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(54) Title: CARBON MANAGEMENT SYSTEM

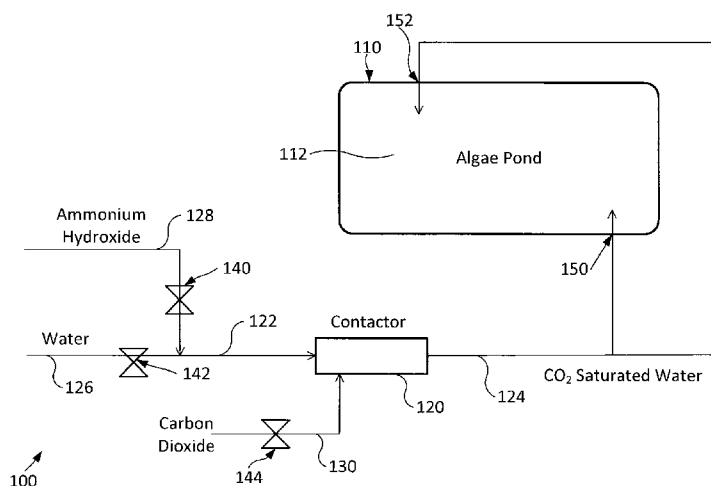


FIG. 1

(57) **Abstract:** Novel methods and systems for the sequestration of carbon dioxide to be used for algae growth and lipid production in open and closed photo bioreactors and in heterotrophic reactors using sugars and other nutrients. Novel methods and systems for augmenting biomass with the temporal use of fixed carbon supplements. Multiple mechanical, chemical and membrane technologies are combined to increase the overall efficiency of carbon dioxide absorption and subsequent conversion into carbohydrates, algae and oils in aqueous medium. Dramatic reductions in energy to drive heterotrophic reactors utilizing algae are disclosed using novel process conditions ideally suited to large scale commercial production of oils.



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CARBON MANAGEMENT SYSTEM

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority from U.S. Provisional Patent Application No. 61/440,686, filed February 8, 2011.

TECHNICAL FIELD

[0002] The disclosed embodiments of the present invention are in the field of carbon sequestration, algal biomass, and biofuel production.

BACKGROUND

[0003] Biofuels will play an increasing role in the United States energy market as energy prices increase, political will to establish national energy independence intensifies and apprehension about climate change continues to grow. The price of petroleum has fluctuated dramatically, reaching record highs of more than US\$140 per barrel in 2008. In part, those price increases reflected economic, political, and supply chain uncertainties. Political concerns about the availability of petroleum supplies have led to the realization that the United States' energy independence is of critical strategic importance, both economically and militarily. The release of CO₂ from fossil fuel combustion may also substantially contribute to global warming and climate change and efforts are intensifying to develop biofuels to reduce this release. The United States has responded by issuing a renewable fuel standard update (RPS2) that encourages a shift to more advanced biofuels in the market. Additionally, many states have responded by enacting their own renewable portfolio standards mandating electricity providers to obtain a certain percentage of their power from renewable energy sources. As a result of these concerns and RPS requirements, domestically produced biofuels have become an increasingly attractive sustainable and environmentally responsible alternative to foreign fossil fuels.

[0004] Microalgae are some of the most productive and therefore desirable sources for

production of renewable biofuels. The Department of Energy (DOE) has determined that biofuel yield per acre from microalgal culture exceeds that of many organisms and land crops. Between the late 1970s and 1990s, the DOE's National Renewable Energy Laboratory (NREL) evaluated the economic feasibility of producing biofuels from a variety of aquatic and terrestrial photosynthetic organisms. Biofuel production from microalgae was determined to have the greatest yield per acre potential of any of the organisms screened. Microalgal biofuel production was estimated to be 8 to 24 fold greater than the best terrestrial biofuel production systems. Current estimates of the potential productivity for algal biofuel production range from 2,000 to 10,000 gallons/acre. According to the DOE, microalgae yield "30 times more energy per acre than land crops such as soybeans." Although existing technologies are promising, there is still a need for systems and methods that create even greater efficiencies in biofuel production from microalgae to meet economic targets needed for successful commercialization.

[0005] Carbon sequestration systems used in combination with algal ponds can both address the concern of the release of CO₂ into the atmosphere and produce a biofuel. Existing methods of carbon sequestration, however, have numerous downfalls that make them impractical for implementation in the production of biofuels. In particular, most methods utilize gas spargers, which require pressurized gas. Obtaining this gas is energy-intensive, which is not only costly but counterproductive in the context of biofuels.

[0006] The most common method of introducing gases to bioreactors used to grow organisms in heterotrophic conditions is to introduce gas with metal spargers in the form of a ring on the bottom of the reactor. Blades and high speed agitators can be used to break up the bubbles. Although commonly used, these designs are very inefficient and consequently require large amounts of energy to compress the gas. Most of the gas passes through the reactor without being absorbed, thus wasting over 90% of the energy in the form of heat from air compression. This method is also very capital intensive. A typical algal heterotrophic reactor requires approximately $0.5V_{\text{gas}}/V_{\text{liquid}}$ each minute (VVM). This constraint requires an enormous amount of compressed gas. Approximately 80% of this compressed gas is nitrogen, which does not enhance algal growth. Therefore, these methods put large volumes of gas through the bioreactor that do not increase the efficiency of the process.

[0007] Although spargers are commonly used, they have numerous limitations. A variety

of gas spargers are used in the commercial introduction of carbon dioxide for algae systems. These are often made from sintered compressed porous metals, foamed glass or ceramics, or few polymeric foam devices. These spargers are prone to plug over time with algae, bacterial growth or mineral deposits. Small pore sizes must be used to achieve the desired small bubble size. As the pore size decreases, the delivery pressure must increase, which translates to more electrical power consumption.

[0008] Porous elastomeric tubes can also be used to introduce carbon dioxide into ponds, bioreactors, or raceways. These tubes however, require 7 to 10 psi to eject gas out of the tube under water. As gas escapes, the delivery pressure required to expel gas the entire length of the submerged tubing increases. As the pressure at one end increases, the size of the bubbles on the input end of the delivery tube increases and the size of the bubbles on the far end of the delivery tube decreases. It is possible to divide the gas distribution system to achieve better uniformity but, by definition, these submerged tubing systems are inherently prone to non-uniformity of gas distribution along the length of the pond, raceway or photobioreactor.

DEFINITIONS

[0009] Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this subject application pertains. Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of the exemplary embodiments, suitable methods and materials are described below. In case of conflict, the present specification, including definitions, will control. In addition, the materials, methods, and examples are illustrative only and not intended to be limiting.

[0010] Microalgae have been variously defined through the ages and it is prudent to describe the microalgae to which this invention could apply. For the purposes of this patent, microalgae include the traditional groups of algae described in Van Den Hoek *et al.* (1995). The subject application is applicable to the photosynthetic, heterotrophic, and mixotrophic culturing of microalgae. This subject application also pertains to the bluegreen algae that are now referred to as cyanobacteria.

[0011] The terminology as set forth herein is for description of the embodiments only and

should not be construed as limiting the subject application as a whole. Unless otherwise specified, “a,” “an,” “the,” and “at least one” are used interchangeably. Furthermore, as used in the description of the invention and the appended claims, the singular forms “a,” “an,” and “the” are inclusive of their plural forms, unless contraindicated by the context surrounding such. The singular “alga” is likewise intended to be inclusive of the plural “algae.”

SUMMARY

[0012] Exemplary embodiments of the compositions, systems, and methods disclosed herein improve the process of producing biofuels from microalgae. This is achieved by using contactors to introduce carbon dioxide at a microscopic level into a liquid medium growing photosynthetic organisms used to sink carbon dioxide.

[0013] Another embodiment of the subject application involves a side arm contactor system and utilizing the side arm contactor system to introduced carbon dioxide at a microscopic level into a liquid medium.

[0014] In another embodiment of the subject application, oxygen-rich waste air is harvested from an air plant and fed to organisms capable of heterotrophic growth.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] A better understanding of the exemplary embodiments of the subject application will be had when reference is made to the accompanying drawings, and wherein:

[0016] Figure 1 is a schematic diagram showing a carbon dioxide sequestration system for use with algae ponds in accordance with an example embodiment;

[0017] Figure 2 is an overhead schematic diagram showing an algal pond flow diagram of a sidearm carbon dioxide dissolution system for use with an algae pond in accordance with an example embodiment;

[0018] Figure 3 is a schematic diagram illustrating an enlarged portion of the sidearm carbon dioxide dissolution system of Figure 2 for clarifying the operational and functional

characteristics of the example embodiment;

[0019] Figure 4 is an illustration of an algae pond system demonstrating a carbon cycle occurring during algae growth;

[0020] Figure 5 are graphical illustrations of results of algae growth using diffused carbon dioxide and demonstrating carbon dioxide utilization and algae growth in accordance with the example embodiments;

[0021] Figure 6 is a schematic diagram of a system used to dissolve carbon dioxide in a fluid in accordance with an example embodiment;

[0022] Figure 7 is a table showing production scale results obtained using the systems and methods for managing carbon through absorption by algae in accordance with the example embodiments; and,

[0023] Figure 8 shows graphical illustrations of experimental results of carbon dioxide utilization and algae growth in using the system of Figures 2 and 3 in accordance with the example embodiments.

DETAILED DESCRIPTION

[0024] In accordance with a first example embodiment, one or more contactors are used to introduce gas into a fluid of a bioreactor, a pond, a raceway or the like. In the examples, components of the gas are sequestered such as by dissolving the gas into the fluid. Further in the example embodiments, the fluid may contain one or more organisms which have growth characteristics that are responsive to the dissolved or sequestered chemical component. By way of illustration only and not for limiting the embodiments, the gas is CO₂ and the fluid is algae in an algal growth medium, such as water, comprising an algal slurry.

[0025] Contactors, specifically hollow fiber contactors, have been used to remove gases from liquids. The example embodiments presented herein, however, uniquely use these contactors in reverse. The systems and methods described herein saturate gases into liquids quickly and at high energy efficiencies.

[0026] Membrane contactors offer a compact and efficient means to uniformly carbonate a liquid without bubbles. Rather than sparging large CO₂ gas bubbles into a liquid containing one or more photosynthetic organisms used to sink carbon dioxide, the systems of the example embodiments herein use membrane contactors diffuse the CO₂ into the liquid on a microscopic level. This produces a much more controlled level of carbonation in the fluid. The amount of carbon dioxide introduced by contractors can be up to ten times higher than that introduced by spargers. The process of dissolving CO₂ into the liquid is much more controlled and less CO₂ gas is required to get to the same level of carbonation as sparging systems. This reduces operating costs to the end user while producing a superior fluid suitable for algae growth or other applications.

[0027] In general, a rate of mass transfer of CO₂ into media can be assumed to be $r_D = k_D A (C_e - C)$ [mg_{transferred}CO₂/s], wherein k_D [mg_{transferred}CO₂*L/(s m² mgCO₂)] and C_e [mg/L] are set. As determined experimentally,

$$k_D = 0.00064T^2 - 0.02408T + 0.4199$$

$$C_e = C_{gas}(-0.063T(^{\circ}C) + 1.1709)$$

$$C_{gas} = \frac{P}{RT} (gas\ law)$$

where A [m²] is the total surface area available for mass transfer (gas bubble size dependent) and where C [g/L] is the dissolved gas amount present in media.

[0028] One nagging unresolved issue with regard to the prior sparger systems is the low residence time for CO₂ transfer into media due to shallow ponds (15 - 20cm height). Current methods tried in industry include sparger systems wherein gas is pushed through small holes. However, the resultant mass transfer is inefficient due to low residence time. Spargers placed at the bottom of a sump have been proposed to increase the residence time. However, these systems have high construction and maintenance costs and have demonstrated about 50% mass transfer efficiency 3 m deep sump.

[0029] Figure 1 is a schematic diagram showing a carbon management system 100 for use with photosynthetic organism ponds 110 such as algae ponds 112 in accordance with an example embodiment wherein the system 100 is useful as a carbon dioxide sequestration system as well as a beneficial photosynthetic organism growth system such as an algal growth system when implemented in the algal context. In the example embodiment illustrated, the system 100 comprises a contactor 120 in fluid communication with an inlet tubing string 122 and an outlet tubing string 124. The inlet tubing string 122 couples the contactor 120 with an associated source of pressurized fresh water 126 and with a pressurized source of a chemical enhancer 128 such as ammonium hydroxide, for example. The outlet tubing string 124 couples the contactor 120 with the algae pond 112. In addition, the contactor 120 of the example embodiment is in operative fluid communication with an associated source of pressurized carbon dioxide 130. It is to be appreciated that the carbon dioxide gas is dissolved into the water at the contactor whereby the outlet tubing string carries or otherwise delivers carbon dioxide saturated water to the algae pond 112. In the example embodiment illustrated, one or more fluid valves 140, 142, 144 are selectively used for controlling the flow rates of the various fluids into the contactor 120 in accordance with predetermined control rules.

[0030] An advantage of the present example embodiment is that the fluids ejected from the contactors 120 can be pumped around the ponds or photobioreactors at multiple entry points 150, 152 to distribute the carbon dioxide evenly throughout the fluid body. This is in stark contrast to porous tubing and spargers, even those that use sump pumps beneath the surface to increase rates of bubble absorption. Although placing a sparger beneath the bottom level of a pond or photobioreactor increases the residence time of the carbon dioxide in the algal aqueous medium, it also produces larger undesirable bubbles. The large size of the bubbles lowers the activation energy of the gas to get into solution. Placing a sparger underneath the pond only slightly increases carbon dioxide absorption but dramatically increases the installed cost of the algae ponds due to the need for additional excavation and underground pipes. Furthermore, repair of these underground pipes is difficult and expensive as it can be challenging to identify the source and location of the leak. This problem is eliminated under the instant invention.

[0031] The example embodiments of the present disclosure selectively use pumps and/or pre-pressurized fluids/gasses and contactors to drive a high level of dissolved gas into the

fluids. This eliminates the need for sub-level excavations and greatly reduces the installed costs of the ponds, one of the largest components of cost in the overall algae oil facility.

[0032] This system could also be used to manage carbon dioxide emissions from power plants and manufacturing facilities. If used in this context, scrubbers could be utilized to ensure that the gas entering the liquid medium is relatively free of particulates and unwanted chemicals (e.g. sulfur).

[0033] In accordance with a further example embodiment, a variation of the contactor, a side arm contactor system 200, is used to introduce gas into a bioreactor, pond, or raceway 202. As shown in Figures 2 and 3, a horizontally above ground pipe network 210, 212 brings the liquid medium into contact with gas. A system could involve a pipe several meters (1-100 m) in length and several centimeters (1-50 cm) in width, with or without static mixers, constructed of plastic or metal. Medium containing algae or other organism(s) would be pumped or otherwise drawn by a pump 220 into an input tubing string 220 of side arm, and discharged therefrom by one or more outlet tubing strings 232. Injector ports 240 spaced evenly along pipe (only one shown for clarity) are functional to add gases, such as carbon dioxide, to be dissolved at points, ensuring maximal dissolution into the passing medium. Pumping speeds through the pipe would be controlled by a controller 250 operatively coupled to one or more gas monitors or sensors 252 along the pipe which would feedback dissolved gas levels in medium so to control pipe volume velocities and amounts of gas injected into system to desired set point concentrations. An operational parameter such as a speed parameter of the pump 220 is responsive to a signal 254 from the controller 250 to regulate a rate of the fluid flow therethrough and a gas valve 260 is responsive to a signal 256 from the controller 250 to regulate a rate of the flow of CO₂ to be injected into the flow of algal growth medium of the subject side arm contactor system 200. The output port 232 would release medium enriched with gases back into open pond systems.

[0034] In accordance with the example embodiment, a system 200 for introducing a chemical into a fluid comprises an inlet tubing string 230 configured to receive the fluid from an associated source 202, an outlet tubing string 232 configured to return the fluid to the associated source 202, a fluid pump 220 operable to motivate a flow of the fluid from the inlet tubing string 230 to the outlet tubing string 232, a chemical conduit member 242 configured to receive the chemical from an associated source, and at least one injection port

240 operatively coupled with the chemical conduit member 242 and disposed in at least one of the inlet tubing string 230, the outlet tubing string 232, or the fluid pump 220 for introducing the chemical into the fluid.

[0035] More particularly, in the example embodiment, the inlet tubing string 230 is configured to receive a slurry comprising algae suspended in a fluid algal growth medium from the associated source 202. In addition, the outlet tubing string 232 is configured to return the slurry to the associated source 202. Further, the fluid pump 220 is operable to motivate a flow of the slurry from the inlet tubing string 230 to the outlet tubing string 232. Still further, the chemical conduit member 242 is configured to receive CO₂ from an associated source, and the at least one injection port 240 is configured to selectively introduce the CO₂ into the slurry.

[0036] It is to be appreciated that the one or more sensor(s) 252 are configured to generate a signal 258 in accordance with a level/concentration of the CO₂ dissolved in the slurry of the system 200. It is to be further appreciated that the controller 250 comprises a memory and a processor and is configured to execute one or more predetermined control rules to adjust an operational parameter of the fluid pump 220 to control a rate of the flow of the slurry in accordance with the signal 258.

[0037] It is to be further appreciated that the valve 260 disposed at the chemical conduit member 242 between the associated source and the at least one injector port 240 is operable to regulate a flow of the CO₂ introduced into the slurry by the injection port 240. More particularly, the valve 260 is responsive to a second signal 256 from the controller to regulate the flow of the CO₂ introduced into the slurry in accordance with the predetermined control rules.

[0038] One of the primary benefits of the systems of the example embodiments is that they require much less head pressure to operate, reducing pumping costs as compared to deep sump based systems. Furthermore, the cost of construction materials is less than other sparging systems because above-ground piping does not need to be rigid and could be made of thinner plastics. Similarly, maintenance costs are lower for this system than for traditional systems because its above-ground configuration makes it easier to repair/replace, detect leaks, clean and install.

[0039] Figure 4 is an illustration of an algae pond system demonstrating a carbon cycle 400 occurring during algae growth. In a first step 402, media mass transfer occurs. Thereafter, carbon uptake 404 into the algae occurs. Respiration occurs at step 406 followed by outgassing at 408.

[0040] Figure 5 presents graphical illustrations of results of algae growth using diffused carbon dioxide and demonstrating carbon dioxide utilization and algae growth in accordance with the example embodiments. More particularly, the results were obtained using a system such as the one described above in connection with Figures 2 and 3 with an algae pond having characteristics of pond dimensions of 10 m x 10 m, pond depth of 15 – 20 cm, a pond temperature of about 28 degrees C, a growth medium pH of about 6.8 – 7.2, using an algae organism strain of *Chlorella*. The characteristics of the system 200 for obtaining the results of Figure 5 included centrifugal pump 220, a sidearm fluid/slurry flowrate of about 3 gpm, a sidearm tube 230, 232 size of about 1 inch diameter, a gas/liquid contactor being of a stainless steel sparger variety having a 1" diameter, 6" long, a system pressure of about 5 psig, a contacting length of about 50 ft, and a carbon dioxide dosage of about 0 – 1000 mg./L during the run in the elongate sparger. In addition, the CO₂ enriched culture was fed back to the pond in the center out of three locations 210, 212, 214 distributed equally along the pond 202.

[0041] As can be seen from the time series graphs 502, 504, 506, and 508 of Figure 5, the amount of CO₂ utilization 510, 512, 514, and 516 increased substantially, while the areal productivity 520, 522, 524, and 526 and average dissolved CO₂ level 530, 532, 534, and 536 in the pond remained substantially constant over the five (5) day period of experimental results.

[0042] Referring to Figure 6, there is illustrated a diagram of a smaller scale prototype side arm sparging system used to introduce gas into a tank or bioreactor. As shown in Figure 6, tap water introduced through tap water inlet 602 and is pumped or otherwise drawn by a pump 604 into the sparger device 606. Pumping speeds of the tap water into the sparger device are controlled by fluid flow meter 604 so as to control the water volume velocity. CO₂ is introduced into the sparger device through CO₂ inlet 608. The amount of CO₂ introduced into the sparger device is controlled by gas flow meter 610 to a desired set point concentration. The CO₂ is introduced into the sparger device with the tap water to form a

solution comprised of at least partially dissolved CO₂ and tap water. The solution is output from the sparger device through a reaction tube 612 to a tank 616. The reaction tube may suitably include static mixers at spaced intervals along the tube for further mixing of the CO₂ and tap water. The reaction tube has a diameter of 0.5 inches. A pressure gauge 614 is at the opposite end of the reaction tube from the sparger device to measure the pressure at the end of the reaction tube. Any undissolved CO₂ is released from the tank via a suitable gas outlet shown at 618. A gas flow meter 620 measures the amount of undissolved CO₂ to measure the efficiency of the sparger device. The solution of tap water and dissolved CO₂ is output from the tank via a suitable outlet as shown at 622.

[0043] Various tests were performed with the smaller scale prototype side arm sparger system, using different parameters. Tests were run with reaction tubes having a length of 70ft, 50 ft, and 30 ft, with CO₂ being fed into the sparger at concentrations of 300 ppm, 500 ppm, and 700 ppm, with CO₂ being fed into the sparger at 0 psig and 5 psig, and with static mixers placed at varying intervals in the reaction tube.

[0044] The results of the tests using the smaller scale prototype side arm sparger device are shown in Figures 7 and 8. Figure 7 illustrates the efficiency of the system with various reaction tube lengths, concentrations of CO₂, and pressures, as shown by the cost per gallon for each test. Figure 8 illustrates the efficiency of the system with various reaction tube lengths, concentrations of CO₂, and pressures, as shown by the percentage of CO₂ dissolved in the tap water in the tank.

Enhancement of Gas Content in Liquid Stream through pH Control

[0045] The subject application enhances the concentration of carbon dioxide in the algal growth medium by controlling the medium's pH. As the pH increases, so does the amount of carbon dioxide saturated in the medium. The pH can be increased in the present invention through buffer solutions which may contain ammonia, citrates and bicarbonates. Common bicarbonates that may be used include, for example and without limitation, sodium and potassium bicarbonate.

Evaporation and Temperature Control through Heat Conductive Piping

[0046] A further modification of the present application is in its use of thin heat conductive piping to control evaporation and temperature. The piping, which should be materially compatible with algae, and other organisms capable of heterotrophic growth, could employ a simple evaporative cooling process on sun exposed surfaces. Other modifications could include an external pipe with radiator fins attached perpendicularly to pipe. When sprayed with water, the evaporative cooling of pipe and the internal medium would minimize unwanted heating of pond material during passage. Carbon dioxide dissolves in solution more readily at lower temperatures, creating an additional benefit for this aspect of the application.

EXAMPLES**Example 1**

[0047] In the system illustrated in Figure 1, the pH of the water or aqueous growth medium is increased to a higher than optimum pH for the organism. For example, if *Chlorella vulgaris* is used, a pH of 8.0 could be achieved. This water or growth medium is fed into the contactor and reacted with carbon dioxide enriched gaseous phase. A commercially available contactor, such as the Liqui-Cel Extra-Flow and the Liqui-Cel Industrial units, may be suitably used. The larger Liqui-Cell Industrial unit can handle up to 400 gallons a minute and introduce into the water a staggering 90 cubic meters of carbon dioxide. An equivalent amount of water using a carbon dioxide sparger would take over 5 times the amount of gas given most would rapidly float to the surface and be released to the atmosphere.

The contactor provides optimal transfer to the liquid phase and higher pH increases the ability of the aqueous medium to hold the carbon dioxide. The water or medium is introduced to the pond at multiple points and mixed with the existing growth medium in the ponds that are low in carbon dioxide. Such mixing minimizes the offgassing of carbon dioxide and introduction at multiple points stabilizes the concentration within the pond.

Example 2

[0048] Figures 2 and 3 illustrate an example of a carbon management system implementing a sidearm contactor of the instant invention. A sidearm pump/tube is used to dissolve high concentrations of carbon dioxide in the culture. The culture is pumped from the pond with a low head axial flow pump. At the inlet or outlet of the pump a sparger introduces gas which flows co-currently with the medium for about 10 - 100 ft. or beyond. Low pressure drop static mixers could be used to maintain small bubble size. The solution would be distributed back to the pond in strategic locations to ensure enough carbon dioxide is available to the algae for rapid growth. Based on empirically derived mass transfer coefficients and gas/liquid equilibrium, it is estimated that this system could achieve greater than 90% mass transfer efficiency and deliver a concentrated solution of > 500 ppm carbon dioxide to the pond. This concentration is roughly 50 times higher than the operating setpoint for dissolved carbon dioxide in the pond (10 ppm) which reduces the need for pumping. The system could be cleaned by pumping a bleach solution through it. Other methods of introduction of gaseous carbon dioxide, including for example and without limitation, the volume-controlled forced vortex by Enevor (<http://homepage.mac.com/mrbach/>), could be located in the side arms to enhance dissolution of the gases into the medium.

CLAIMS

What is claimed is:

1. An integrated system of increasing and maintaining the amount of carbon dioxide in a liquid medium comprising:
 - a conduit member operatively coupled with an associated source of carbon dioxide;
 - a vessel containing a liquid medium; and
 - a contactor operatively coupled with the conduit member and the vessel, the contactor being configured to bring the carbon dioxide into contact with the liquid medium.
2. The system of claim 1 wherein:
 - the vessel contains water and the contactor is configured to bring the carbon dioxide into contact with the water; and,
 - the conduit member is operatively coupled with an associated source of carbon dioxide selectively comprising an industrial point source.
3. The system of claim 2 wherein the conduit member is operatively coupled with an associated industrial point source of carbon dioxide comprising a coal, fossil fuel, or biofuel fired power plant, refinery, or other manufacturing facility.
4. The system of claim 2 wherein the conduit member is operatively coupled with an associated source of carbon dioxide gas, and the system further comprising:
 - a scrubber or equivalent device operatively coupled with the conduit member or the contactor for removing particulates from the carbon dioxide gas.
5. The system of claim 1, wherein the contactor comprises:
 - an elongate sidearm flow device configured to introduce the carbon dioxide into the liquid medium along a length of the contactor.
6. The system of claim 5 wherein the elongate sidearm flow device has a length of about between 20 and 100 feet.

7. The system of claim 1 comprising one or more static mixers in the contactor configured to break or reduce the size of carbon dioxide bubbles formed by the carbon dioxide in the contactor.
8. The system of claim 1 further comprising a pressure control valve configured to control a pressure of the carbon dioxide from the associated source for dissolving the carbon dioxide using a backpressure of about between around 0 and 30 psig.
9. The system of claim 1 further comprising a temperature controller configured to selectively cool the liquid medium to less than 10°C to enhance carbon dioxide saturation.
10. The system of any of claims 1-9 wherein further comprising heat conductive piping configured to selectively cool the liquid medium.
11. The system of claim 1 further comprising one or more mixing blades, wherein the fluid ejected from the contactor, saturated with the carbon dioxide is introduced into the liquid medium by pumping the liquid medium through edges of the one or more mixing blades to greatly reduce drag and electrical power requirements for the mixing.
12. The system of claim 1 wherein the liquid medium contains algae, protists, or bacteria that can be grown in a combination of heterotrophic and phototrophic conditions.
13. The system of claim 12 wherein the algae, protists, or bacteria organisms can be sequentially grown in phototrophic or mixotrophic then heterotrophic conditions.
14. The system of claims 12 wherein a pH of the liquid medium is between 6 and 9 to increase the amount of the carbon dioxide in the liquid medium.
15. The system of claim 12 wherein the vessel is configured to enhance a concentration of the carbon dioxide in the liquid medium by:
 - growing the algae, protists, or bacteria in a combination of heterotrophic and phototrophic conditions; and

feeding the algae, protists, or bacteria fixed carbon having a concentration per liter sufficient to prevent catabolism within the organism.

16. The system of claim 12 wherein the carbon dioxide comprises fixed carbon, the fixed carbon being one or a combination of: short-chained alcohols, acetic acid, acetate, formic acid, glucose, xylose, arabinose, mannose, maltose, maltodextrins, fructose, triose, cellulose, complex polysaccharides, lignocellulosic C5 and C6 sugars or hydrolysates, and an acid or enzyme hydrolysis of an agricultural crop or forest biomass.

17. The system of claim 12 wherein conduit is configured to deliver a gas fed to the contactor for contact with the liquid medium, the gas having enhanced concentrations of oxygen selectively obtained from an air plant.

18. The system of claim 12 further comprising one or more tubing strings wherein the liquid medium exiting the contactor is introduced back into the bioreactor, pond, or raceway through the use of sumps made below grade to allow for greater absorption of the carbon dioxide as they agglomerate into bubbles from homogenous gas saturated fluids.

19. The system of claim 12 wherein an amount of fixed carbon introduced to the system is such that it is mostly consumed before sunrise.

20. The system of claim 12 wherein the carbon dioxide fed into the liquid medium is carbon dioxide gas fed into the liquid medium having enhanced concentrations of oxygen selectively obtained from an air plant.

21. The system of claim 1 further comprising one or more tubing strings including porous tubes, wherein fluid exiting from the contactor is subsequently pumped through the porous tubes on a bottom of the bioreactor, pond, or raceway to further delay coalescence into bubbles or carbon dioxide.

22. The system of claim 1 further comprising spargers or porous polymeric tubes, wherein fluid exiting from the contactor is introduced into the bioreactor, pond, or raceway using either the spargers, the porous polymeric tubes or a combination of the spargers and the

porous polymeric tubes to reduce an electrical power load required for air saturation in the medium.

23. A system for introducing a chemical into a fluid, the system comprising:
an inlet tubing string configured to receive the fluid from an associated source;
an outlet tubing string configured to return the fluid to the associated source;
a fluid pump operable to motivate a flow of the fluid from the inlet tubing string to the outlet tubing string;
a chemical conduit member configured to receive the chemical from an associated source; and,
at least one injection port operatively coupled with the chemical conduit member and disposed in at least one of the inlet tubing string, the outlet tubing string, or the fluid pump for introducing the chemical into the fluid.
24. The system according to claim 23, wherein:
the inlet tubing string is configured to receive a slurry comprising algae suspended in a fluid algal growth medium from the associated source;
the outlet tubing string is configured to return the slurry to the associated source;
the fluid pump is operable to motivate a flow of the slurry from the inlet tubing string to the outlet tubing string;
the chemical conduit member is configured to receive CO₂ from an associated source;
and,
the at least one injection port is configured to selectively introduce the CO₂ into the slurry.
25. The system according to claim 24, further comprising:
a sensor configured to generate a signal in accordance with a level/concentration of the CO₂ dissolved in the slurry; and,
a controller configured to execute predetermined control rules to adjust an operational parameter of the fluid pump to control a rate of the flow of the slurry in accordance with the signal.
26. The system according to claim 25, further comprising:

a valve disposed at the chemical conduit member between the associated source and the at least one injector port, the valve being operable to regulate a flow of the CO₂ introduced into the slurry by the injection port.

27. The system according to claim 26, wherein the valve is responsive to a second signal from the controller to regulate the flow of the CO₂ introduced into the slurry in accordance with the predetermined control rules.

28. A method of introducing a chemical into a fluid, the method comprising:
receiving the fluid from an associated source by an inlet tubing string;
returning the fluid to the associated source by an outlet tubing string;
motivating a flow of the fluid from the inlet tubing string to the outlet tubing string by a fluid pump;
receiving the chemical from an associated source by a chemical conduit member; and,
introducing the chemical into the fluid by at least one injection port operatively coupled with the chemical conduit member and disposed in at least one of the inlet tubing string, the outlet tubing string, or the fluid pump.

29. The method according to claim 28, wherein:
the receiving the fluid comprises receiving a slurry comprising algae suspended in a fluid algal growth medium from the associated source;
the returning the fluid comprises returning the slurry to the associated source;
the motivating the flow comprises motivating a flow of the slurry from the inlet tubing string to the outlet tubing string;
the receiving the chemical comprises receiving CO₂ from an associated source; and,
the introducing the chemical comprises selectively introducing the CO₂ into the slurry.

30. The method according to claim 29, further comprising:
generating by a sensor a signal in accordance with a level/concentration of the CO₂ dissolved in the slurry; and,

executing by a controller predetermined control rules to adjust an operational parameter of the fluid pump to control a rate of the flow of the slurry in accordance with the signal.

31. The method according to claim 30, further comprising:
operating a valve disposed at the chemical conduit member between the associated source and the at least one injector port to thereby regulate a flow of the CO₂ introduced into the slurry by the injection port.
32. The method according to claim 31, wherein operating the valve comprises operating the valve in response to a second signal from the controller to thereby regulate the flow of the CO₂ introduced into the slurry in accordance with the predetermined control rules.
33. A system for introducing a chemical into a fluid, the system comprising:
an inlet tubing string configured to receive the fluid from an associated source;
an outlet tubing string configured to return the fluid to the associated source;
a fluid pump operable to motivate a flow of the fluid from the inlet tubing string to the outlet tubing string;
a chemical conduit member configured to receive the chemical from an associated source; and,
at least one membrane contactor operatively coupled with the chemical conduit member and disposed in at least one of the inlet tubing string, the outlet tubing string, or the fluid pump for bringing the chemical into operative contact with the fluid via the membrane.
34. The system according to claim 33, wherein:
the inlet tubing string is configured to receive a slurry comprising algae suspended in a fluid algal growth medium from the associated source;
the outlet tubing string is configured to return the slurry to the associated source;
the fluid pump is operable to motivate a flow of the slurry from the inlet tubing string to the outlet tubing string;
the chemical conduit member is configured to receive CO₂ from an associated source;
and,

the at least one contactor is configured to selectively bring the CO₂ into operative contact with the slurry via the membrane.

35. The system according to claim 34, further comprising:
a sensor configured to generate a signal in accordance with a level/concentration of the CO₂ dissolved in the slurry; and,
a controller configured to execute predetermined control rules to adjust an operational parameter of the fluid pump to control a rate of the flow of the slurry in accordance with the signal.
36. The system according to claim 35, further comprising:
a valve disposed at the chemical conduit member between the associated source and the at least one injector port, the valve being operable to regulate a flow of the CO₂ introduced into contact with the slurry by the contactor.
37. The system according to claim 36, wherein the valve is responsive to a second signal from the controller to regulate the flow of the CO₂ introduced into contact with the slurry by the contactor in accordance with the predetermined control rules.
38. A method of introducing a chemical into a fluid, the method comprising:
receiving the fluid from an associated source by an inlet tubing string;
returning the fluid to the associated source by an outlet tubing string;
motivating a flow of the fluid from the inlet tubing string to the outlet tubing string by a fluid pump;
receiving the chemical from an associated source by a chemical conduit member; and,
introducing the chemical into the fluid by at least one contactor operatively coupled with the chemical conduit member and disposed in at least one of the inlet tubing string, the outlet tubing string, or the fluid pump.
39. The method according to claim 38, wherein:
the receiving fluid comprises receiving a slurry comprising algae suspended in a fluid algal growth medium from the associated source;
the returning fluid comprises returning the slurry to the associated source;

the motivating flow comprises motivating a flow of the slurry from the inlet tubing string to the outlet tubing string;

the receiving chemical comprises receiving CO₂ from an associated source; and,

the introducing chemical comprises selectively introducing the CO₂ into operative contact with the slurry by the contactor.

40. The method according to claim 39, further comprising:

generating by a sensor a signal in accordance with a level/concentration of the CO₂ dissolved in the slurry; and,

executing by a controller predetermined control rules to adjust an operational parameter of the fluid pump to control a rate of the flow of the slurry in accordance with the signal.

41. The method according to claim 40, further comprising:

operating a valve disposed at the chemical conduit member between the associated source and the at least one contactor to thereby regulate a flow of the CO₂ introduced into operative contact with the slurry by the contactor.

42. The method according to claim 41, wherein operating the valve comprises operating the valve in response to a second signal from the controller to thereby regulate the flow of the CO₂ introduced into operative contact with the slurry by the contactor in accordance with the predetermined control rules.

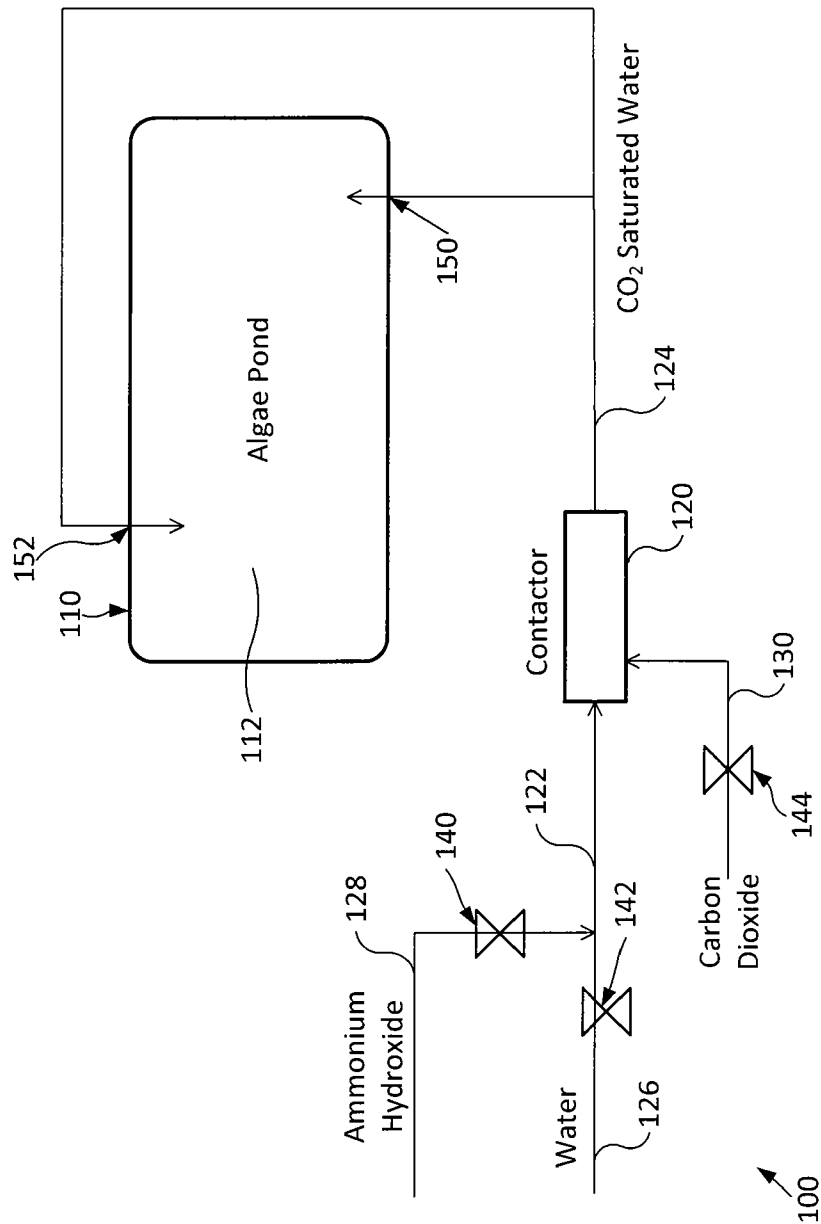


FIG. 1

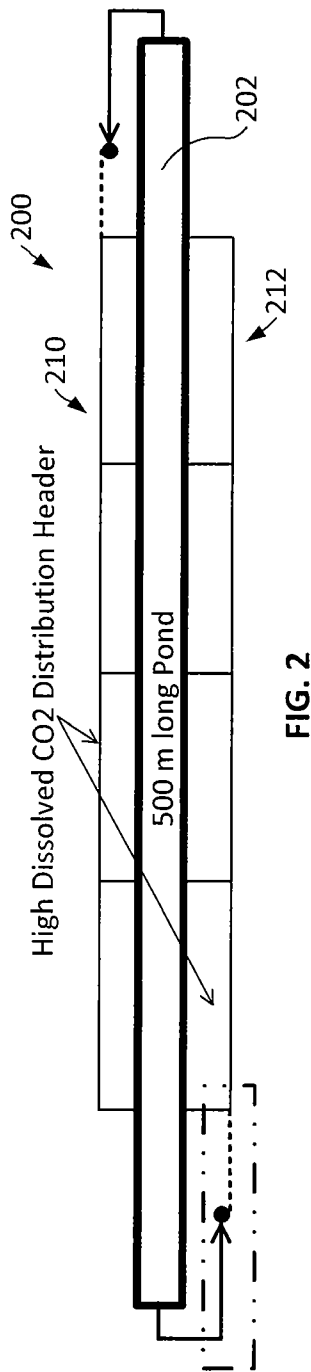
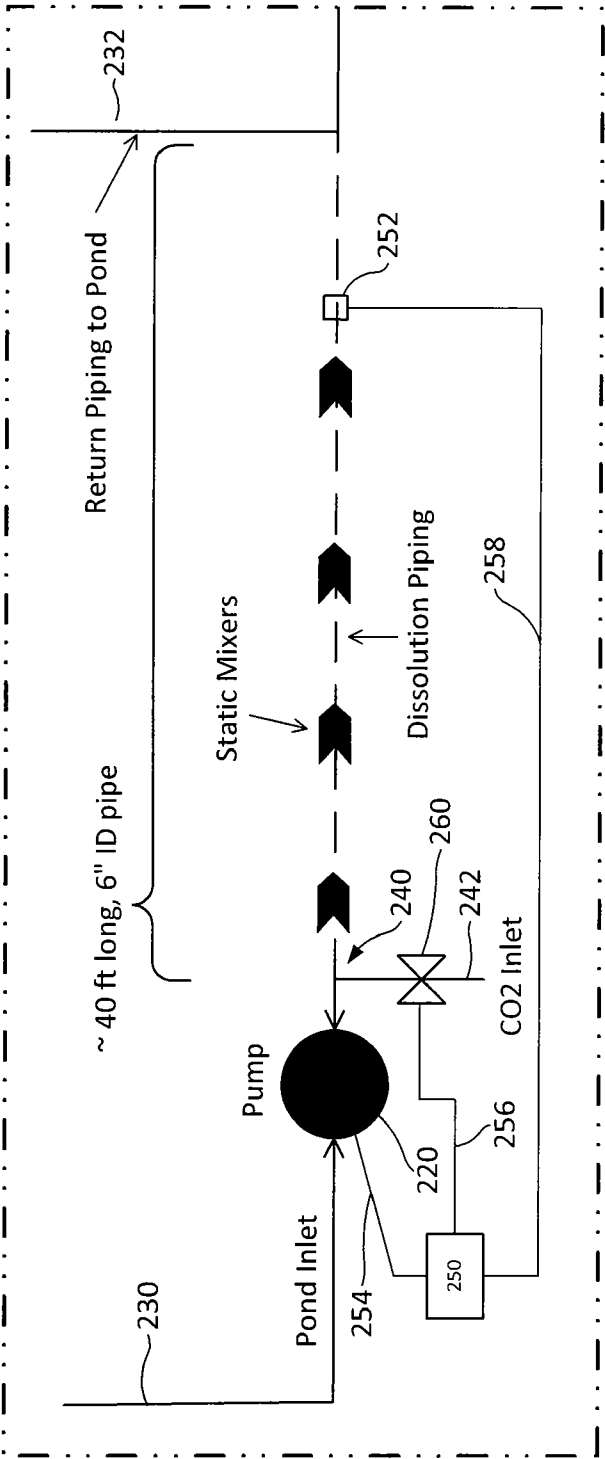


FIG. 2



Zoom view of Pond Dissolution System

FIG. 3

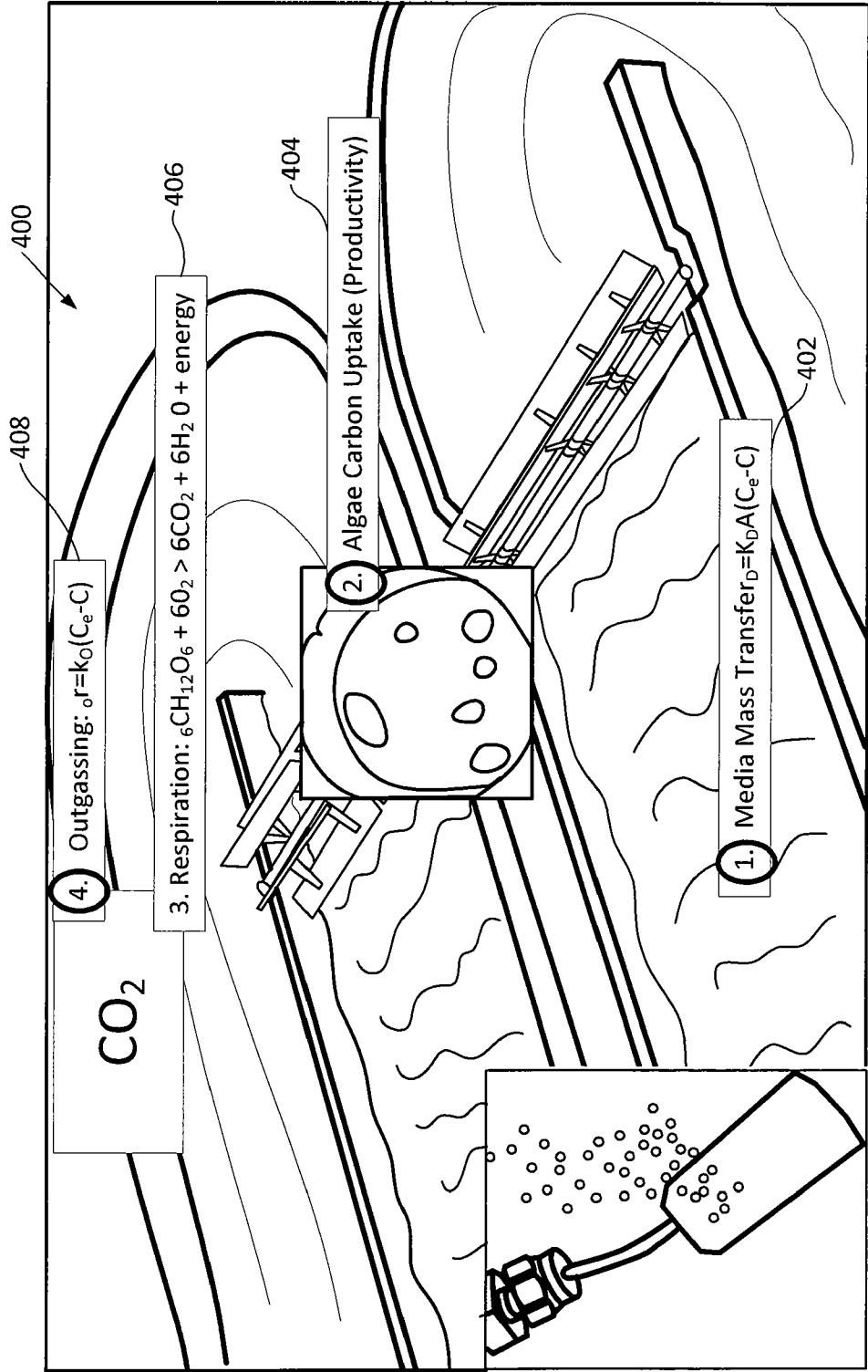


FIG. 4

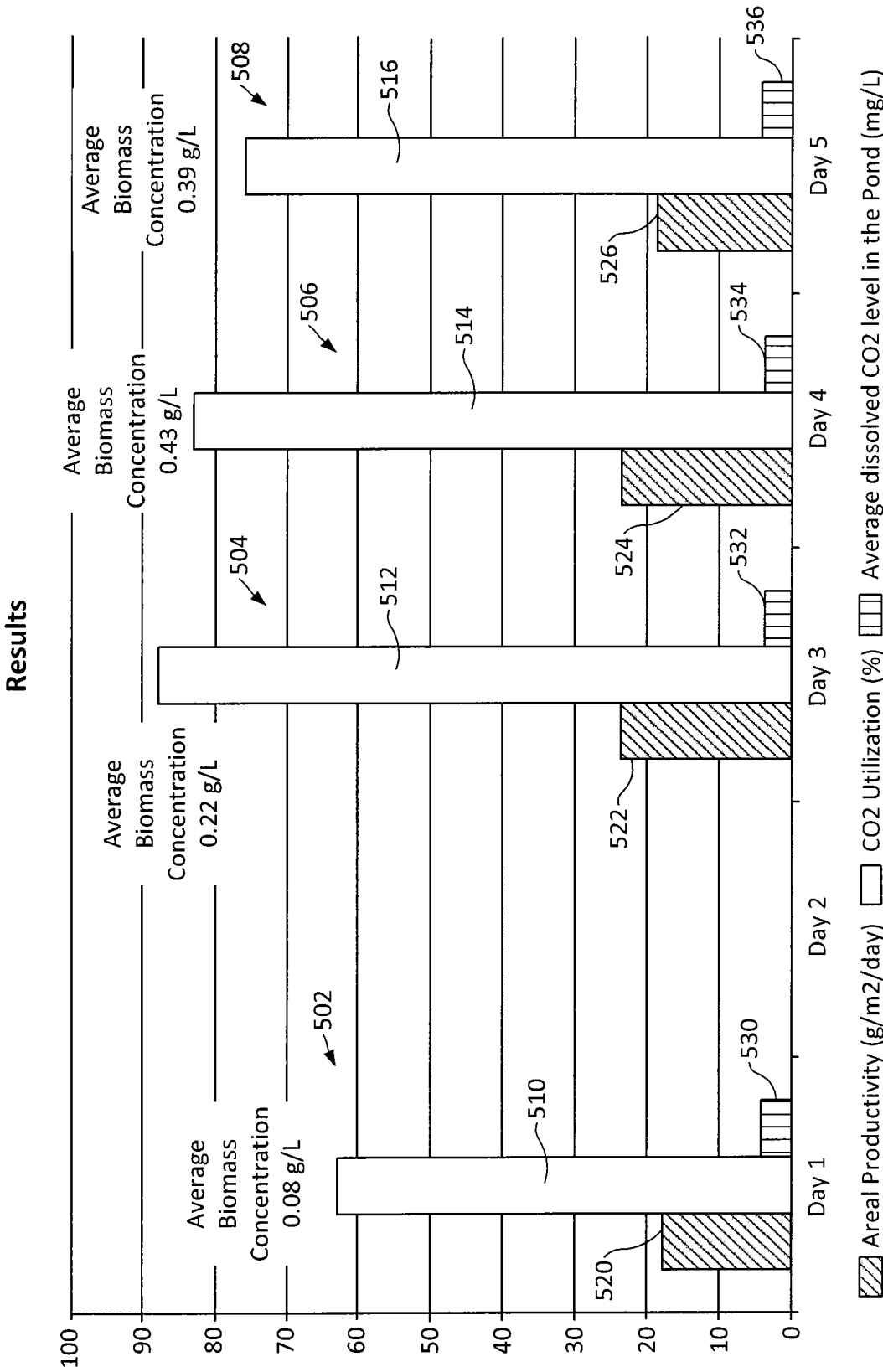


FIG. 5

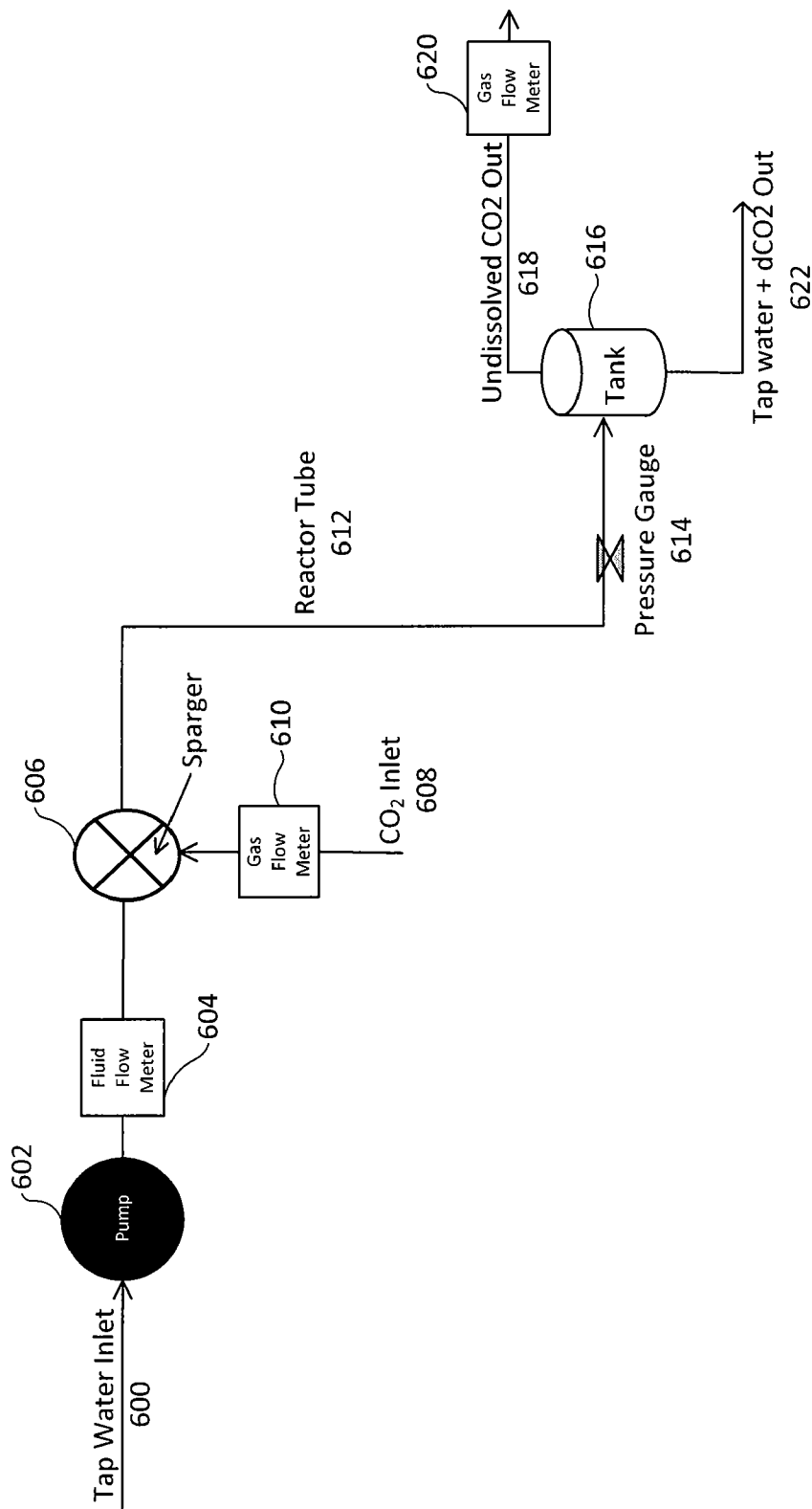


FIG. 6

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Side-arm/Sparger Operation		
Efficiency, Fed CO ₂ , Pressure	Pipe Length [feet]	Cost (\$/gal)
90 %, 500 mg/L, Opsig	77	\$0.040
90 %, 500 mg/L, 3psig	58	\$0.038
90 %, 500 mg/L, 5psig	50	\$0.039
90 %, 500 mg/L, 10psig	37	\$0.045
90 %, 750 mg/L, 0psig	96	\$0.015
90 %, 750 mg/L, 3psig	64	\$0.015
90 %, 750 mg/L, 5psig	53	\$0.017
90 %, 750 mg/L, 10psig	37	\$0.023
90 %, 1000 mg/L, 5psig	65	\$0.012
90 %, 1000 mg/L, 10psig	41	\$0.016
*All costs include static mixers every 10 ft		

FIG. 7

Side-arm / Sparger Device
Experiments Results

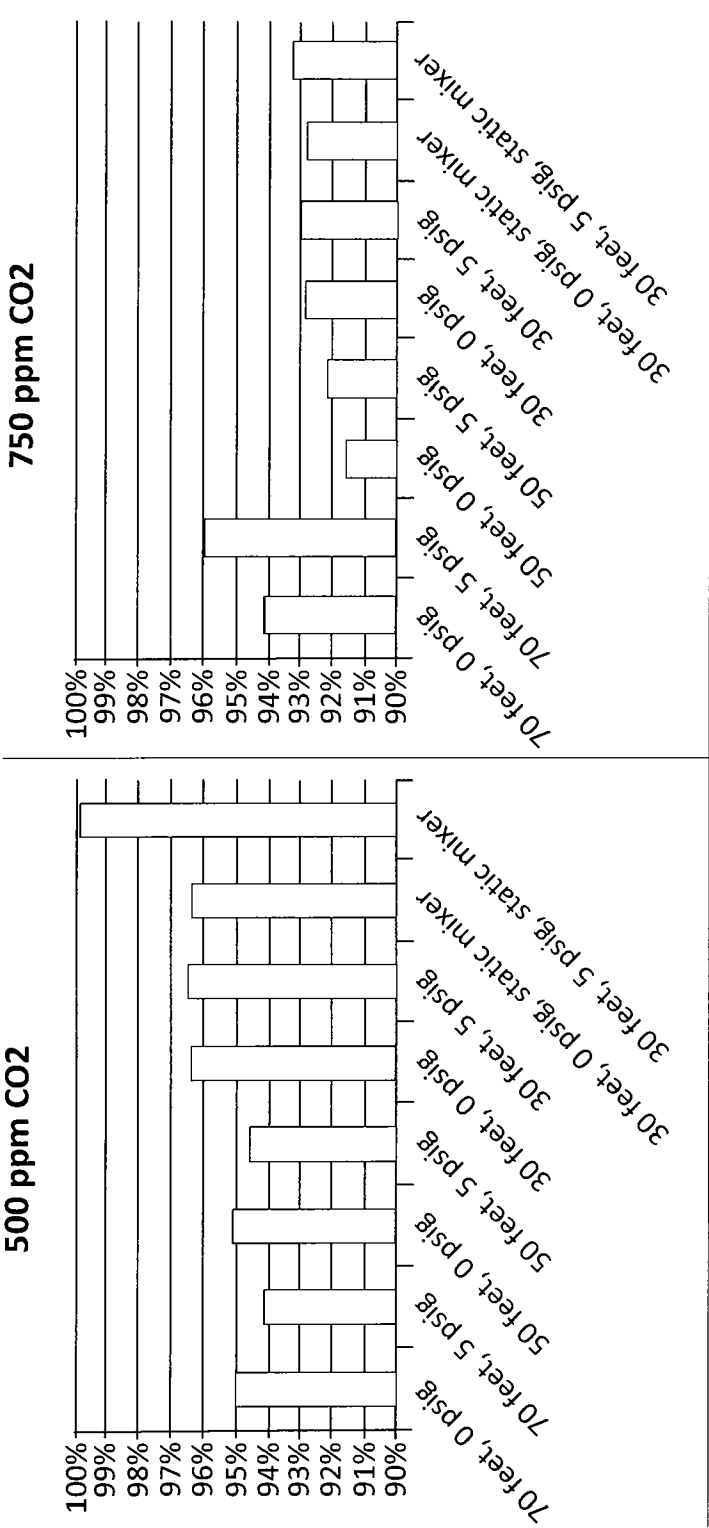


FIG. 8