, $\mu = k\gamma\, x_2 - Me$ Eq.5

In these equations, α is a rate constant of photon utilization to transfer the algal culture from x_1 to x_2, β is a rate constant describing transfer from x_2 to x_3 (photoinhibition process), γ is a rate constant describing transfer from mode x_2 to x_1 (dark reaction for biomass production), δ is a rate constant describing transfer from x_3 to x_1 (recovery process from photoinhibition), μ is the specific growth rate, *Me* is the maintenance coefficient, and k is the dimensionless yield of photosynthesis production to the transition x_2 to x_1.

In a photobioreactor apparatus such as photobioreactor 100, illumination intensity I will be a complex function of time, depending on the fluid dynamics, light intensity of exposure, and algal concentration within photobioreactor 100. Illumination I as a function of time (i.e. the time history of illumination intensity of the algae as it flows through the photobioreactor) can be determined, as described in more detail below, using a simulation of the fluid dynamics within the photobioreactor. (see also: Wu X. and Merchuk J. "Simulation of Algae Growth in a Bench-Scale Bubble Column Reactor" *Biotechnology and Bioengineering*, 80:pp. 156-168 (2002)(hereinafter "Wu and Merchuk, 2002"); and Wu X. and Merchuk J. "Simulation of algae growth in a bench scale internal loop airlift reactor" *Chemical Engineering Science*, 59:pp. 2899-2912 (2004)(hereinafter "Wu and Merchuk, 2004"); both incorporated herein by reference). Once this parameter is determined, and once the constants α, γ, β, δ, k, and *Me* are determined, specific growth rate μ can be determined for a given illumination history around a flow loop cycle. Solution of these equations may be effected utilizing a wide variety of known numerical techniques for solving differential equations. Such numerical techniques can be facilitated by equation-solving software that is commonly

commercially available or can be readily prepared by one of ordinary skill in the art of applied mathematics.

While it can be possible to utilize controlled experiments within a production-scale photobioreactor, such as photobioreactor 100, to determine the appropriate values of the various constants in the above mathematical model via fitting the model to experimental data, in certain embodiments, for simplicity and accuracy, it may be desirable to utilize a pilot photobioreactor system being able to permit precise and direct manipulate of parameters such as the duration, frequency, and intensity of light exposure of the culture. For example, for a photobioreactor system wherein the algal culture is exposed to an essentially uniform light intensity throughout the entire culture and to a series of essentially identical light/dark exposure cycles (i.e. in which successive light/dark exposure cycles are essentially identical), a quasi-steady state analytical solution of the above-equations is possible (see, Wu and Merchuk, 2001).

Such an experimental photobioreactor system could comprise, for example, a small-scale photobioreactor in an automated cell culture system in which the algal cells are subjected to precisely controlled intervals of light and dark exposure at a regular, constant frequency. Alternatively, a pilot-scale, thin-film, bioreactor having fluid flow behavior providing an exact, repetitive light/dark exposure ratio, such as that disclosed in Wu and Merchuk, 2001, could be utilized. Under such quasi-steady state conditions, the mean specific growth rate for one cycle is given by (Wu and Merchuk, 2001):

$$\bar{\mu} = \frac{k\gamma}{t_c}\int_0^{t_c} x_2(t)dt - Me$$

$$= \frac{k\gamma}{t_c}\left[\int_0^{t_l} x_{2,l}(t)dt + \int_{t_l}^{t_c} x_{2,d}(t)dt\right] - Me$$

$$= \frac{k\gamma}{t_c}\left[\frac{c}{b}t_l + \frac{C_1}{A}(s-1) + \frac{C_2}{B}(n-1) + \left(\frac{c}{b} + C_1 s + C_2 n\right)\frac{u-1}{u\gamma}\right] - Me \qquad \text{Eq.6}$$

where,

$$a = \alpha I + \beta I + \gamma + \delta,$$
$$b = \alpha\beta I^2 + \delta\gamma + \alpha I\delta + \beta I\delta,$$
$$c = \alpha I\delta;$$
and
$$A = -\frac{a + \sqrt{a^2 - 4b}}{2},$$
$$B = -\frac{a - \sqrt{a^2 - 4b}}{2}$$

and,

$$C_1 = -\frac{Bc(u-1)(n-v) + \alpha Ib(n-u)(v-1) + c(\alpha I + \beta I + \gamma)(n-1)(u-v)}{b[B(s-u)(n-v) - A(n-u)(s-v) + (\alpha I + \beta I + \gamma)(s-n)(u-v)]}$$

$$C_2 = -\frac{Ac(u-1)(s-v) + \alpha Ib(s-u)(v-1) + c(\alpha I + \beta I + \gamma)(s-1)(u-v)}{b[B(s-u)(n-v) - A(n-u)(s-v) + (\alpha I + \beta I + \gamma)(s-n)(u-v)]}$$

where $s = e^{At_l}, n = e^{Bt_l}, u = e^{\gamma t_d}, v = e^{\delta t_d}$

In these equations, t is time, t_l is the time during the cycle in which the algal culture is exposed to light at an intensity capable of driving photosynthesis, t_d is the time during the cycle during which the algal culture is exposed to dark or light at an intensity incapable of driving photosynthesis and t_c is the total cycle time (i.e. $t_l + t_d$).

The above equations describing the analytical solution may be curve fit to experimental data of algal growth rate as a function of time to determine the values of the various constants (e.g., as described in Wu and Merchuk, 2001). For example, using the above approach, Wu and Merchuk, 2001 determined the following values for the constants in Eqs. 1-5 for a culture of red marine algae, *Porphyridium sp.* (UTEX 637) to be:

Table 1 – Adjustable Parameter Values and 95% confidence intervals

Parameter	Value	95% confidence interval
α	0.001935 $\mu E\ m^{-2}$	-0.00189-0.00576
β	5.7848 x 10^{-7} $\mu E\ m^{-2}$	-0.000343-0.000344
γ	0.1460 s^{-1}	-0.133-0.425
δ	0.0004796 s^{-1}	-0.284-0.285
k	0.0003647 (dimensionless)	-0.000531-0.00126
Me	0.05908 h^{-1}	-0.0126-0.131

The mathematical model utilized by computer-implemented control system 602 to determine liquid flow patterns within the photobioreactor as a function of liquid flow rate and/or overall gas injection rate and gas-injection distribution to spargers 122 and 124 can comprise a commercially available Computational Fluid Dynamics (CFD) software package, such as FLUENT™ (e.g. FLUENT 6.1) or FIDAP™ (Fluent Incorporated, Lebanon, NH), or another known software package, or custom-designed CFD software program providing a two-dimensional, or preferably three-dimensional solution to the Navier-Stokes Equations of Motion (e.g. see, Doering, Charles R. and J. D. Gibbon, Applied Analysis of the Navier-Stokes Equations, Cambridge University Press 2001, incorporated herein by reference). Those of ordinary skill in the art of fluid mechanics and computational fluid dynamics can readily devise such fluid flow simulations and, alone or in combination with one of ordinary skill in the art of computer programming, prepare software to implement such simulations. In such simulations, finite element mathematical techniques may be utilized and such computations may be performed or assisted using a wide variety of readily available general purpose or fluid-flow specific finite element software packages (for example one or more of those available from ALGOR, Inc., Pittsburgh, PA (e.g. ALGOR's "Professional Fluid Flow" software package)).

For example, in certain embodiments for simulating fluid flow using CFD, a Euler-Euler approach can be used for the 3-D numerical calculation of the multiphase (liquid-air) flows. In the Euler-Euler approach, the different phases are treated mathematically as interpenetrating continua. Since the volume of a phase cannot be occupied by the other phases, the concept of phase volume fraction is introduced. These volume fractions are assumed to be continuous functions of space and time and their sum is equal to one. Conservation equations for each phase are derived to obtain a set of equations, which have similar structure for all phases. More specially, the mixture model is designed for two or more phases (fluid or particulate) and treats phases as interpenetrating continua. The mixture model solves for the mixture momentum equation and prescribes relative velocities to describe the dispersed phases. The mixture model allows the phases to be interpenetrating. The volume fractions α_p and α_q for a control volume can be equal to any value between 0 and 1, depending on the space

occupied by the phases p and q. The mixture model allows the phases to move at different velocities, using the concept of slip velocities.

The mixture model solves the continuity equation for the mixture, the momentum equation for the mixture, the energy equation for the mixture, and the volume fraction equation for the secondary phases, as well as algebraic expressions for the relative velocities. Governing equations for one embodiment of a CFD simulation are listed below:

Continuity equation:

$$\frac{\partial}{\partial t}(\rho_m) + \nabla \cdot (\rho_m \vec{v}_m) = \dot{m} \qquad \text{(Eq. 7)}$$

Momentum equation:

$$\frac{\partial}{\partial t}(\rho_m \vec{v}_m) + \nabla \cdot (\rho_m \vec{v}_m \vec{v}_m) = -\nabla p + \nabla \cdot [\mu_m (\nabla \vec{v}_m + \nabla \vec{v}_m^T)] + \rho_m \vec{g} + \vec{F} + \nabla \cdot (\sum_{k=1}^{n} \alpha_k \rho_k \vec{v}_{dr,k} \vec{v}_{dr,k}) \qquad \text{(Eq. 8)}$$

$$\vec{v}_{dr,k} = \vec{v}_k - \vec{v}_m \qquad \text{(Eq. 9)}$$

Energy equation:

$$\frac{\partial}{\partial t} \sum_{k=1}^{n} (\alpha_k \rho_k E_k) + \nabla \cdot \sum_{k=1}^{n} (\alpha_k \vec{v}_k (\rho_k E_k + p)) = \nabla \cdot (k_{eff} \nabla T) + S_E \qquad \text{(Eq. 10)}$$

Volume fraction equation for phase p:

$$\frac{\partial}{\partial t}(\alpha_p \rho_p) + \nabla \cdot (\alpha_p \rho_p \vec{v}_m) = -\nabla \cdot (\alpha_p \rho_p \vec{v}_{dr,p}) \qquad \text{(Eq. 11)}$$

where $\vec{v}_m$ is the mass-averaged velocity, ρ_m is the mixture density, and $\dot{m}$ is the mass transfer due to cavitation, where n is the number of phases, $\vec{F}$ is a body force, μ_m is the viscosity of the mixture, and $\vec{v}_{dr,k}$ is the drift velocity for secondary phase k, k_{eff} is the effective conductivity (equal to $k + k_t$, where k_t is the turbulent thermal conductivity, defined according to any turbulence model being used), and S_E includes any other volumetric heat sources. The equations may be solved using known CFD schemes and can be simulated using FLUENT 6.1. Turbulent effects may also be considered by solving a standard $k-\varepsilon$ two-equation model.

In the photobioreactor system 600 illustrated in FIG. 7A utilizing photobioreactor 100, the CFD simulation performed by computer implemented control system 602 in certain embodiments can determine, for each passage of algae around the flow loop (i.e., each cycle of the algae as it moves around the flow path provided by channels 104 and 106 of photobioreactor 100), the duration and frequency of the light and dark intervals to which the algae is exposed (i.e. the photomodulation pattern). In certain embodiments, the CFD model can account for the physical geometry of the photobioreactor and the various flow sources and sinks of the photobioreactor to determine the bulk flow and liquid flow patterns of the liquid medium in each of two channels of photobioreactor 100. A moderate-to-tight finite element grid spacing could be selected to discern and analyze flow streamlines at the algae scale, for example on the order of ten algal cell diameters. The output of the CFD simulation will be the expected streamlines which show the path of fluid-driven cells into and out of light and dark regions and the photobioreactor. From these streamlines, the duration of light and dark exposure and the frequency with which the algae moves from light to dark exposure as it traverses the flow loop can be determined, and this illumination versus time relationship can be utilized in the above-described cell growth/photo modulation model to determine average growth rate around the flow loop. In some cases, the simulation also takes into consideration the effect of cell concentration/growth/polysacahharide secretion on the viscosity of the liquid medium and/or the effect of shear stress on the growth dynamics of the cells, as discussed, for example in Wu and Merchuk, 2002 and Wu and Merchuk, 2004. For example, to account for shear stress effects, the maintenance coefficient, *Me*, can be taken to be a function of the shear rate/stress above a critical shear stress, τ_c found to be a threshold for affecting growth rate, as follows:

$$Me = \overline{Me} \bullet e^{k_m(\tau-\tau_c)}$$

With the global shear rate (γ') in a bubbling duct of length L_R, gas liquid contact area a, flow behavior index n, fluid consistency index κ (Pa·s^n), gas superficial velocity J_G and pressure p_1, p_2 in the bottom and top given by:

$$\gamma' = \left(\frac{p_1 J_G \ln(p_1 / p_2)}{a L_R^{\,2} \kappa}\right)^{\frac{1}{n}}$$

(see, e.g. Wu and Merchuk, 2002 and Wu and Merchuk, 2004). Examples of fluid flow simulations for a bubble column reactor design and an internal loop airlift reactor design

and their integration with the above-discussed growth model of Wu and Merchuk, 2001 have recently been published in Wu and Merchuk, 2002 and Wu and Merchuk, 2004, respectively.

If desired, experimental validation of the results of the CFD simulations can be performed using flow visualization studies of the actual flow trajectories in the photobioreactor. Such studies may be conducted by utilizing neutrally buoyant microspheres, simulating algal cells. In one particular embodiment, a laser can be configured and positioned to create a longitudinal sheet of coherent light through the active segment (i.e., channel 104) of the photobioreactor. Such a plane of laser illumination can be positioned to represent the boundary between "light" and "dark" regions. Its position can be adjusted to represent various expected light-dark transition depths within the conduit expected over the range of algal concentrations and illumination intensities that may be present during operation of the photobioreactor. In one embodiment, a combination of clear silica and fluorescent microspheres (available from Duke Scientific Corporation, Palo Alto, California) could be used to model algae particles. The diameter and density of the microspheres may be selected to correspond to the particular strain of algae expected to be used in the photobioreactor. As the fluorescent microspheres cross the laser plane, they would scatter the laser beam and create a detectable "flash." A video camera can be positioned to record such flashes, and the time between flashes can be used to measure the residence time of the particle in each of the two areas (i.e. the light and dark areas). A second laser plane could be generated, if desired, to visualize flow within an essentially perpendicular plane to the above longitudinal sheet, if it is desired to have a more detailed representation of the actual position of the various fluorescent microspheres within the cross section of the illuminated conduit. One example of an optical trajectory tracking system and method for determining flow patterns in an internal loop airlift bioreactor, which could be utilized in the present context, was recently described in Wu X. and Merchuk J. "Measurement of fluid flow in the downcomer of an internal loop airlift reactor using an optical trajectory-tracking system" *Chemical Engineering Science*, 58:pp. 1599-1614 (2003)(hereinafter "Wu and Merchuk, 2003"), incorporated herein by reference.

In general, a wide variety of known non-invasive measuring technologies may be utilized or adapted to study multiphase flows in the photobioreactors of the invention,

such as, for example Laser Doppler Velocimetry (LDV), Radioactivity Particle Tracking (RPT) (Larachi, F., Chaouki, J., Kennedy, G. And Dudukovic, M.P., 1996. Radioactivity Particle Tracking in Multiphase Reactors: Principles and Applications. J. Chauki, F. Larachi and M.P. Dudukovic, editor. Non-Invasive Monitoring of Multiphase Flow. Elsevier Science B. V.. 335-406, incorporated herein by reference (hereinafter "Larachi 1996")), Particle Image Velocimetry (PIV), X-ray tomography, NMR image technology, and Computer Automated Radioactive Particle Tracking (CARPT) and and gamma ray Computed Tomography (CT) (Larachi 1996; Larachi, F., Kennedy, G. and Chaouki, J., "A γ -ray Detection System for 3-D Particle Tracking in Multiphase Reactors", Nucl. Instr. & Meth., A338, 568 (1994) (hereinafter "Larachi 1994"); Devanathan, N., Moslemian, D. And Dudukovic, M. P., 1990. Flow Mapping in Bubble Columns Using CARPT. Chem. Eng. Sci.. 45:2285-2291; Kumar, B.S., Moslemian, D. and, Dudukovic, M.P., "A γ -ray Tomographic Scanner for Imaging of Void Distribution in Two-Phase Flow Systems", Flow Meas. Instrum., 6(3), 61 (1995); Kumar, S.B., Moslemian, D. and Dudukovic, M.P., "Gas Holdup Measurements in Bubble Columns Using Computed Tomography", AIChE J., 43(6), 1414 (1997); each incorporated herein by reference).

Computer Automated Particle Tracking Technique (CARPT) is based on following the motion of a single tracer particle and is a method of Lagrangian mapping of the velocity field in the whole system. The technique was introduced for monitoring the solids in fluidized beds by Lin et al. (1985) (Lin, J.S., Chen, M.M. and Chao, B.T., "A Novel Radioactive Particle Tracking Facility for Measurement of Solids Motion in Gas Fluidized Beds", AIChE J., 31, 465 (1985); incorporated herein by reference) and can be adapted for measurement of liquid velocities in bubble columns. For tracing liquid phase flow, a single neutrally buoyant radioactive particle dynamically similar to the liquid phase may be introduced into the system. For tracing biomass, a particle of the same size and density as the biomass may be introduced. Specifically, in certain embodiments, a hollow polypropylene bead, about 2 mm in diameter, can be used. A small amount of Scandium 46 (e.g. approximately 250 μ Cu for the purpose of proposed measurements) may be injected into the bead. It is desirable that the density of the composite particle comprising polypropylene, scandium and air gap is matching that of the liquid as closely as possible. In certain embodiments, a thin film metallic coating may assure that bubbles do not preferentially adhere to the particle.

An array of scintillation detectors can be located around the channel(s)/conduit(s) of the photobioreactor under study. In certain embodiments, up to 32 NaI two (2) inch detectors are used. The detectors may be calibrated in situ with the tracer particle to be used to get the counts-positions maps. CARPT calibration is routinely done by positioning the tracer particle (e.g. containing 250 μ Cu of Sc-46) at about 1000 known locations and recording the counts obtained at each detector. his calibration is performed to take into account the relative position of the sensors, and the effects of the different materials such as water, the reactor wall, etc on the output.

The processing of data obtained from the flow trajectory experiments may proceed as follows. From filtered particle positions at subsequent times the instantaneous velocity can be calculated and assigned to a fictitious column compartment (for embodiments where a compartmental grid is pre-established for the column) into which the midpoint falls. The time of tracking should be adjusted ensure that statistical significance is ensured (e.g. for typical photobioreactors, data recorded over 24 hours of tracking yield good statistical significance). For each compartment studied, average velocities of tracking particles can be evaluated, and the fluctuating velocity vector can be calculated from the difference between the instantaneous and average velocity. This can allow for the evaluation of most important Eulerian autocorrelations and cross-correlations. Kinetic turbulent energy and components of the Reynolds stresses can then be obtained. The Lagrangian auto-correlations can enable the evaluation of eddy diffusivities by known methods.

An alternative way of constructing flow maps is via modeling of particle emission of photons and their transmission and subsequent detection at the detectors. The Monte Carlo method (Gupta, P., "Monte Carlo Simulation of NaI Detectors Efficiencies for Radioactive Particle Tracking in Multiphase Flows", CREL Annual Report, Washington University, p. 117 (1998); incorporated herein by reference) in which the photon histories are tracked in their flight from the source, through the attenuating medium and their final detection (or lack of it) at the detector can be used for this purpose. Thus, both the geometry and radiation effects may be accounted for in the estimation of the detector efficiencies in capturing and recording the photons. This involves evaluation of three-dimensional integrals which are calculated using the Monte Carlo approach by sampling modeled photon histories over many directions of their

flight from the source. Once the calibration is complete, the tracer particle may be let loose in the system and the operating conditions are controlled for the entire duration of particle tracking. A least-squares regression method can be used to evaluate the position of the particle. Sampling frequency may be adjusted to assure desired accuracy. In certain embodiments, for example, it is selected to be about 50Hz. A wavelet based filtering algorithm may be employed to remove/reduce noise in position readings created by the statistical nature of gamma radiation.

By employing CARPT, it is possible to obtain multiple particle trajectories (e.g. many thousands) from which mean velocity profiles and radial and axial eddy diffusivities may be calculated. CARPT results can allow the calculation of the turbulent shear field to which the particle is exposed at each operating condition. Since CARPT provides Lagrangian data, eddy diffusivities can be obtained from first principles.

In addition, by positioning additional scintillation detectors at the entry and exit of the channel(s) of the photobioreactor it also possible to determine via CARPT the residence time distribution in each channel as well as the particle trajectory length distribution. Moreover, since it is possible to obtain a substantially complete spatial description of multiple particle trajectories, based on Beer Lambert's law it is possible to define the zone of illumination of certain magnitude and describe the sojourn time distribution of biomass in the illumination and dark zones.

The captured trajectories of the tracer particles can be used to generate velocity vectors. To do this, for an embodiment where a photobioreactor of a configuration such as illustrated in FIG. 1A is under study, the solar channel 104 of inclined conduit 102 of the photobioreactor can be meshed. The velocity vectors in each meshed unit can be long-term averaged and a representative velocity vector of that mesh can be obtained. Then by averaging the velocities in the same cross sectional plane, the superficial liquid velocity profile along axis direction of the inclined channel can be calculated according to:

$$\overline{U_i} = \frac{\sum \overline{u_{r,\theta,i}}}{n} \quad \text{(Eqn. 12)}$$

Where $\overline{u_{r,\theta,i}}$ is the average liquid velocity at mesh position (r, θ, i); $\overline{U_i}$ is the superficial liquid velocity at cross sectional plane i; n is the number of meshes in the cross sectional plane; i is the cross sectional plane index; r and θ are position index for radius and phase

angle direction. From this the residence time T_S of a liquid package in the solar channel 104 can then be determined.

One method to measure the residence time distribution (RTD) is to measure the time required for a neutral buoyancy tracer particle to pass through the inclined channel. For example, 3-6 passes can be measured and an average RTD can be obtained. The measured RTD by this method can be compared to that obtained by CARPT for a consistency check. The results for both methods can be used to estimate the residence time in the other channel(s) of the photobioreactor by applying a basic mass balance; for example for a photobioreactor configuration as illustrated in FIG. 1A:

$$J_{L,S} = \frac{L_S}{T_S} \quad \text{(Eqn. 13)}$$

$$J_{L,S} A_S (1-\varepsilon_S) = J_{L,D} A_D (1-\varepsilon_D) \quad \text{(Eqn. 14)}$$

$$T_D = \frac{L_D}{J_{L,D}} \quad \text{(Eqn. 15)}$$

Where J is the superficial liquid velocity; T is the residence time; A is the cross sectional area; ε is gas holdup; L for the length for the channels; the subscript L is for liquid, S for solar channel 104, D for dark channel 106.

Gamma Ray Computed Tomography is a well-established technique for measuring the phase holdup distribution at any desired cross-section of an air-lift reactor. In certain embodiments, a gamma source based fan beam type CT unit can be utilized. For example, in an exemplary embodiment, a collimated hard source (e.g. about 100 mCi of Cs-137) may be positioned opposite eleven 2 inch NaI detectors in a fan beam arrangement. The lead collimators in front of the detectors may have manufactured slits and the lead assembly may be configured to move so as to allow repeated use of the same detectors for additional projections. A 360° scan can be executed at essentially any desired axial location to facilitate scanning of a wide range of channel dimensions.

The principle of computed tomography is relatively simple. From the measured attenuation of the beams of radiation through the two phase mixture (projections) it is possible to calculate, due to the different attenuation by each phase, the distribution of phases in the cross-section that was scanned. In certain embodiments, it is possible to achieve, for example, about 3465 to about 4000 projections and obtain a spatial resolution of about 2 mm and density resolution of about 0.04 g/cm^3. Because of the time

that may be required to scan the entire cross-section, it may be advantageous to assess time-averaged density distributions. A variety of techniques for reconvolution or filtered back projection may be employed, such as algebraic reconstruction and estimation-maximization algorithms (E-M) (Larachi et al, 1994).

Referring now to FIGs. 9A and 9B, two alternative computational and control methodologies for controlling and optimizing photomodulation in the photobioreactor of system 600 are described. The methodologies are similar and differ, primarily, in the computational parameters utilized for convergence (i.e. light/dark exposure intervals in the method of FIG. 9A, and predicted growth rate in the FIG. 9B method).

Reference is made now to FIG. 9A, in which one embodiment for creating and controlling photomodulation within a photobioreactor of a gas treatment system is disclosed. Initial step 702 is an optional model fitting step, which may be conducted off-line with a pilot-scale or small-scale automated cell culture and testing system, as discussed above. Optional step 702 involves determining appropriate values of the various adjustable parameters comprising the constants of the growth rate/photomodulation mathematical model described above by fitting the model equations to experimental growth rate versus light/dark exposure interval data, as described above and in Wu and Merchuk, 2001.

In step 704, cell concentration within photobioreactor 100 is measured, for example through use of spectrophotometer 632. In step 706, the light intensity incident upon the active channel 104 of the photobioreactor is measured utilizing a light intensity measuring device (e.g., a light meter) 633. The measured cell concentration and illumination intensity may together be used to calculate, in step 708, the light penetration depth within tubular conduit 102 or channel 104 according to standard, well known methods (e.g., as described in Burlew, 1961).

In step 710, a mathematical calculation is performed to calculate, from the growth rate/photomodulation mathematical model, predicted light/dark exposure intervals (i.e. duration and frequency of light/dark exposure) required to yield a desired average growth rate, for example a maximal growth rate achievable (i.e. given the non-adjustable operating constraints of the system).

In step 712, computer-implemented system 602 performs a simulation (e.g., CFD simulation) of the liquid medium flow and determines the flow streamlines and patterns

within the photobioreactor for a particular total gas flow rate and gas flow distribution to spargers 122 and 124. From the simulation, actual light/dark exposure intervals and photomodulation of the algae as it flows around the flow loop can be determined. The system can determine when algae within the liquid medium is exposed to light within active channel 104 by determining when it is within a region of the channel separated from the light exposed surface 132 by a distance not exceeding that which, as determined in the light penetration depth determination of step 708, would expose the algae to light at an intensity above that which is sufficient to drive photosynthesis (i.e. above that required to render the algae in the "active" photosynthetic mode as described in the above-discussed growth/photomodulation model). The precise light intensity, and corresponding penetration depth, required for active photosynthesis for a particular type or mixture of algae can be determined using routine experimental studies of algal growth versus light intensity in a model photobioreactor system.

In step 714, the light/dark exposure intervals and photomodulation characteristics determined in step 710 required to give a desired average growth rate are compared with the actual light/dark exposure intervals and photomodulation characteristics prevailing in the photobioreactor as determined in step 712. The simulation of step 712 is then repeated utilizing different gas flows and gas flow distributions until the difference between the exposure intervals determined in steps 710 and 712 is minimized and the simulations converge.

In step 716, computer-implemented system 602 adjusts and controls the liquid flow rate within the photobioreactor and the liquid flow patterns (e.g., recirculation vortices) by, for example, adjusting the gas flow and gas distribution to spargers 122 and 124 so as to match the optimal values determined in step 714.

The alternative photomodulation determination and control methodology in FIG. 9B is similar to that disclosed in FIG. 9A, except that instead of the CFD and growth rate/photomodulation mathematical models converging upon calculated light/dark exposure intervals, the system is configured to run the simulations to determine flow parameters required to yield a desired predicted (i.e. by the growth rate/photomodulation model) growth rate.

Steps 702, 704, 706, 708, 712 and 716 can be performed essentially identically as described above in the context of the method outlined in FIG. 9A. In the method shown

in FIG. 9B, however, the actual light/dark exposure intervals and photomodulation data determined from the CFD simulation of step 712 is then utilized in step 710' to calculate, utilizing the growth rate/photomodulation mathematical model, an average predicted growth rate that would result from such light/dark exposure characteristics. Step 712 is then repeated with different values of gas flow and gas distribution and a new predicted average growth rate is determined in step 710'. The computational procedure is configured to adjust the values in step 712 in order to converge in step 714' upon a desired average growth rate as determined in step 710', for example a maximum achievable growth rate. Once gas flow and gas distribution values resulting in such a predicted desired growth rate are determined, computer-implemented control system 602 then applies these gas flow rates and distributions to the photobioreactor to induce the desired liquid flow dynamics in the system in step 716.

It should be appreciated that the above-described photomodulation control methodologies and systems can advantageously enable automated operation of the photobioreactor under conditions designed to create an optimal level of photomodulation. Advantageously, the system can be configured to continuously receive input from the various sensors and implement the methodologies described above so as to optimize photomodulation in essentially real time (i.e. with turn-around as fast as the computations can be performed by the system). This can enable the system to be quickly and robustly responsive to environmental condition changes that can change the nature and degree of photomodulation within the system. For example, in a particular embodiment and under one exemplary circumstance, computer-implemented control system 602 could quickly and appropriately adjust the gas flow rates and distribution and, thereby, the liquid flow patterns and photomodulation within the photobioreactor, so as to account for transient changes in illumination, such as the transient passing of cloud cover, over a period of operation of the photobioreactor system.

The calculation methods, steps, simulations, algorithms, systems, and system elements described above may be implemented using a computer-implemented system, such as the various embodiments of computer-implemented systems described below. The methods, steps, systems, and system elements described above are not limited in their implementation to any specific computer system described herein, as many other different machines may be used.

The computer-implemented system can be part of or coupled in operative association with a photobioreactor, and, in some embodiments, configured and/or programmed to control and adjust operational parameters of the photobioreactor as well as analyze and calculate values, as described above. In some embodiments, the computer-implemented system can send and receive control signals to set and/or control operating parameters of the photobioreactor and, optionally, other system apparatus. In other embodiments, the computer-implemented system can be separate from and/or remotely located with respect to the photobioreactor and may be configured to receive data from one or more remote photobioreactor apparatus via indirect and/or portable means, such as via portable electronic data storage devices, such as magnetic disks, or via communication over a computer network, such as the Internet or a local intranet.

Referring to FIGs. 4 and 7A, computer-implemented control systems 312 and 602 may include several known components and circuitry, including a processing unit (i.e. processor), a memory system, input and output devices and interfaces (e.g., an interconnection mechanism), as well as other components, such as transport circuitry (e.g., one or more busses), a video and audio data input/output (I/O) subsystem, special-purpose hardware, as well as other components and circuitry, as described below in more detail. Further, the computer system may be a multi-processor computer system or may include multiple computers connected over a computer network.

The computer-implemented control systems may include a processor, for example, a commercially available processor such as one of the series x86, CELERON-, XScale- and PENTIUM-type processors, available from Intel, similar devices from AMD and Cyrix, the 680X0 series microprocessors and DragonBall processors available from Motorola, and the PowerPC microprocessor, HPC from IBM, the Sun UltraSPARC, Hewlett-Packard PA-RISC processors, or any of a variety of processors available from Advanced Micro Devices (AMD). Many other processors are available, and the computer system is not limited to a particular processor.

A processor typically executes a program called an operating system, of which Windows NT, Windows95 or 98, Windows 2000 (Windows ME), Windows XP, Windows CE, Pocket PC, UNIX, Linux, DOS, VMS, MacOS and OS8, the Solaris operating system (Sun Microsystems), Palm OS are examples, which controls the execution of other computer programs and provides scheduling, debugging, input/output

control, accounting, compilation, storage assignment, data management and memory management, communication control and related services. The processor and operating system together define a computer platform for which application programs in high-level programming languages are written. The computer implemented control systems are not limited to a particular computer platform.

The computer-implemented control systems may include a memory system, which typically includes a computer readable and writeable non-volatile recording medium, of which a magnetic disk, optical disk, a flash memory and tape are examples. Such a recording medium may be removable, for example, a floppy disk, read/write CD or memory stick, or may be permanent, for example, a hard drive.

Such a recording medium stores signals, typically in binary form (i.e. a form interpreted as a sequence of one and zeros). A disk (e.g., magnetic or optical) has a number of tracks, on which such signals may be stored, typically in binary form, i.e. a form interpreted as a sequence of ones and zeros. Such signals may define a software program, e.g., an application program, to be executed by the microprocessor, or information to be processed by the application program.

The memory system of the computer-implemented control systems also may include an integrated circuit memory element, which typically is a volatile, random access memory such as a dynamic random access memory (DRAM) or static memory (SRAM). Typically, in operation, the processor causes programs and data to be read from the non-volatile recording medium into the integrated circuit memory element, which typically allows for faster access to the program instructions and data by the processor than does the non-volatile recording medium.

The processor generally manipulates the data within the integrated circuit memory element in accordance with the program instructions and then copies the manipulated data to the non-volatile recording medium after processing is completed. A variety of mechanisms are known for managing data movement between the non-volatile recording medium and the integrated circuit memory element, and the computer-implemented control systems that implements the methods, steps, systems and system elements described above in relation to FIGs. 4, 7A, 9A and 9B are not limited thereto. The computer-implemented control systems are not limited to a particular memory system.

At least part of such a memory system described above may be used to store one or more data structures (e.g., look-up tables) or equations described above. For example, at least part of the non-volatile recording medium may store at least part of a database that includes one or more of such data structures. Such a database may be any of a variety of types of databases, for example, a file system including one or more flat-file data structures where data is organized into data units separated by delimiters, a relational database where data is organized into data units stored in tables, an object-oriented database where data is organized into data units stored as objects, another type of database, or any combination thereof.

The computer-implemented control systems may include a video and audio data I/O subsystem. An audio portion of the subsystem may include an analog-to-digital (A/D) converter, which receives analog audio information and converts it to digital information. The digital information may be compressed using known compression systems for storage on the hard disk to use at another time. A typical video portion of the I/O subsystem may include a video image compressor/decompressor of which many are known in the art. Such compressor/decompressors convert analog video information into compressed digital information, and vice-versa. The compressed digital information may be stored on hard disk for use at a later time.

The computer-implemented control systems may include one or more output devices. Example output devices include a cathode ray tube (CRT) display 603, liquid crystal displays (LCD) and other video output devices, printers, communication devices such as a modem or network interface, storage devices such as disk or tape, and audio output devices such as a speaker.

The computer-implemented control systems also may include one or more input devices. Example input devices include a keyboard, keypad, track ball, mouse, pen and tablet, communication devices such as described above, and data input devices such as audio and video capture devices and sensors. The computer-implemented control systems are not limited to the particular input or output devices described herein.

The computer-implemented control systems may include specially programmed, special purpose hardware, for example, an application-specific integrated circuit (ASIC). Such special-purpose hardware may be configured to implement one or more of the methods, steps, simulations, algorithms, systems, and system elements described above.

The computer implemented control systems and components thereof may be programmable using any of a variety of one or more suitable computer programming languages. Such languages may include procedural programming languages, for example, C, Pascal, Fortran, COBOL and BASIC, object-oriented languages, for example, C# (C-Sharp), C++, SmallTalk, Java, Ada and Eiffel, Lab View, and other languages, such as a scripting language or even assembly language. Various aspects of the invention may be implemented in a non-programmed environment (e.g., documents created in HTML, XML or other format that, when viewed in a window of a browser program, render aspects of a graphical-user interface (GUI) or perform other functions). Various aspects of the invention may be implemented as programmed or non-programmed elements, or any combination thereof. Further, various embodiments of the invention may be implemented using Microsoft.NET technology available from Microsoft Corporation.

The methods, steps, simulations, algorithms, systems, and system elements may be implemented using any of a variety of suitable programming languages, including procedural programming languages, object-oriented programming languages, other languages and combinations thereof, which may be executed by such a computer system. Such methods, steps, simulations, algorithms, systems, and system elements can be implemented as separate modules of a computer program, or can be implemented individually as separate computer programs. Such modules and programs can be executed on separate computers.

The methods, steps, simulations, algorithms, systems, and system elements described above may be implemented in software, hardware or firmware, or any combination of the three, as part of the computer-implemented control systems described above or as an independent component.

Such methods, steps, simulations, algorithms, systems, and system elements, either individually or in combination, may be implemented as a computer program product tangibly embodied as computer-readable signals on a computer-readable medium, for example, a non-volatile recording medium, an integrated circuit memory element, or a combination thereof. For each such method, step, simulation, algorithm, system, or system element, such a computer program product may comprise computer-readable signals tangibly embodied on the computer-readable medium that define

instructions, for example, as part of one or more programs, that, as a result of being executed by a computer, instruct the computer to perform the method, step, simulation, algorithm, system, or system element.

Algae, or other photosynthetic organisms may be pre-adapted and/or pre-conditioned to specific environmental and operating conditions expected to be experienced in a full scale photobioreactor during use. Methods and apparatus for adaption and pre-conditioning algae may be found in commonly owned U.S Patent Application Publication No. US-2005/0064577 A1, which is hereby incorporated by reference in its entirety.

FIG. 10 illustrates one embodiment of an integrated system for performing an integrated combustion method, wherein combustion gases are treated with a photobioreactor system to mitigate pollutants and to produce biomass, for example in the form of harvested algae, with the photobioreactor system, which can be utilized as a fuel for the combustion device and/or for the production of other products, such as products comprising organic molecules (e.g. fuel grade oil (e.g. biodiesel) and/or organic polymers). Integrated system 900 can be advantageously utilized to both reduce the level of pollutants emitted from a combustion facility into the atmosphere and, in certain embodiments, to reduce the amount of fossil fuels, such as coal, oil, natural gas, etc., burned by the facility and/or to produce a non-fossil, clean fuel, such as hydrogen, from the biomass . Such a system can potentially be advantageously utilized for treating gases emitted by facilities such as fossil fuel (e.g., coal, oil, and natural gas) – fired power plants, industrial incineration facilities, industrial furnaces and heaters, internal combustion engines, etc. Integrated gas treatment/biomass-producing system 900 can, in certain embodiments, substantially reduce the overall fossil fuel requirements of a combustion facility, while, at the same time, substantially reducing the amount of CO_2 and/or NO_x released as an environmental pollutant, and, in certain embodiments providing biomass useful in producing clean fuel products, such as hydrogen and biodiesel.

Integrated system 900 includes one or more photobioreactors or photobioreactor arrays 902, 904, and 906. In certain embodiments, these photobioreactors can be similar or identical in design and configuration to those previously-described in any of FIGs. 1A, 1B, 3A-3D, 5A-5E, 6A, 6B, and 7A. In alternative embodiments, other embodiments of

the inventive photobioreactors could be utilized or conventional photobioreactors could be utilized. Except for embodiments wherein system 900 utilizes photobioreactors provided according to the present invention (in which the photobioreactors are inventive and not conventional), the unit operations illustrated in FIG. 10 can be of conventional designs, or of straightforward adaptations or extensions of conventional designs, and can be selected and designed by those of ordinary skill in the chemical engineering arts using routine engineering and design principles.

In the illustrated, exemplary system, hot flue gases produced by electrical generating power plant facility 908 are, optionally, compressed in a compressor 910 and passed through a heat exchanger comprising a dryer 912, the function of which is explained below. Heat exchanger 912 is configured and controllable to allow the hot flue gas to be cooled to a desired temperature for injection into the photobioreactor arrays 902, 904, and 906. The gas, upon passing through the photobioreactors is treated by the algae or other photosynthetic organisms therein to remove one or more pollutants therefrom, for example, CO_2 and/or NO_x. Treated gas, containing a lower concentration of CO_2 and/or NO_x than the flue gas, is released from gas outlets 914, 916, and 918 and, in one embodiment, vented to the atmosphere.

As described above, algae or other photosynthetic organisms contained within the photobioreactors can utilize the CO_2 of the flue gas stream for growth and reproduction thereby producing biomass. As described above, in order to maintain optimal levels of algae or other photosynthetic organisms within the photobioreactors, periodically biomass, for example in the form of wet algae, is removed from the photobioreactors through liquid medium outlet lines 921, 922, and 924.

From there, the wet algae is directed to dryer 912, which is fed with hot flue gas as described above. In the dryer, the hot flue gas can be utilized to vaporize at least a portion of the water component of the wet algae feed, thereby producing a dried algae biomass, which is removed via line 926. In certain embodiments, advantageously, dryer 912, in addition to drying the algae and cooling the flue gas stream prior to injection in the photobioreactors, also serves to humidify the flue gas stream, thereby reducing the level of particulates in the stream. Since particulates can potentially act as a pollutant to the photobioreactor and/or cause plugging of gas spargers within the photobioreactors, particulate removal prior to injection into the photobioreactors can be advantageous.

The water, or a portion thereof, removed from the wet algae stream fed to dryer 912 can be fed via line 928 to a condenser 930 to produce water that can be used for preparation of fresh photobioreactor liquid medium. In the illustrated embodiment, water recovered from condenser 930 (at "A"), after optional filtration to remove particulates accumulated in dryer 912, or other treatment to remove potential contaminants, can be pumped by a pump 932 to a medium storage tank 934, which feeds make up medium to the photobioreactors.

The dried algae biomass recovered from dryer 912 can be utilized directly as a solid fuel for use in a combustion device of facility 908 and/or could be converted into a fuel grade oil (e.g., "biodiesel") and/or a combustible organic fuel gas. In certain embodiments, at least a portion of the biomass, either dried or before drying, can be utilized for the production of products comprising organic molecules, such as fuel-grade oil (e.g. biodiesel) and/or organic polymers, therefrom. Algal biomass earmarked for fuel-grade oil (e.g. biodiesel) production, or fuel gas production or the like can be decomposed in a pyrolysis or other known gasification processes and/or a thermochemical liquefaction process to produce oil and/or combustible gas from the algae. Such methods of producing fuel grade oils and gases from algal biomass are well known in the art (e.g., see, Dote, Yutaka, "Recovery of liquid fuel from hydrocarbon rich microalgae by thermochemical liquefaction," *Fuel*. 73:Number 12. (1994); Ben-Zion Ginzburg, "Liquid Fuel (Oil) From Halophilic Algae: A renewable Source of Non-Polluting Energy, Renewable Energy," Vol. 3, No 2/3. pp. 249-252, (1993); Benemann, John R. and Oswald, William J., "Final report to the DOE: System and Economic Analysis of Microalgae Ponds for Conversion of CO_2 to Biomass." DOE/PC/93204-T5, March 1996; and Sheehan et al., 1998; each incorporated by reference).

In certain embodiments, especially those involving combustion facilities for which it may be required by regulation to release the photobioreactor-treated gases into the atmosphere through a smoke stack of a particular height (i.e. instead of venting the treated gas directly to atmosphere as previously described), treated gas stream 936 could be injected into the bottom of a smoke stack 938 for release to the atmosphere. In certain embodiments, treated gas stream 936 may have a temperature that is not sufficient to enable it to be effectively released from a smoke stack 938. In such embodiments, cool treated flue gas 936 may be passed through a heat exchanger 940 to increase its

temperature to a suitable level before injection into the smoke stack. In one such embodiment, cooled treated flue gas stream 936 is heated in heat exchanger 940 via heat exchange with the hot flue gas released from the combustion facility, which is fed as a heat source to heat exchanger 940.

As is apparent from the above description, integrated photobioreactor gas treatment system 900 can provide a biotechnology-based air pollution control and renewable energy solution to fossil fuel burning facilities, such as power generating facilities. The photobioreactor systems can comprise emissions control devices and regeneration systems that can remove gases and other pollutants, such as particulates, deemed to be hazardous to people and the environment. Furthermore, the integrated photobioreactor system provides biomass that can be used as a source of renewable energy, and as a source of products comprising organic molecules, such as diesel fuel/gasoline substitutes and plastics, which are currently typically manufactured from fossil fuels, thereby reducing the requirement of burning fossil fuels. In addition to the combustion and biological processes described herein, an integrated photobioreactor gas treatment system may include a non-combustion chemical process.

In addition, in certain embodiments, integrated photobioreactor combustion gas treatment system 900 can further include, as part of the integrated system, one or more additional gas treatment apparatus in fluid communication with the photobioreactors. For example, an effective, currently utilized technology for control of mercury and/or mercury-containing compounds in flue gases is the use of activated carbon or silica injection (e.g. see, "Mercury Study Report to Congress," EPA-452/R-97-010, Vol. VIII, (1997); (hereinafter "EPA, 1997"), which is incorporated herein by reference). The performance of this technology, however, is highly temperature dependant. Currently, effective utilization of this technology requires substantial cooling of flue gases before the technology can be utilized. In conventional combustion facilities, this requires additional capital outlay and operational costs to install flue gas cooling devices.

Advantageously, because flue gases are already cooled within integrated system 900 through utilization of the flue gases for drying the algae in dryer 912, mercury and mercury-containing removal apparatus and treatments can readily and advantageously be integrated into the cool flue gas flow path, upstream 942 of the photobioreactors and/or downstream 944 of the photobioreactors. In either case, the reduced-temperature flue

gas produced within integrated system 900 is highly compatible with known mercury controlled technologies, allowing a multi-pollutant (NO_x, CO_2, mercury) control system.

Similarly, a variety of known precipitation-based SO_x removal technologies also require cooling of flue gas (e.g. see, EPA, 1997). Accordingly, as with the mercury removal technologies discussed above, such SO_x precipitation and removal technologies could be installed in fluid communication with the photobioreactors in system 900 in similar locations (e.g., 942 and 944) as the above-described mercury removal systems.

FIG. 11 illustrates one embodiment of an integrated system for performing an industrial biological process, such as fermentation or waste (e.g. agricultural waste or sewage/wastewater) digestion wherein gases are treated with a photobioreactor system to mitigate pollutants and to produce biomass, for example in the form of harvested algae. As with system 900 for performing an integrated combustion method described above, integrated system 1000 can be advantageously utilized to both reduce the level of pollutants emitted from a facility into the atmosphere and, in certain embodiments, to produce a biomass fuel and/or produce a non-fossil, clean fuel, such as hydrogen or biodiesel, from the biomass. Such a system can potentially be advantageously used for treating gases emitted by facilities such as wastewater treatment plants, industrial fermenters, agricultural waste digestors, or other facilities housing biological processes.

Integrated system 1000 includes one or more photobioreactors or photobioreactor arrays 1002, 1004, and 1006. In certain embodiments, these photobioreactors can be similar or identical in design and configuration to those previously-described in any of FIGs. 1A, 1B, 3A-3D, 5A-5E, 6A, 6B, and 7A. In alternative embodiments, other embodiments of the inventive photobioreactors could be utilized or conventional photobioreactors could be utilized. Except for embodiments wherein system 1000 utilizes photobioreactors provided according to the present invention (in which the photobioreactors are inventive and not conventional), the unit operations illustrated in FIG. 11 can be of conventional designs, or of straightforward adaptations or extensions of conventional designs, and can be selected and designed by those of ordinary skill in the chemical engineering arts using routine engineering and design principles.

In the illustrated, exemplary system, gases produced by biological processes in plant facility 1008 are injected into the photobioreactor arrays 1002, 1004, and 1006. The gas, upon passing through the photobioreactors is treated by the algae or other

photosynthetic organisms therein to remove one or more pollutants therefrom, for example, CO_2. Treated gas, containing a lower concentration of CO_2 (and/or other pollutants removed by the organisms) than the injected gas, is released from gas outlets 1014, 1016, and 1018 and, in one embodiment, vented to the atmosphere.

As described above, algae or other photosynthetic organisms contained within the photobioreactors can utilize the CO_2 of the feed gas stream for growth and reproduction thereby producing biomass. As described above, in order to maintain optimal levels of algae or other photosynthetic organisms within the photobioreactors, periodically, biomass, for example in the form of wet algae, is removed from the photobioreactors through liquid medium outlet lines 1021, 1022, and 1024.

From there, the wet algae may be directed to a centrifuge (not shown) and/or dryer 1012, thereby producing a dried algae biomass, which is removed via line 1026.

The water, or a portion thereof, that is removed from the wet algae stream that was fed to dryer 1012 can be fed via line 1028 to a condenser 1030 to produce water that can be used for preparation of fresh photobioreactor liquid medium. In the illustrated embodiment, water recovered from condenser 1030 (at "A"), after optional filtration to remove particulates accumulated in dryer 1012, or other treatment to remove potential contaminants, can be pumped by a pump 1032 to a medium storage tank 1034, which feeds make up medium to the photobioreactors.

The function and advantage of these and other embodiments of the present invention may be more fully understood from the examples below. The following examples, while illustrative of certain embodiments of the invention, do not exemplify the full scope of the invention.

Example: Mitigation of CO_2 and NO_x and Algae Production in Inclined Split Tube Photobioreactor Systems and a Triangular Tubular Photobioreactor System

Four different photobioreactor systems were tested to investigate their algae production capabilities per photobioreactor footprint area. System 1 included an array of ten substantially triangular photobioreactors similar to those described in commonly owned PCT Publication No. WO 03/094598, incorporated herein by reference. System 1 included a solar panel conduits inclined at approximately 60 degrees relative to horizontal. Each conduit had an about 4 inch inner diameter and a length of about 9 feet 7 inches and the overall system had a working volume of approximately 900 liters. The

reactors of system 1 had a total footprint area of about 1.435 m^2. Each of systems 2-4 included a single conduit photobioreactor including a partition therein forming two channels, as described previously in the context of FIG. 1A, each conduit had a length of about 9 feet 7 inches and was inclined at approximately 60 degrees. System 2 had an about 10 inch inner diameter conduit, an approximate volume of 140 liters, and a photobioreactor footprint area of about 0.3588 m^2. System 3 had an about 12 inch inner diameter conduit, an approximate volume of 200 liters, and a footprint area of about 0.4306 m^2. System 4 had an about 14 inch inner diameter conduit, an approximate volume of 270 liters, and a footprint area of about 0.5023 m^2.

A modified F/2 liquid medium containing *Chaetoceros Muelleri* (CCMP1316) algae was introduced into the photobioreactors. The liquid medium contained: 22 g/l NaCl, 16 g/l Artificial Sea Water Sea Salts (INSTANT OCEAN®, Aquarium Systems, Inc. Mentor, OH), 0.425 g/l $NaNO_3$, 1 ml of 30 g/l $Na_2SiO_3 \cdot 9H_2O$ solution per liter medium, 1 ml of 5 g/l NaH_2PO_4 solution per liter medium, and 1 ml Metal Solution per liter medium (see contents of stock solution below) + 5 ml Vitamin Solution (see contents of stock solution below) per liter medium. The pH was maintained at pH 8.

Stock Solution Compositions:

Metal Solution- Trace metals stock solution (chelated) per liter

$EDTANa_2$	4.160 g
$FeCl_3.6H_2O$	3.150 g
$CuSO_4.5\ H_2O$	0.010 g
$ZnSO_4.7\ H_2O$	0.022 g
$CoCl_2.6\ H_2O$	0.010 g
$MnCl_2.4\ H_2O$	0.180 g
$Na_2MoO_4.2\ H_2O$	0.006 g

Vitamin Solution- Vitamin stock solution per liter

Cyanocobalamin	0.0005 g
Thiamine HCl	0.1 g
Biotin	0.0005 g

Gas input was via direct injection of flue gas from the Massachusetts Institute of Technology's (MIT's) Cogeneration Plant in Cambridge MA.. The flue gas was cooled

to approximately 100 degrees F and then injected directly into the photobioreactors without any pretreatment. The volume of gas per volume of liquid medium per minute (vvm) was approximately 0.03 for each of the four systems, the volume being split approximately evenly between the two spargers of each system, resulting in a flow rate of approximately 0.015 vvm per sparger. The flue gas had a typical CO_2 concentration of 2-4% and a typical NO_x concentration of 8-15 ppm. The liquid medium was maintained at a temperature of between 20 and 30 degrees centigrade using an internal heat exchanger as illustrated in FIGs. 8A-8C. On weekdays, each day, 30% of the liquid medium was drained from the photobioreactors and then an equal amount of fresh medium was added to the photobioreactors.

Before draining the liquid medium, the optical density of the liquid medium was measured at a wavelength of 727 nanometers. This optical density measurement is assumed to be linearly related to biomass concentration. Cell density was calculated using spectrophotometer measurements at 727 nm (see, Hiroyasu et al., 1998). To calculate the daily productivity of each system, the total harvested biomass for one week was divided by seven days. This daily productivity was then divided by the photobioreactor footprint area to arrive at a value for daily productivity per square meter of photobioreactor footprint. The following chart shows the productivity results for each of systems 1-4 for each of three weeks of testing. Each value provides the average daily productivity of algae in grams per square meter of photobioreactor footprint for a given week.

	System 1 (triangular system with 4" solar conduit)	System 2 (single conduit with 10" diameter)	System 3 (single conduit with 12" diameter)	System 4 (single conduit with 14" diameter)
Week 1	21.9	40.5	51.6	60.6
Week 2	14.4	31.9	35.6	43.3
Week 3	25.5	51.0	53.8	59.9

While several embodiments of the invention have been described and illustrated herein, those of ordinary skill in the art will readily envision a variety of other means and

structures for performing the functions and/or obtaining the results or advantages described herein, and each of such variations, modifications and improvements is deemed to be within the scope of the present invention. More generally, those skilled in the art would readily appreciate that all parameters, dimensions, materials, and configurations described herein are meant to be exemplary and that actual parameters, dimensions, materials, and configurations will depend upon specific applications for which the teachings of the present invention are used. Those skilled in the art will recognize, or be able to ascertain using no more than routine experimentation, many equivalents to the specific embodiments of the invention described herein. It is, therefore, to be understood that the foregoing embodiments are presented by way of example only and that, within the scope of the appended claims and equivalents thereto, the invention may be practiced otherwise than as specifically described. The present invention is directed to each individual feature, system, material and/or method described herein. In addition, any combination of two or more such features, systems, materials and/or methods, provided that such features, systems, materials and/or methods are not mutually inconsistent, is included within the scope of the present invention. In the claims (as well as in the specification above), all transitional phrases or phrases of inclusion, such as "comprising," "including," "carrying," "having," "containing," "composed of," "made of," "formed of," "involving" and the like shall be interpreted to be open-ended, i.e. to mean "including but not limited to" and, therefore, encompassing the items listed thereafter and equivalents thereof as well as additional items. Only the transitional phrases or phrases of inclusion "consisting of" and "consisting essentially of" are to be interpreted as closed or semi-closed phrases, respectively. The indefinite articles "a" and "an," as used herein in the specification and in the claims, unless clearly indicated to the contrary, should be understood to mean "at least one." The phrase "and/or," as used herein in the specification and in the claims, should be understood to mean "either or both" of the elements so conjoined, i.e. elements that are conjunctively present in some cases and disjunctively present in other cases. Other elements may optionally be present other than the elements specifically identified by the "and/or" clause, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, a reference to "A and/or B" can refer, in one embodiment, to A only (optionally including elements other than B); in another embodiment, to B only

(optionally including elements other than A); in yet another embodiment, to both A and B (optionally including other elements); etc. As used herein in the specification and in the claims, "or" should be understood to have the same meaning as "and/or" as defined above. For example, when separating items in a list, "or" or "and/or" shall be interpreted as being inclusive, i.e. the inclusion of at least one, but also including more than one, of a number or list of elements, and, optionally, additional unlisted items. Only terms clearly indicated to the contrary, such as "only one of" or "exactly one of," will refer to the inclusion of exactly one element of a number or list of elements. In general, the term "or" as used herein shall only be interpreted as indicating exclusive alternatives (i.e. "one or the other but not both") when preceded by terms of exclusivity, such as "either," "one of," "only one of," or "exactly one of." As used herein in the specification and in the claims, the phrase "at least one," in reference to a list of one or more elements, should be understood to mean at least one element selected from any one or more of the elements in the list of elements, but not necessarily including at least one of each and every element specifically listed within the list of elements and not excluding any combinations of elements in the list of elements. This definition also allows that elements may optionally be present other than the elements specifically identified within the list of elements that the phrase "at least one" refers to, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, "at least one of A and B" (or, equivalently, "at least one of A or B," or, equivalently ""at least one of A and/or B") can refer, in one embodiment, to at least one, optionally including more than one, A, with no B present (and optionally including elements other than B); in another embodiment, to at least one, optionally including more than one, B, with no A present (and optionally including elements other than A); in yet another embodiment, to at least one, optionally including more than one, A, and at least one, optionally including more than one, B (and optionally including other elements); etc. In cases where the present specification and a document incorporated by reference and/or referred to herein include conflicting disclosure, and/or inconsistent use of terminology, and/or the incorporated/referenced documents use or define terms differently than they are used or defined in the present specification, the present specification shall control.

What is claimed is:

CLAIMS

1. A photobioreactor apparatus comprising:

a conduit having a generally longitudinal partition that is constructed and arranged to divide the conduit into at least a first and a second fluidically interconnected channels contained within the conduit, at least one of which has at least one surface that is at least partially transparent to light of a wavelength capable of driving photosynthesis, the channels together providing at least a portion of a flow loop enabling a liquid medium contained within the photobioreactor to flow sequentially from a region of origin within the flow loop through the first and second channels and back to the region of origin, the conduit forming an angle, with respect to the horizontal, of less than 90 degrees.

2. A photobioreactor apparatus as in claim 1, wherein the conduit is inclined and forms an angle with respect to the horizontal of at least 10 degrees.

3. A photobioreactor apparatus as in claim 2, wherein the conduit forms an angle, with respect to the horizontal, of less than or equal to 85 degrees.

4. A photobioreactor apparatus as in claim 3, wherein the conduit forms an angle, with respect to the horizontal, of between 35 degrees and 65 degrees inclusive.

5. A photobioreactor apparatus as in claim 1, wherein the conduit has a length and the partition has a length that is at least 20% of the conduit length.

6. A photobioreactor apparatus as in claim 5, wherein the conduit has a length and the partition has a length that is at least 85% of the conduit length.

7. A photobioreactor apparatus as in claim 5, wherein the conduit has a length and the partition has a length that is less than 85% of the conduit length.

8. A photobioreactor apparatus as in claim 7, wherein the conduit has a length and the partition has a length that is between 80% and 85% of the conduit length.

9. A photobioreactor apparatus as in claim 1, wherein the partition is generally planar, wherein the conduit has a width along a plane of the partition, and wherein the width of the partition is at least 50% of the conduit width along the plane of the partition.

10. A photobioreactor apparatus as in claim 9, wherein the width of the partition is at least 75% of the conduit width along the plane of the partition.

11. A photobioreactor apparatus as in claim 10, wherein the width of the partition is at least 90% of the conduit width along the plane of the partition.

12. A photobioreactor apparatus as in claim 11, wherein the width of the partition is at least 95% of the conduit width along the plane of the partition.

13. A photobioreactor apparatus as in claim 12, wherein the partition is generally planar, wherein the conduit has a width along a plane of the partition, and wherein the width of the partition is the same as the conduit width along the plane of the partition.

14. A photobioreactor apparatus as in claim 1, wherein the partition is tubular in shape such that an annular space is formed between the partition and the conduit, which surrounds the partition, and wherein one of the channels comprises a lumen surrounded by the tubular partition and the other of the channels comprises the annular space.

15. A photobioreactor apparatus as in claim 1, wherein the first channel is substantially parallel to the second channel.

16. A photobioreactor apparatus as in claim 1, wherein the conduit is in the shape of a substantially circular cylinder.

17. A photobioreactor apparatus as in claim 1, wherein the conduit is in the shape of a cylinder having a substantially ovoid shape.

18. A photobioreactor apparatus as in claim 1, wherein the conduit is in the shape of a substantially rectangular cylinder.

19. A photobioreactor apparatus as in claim 1, wherein the conduit has an inner wall perimeter that remains substantially constant in size along the length of the conduit length.

20. A photobioreactor apparatus as in claim 1, wherein the conduit has an inner wall perimeter that remains substantially constant in shape along the length of the conduit length.

21. A photobioreactor apparatus as in claim 1, wherein the partition is substantially continuous and impermeable to liquid along its entire length and width.

22. A photobioreactor apparatus as in claim 21, wherein the partition essentially bisects the conduit along the length of the partition to form the first channel and the second channel, such that the first channel and the second channel have essentially equal volumes.

23. A photobioreactor apparatus as in claim 21, wherein the volume of the first channel is different from the volume of the second channel.

24. A photobioreactor apparatus as in claim 1, wherein the photobioreactor apparatus contains the liquid medium therein, and wherein the liquid medium comprises at least one species of photosynthetic organisms.

25. A photobioreactor apparatus as in claim 24, wherein the photobioreactor apparatus comprises at least one gas inlet configured and positioned to introduce a stream of gas to be treated into the photobioreactor, and wherein the photosynthetic

organisms within the liquid medium, once it has been exposed to the stream of gas are able to at least partially remove from the gas CO_2 and/or NO_x.

26. A photobioreactor apparatus as in claim 24, wherein the photobioreactor apparatus comprises at least one gas inlet configured and positioned to introduce a stream of gas to be treated into the photobioreactor, and wherein the photobioreactor apparatus is able to at least partially remove from the gas at least one of SO_x, fly ash, heavy metals, ammonia, VOCs, and phosphate ash.

27. A photobioreactor apparatus as in claim 25, wherein the at least one gas inlet is connected in fluid communication with a source of combustion gas derived from at least one of a power generating apparatus, an industrial furnace, an internal combustion engine, and/or an incinerator.

28. A photobioreactor apparatus as in claim 25, wherein the at least one gas inlet is connected in fluid communication with a source of CO_2 derived from a non-combustion chemical process.

29. A photobioreactor apparatus as in claim 28, wherein the chemical process comprises fermentation.

30. A photobioreactor apparatus as in claim 25, wherein the at least one gas inlet is connected in fluid communication with a source of gas from a wastewater treatment facility.

31. A photobioreactor apparatus as in claim 24, wherein the at least one species of photosynthetic organisms comprises algae.

32. A photobioreactor apparatus comprising:

at least a first and a second fluidically interconnected channels that are substantially parallel to each other, at least one of which has at least one surface that is at least partially transparent to light of a wavelength capable of driving photosynthesis, the

channels together providing at least a portion of a flow loop enabling a liquid medium contained within the photobioreactor to flow sequentially from a region of origin within the flow loop through the first and second flow channels and back to the region of origin, each channel forming an angle, with respect to the horizontal, of greater than 10 degrees and less than 90 degrees;

a first gas sparger configured and positioned to introduce a gas stream into the first channel;

a second gas sparger configured and positioned to introduce a gas stream into the second channel; and

at least one outlet configured to release gas from the photobioreactor.

33. A photobioreactor apparatus as in claim 32, wherein the photobioreactor apparatus contains the liquid medium therein, and wherein the liquid medium comprises at least one species of photosynthetic organisms; and wherein

the photobioreactor apparatus is controlled by a controller configured to control the overall flow rate of a gas to be treated by the photobioreactor and the distribution of the overall flow rate to the first and second gas spargers so as to induce a liquid flow in the first channel having a direction that is counter-current to a direction of flow of gas bubbles in the first channel and so as to induce a liquid flow in the second channel having a direction that is co-current to a direction of flow of gas bubbles in the second channel.

34. A photobioreactor apparatus as in claim 32, wherein each channel forms an angle, with respect to the horizontal, of less than or equal to 85 degrees.

35. A photobioreactor apparatus as in claim 32, wherein each channel forms an angle, with respect to the horizontal, of less than or equal to 65 degrees.

36. A photobioreactor apparatus as in claim 35, wherein each channel forms an angle, with respect to the horizontal, of greater than or equal to 35 degrees.

37. A photobioreactor apparatus as in claim 32, wherein both channels are within a single conduit.

38. A photobioreactor apparatus as in claim 32, wherein each channel comprises a separate conduit.

39. A photobioreactor apparatus as in claim 37, wherein the first and second channels are formed by a partition within the conduit.

40. A photobioreactor apparatus as in claim 39, wherein the partition is tubular in shape such that an annular space is formed between the partition and the conduit, which surrounds the partition, and wherein one of the channels comprises a lumen surrounded by the tubular partition and the other of the channels comprises the annular space.

41. A photobioreactor apparatus as in claim 33, wherein the controller is configured to control the overall flow rate of the gas to be treated by the photobioreactor and the distribution of the overall flow rate to the first and second gas spargers so as to induce a liquid flow in at least one of the first and second channels characterized by a plurality of recirculation vortices and/or turbulent eddies.

42. A photobioreactor apparatus as in claim 41, wherein the controller is configured to control the overall flow rate of the gas to be treated and the distribution of the overall flow rate to the first and second gas spargers so as to induce a liquid flow having an overall flow rate and flow pattern providing the photosynthetic organisms in the liquid medium with a desired pattern of exposure to light at an intensity sufficient to drive photosynthesis and exposure to dark, or to light at an intensity insufficient to drive photosynthesis, during operation of the photobioreactor.

43. A photobioreactor apparatus as in claim 32, wherein the photobioreactor apparatus contains the liquid medium therein, and wherein the liquid medium comprises at least one species of photosynthetic organisms.

44. A photobioreactor system comprising:

a photobioreactor comprising at least a first and a second fluidically interconnected channels that are substantially parallel to each other, at least one of which has at least one surface that is at least partially transparent to light of a wavelength capable of driving photosynthesis, the channels together providing at least a portion of a flow loop enabling a liquid medium contained within the photobioreactor to flow sequentially from a region of origin within the flow loop through the first and second channels and back to the region of origin, each channel forming an angle, with respect to the horizontal, of less than 90 degrees; and

a controller configured to control the flow of the liquid medium to yield a desired level of photomodulation within the photobioreactor.

45. A photobioreactor apparatus as in claim 44, wherein the conduit is inclined and forms an angle with respect to the horizontal of at least 10 degrees.

46. A photobioreactor system as in claim 44, wherein the photobioreactor contains the liquid medium therein, and wherein the liquid medium comprises at least one species of photosynthetic organisms; and wherein

the controller is configured to control the flow of the liquid medium by controlling an overall flow rate of a gas to be treated by the photobioreactor.

47. A photobioreactor system as in claim 46, further comprising:

a first gas sparger configured and positioned to introduce a gas stream into the first channel;

a second gas sparger configured and positioned to introduce a gas stream into the second channel; and

at least one outlet configured to release gas from the photobioreactor; wherein

the controller is configured to control the flow of the liquid medium by controlling the distribution of the overall flow rate of the gas to the first and second gas spargers.

48. A photobioreactor system as in claim 47, wherein the controller is configured to control the distribution of the overall flow rate of the gas to the first and second gas spargers so as to induce a liquid flow in the first channel having a direction that is counter-current to a direction of flow of gas bubbles in the first channel and so as to induce a liquid flow in the second channel having a direction that is co-current to a direction of flow of gas bubbles in the second channel.

49. A photobioreactor system as in claim 47, wherein the controller is configured to control the distribution of the overall flow rate of the gas to the first and second gas spargers so as to stop or reverse the direction of liquid flow in at least one of the first and second channels during operation.

50. A photobioreactor system as in claim 46, wherein the controller is configured to perform a simulation of liquid flow patterns within the photobioreactor apparatus and, from the simulation, to calculate a first exposure interval of the photosynthetic organisms to light at an intensity sufficient to drive photosynthesis and a second exposure interval of the photosynthetic organisms to dark or light at an intensity insufficient to drive photosynthesis and to control the flow of the liquid medium within the photobioreactor apparatus so as to yield a selected first exposure interval and a selected second exposure interval of the photosynthetic organisms.

51. A photobioreactor system as in claim 50, wherein liquid flow patterns within the photobioreactor are characterized by at least one of recirculation vortices and turbulent eddies.

52. A photobioreactor system as in claim 50, wherein the controller is further configured to calculate the selected first exposure interval of the photosynthetic organisms to the light at an intensity sufficient to drive photosynthesis and the selected second exposure interval of the photosynthetic organisms to dark or light at an intensity insufficient to drive photosynthesis required to yield a desired growth rate of the photosynthetic organisms within the photobioreactor utilizing a mathematical model that

simulates the growth rate of the photosynthetic organisms when exposed to alternating periods of exposure to light at an intensity sufficient to drive photosynthesis and exposure to light at an intensity insufficient to drive photosynthesis, and to establish a flow of the liquid medium within the photobioreactor selected to minimize the difference between the first and second exposure intervals calculated from the simulation of liquid flow patterns and the selected first and second exposure intervals calculated from the mathematical model that simulates the growth rate of the photosynthetic organisms.

53. A photobioreactor system as in claim 46, further comprising at least one sensor that is configured to monitor at least one environmental or performance condition of the photobioreactor during operation, wherein the controller is further configured to receive a signal from the at least one sensor.

54. A photobioreactor system as in claim 53, wherein the at least one sensor is configured to monitor at least one condition selected from the group consisting of: light intensity incident on the photobioreactor; optical density and/or turbidity of the liquid medium within the photobioreactor; gas input flow rate to the photobioreactor; liquid medium flow rate within the photobioreactor; temperature of the liquid medium within the photobioreactor; and temperature of a gas stream supplied to the photobioreactor.

55. A photobioreactor system as in claim 53, wherein the controller is configured to account for changes in the at least one signal received from the at least one sensor in controlling the flow of the liquid medium within the photobioreactor in essentially real-time.

56. A photobioreactor system as in claim 44, wherein the photobioreactor contains the liquid medium therein, and wherein the liquid medium comprises at least one species of photosynthetic organisms.

57. A photobioreactor apparatus comprising:

a conduit having a surface that is at least partially transparent to light of a wavelength capable of driving photosynthesis, the conduit forming an angle, with respect to the horizontal, of greater than 10 degrees and less than or equal to 90 degrees;

a first gas sparger configured and positioned to introduce a gas stream into the conduit at a first height;

a second gas sparger configured and positioned to introduce a gas stream into the conduit at a second height, different from the first height; and

at least one outlet configured to release gas from the photobioreactor.

58. A photobioreactor as in claim 57, wherein the conduit forms an angle, with respect to the horizontal, of less than 90 degrees.

59. A photobioreactor as in claim 57, wherein the conduit forms an angle, with respect to the horizontal, of less than or equal to 85 degrees.

60. A photobioreactor as in claim 57, wherein the conduit forms an angle, with respect to the horizontal, of between 35 degrees and 65 degrees inclusive.

61. A photobioreactor apparatus as in claim 57, wherein the photobioreactor apparatus contains a liquid medium therein, and wherein the liquid medium comprises at least one species of photosynthetic organisms.

62. A photobioreactor apparatus comprising a conduit having a surface that is at least partially transparent to light of a wavelength capable of driving photosynthesis, the conduit having a cross-sectional dimension that is at least 1 meter.

63. A photobioreactor apparatus as in claim 62, wherein the photobioreactor apparatus contains a liquid medium therein, and wherein the liquid medium comprises at least one species of photosynthetic organisms.

64. A photobioreactor apparatus as in claim 63, further comprising a first gas sparger configured and positioned to introduce a gas stream into the conduit.

65. A photobioreactor apparatus as in claim 63, further comprising at least a first and a second fluidically interconnected channels that are substantially parallel to each other, at least one of which has at least one surface that is at least partially transparent to light of a wavelength capable of driving photosynthesis, the channels together providing at least a portion of a flow loop enabling the liquid medium contained within the photobioreactor apparatus to flow sequentially from a region of origin within the flow loop through the first and second channels and back to the region of origin; and wherein

the photobioreactor apparatus is controlled by a controller configured to control the flow of the liquid medium to yield a desired level of photomodulation within the bioreactor.

66. A photobioreactor apparatus as in claim 65, wherein each channel forms an angle, with respect to the horizontal, of greater than 10 degrees and less than 90 degrees.

67. A method comprising acts of:

producing gas comprising at least CO_2 with a biological process;

passing the gas to an inlet of an enclosed photobioreactor containing a liquid medium therein comprising at least one species of photosynthetic organisms and exposed to the sun as a source of light driving photosynthesis; and

at least partially removing the CO_2 from the gas with the photosynthetic organisms, the CO_2 being utilized by the organisms for growth and reproduction.

68 A method as in claim 67, further comprising an act of:

removing at least a portion of the liquid medium comprising the at least one species of photosynthetic organisms from the photobioreactor.

69. A method as in claim 68, further comprising acts of:

drying the liquid medium removed in the removing act to produce a dried algal biomass product; and

using the dried algal biomass product as a fuel and/or to produce a fuel.

70. A method as in claim 67, wherein the biological process comprises fermentation.

71. a method as in claim 67, wherein the biological process takes place in a wastewater treatment facility.

72. A method as recited in claim 67, further comprising, after the at least partially removing act, an act of:

releasing treated gas from a gas outlet of the photobioreactor.

73. A method as recited in claim 68, wherein an algal biomass product comprising or produced from the liquid medium removed in the removing act is used to produce at least one fuel product comprising an oil and/or a combustible gas.

74. A method of treating a source of gas derived from a fermentation process with a photobioreactor, the method comprising acts of:

receiving a gas from a fermentation process;

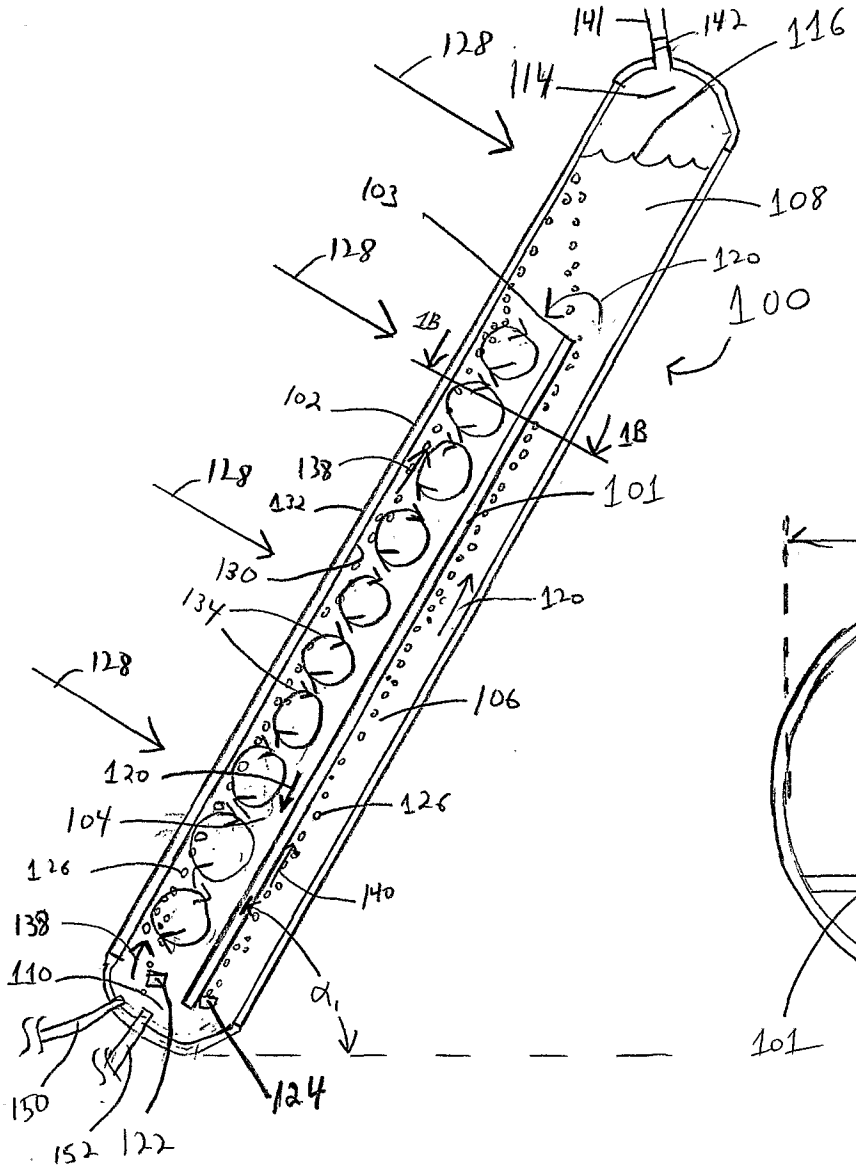
passing the gas through a photobioreactor; and

at least partially removing at least one substance from the gas in the photobioreactor.

75. A method as in claim 74, wherein CO_2 is removed from the gas in the photobioreactor.

76. A method as in claim 74, wherein the gas is received from a wastewater treatment facility or agricultural waste digestor.

77. A method as in claim 76, wherein CO_2 is removed from the gas in the photobioreactor.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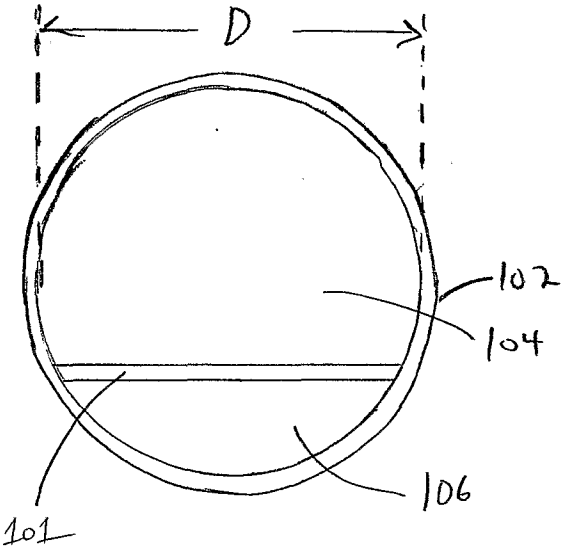
142
116
128
114
103
108
128
120
100
1B
102
1B
128
138
101
132
130
120
134
128
106
120
104
126
126
140
138
110
α_1
150
124
152
122

FIG. 1A


D
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101

FIG. 1B

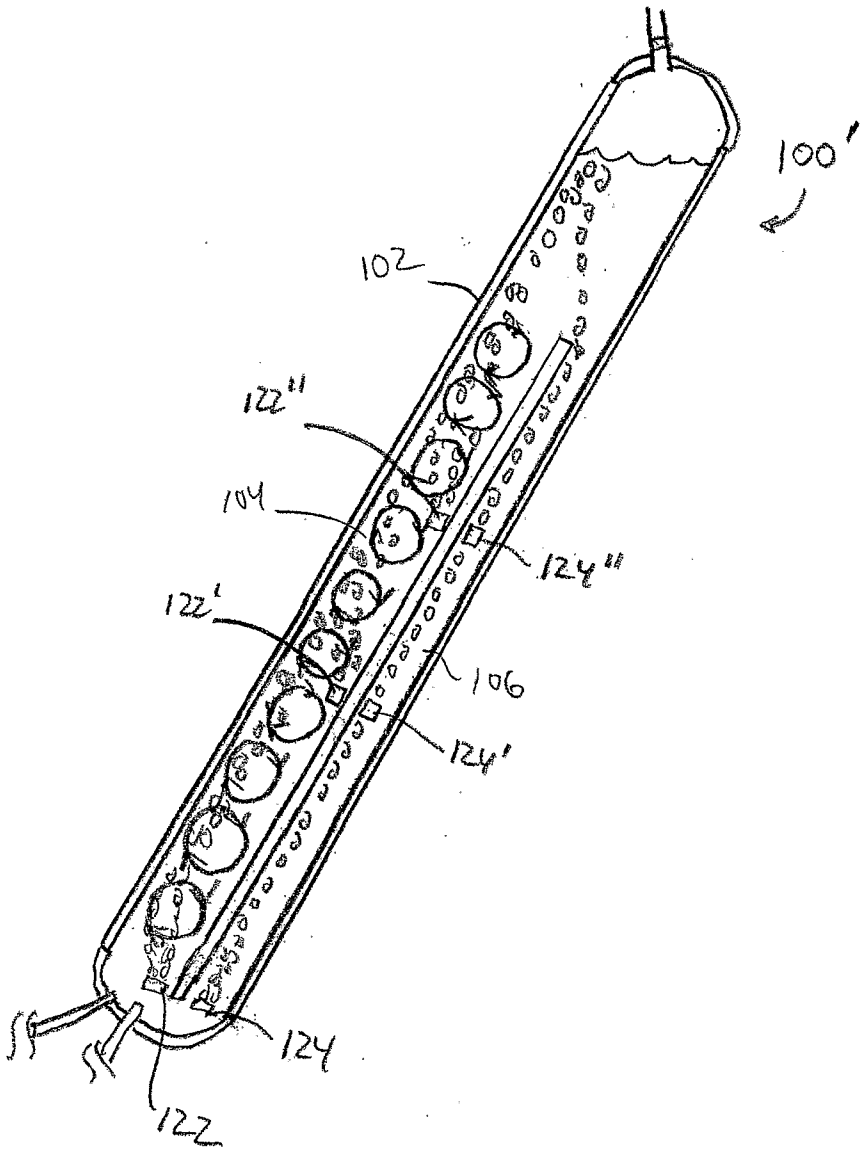


FIG. 1C

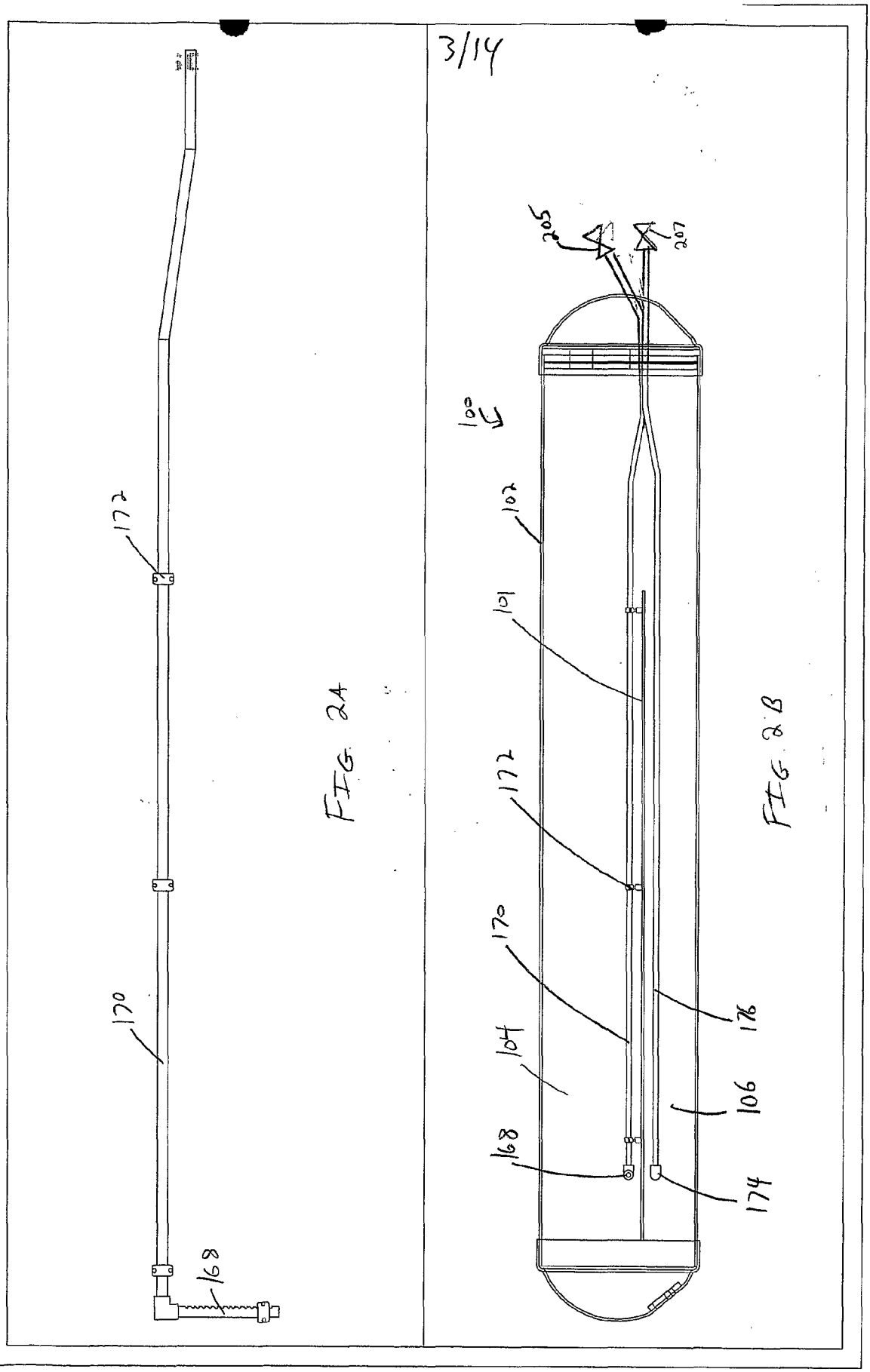
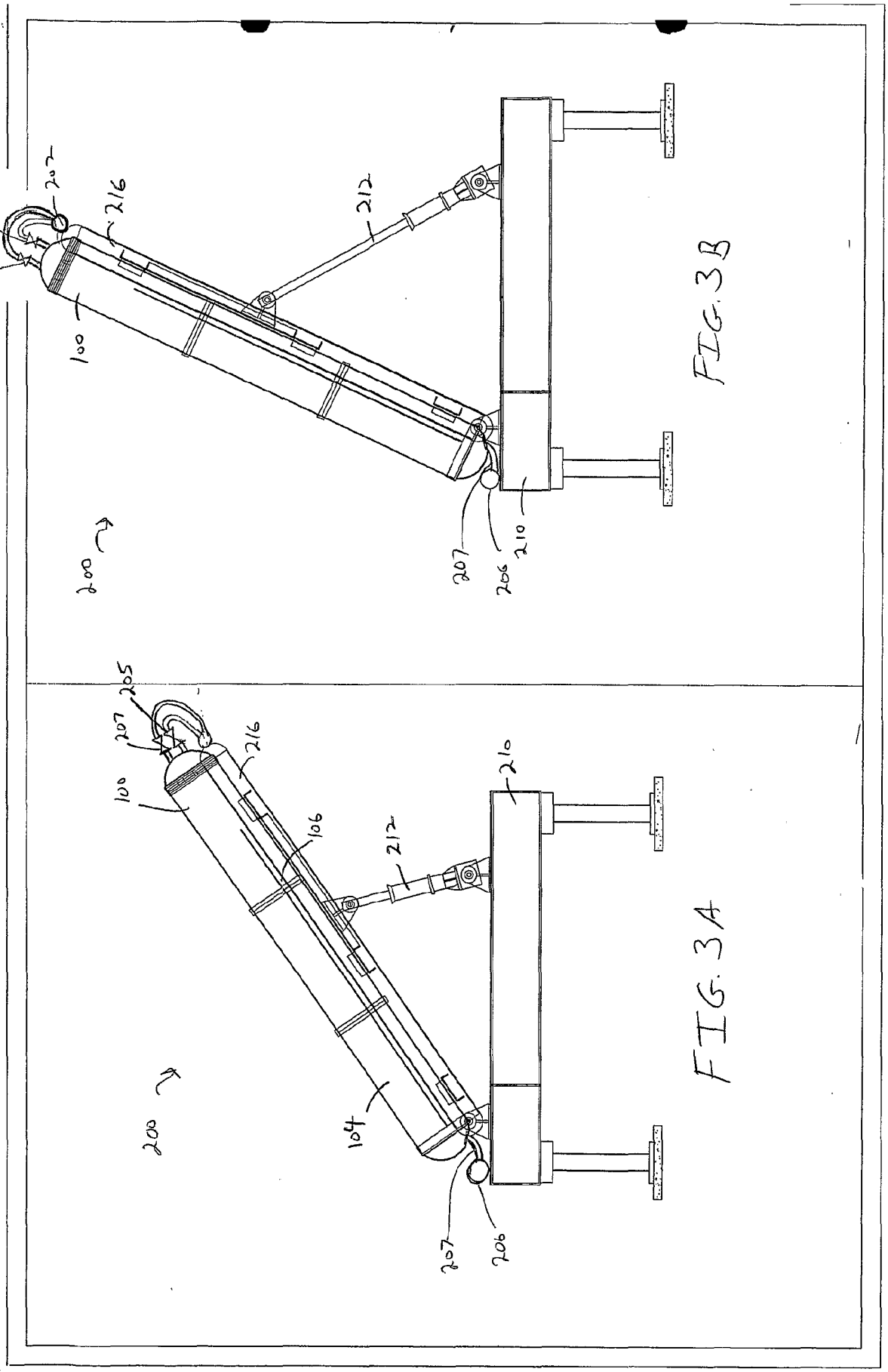
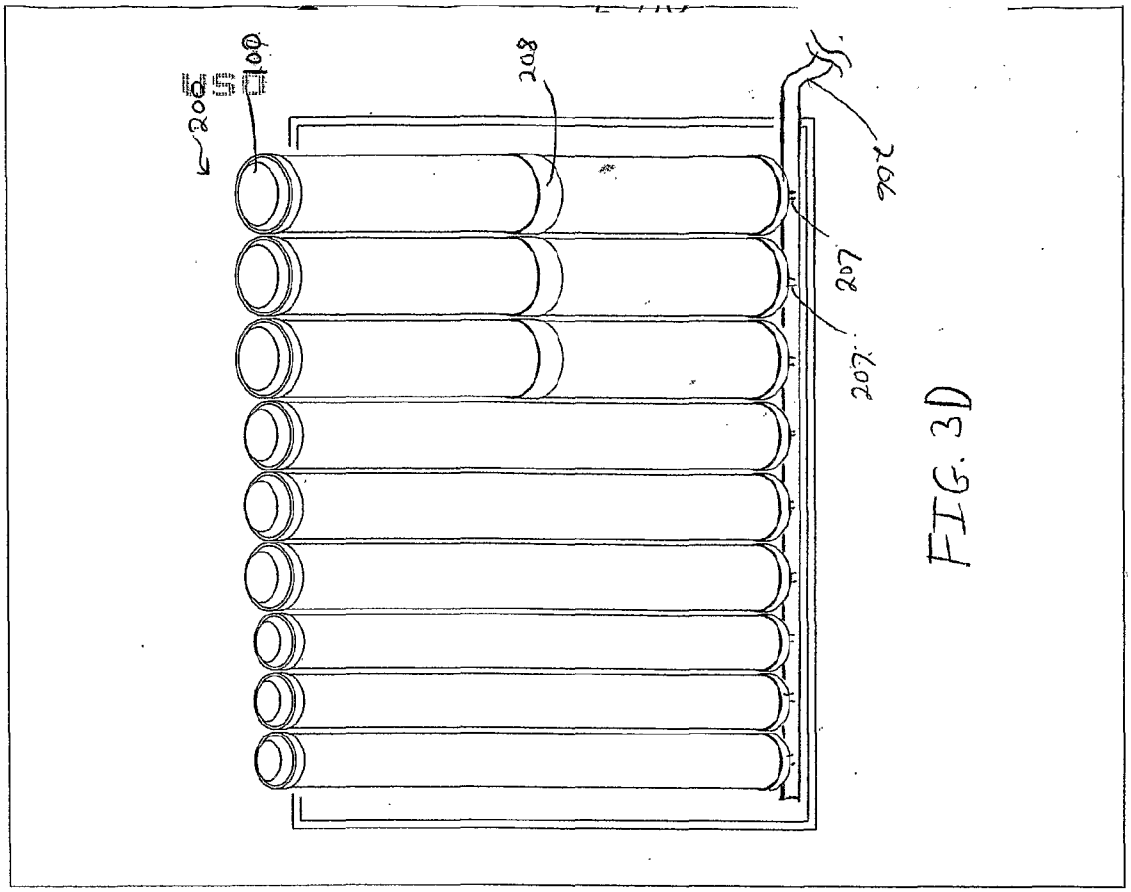


FIG. 2A

FIG. 2B


205
207
202
216
212
100
200
207
206
210
FIG. 3B
205
207
216
210
100
106
212
200
104
207
206
FIG. 3A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207

FIG. 3D

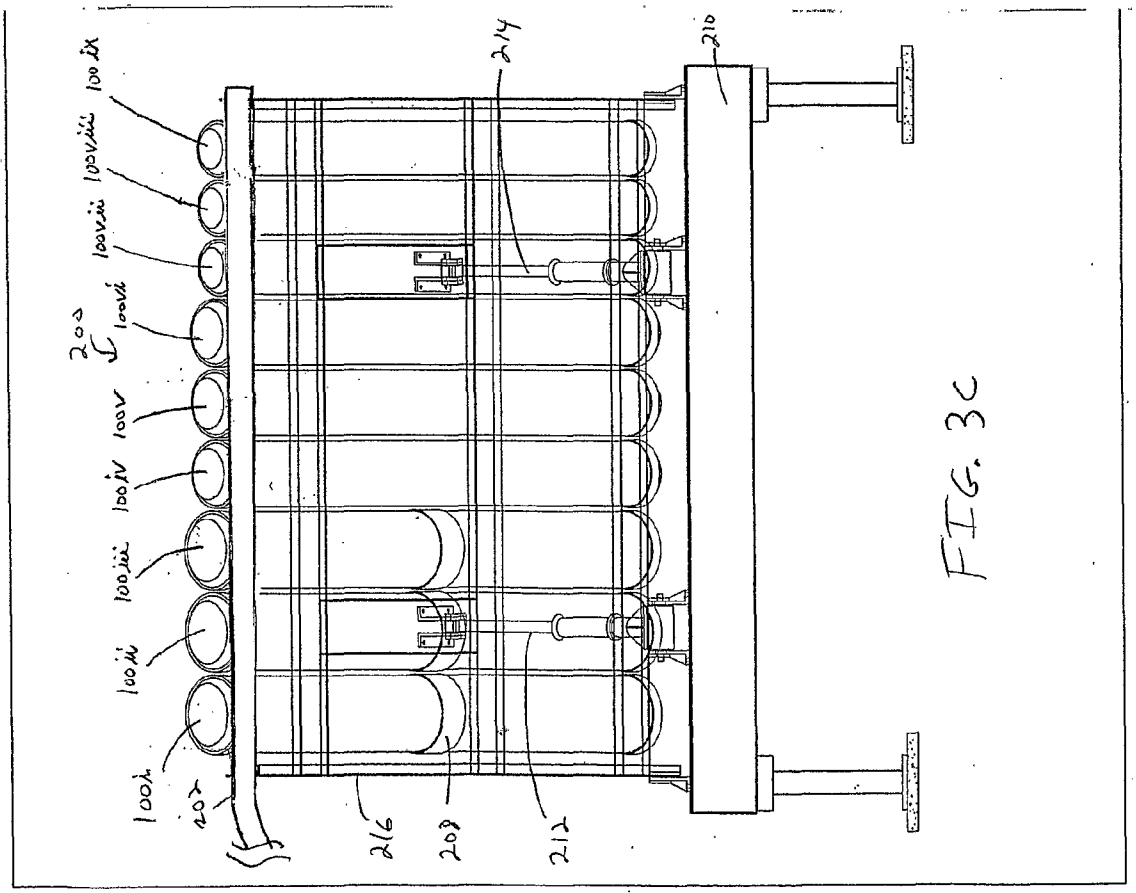

214
210
100x
100xi
100xii
100xiii
200
100v
100iv
100iii
100ii
100i
202
216
208
212

FIG. 3C

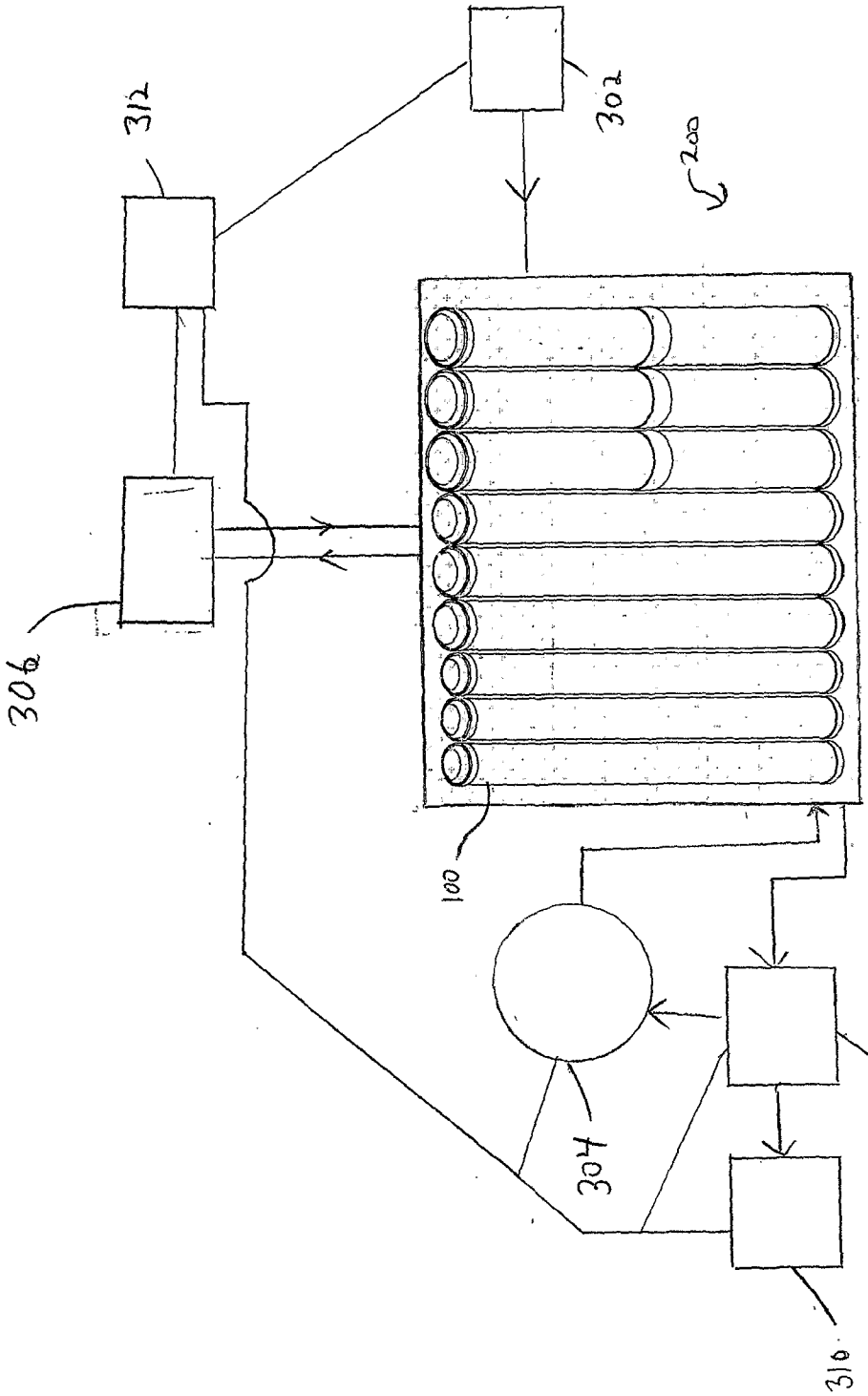


FIG. 4

FIG. 5A

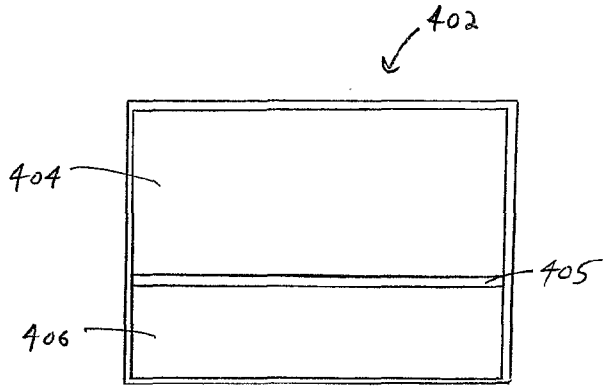
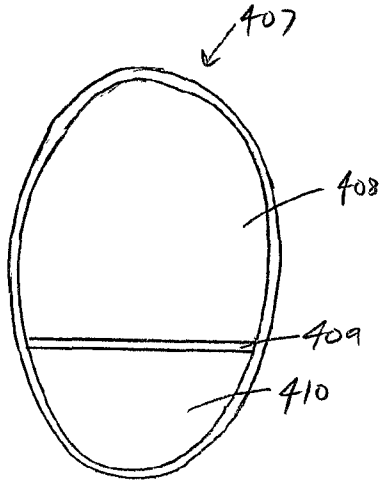


FIG. 5B



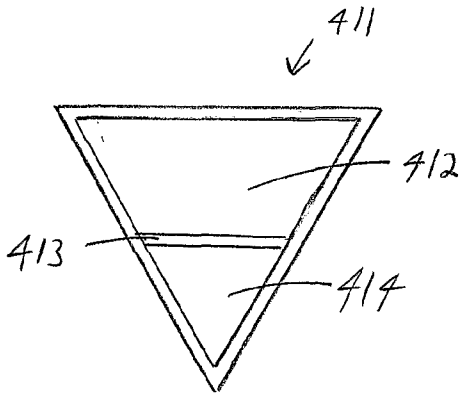


FIG. 5C

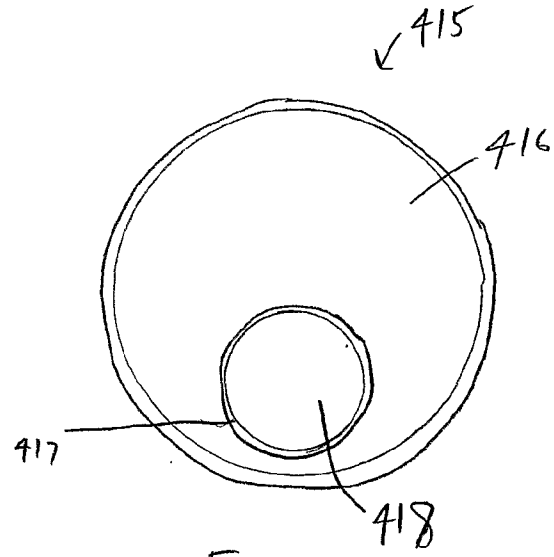


FIG. 5D

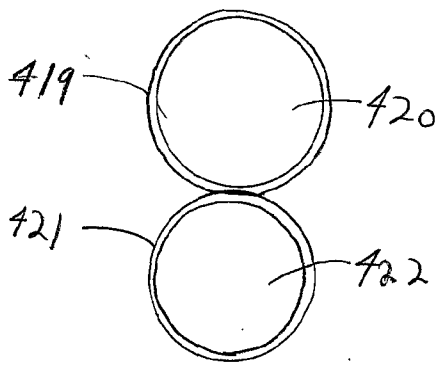


FIG. 5E

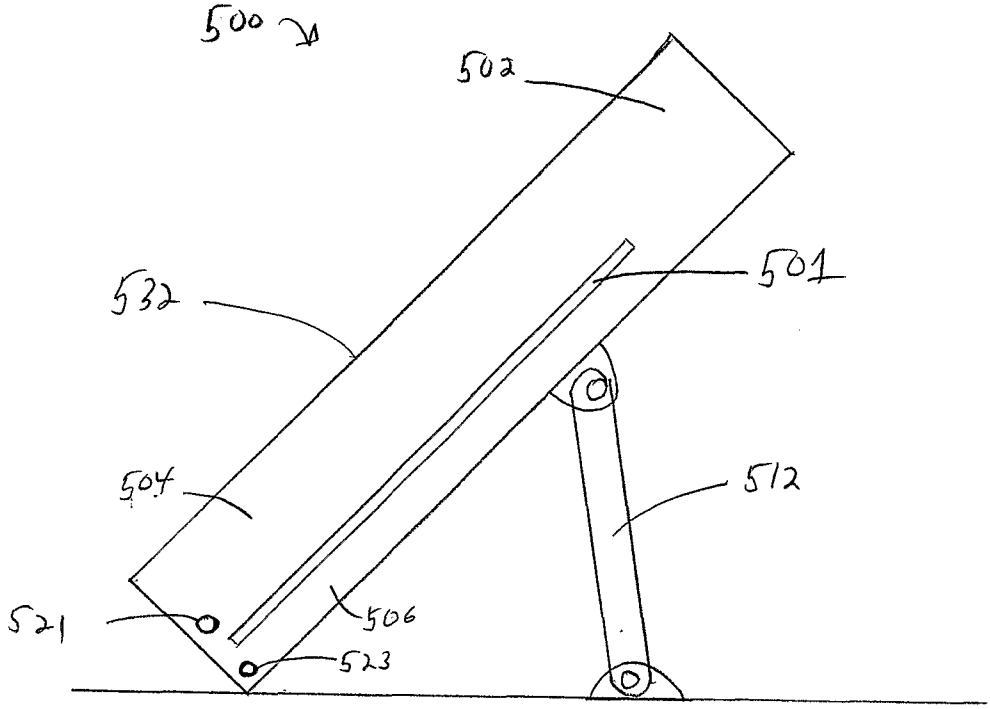


FIG. 6A

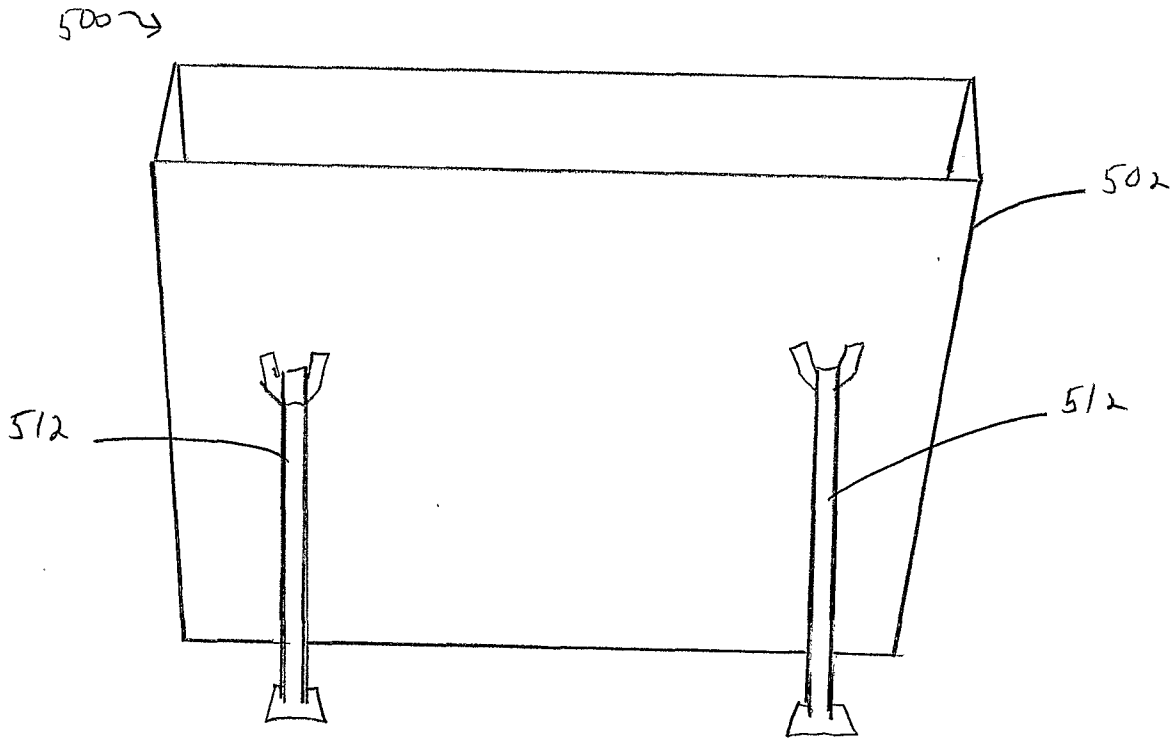


FIG. 6B

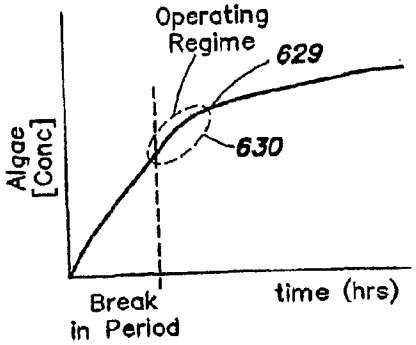
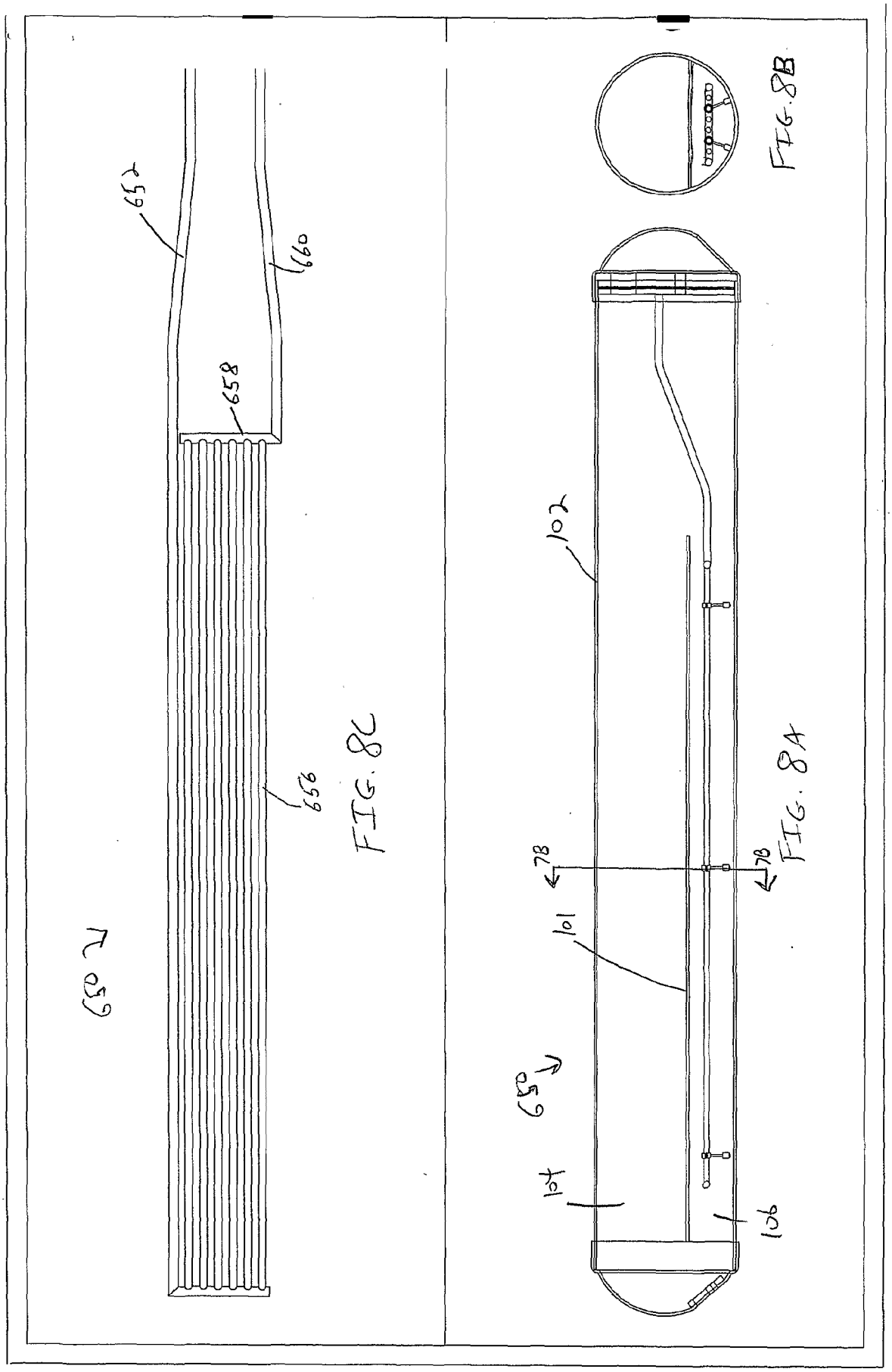

Operating Regime
629
630
Algae [Conc]
Break in Period
time (hrs)

FIG. 7B

600
Comp
628
141
142
116
114
128
108
120
100
633
102
614
pH
101
604
T
130
134
606
106
603
602
LF
624
626
Comp
140
OD
632
110
138
126
104
120
205
122
124
150
Liquid Medium In/Out
207
622
620
616
P
612
Gas Source
608

FIG. 7A


652
660
658
656
650
FIG. 8C
102
78
78
101
650
104
106
FIG. 8A
FIG. 8B

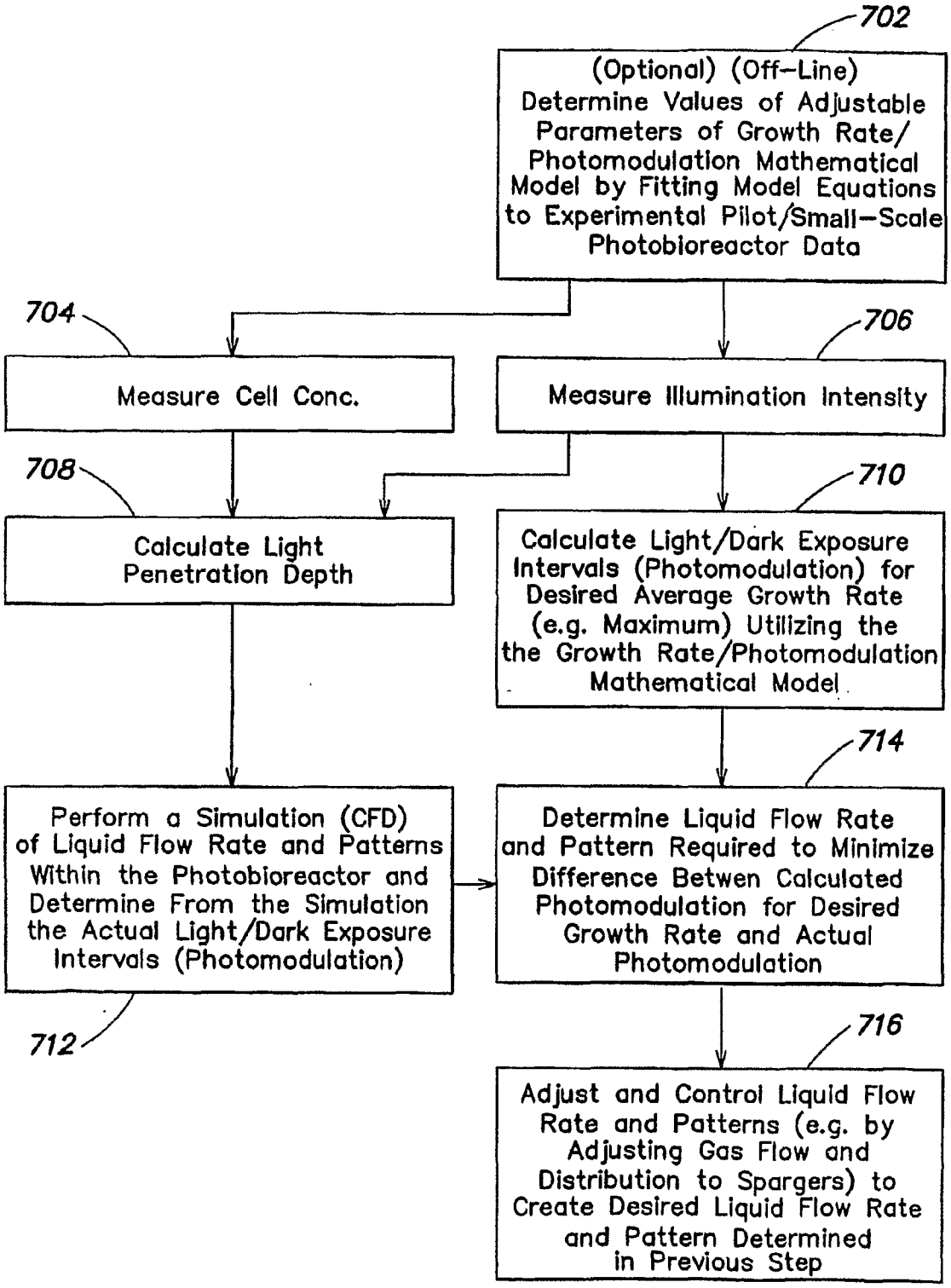

702
(Optional) (Off-Line) Determine Values of Adjustable Parameters of Growth Rate/ Photomodulation Mathematical Model by Fitting Model Equations to Experimental Pilot/Small-Scale Photobioreactor Data
704
Measure Cell Conc.
706
Measure Illumination Intensity
708
Calculate Light Penetration Depth
710
Calculate Light/Dark Exposure Intervals (Photomodulation) for Desired Average Growth Rate (e.g. Maximum) Utilizing the the Growth Rate/Photomodulation Mathematical Model
714
Perform a Simulation (CFD) of Liquid Flow Rate and Patterns Within the Photobioreactor and Determine From the Simulation the Actual Light/Dark Exposure Intervals (Photomodulation)
Determine Liquid Flow Rate and Pattern Required to Minimize Difference Betwen Calculated Photomodulation for Desired Growth Rate and Actual Photomodulation
712
716
Adjust and Control Liquid Flow Rate and Patterns (e.g. by Adjusting Gas Flow and Distribution to Spargers) to Create Desired Liquid Flow Rate and Pattern Determined in Previous Step

FIG. 9A

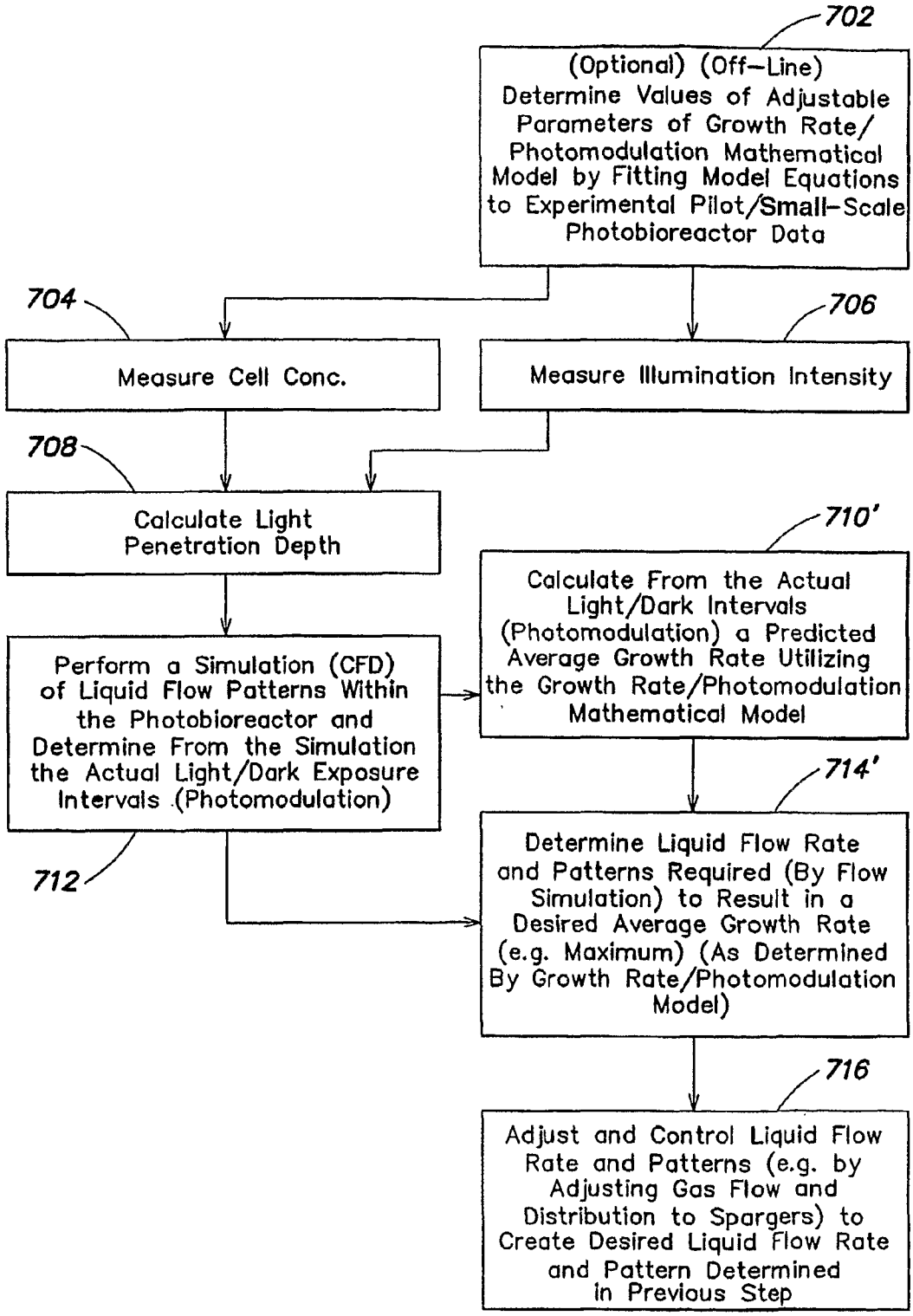

702
(Optional) (Off-Line) Determine Values of Adjustable Parameters of Growth Rate/ Photomodulation Mathematical Model by Fitting Model Equations to Experimental Pilot/Small-Scale Photobioreactor Data
704
Measure Cell Conc.
706
Measure Illumination Intensity
708
Calculate Light Penetration Depth
710'
Calculate From the Actual Light/Dark Intervals (Photomodulation) a Predicted Average Growth Rate Utilizing the Growth Rate/Photomodulation Mathematical Model
Perform a Simulation (CFD) of Liquid Flow Patterns Within the Photobioreactor and Determine From the Simulation the Actual Light/Dark Exposure Intervals (Photomodulation)
712
714'
Determine Liquid Flow Rate and Patterns Required (By Flow Simulation) to Result in a Desired Average Growth Rate (e.g. Maximum) (As Determined By Growth Rate/Photomodulation Model)
716
Adjust and Control Liquid Flow Rate and Patterns (e.g. by Adjusting Gas Flow and Distribution to Spargers) to Create Desired Liquid Flow Rate and Pattern Determined in Previous Step

FIG. 9B

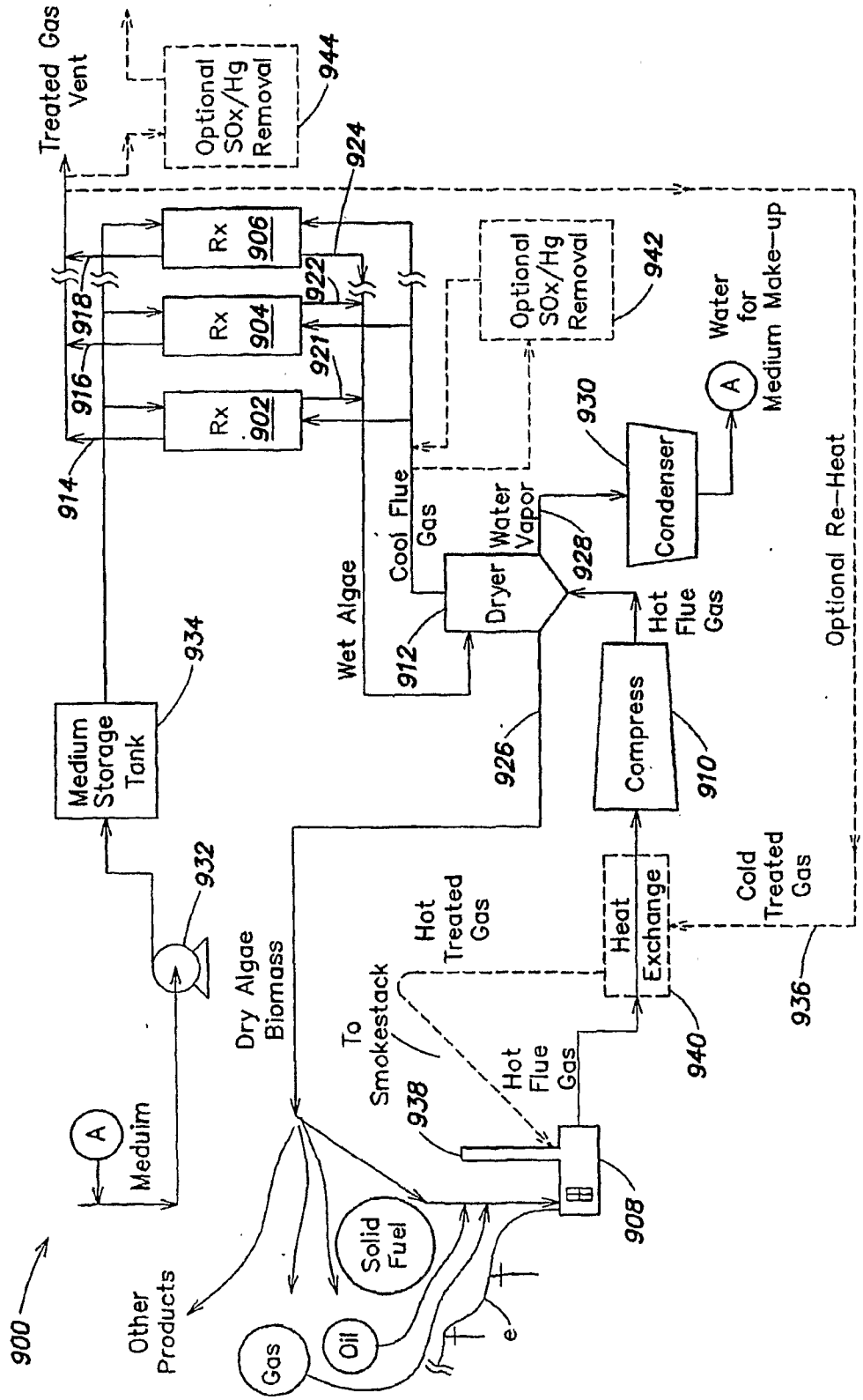

Treated Gas Vent
Optional SOx/Hg Removal
944
924
Rx 906
Rx 904
Rx 902
922
921
918
916
914
Optional SOx/Hg Removal
942
Water for Medium Make-up
A
930
Condenser
Water Vapor
928
Cool Flue Gas
Dryer
912
Wet Algae
Hot Flue Gas
Optional Re-Heat
926
Compress
910
Medium Storage Tank
934
932
Hot Treated Gas
Heat Exchange
Cold Treated Gas
936
940
Dry Algae Biomass
To Smokestack
938
Hot Flue Gas
908
A
Meduim
Solid Fuel
Other Products
Gas
Oil
e
900

FIG. 10

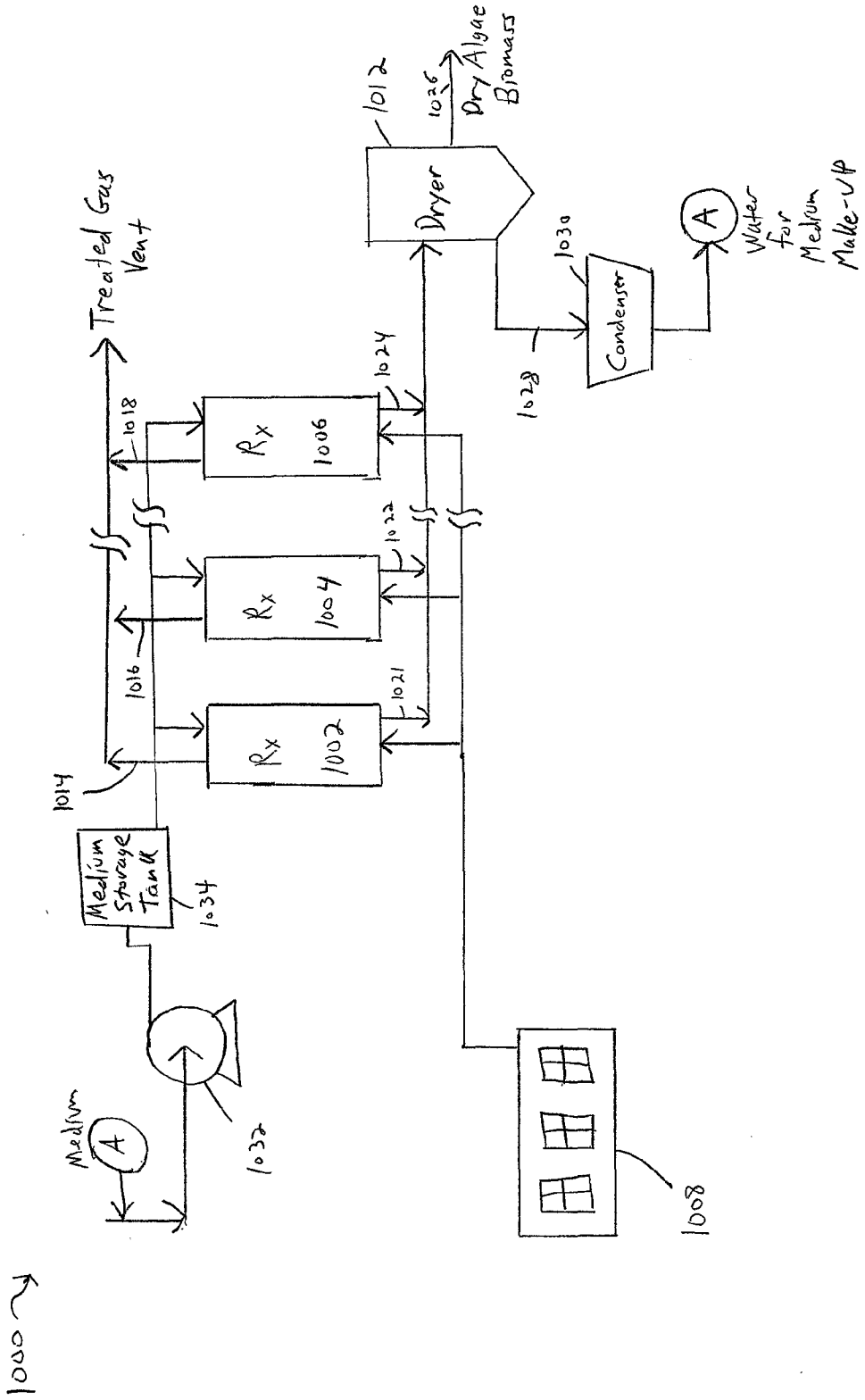

1000
Medium
A
1032
Medium Storage Tank
1034
1014
1016
1018
Treated Gas Vent
Rx 1002
Rx 1004
Rx 1006
1021
1022
1024
1012
Dryer
1026
Dry Algae Biomass
1028
1030
Condenser
A
Water for Medium Make-up
1008

FIG. 11

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US05/25249

A. CLASSIFICATION OF SUBJECT MATTER
IPC: **A01G 7/00**(2006.01);**A61L 9/00**(2006.01);**C12M 1/00**(2006.01)

USPC: 47/1.4;435/266,292.1,286.5
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 47/1.4; 435/266, 292.1, 286.5, 295.1, 295.2, 296.1

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 03/094598 A1 (BERZIN) 20 November 2003 (20.11.2003), see entire document.	67-77
---		---
Y		1-66
Y	EP 0 343 885 A1 (KALFON) 29 November 1989 (29.11.1989), see entire document.	1-66
Y	JP 61-35736 A (KURACHI) 20 February 1986 (20.02.1986), see entire document.	1-66
Y	US 5,443,985 A (LU et al.) 22 August 1995 (22.08.1995), see entire document.	1-66
A	US 4,044,500 A (HITZMAN) 30 August 1977 (30.08.1977), see entire document.	1-77
A	US 3,420,739 A (BONGERS et al.) 07 January 1969 (07.01.1969), see entire document.	1-77

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
08 June 2006 (08.06.2006)	21 JUL 2006
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450 Alexandria, Virginia 22313-1450 Facsimile No. (571) 273-3201	Authorized officer William H. Beisner Telephone No. 571-272-1700

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US05/25249

C. (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2,732,663 A (DEWEY II) 31 January 1956 (31.01.1956), see entire document.	1-77