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(54) **ELECTRODIALYTIC SEPARATION OF CO_2 GAS FROM SEAWATER**

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C02F 103/08	(2006.01)

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CPC ***B01D 61/445*** (2013.01); ***C02F 1/4693*** (2013.01); *B01D 2311/18* (2013.01); *B01D 2311/2626* (2013.01); *B01D 2311/2653* (2013.01); *C02F 2103/08* (2013.01); *C02F 2201/4618* (2013.01); *Y02C 10/04* (2013.01); *Y02C 10/06* (2013.01)

(58) **Field of Classification Search**
USPC 204/529, 531, 534, 537
See application file for complete search history.

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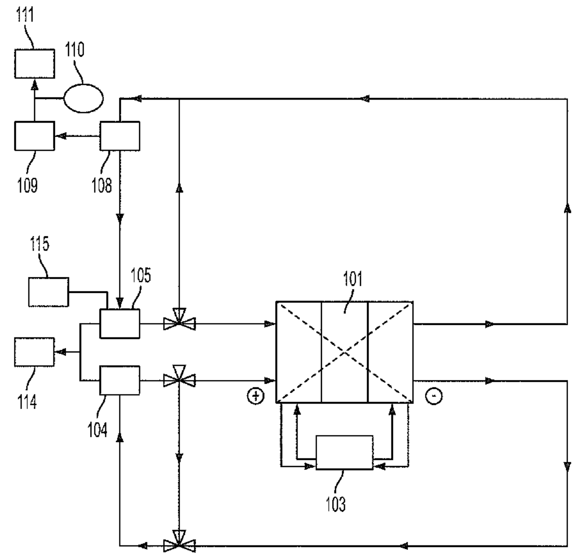
(57) **ABSTRACT**

A method comprises flowing process solution and electrode solution into a BPMED apparatus, applying a voltage such that the process solution is acidified and basified and dissolved CO_2 is generated, flowing the process solution out of the apparatus, and desorbing CO_2 out of the process solution. A method for desorbing CO_2 from an ocean comprises flowing seawater and electrode solution into a BPMED apparatus, applying a voltage such that dissolved CO_2 is generated, flowing the seawater out of the apparatus, and desorbing CO_2 out of the seawater. A method for producing a desalted solution and CO_2 gas comprises flowing process solution and electrode solution into a BPMED apparatus that includes one or more three-compartment cells, applying a voltage such that the process solution is acidified, basified, and desalted, flowing the process solution out of the apparatus, and desorbing CO_2 out of the process solution.

14 Claims, 9 Drawing Sheets



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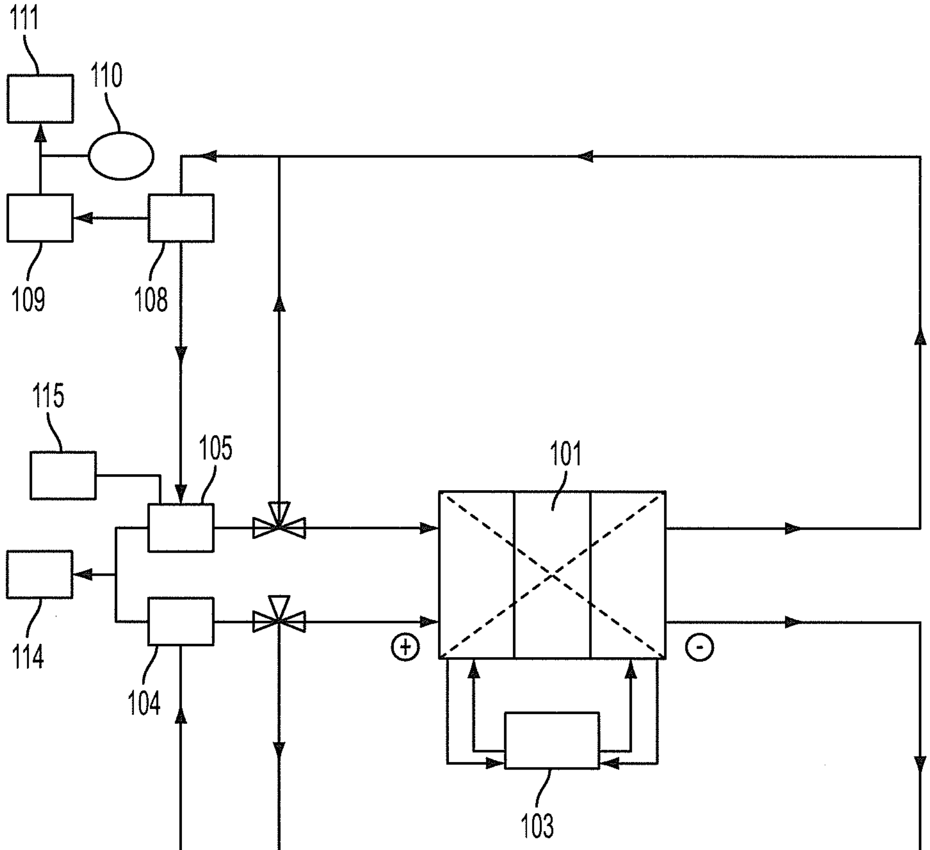


FIG. 1

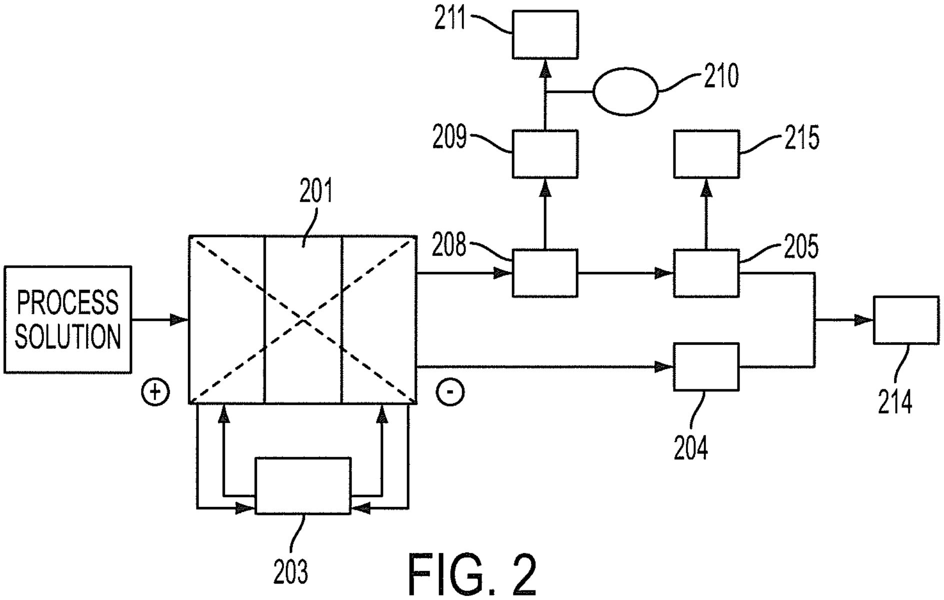
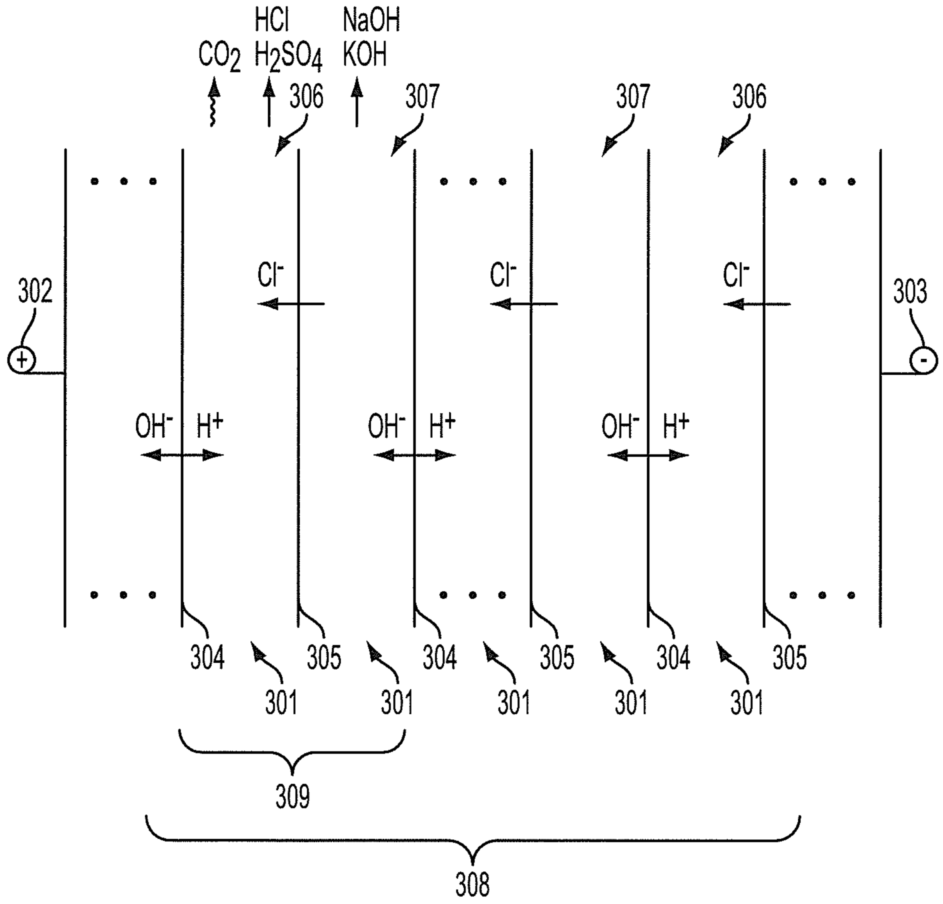


FIG. 2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HCl
H_2SO_4
NaOH
KOH
306
307
307
306
302
303
Cl^-
Cl^-
Cl^-
OH^-
H^+
OH^-
H^+
OH^-
H^+
+
-
304
305
304
305
304
305
301
301
301
301
301
309
308

FIG. 3

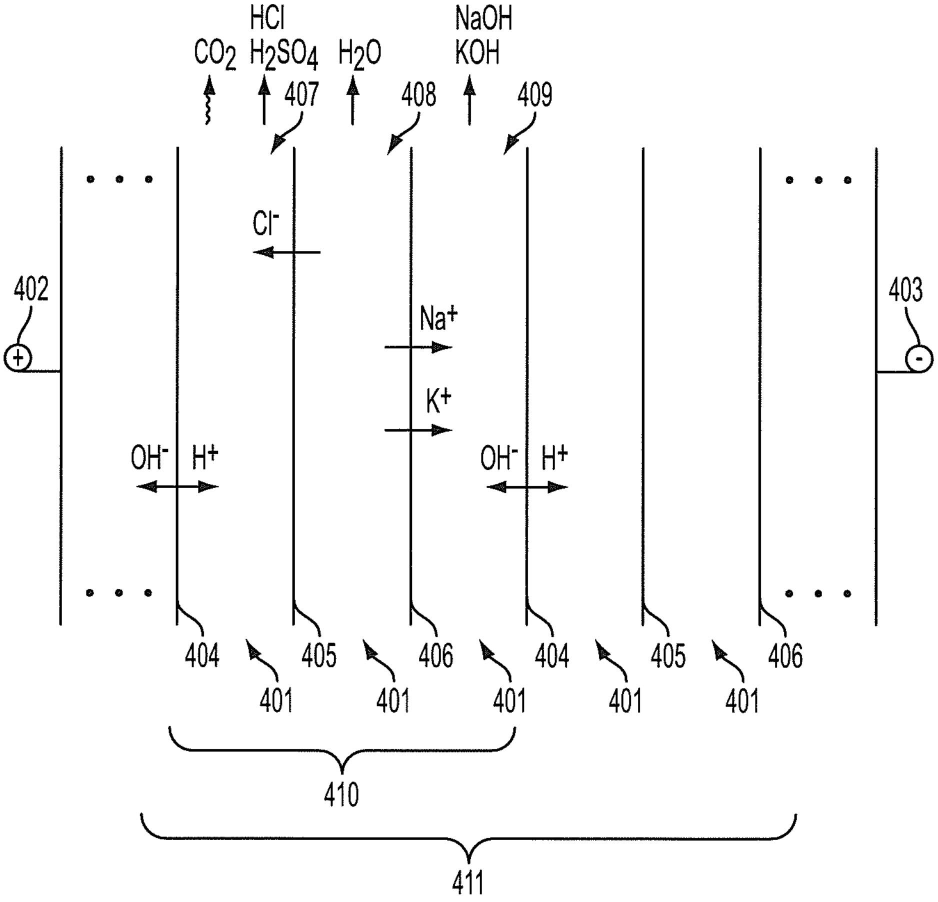
CO_2
HCl
H_2SO_4
H_2O
NaOH
KOH
407
408
409
Cl^-
402
403
Na^+
K^+
OH^-
H^+
OH^-
H^+
404
405
406
404
405
406
401
401
401
401
401
410
411

FIG. 4

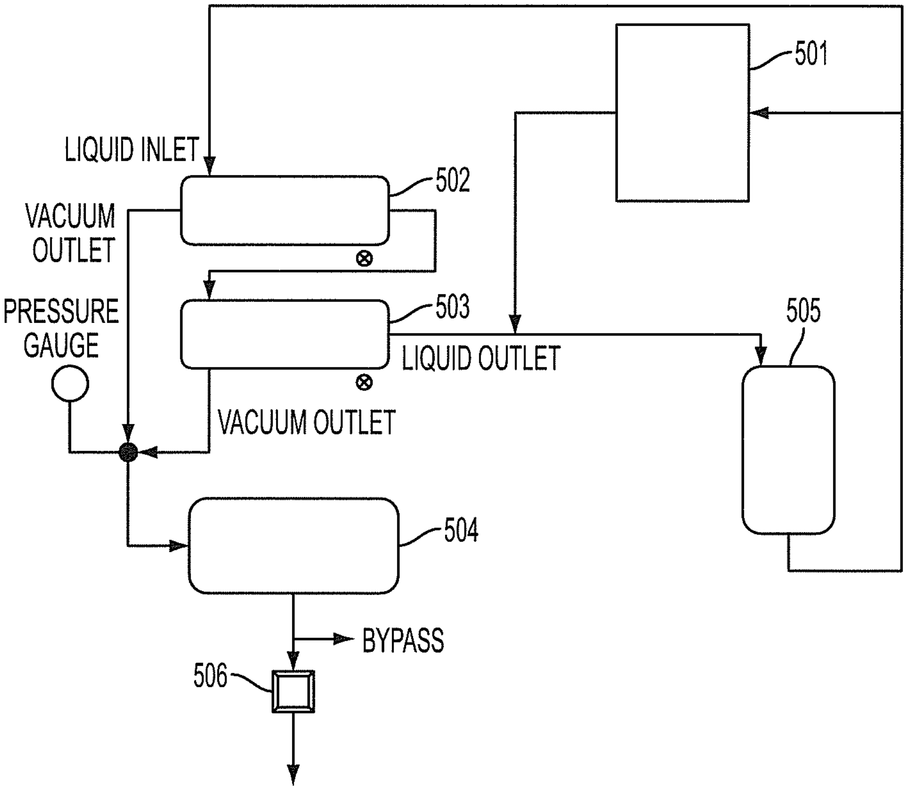
501
LIQUID INLET
502
VACUUM OUTLET
503
PRESSURE GAUGE
505
LIQUID OUTLET
VACUUM OUTLET
504
BYPASS
506

FIG. 5

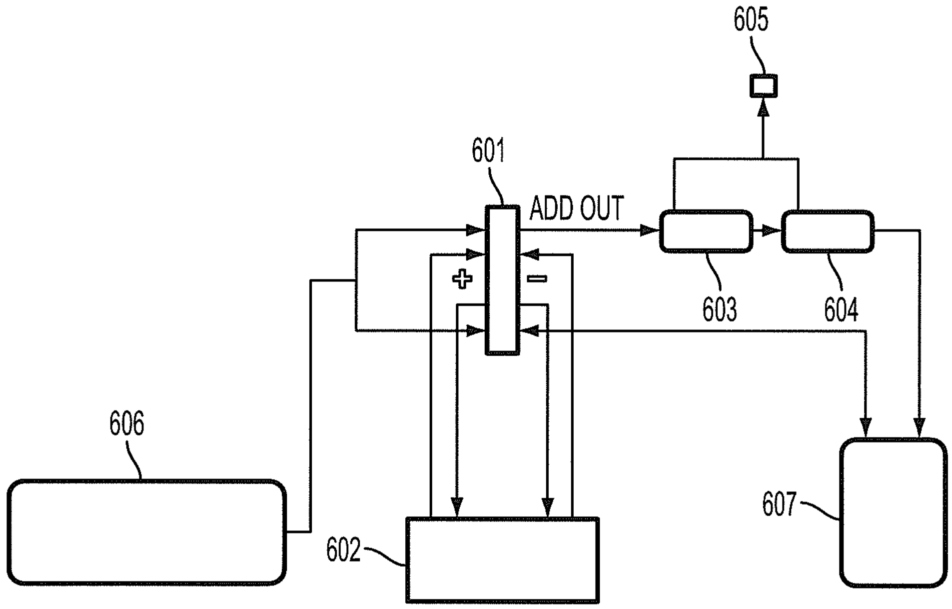

FIG. 6

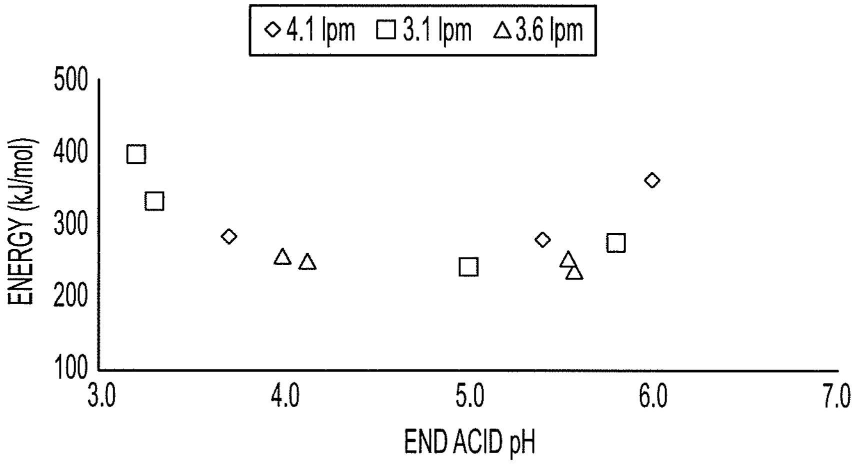
◇ 4.1 lpm
□ 3.1 lpm
△ 3.6 lpm
500
400
300
200
100
ENERGY (kJ/mol)
3.0
4.0
5.0
6.0
7.0
END ACID pH

FIG. 7

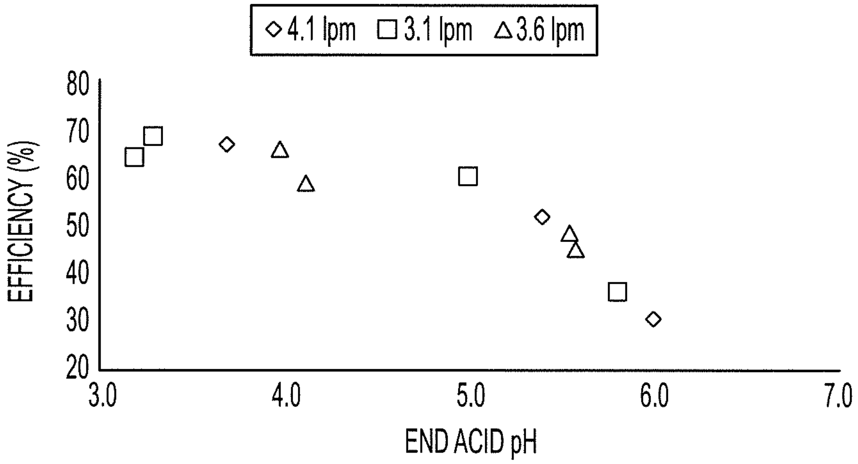
◇ 4.1 lpm
□ 3.1 lpm
△ 3.6 lpm
EFFICIENCY (%)
80
70
60
50
40
30
20
3.0
4.0
5.0
6.0
7.0
END ACID pH

FIG. 8

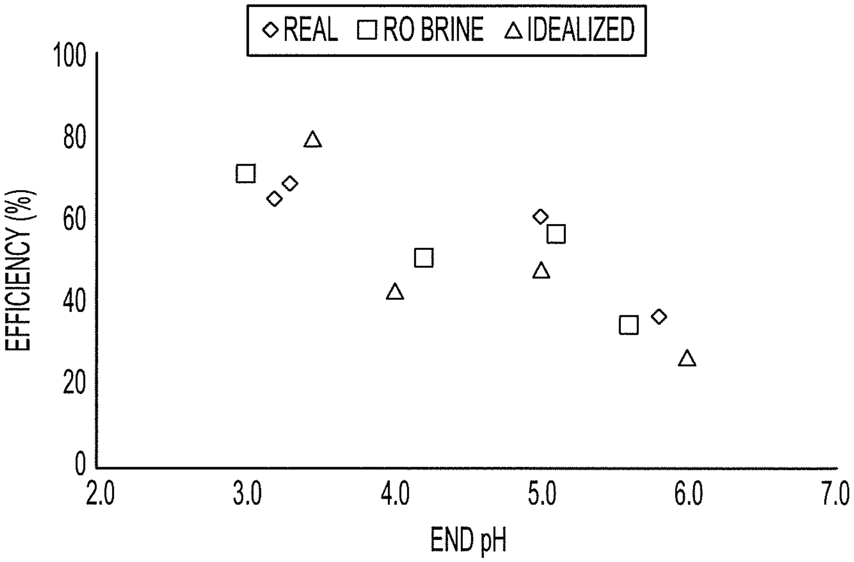
◇ REAL
□ RO BRINE
△ IDEALIZED
100
80
60
40
20
0
EFFICIENCY (%)
2.0
3.0
4.0
5.0
6.0
7.0
END pH

FIG. 9

ELECTRODIALYTIC SEPARATION OF CO_2 GAS FROM SEAWATER

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

This invention was made with Government support under contract HR0011-10-C-0147 awarded by DARPA, an agency of the United States Department of Defense. The Government has certain rights in this invention.

BACKGROUND

The concentration of atmospheric carbon dioxide (CO_2) continues to rise, as shown by, for example, IPCC, *Climate Change* 2007*: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* 2007 [Core Writing Team, Pachauri, R. K and Reisinger, A. (eds.)], IPCC, Geneva, Switzerland, 104 pp. The concentration of atmospheric CO_2 is rising at the rate of approximately 2 parts per million per year (ppm/yr). The concentration of CO_2 in the atmosphere is approximately 385 ppm.

The world's oceans have been absorbing and releasing atmospheric CO_2 for eons. Atmospheric CO_2 dissolves in the oceans' water, reacting with the seawater to form carbonic acid. Carbonic acid in turn releases hydrogen ions (H^+), forming bicarbonate (HCO_3^-) and carbonate (CO_3^{-2}) ions. The pH of seawater, which determines the relative fractions of dissolved CO_2, HCO_3^- and CO_3^{-2}, is typically around 8.3, meaning that most of the dissolved total carbon in seawater is in the form of HCO_3^-, as discussed in, for example, James N. Butler, *Carbon Dioxide Equilibria and Their Applications*, Addison-Wesley Publishing Company, Menlo Park, Calif., 1982. As the atmospheric concentration of CO_2 increases, so too does the oceanic concentration of dissolved CO_2 increase. See, e.g., Holli Riebeek, *The Ocean's Carbon Balance*, NASA Earth Observatory Feature Article, http://earthobservatory.nasa.gov/Features/OceanCarbon/printall.php (last visited Jun. 20, 2011). The volumetric concentration of CO_2 in seawater is comparatively much higher than that in the atmosphere, with approximately 100 times as much CO_2 in one liter of seawater as there is in one liter of air.

Techniques for separating CO_2 from streams of mixed gases, such as separating CO_2 from the atmosphere, typically involve a two-step process of capture and desorption/regeneration. First, the gas is contacted with an aqueous "pre-capture solution" that reacts with the CO_2 gas in the mixed-gas stream, "capturing" the CO_2 into what is then referred to as a "post-capture solution." A stream of pure CO_2 gas can then be desorbed from the CO_2-rich aqueous post-capture solution, while at the same time regenerating the post-capture into a pre-capture solution that can be reused for additional capture cycles.

The pre-capture solution is contained in a "contactor," a structure that contacts the mixed-gas stream from which the CO_2 is to be separated with the pre-capture solution. Various pre-capture solutions exist, including aqueous hydroxide pre-capture solutions such as potassium hydroxide (KOH) or sodium hydroxide (NaOH); aqueous carbonate pre-capture solutions such as potassium carbonate (K_2CO_3) or sodium carbonate (Na_2CO_3); and aqueous bicarbonate pre-capture solutions such as potassium bicarbonate ($KHCO_3$) or sodium bicarbonate ($NaHCO_3$). Other pre-capture solutions are known, for example, monoethanolamine (MEA), which is used in gas-stream scrubbing applications to remove, for example, CO_2 from flue gas. The capture of CO_2 gas into hydroxide/carbonate/bicarbonate pre-capture solutions converts the original pre-capture solution into a more acidic post-capture solution consisting of a mixture of hydroxide (KOH or NaOH), carbonate (K_2CO_3 or Na_2CO_3), and/or potassium bicarbonate ($KHCO_3$) or sodium bicarbonate ($NaHCO_3$) post-capture solutions, as examples.

After CO_2 capture and desorption/regeneration, the post-separation CO_2 can be, for example, geologically sequestered, or incorporated into useful products such as concrete, as shown by Calera, Green Cement for a Blue Planet, http://dev.calera.com/index.ppp/technology/technology_vision/index.html (last visited Jun. 20, 2011); plastics, as shown by G. A. Olah et al., *Beyond Oil and Gas: The Methanol Economy*, Wiley-VCH (2006); or liquid hydrocarbon fuels, as shown by F. S. Zeman & D. W. Keith, Carbon Neutral Hydrocarbons, *Phil. Trans. R. Soc. A,* 366, 3901-3918 (2008), and PARC, Energy Efficiency, http://www.parc.com/work/focus-area/adaptive-energy/ (last visited Jun. 20, 2011).

Generation of liquid hydrocarbon fuel, such as gasoline, diesel, or JP-8, from CO_2 separated from mixed-gas streams may be of particular importance in remote field operations, such as those engaged in by the U.S. military (see, for example, JASON, "Reducing DOD Fossil-Fuel Dependence," JSR-06-135, 2006, p. 30) or the U.S. NSF Antarctic Program (see, for example, J. Swift, et. al., "Report of the Subcommittee on US Antarctic Program Resupply," NSF Office of Polar Programs Advisory Committee, Arlington, Va., 2005). However, due to the large size of contactors needed for traditional CO_2 separation, the remote, on-site generation of liquid hydrocarbon fuel has so far not been realized.

Bipolar membrane electrodialysis (BPMED) can be used to convert aqueous salt solution into acids and bases without the addition of other chemicals. BPMED devices use ion exchange membranes to separate ionic species in solution when a voltage is applied across a stack of membranes. BPMED of aqueous carbonate solutions at pressures above ambient pressure has been shown to efficiently desorb CO_2 gas from post-capture solutions. See U.S. patent application Ser. No. 12/969,465; U.S. patent application Ser. No. 12/269,485. Because of the very low (385 ppm) concentration of CO_2 in the atmosphere, large volumes of air must be processed to capture CO_2 from the atmosphere into aqueous carbonate solution systems. This results in a system that may not be as compact as required for certain applications, such as deployment in remote locations. Because the surface of the ocean essentially serves as a contactor, CO_2 desorption directly from seawater eliminates the need for contactors, resulting in a more compact system for CO_2 separation.

Example embodiments address these and other disadvantages.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic of a BPMED system, operated in "batch" mode, that is used to extract CO_2 from a process solution according to embodiment processes.

FIG. **2** is a schematic of a BPMED system, operated in "once-through" mode, that is used to extract CO_2 from a process solution according to embodiment processes.

FIG. **3** is a schematic of a BPMED membrane stack operation used to generate CO_2 gas from a process solution using a "two-compartment" BPMED stack.

FIG. **4** is a schematic of a BPMED membrane stack operation used to generate CO_2 gas from a process solution using a "three-compartment" BPMED stack.

FIGS. **5** and **6** are schematics of a BPMED system used for experiments testing embodiment processes of separating CO_2 gas from process solutions using electrodialysis.

FIG. **7** is a plot of energy consumption at various acid-solution end-pH values and flow rates for real seawater.

FIG. **8** is a plot of efficiency of CO_2 separation at various acid-solution end-pH values and flow rates for real seawater.

FIG. **9** is a plot of efficiency of CO_2 separation at various acid-solution end-pH values for various process solutions at a flow rate of 3.1 lpm.

DETAILED DESCRIPTION

As discussed above, there is a need to develop remote, on-site generation of liquid hydrocarbon fuels. Efforts have been made to capture and regenerate CO_2 from the atmosphere, which can then be incorporated into a variety of useful products, include liquid hydrocarbon fuels. However, to capture and regenerate CO_2 from the atmosphere, inherently large volumes of air must be processed using large "contactors," resulting in a system that may not be as compact as required for some applications.

These disadvantages can be overcome by example embodiments, which obtain CO_2 directly from a process solution using bipolar membrane electrodialysis (BPMED). The process solution can be a seawater solution, either "idealized" (without divalent cations), or non-idealized (with divalent cations, as found in the ocean); a reverse osmosis (RO) brine solution; or any other solution containing dissolved CO_2 gas or HCO_3^- or CO_3^{2-} ions. Non-idealized seawater solution can be either made from a solution containing divalent cations, such as Instant Ocean® Sea Salt, or can be real seawater taken from an ocean. In the case of a process solution that is a seawater solution, not only is the amount of CO_2 in one liter of seawater—predominately in the form of bicarbonate ions—about 100 times the amount in one liter of air, but extracting CO_2 directly from seawater eliminates the need for a contactor that is inherent when capturing CO_2 from the air because in a seawater system, the surface of the ocean effectively acts as one large contactor. This greatly reduces the volumetric footprint of a CO_2-from-seawater system compared to a CO_2-from-air system. Further, for the CO_2-from-seawater system, no external chemicals other than electrode rinse solutions are needed. Seawater and electrical power are the only inputs into the system.

To understand how example embodiments work, it is first necessary to understand BPMED. BPMED converts aqueous salt solutions into acids and bases. Currently available BPMED apparatuses include an electrodialysis membrane stack made up of at least one electrodialysis cell. The electrodialysis cell includes at least one bipolar membrane (BPM) such that, when an electrical potential is applied across the cell, the dissociation of water into hydrogen ions (H^+) and hydroxide ions (OH^-) occurs.

A BPM is formed from a cation-exchange layer laminated together with an anion-exchange layer, as well as a junction layer between the cation and anion layers. Water diffuses into the junction layer, reaching the usual equilibrium with H^+ and OH^- ions according to its dissociation constant. Typically, a BPM is oriented such that the anion-exchange layer faces the anode (positive electrode) end of the BPMED apparatus and the cation-exchange layer faces the cathode (negative electrode) end of the apparatus. This orientation allows the OH^- ions to be transported across the anion-exchange layer and the H^+ anions to be transported across the cation-exchange layer when an electrical potential is applied across the membrane stack. Simultaneously, the constituent cations and anions of an input salt solution are separated under the applied electrical potential via ion exchange membranes—either anion exchange membranes (AEMs), cation exchange membranes (CEMs), or some combination of the two. The OH^- (H^+) ions "produced" by the BPM then combine with the cations (anions) separated from the input salt solution to produce basic (acidic) output solutions containing the parent acid and base of the input salt. Depending on the membrane configuration—for example, in a membrane stack composed of one or more "three-compartment" cells—a diluted salt solution may also be produced as output in addition to the acid and base output solutions.

A BPMED membrane stack can have either a two-compartment or a three-compartment configuration. In a two-compartment configuration, adjacent membranes may alternate between BPM and AEM to form a membrane stack of the form BPM, AEM, BPM, AEM, etc.; or adjacent membranes may alternate between BPM and CEM to form a membrane stack of the form BPM, CEM, BPM, CEM, etc. In a three-compartment cell, adjacent membranes may cycle from BPM to AEM to CEM, forming a membrane stack of the form BPM, AEM, CEM, BPM, AEM, CEM, etc. Electrodialysis without bipolar membranes is also possible, and consists of a two-compartment configuration formed by an alternating series of AEM and CEM to form a membrane stack of the form AEM, CEM, AEM, CEM, AEM, etc. For any of these configurations, each of the end membranes at the two ends of the membrane stack may be an AEM, CEM, or BPM, depending on the configuration and process conditions.

FIGS. **1** and **2** show schematics of a BPMED system used to extract CO_2 from a process solution such as, for example, a seawater solution or RO brine. The system includes a BPMED apparatus **101**/**201**, which includes a BPMED membrane stack. The membrane stack can consist of either one or more two-compartment cells (for example, FIG. **3**), or one or more three-compartment cells (for example, FIG. **4**).

FIG. **1** depicts a BPMED system operated in "batch mode." FIG. **2** depicts a BPMED system operated in "once-through" mode. The differences between a BPMED system operated in "batch mode" and a BPMED system operated in "once-through" mode will be described below with respect to these figures.

"Batch" Mode

FIG. **1** is a schematic of a BPMED system, operated in "batch" mode, that is used to extract CO_2 from a process solution according to embodiment processes. In batch mode, a process solution is flowed through the apparatus more than one time. In the case of seawater, the seawater may be pumped directly from the ocean into the apparatus, pumped through the apparatus **101** multiple times to undergo one of the described processes, and then be returned directly to the sea.

The BPMED system in FIG. **1** includes a BPMED apparatus **101**, which has a membrane stack with either one or more two-compartment cells (see FIG. **3**), or one or more three-compartment cells (see FIG. **4**). In a system where the BPMED apparatus **101** includes a membrane stack with one or more two-compartment cells, a process solution, such as a seawater solution or an RO brine, is loaded into the solution tanks **104** and **105**. Once the "batch" of process solution has been loaded into the tanks, the solution is then pumped from tanks **104** and **105** into the BPMED apparatus **101**. A voltage is applied to the BPMED apparatus **101** by a power supply (not shown). Electrode solution **103** is also flowed through the BPMED apparatus **101** at either end of the apparatus; electrode solution **103** is flowed across the electrodes of the BPMED apparatus **101** only. As the process solution flows through the BPMED apparatus **101**, BPMED occurs; the process solution becomes acidified in the acidified solution compartments of the membrane stack, and becomes basified in the basified solution compartments of the membrane stack (see FIG. **3**). Two solution streams leave the apparatus **101**—an acidified solution stream, which flows into tank **105**, and a basified solution stream, which flows into tank **104**.

In a system where the BPMED apparatus **101** includes a membrane stack with one or more three-compartment cells (see FIG. **4**), the same general process occurs: a process solution is flowed into the apparatus **101**, electrode solution **103** is flowed into the apparatus **101** at either end and across the electrodes, a voltage is applied using a power supply, and as the process solution flows through the apparatus **101**, BPMED occurs. As with the two-compartment cell, the process solution becomes acidified in the acidified solution compartments of the membrane stack, and becomes basified in the basified solution compartments of the membrane stack (see FIG. **4**). Additionally, in the case of a three-compartment cell, the process solution becomes desalinated in the third compartments of the membrane stack (see FIG. **4**). Three solution streams then leave the apparatus **101**—an acidified solution stream, which flows into tank **105**; a basified solution stream, which flows into tank **104**; and desalinated solution, which flows into a third tank (not shown). The desalinated solution may be used, for example, as drinking water.

In an embodiment, the acidified solution stream does not flow directly from the apparatus **101** to the acidified solution tank **105**, but rather first flows through a CO_2 desorption unit **108**, which is connected to a vacuum pump **109** so that CO_2 gas can be actively extracted from the acidified solution as it passes through the CO_2 desorption unit **108**. Once the CO_2 is extracted from the acidified solution, the acidified solution exits the CO_2 desorption unit **108** and flows to the acidified solution tank **105**. The vacuum pump **109** may be connected to a CO_2 collection unit **111**, such as a tank, that collects the extracted CO_2. The system may also include a CO_2 flow meter **110** between the CO_2 desorption unit **108** and the vacuum pump **109** in order to monitor the flow of the CO_2 gas extracted from the acidified solution. The CO_2 desorption unit **108** and vacuum pump **109** may be used with either a two-compartment or a three-compartment BPMED unit **101**.

In an embodiment, the CO_2 desorption unit **108** consists of one or more membrane contactors in series (see, for example, Liqui-Cel, Carbon Dioxide Removal from Water, http://www.liquicel.com/applications/CO2.cfm, last visited Jun. 20, 2011). In another embodiment, the CO_2 desorption unit **108** is a tank with a means of agitating the solution, for example, a showerhead fixture. It will be appreciated that other means for agitating the acidified solution and/or mixing the gas headspace in the acidified solution tank **105** may also be used.

In another embodiment, the system does not include a CO_2 desorption unit **108** such that the acidified solution stream flows directly from the BPMED apparatus **101** to the acidified solution tank **105**. The CO_2 gas may passively evolve from the acidified solution in the acidified solution tank **105**, and may be collected in a CO_2 collection unit **115** attached to the acidified solution tank **105**. Alternatively, the system may include a means for agitating the acidified solution in the acidified solution tank such that CO_2 gas is actively evolved from the acidified solution, for example, a showerhead fixture or a vacuum pump. The actively evolved CO_2 gas may be collected by a CO_2 collection unit **115** attached to the acidified solution tank **105**.

Once the acidified and basified solutions flow from the BPMED apparatus **101** and into the acidified and basified solution tanks **104** and **105**, the acidified and basified solutions may be flowed back into the BPMED apparatus. In this manner, the process solution is flowed through the apparatus more than one time.

In an embodiment, the system includes a recombination unit **114**. The recombination unit **114** may be, for example, a separate tank which receives the acidified and basified solutions from their respective tanks **105** and **104** after the solutions have made the desired number of passes through the BPMED apparatus. When the acidified and basified solutions are recombined, they once again become neutralized, and in the case of seawater can be pumped directly back into the sea. Because no additional chemicals need to be added to the solution, pumping the neutralized solution back into the sea will have little to no harmful effects. It also enables the system to be used as a method of "scrubbing" CO_2 from the earth's oceans.

In an embodiment, the BPMED unit **101** can be descaled by periodically flowing an acidic solution through the unit. The acidic solution used may be the output acidic solution that results from the BPMED process. In this manner, any scaling that results from any divalent cations in the basified solution—for example Mg^{2+} and Ca^{2+}—that are present in the process solution will be periodically cleaned via contact with the acidic solution.

"Once-Through" Mode

FIG. **2** is a schematic of a BPMED system, operated in "once-through" mode, that is used to extract CO_2 from a process solution according to embodiment processes. In once-through mode, a process solution is flowed through the apparatus only one time. In the case of seawater, the seawater may be pumped directly from the ocean into the apparatus, undergo one of the described processes, and then be returned directly to the sea.

The BPMED system in FIG. **2**, like the BPMED system in FIG. **1**, includes a BPMED apparatus **201**, which has a membrane stack with either one or more two-compartment cells (see FIG. **3**), or one or more three-compartment cells (see FIG. **4**).

A BPMED system operated in "once-through" mode operates similarly to a BPMED system operated in "batch" mode (FIG. **1**): a process solution is flowed into the apparatus **201**, a voltage is applied, electrode solution **203** is flowed into the BPMED apparatus **201** at either end, and, as the solution flows through the apparatus **201**, BPMED occurs. In the case of a BPMED apparatus **101** with a membrane stack composed of one or more two-compartment cells, an acidified stream and a basified stream leave the apparatus **201**. In the case of a BPMED apparatus **201** with a membrane stack composed of one or three-compartment cells, an acidified stream, a basified stream, and desalinated solution leave the apparatus **201**.

Also similarly to a BPMED system operated in batch mode (FIG. **1**), the acidified solution stream can either flow directly from the apparatus **201** to the acidified solution tank **205**, or it can first flow through a CO_2 desorption unit **208**. The CO_2 desorption unit **208** may be connected to a vacuum pump **209** so that CO_2 gas can be actively extracted; the vacuum pump **209** can be connected to a CO_2 collection unit **211**, such as a tank, that collects the extracted CO_2. The system may also include a CO_2 flow meter **210** between the CO_2 desorption unit **208** and the vacuum pump **209** in order to monitor the flow of the CO_2 gas extracted from the acidified solution. Alternatively, the CO_2 desorption unit **208** may consist of one or more membrane contactors in series, or may be a tank with a means of agitating the solution, for example, a showerhead fixture. In another embodiment, the system does not include a CO_2 desorption unit **208**; the acidified solution flows directly from the apparatus **201** into the acidified solution tank **205**, where the CO_2 may either passively evolve in the tank **205** or be actively evolved in the tank **205**. The gas, whether passively or actively evolved, may be collected by a CO_2 collection unit **215** attached to the acidified solution tank **205**.

The difference between a BPMED apparatus operated in "once through" mode (FIG. **2**) and a BPMED apparatus operated in "batch" mode (FIG. **1**) is that for a system operated in "once through" mode, once the acidified and basified solutions flow from the apparatus **201** into their respective tanks **204** and **205**, the acidified and basified solutions are not flowed back into the BPMED apparatus. Thus, the process solution is only flowed through the apparatus **201** one time.

In an embodiment, the system includes a recombination unit **214**, for example, a separate tank which receives the acidified and basified solutions from their respective tanks **205** and **204** after the solutions pass once through the BPMED apparatus. When the acidified and basified solutions are recombined, they once again become neutralized, and in the case of seawater can be pumped directly back into the sea. Because no additional chemicals need to be added to the solution, pumping the neutralized solution back into the sea will have little to no harmful effects. It also enables the system to be used as a method of "scrubbing" CO_2 from the earth's oceans.

As with the BPMED system operated in "batch" mode (FIG. **1**), the BPMED unit **201** can be descaled by periodically flowing an acidic solution through the unit. The acidic solution used may be the output acidic solution that results from the BPMED process. In this manner, any scaling that results from any divalent cations in the basified solution—for example Mg^{2+} and Ca^{2+}—that are present in the process solution will be periodically cleaned via contact with the acidic solution.

BPMED Membrane Stack Operation

FIG. **3** shows a schematic of BPMED membrane stack operation used to generate CO_2 gas from a single process solution, such as a seawater solution or RO brine using a "two-compartment" BPMED stack. A voltage is applied across an alternating stack of BPMs **304** and AEMs **305**. An acidified solution compartment **306** is formed between the BPMs **304** and their adjacent AEMs **305**, and a basified solution compartment **307** is formed between the AEMs **305** and their adjacent BPMs **304**. The number of acidified solution compartments **306** and basified solution compartments **307** in a given electrodialysis stack **308** is a function of the number of electrodialysis cells **309** in the stack **308**.

An electrodialysis apparatus can be adapted to receive any number of electrodialysis cells **309**. The electrodialysis stack **308** also includes two end membranes, one at either end of the BPMED stack **308** (not shown). Each of these end membranes may be a BPM, AEM, or CEM, depending on the membrane stack configuration and the process solutions and conditions used.

A single process solution **301** is flowed through all compartments **306** and **307** of the electrodialysis stack **308**. In an embodiment, the process solution **301** is a seawater solution. For example, the electrodialysis apparatus may be used on a ship at sea, and seawater may be taken directly from the ocean and flowed into the electrodialysis apparatus. Alternatively, the seawater solution may be a manmade seawater solution, such as that made with Instant Ocean® Sea Salt. Alternatively, the process solution **301** may be a concentrated process solution, such as RO brine. The only other solution flowed into the electrodialysis apparatus is an electrode solution, such as KOH or H_2SO_4/Na_2SO_4, which is flowed into the two electrode compartments (not shown) located each end of the electrodialysis stack **308** such that it flows across the electrodes **302** and **303** located at each end of the stack **308**.

Under the voltage applied at electrodes **302** and **303**, the AEMs **305** permit negatively charged anions to pass across the membrane from the negative electrode **303** to the positive electrode **302**. In the case of a seawater solution, almost all of the ionic transport across the AEMs **305** is in the form of Cl^- ions, since Cl^- ions are in high proportion in seawater (approximately 546 mM). The BPMs **304** effectively dissociate water into H^+ and OH^- ions under the applied voltage, with the H^+ ions transported from the middle of the BPMs **304** toward the negative electrode **303** and the OH^- ions transported from the middle of the BPMs **304** toward the positive electrode **302**. Through this process, the process solution **301** becomes acidified in the acidified solution compartments **306** because of the transport of the H^+ ions into the acidified solution compartments **306**. The process solution **301** also becomes basified in the basified solution compartments **307** because of the transport of the OH^- ions into the basified solution compartments **307**.

For each Cl^- ion that is transported from the basified compartments **307** to the acidified compartments **306**, a H^+ ion is transported from the middle of the adjacent BPM **304** into the acidified compartments **306**, and a OH^- ion is transported from the middle of the adjacent BPM **304** into the basified compartments **307**. In this way, operation of the electrodialysis apparatus decreases the pH of the acidified solution compartments **306** and increases the pH of the basified solution compartments **307**. The change in pH from input to output depends on the composition of the process solution **301**; the rate of ion transport, which is governed by the applied current and system efficiencies; and the flow rate of the solution **301** through the apparatus.

CO_2 is extracted from the process solution **301** flowing through the acidified compartments **306** via conversion of bicarbonate (HCO_3^-) ions into dissolved CO_2 as the pH of the acidified compartments **306** decreases. The process solution **301** flowing through the acidified compartments **306** is essentially being titrated by HCl. When the pH of the single solution **301** is decreased down to about pH 4, approximately 99% of the HCO_3^- ions are converted to CO_2 (see, for example, James N. Butler, *Carbon Dioxide Equilibria and Their Applications*, Addison-Wesley Publishing Company, Menlo Park, Calif., 1982, p. 123, FIG. 5.1).

FIG. **4** shows a schematic of a BPMED membrane stack configuration **411** used to generate CO_2 gas from a process solution, such as a seawater solution or RO brine, using a "three-compartment" BPMED stack. A voltage is applied across an alternating stack of BPMs **404**, AEMs **405**, and CEMs **406**. In the embodiment shown in FIG. **4**, the alternating BPMs **404**, AEMs **405**, and CEMs **406** form a "three-compartment" BPMED stack. An acidified solution compartment **407** is formed between the BPMs **404** and their adjacent AEMs **405**; a basified solution compartment **409** is formed between the CEMs **406** and their adjacent BPMs **404**; and desalinated solution is produced in the center compartment **408** between the AEM **405** and its adjacent CEM **406**. Thus, in the embodiment shown in FIG. **4**, the BPMED membrane stack **411** not only generates CO_2 gas from the a seawater solution **401**, it also generates desalinated water which can be used as drinking water. RO brine, as well as other aqueous salt solutions, will also generate a desalted solution in the center compartment **408**, but the degree to which the process solution **401** is desalted depends on the flow rate of the process solution **401**, the applied current density, and the efficiency of ion transport.

The number of acidified solution compartments **407**, basified solution compartments **409**, and center compartments **408** in a given BPMED stack **411** is a function of the number of cells **410** in the stack **411**. A BPMED apparatus can be adapted to receive any number of cells **410**. The BPMED stack **411** also includes two end membranes, one at either end of the BPMED stack **411** (not shown). Each end membrane may be a BPM, AEM, or CEM, depending on the membrane stack configuration and process solutions and conditions.

When a voltage is applied at electrodes **402** and **403**, the AEMs **405** permit negatively charged anions—mostly Cl^- ions in the case of a process solution **401** that is seawater—to pass across the membrane from the negative electrode **403** to the positive electrode **402**. The BPMs **404** effectively dissociate water into H^+ and OH^- ions under the applied voltage, with the H^+ ions transported from the middle of the BPMs **404** toward the negative electrode **403** and the OH^- ions transported from the middle of the BPMs **404** toward the positive electrode **402**. The CEMs **406** permit positively charged anions, such as Na^+ and K^+, to pass across the membrane from the positive electrode **402** to the negative electrode **403**. Through this process, the process solution **401** becomes acidified in the acidified solution compartments **407** and basified in the basified solution compartments **409**; and desalted solution is generated in the center compartments **408**.

As with the two-compartment configuration shown in FIG. **3**, CO_2 is extracted from the single process solution **401** flowing through the acidified compartments **407** via conversion of HCO_3^- ions into dissolved CO_2 as the pH of the acidified compartments **407** decreases. The process solution **401** flowing through the acidified compartments **407** is essentially being titrated by HCl. When the pH of the process solution **401** is decreased down to about pH 4, approximately 99% of the HCO_3^- ions are converted to CO_2 (see, for example, James N. Butler, *Carbon Dioxide Equilibria and Their Applications*, Addison-Wesley Publishing Company, Menlo Park, Calif., 1982, p. 123, FIG. 5.1).

The acidified and basified solutions generated by the processes shown in FIGS. **3** and **4** can be recombined after the CO_2 gas is extracted from the acidified solution. When the acidified and basified solution streams are recombined, they become neutralized. In the case of a solution **301**/**401** that is a seawater solution, this recombined solution can be put straight back into the ocean. Because no additional chemicals are needed for the process, the post-process recombined solution is not ecologically harmful in the way that a post-process solution containing added chemicals could be.

For the embodiments shown in FIGS. **3** and **4**, CO_2 gas is regenerated from the acidified solution. The process solution acidifies in the acidified solution compartments **306**/**407** because of the transport of H^+ ions across the BPMs **304**/**404** and into the acidified solution compartments **306**/**407**. Reducing the pH of 50 mL of seawater from pH 8 to pH 4 requires 5 mL of 0.025M HCl, corresponding to the addition of 2.5 mmol of HCl per liter of seawater. HCO_3^- ions are found in seawater at concentrations of 2.2 to 2.5 mM, so converting all the HCO_3^- in seawater via acidification will generate approximately 2.2 to 2.5 mmol of CO_2 per liter of seawater, equivalent to 49.2 to 56 mL of CO_2 per liter of seawater. The initial concentration of HCO_3^- in seawater (2.2 to 2.5 mM) combined with Henry's Law constant for CO_2 in seawater of $10^{-1.536}$ mole/(L atm) means that the dissolved CO_2 converted from HCO_3^- is in equilibrium with a pure CO_2 atmosphere at a pressure of 0.076 to 0.086 atm. Therefore, in order to extract a stream of pure CO_2, the acidified solution can be pumped on with a vacuum pump to extract the dissolved CO_2 gas from the acidified solution. In another embodiment, the acidified solution is agitated and the gas headspace in the acidified solution tank is mixed in order to extract the dissolved CO_2 gas. In another embodiment, the acidified solution is passed at least once over at least one membrane contactor that uses a vacuum pump or sweep gas in order to extract the dissolved CO_2. Alternatively, the CO_2 gas can simply be allowed to passively evolve out of solution at whatever levels it may come out of solution, without pumping, agitating, mixing, or flowing the solution over a membrane contactor.

These and other features of embodiments will be better understood by turning to the following experimental results.

Batch-Mode Experimental Results for an Embodiment Process of Separating CO_2 Gas from Process Solutions Using Electrodialysis

The membrane stack configuration shown in FIG. **3**, operating in batch mode (FIG. **1**), was used to perform a suite of experiments to characterize the performance of BPMED for removal of CO_2 from the following process solutions: "idealized" seawater, prepared using DI water, 0.5M NaCl, and 2.5 mM $NaHCO_3$ but no divalent cations such as Mg^{2+} and Ca^{2+}; ""real" seawater, prepared using Instant Ocean® Sea Salt which includes divalent cations like Mg^{2+} and Ca^{2+}; and "real" RO brine, prepared using 2× Instant Ocean® Sea Salt. Excluding divalent cations and other ions from "idealized" seawater allowed the performance to be determined without the additional effects of scaling and reduced transport efficiency due to the presence of other ions, such as Mg^{2+} and Ca^{2+}. For these experiments, two separate units—a BPMED unit and a membrane contactor unit—were used, the two units separated by time, as represented by the schematic in FIG. **5**.

For each experiment, an eight-cell two-compartment electrodialysis stack was used of the BPM, AEM, BPM, AEM type with CEM end membranes. The cross-sectional area of each membrane was approximately 180 cm^2. It will be understood that an electrodialysis stack composed of any number n of cells can be used; the eight-cell stack used in these experiments is not the only possible configuration. Further, it will be understood that three-compartment stacks of any number n of cells could alternatively be used, such as the configuration shown in FIG. **4**. It will also be understood that membranes of different cross-sectional areas may be used.

In the experiments, the AEM/CEM/BPM used were Neosepta AMX/C66-10F/BP-1E from Ameridia Corporation. The electrode solution was 2M NaOH with nickel electrodes. It will be understood that other AEM/CEM/BPM types from other manufacturers can be used. It will also be understood that other electrode solutions of other concentrations with electrodes made of different metals could be used. For example, electrodes made of iridium-ruthenium coated Ti with an H_2SO_4/Na_2SO_4 electrode solution could be used, as described below.

Table 1 summarizes the different experiments conducted.

TABLE 1

Summary of Experiments Performed

Ex. No.	Seawater Solution	Flow rate (lpm)	Current (A)	Current Density (mA/cm^2)	Remarks
1	Idealized	3.75	4.5	25	
2	Real	3.75	4	22	
3	Real	3.75	4.5	25	
4	Real	3	3.5	19	
5	Real	3	4	22	
6	Real	4.25	4.5	25	
7	Real	4.25	5	28	
8	Real	5	5.5	31	
9	Real	5	6	33	
10	Real	5	6	33	w/30 s pause

As Table 1 shows, a comparison was made between "idealized" and "real" seawater at the flow rate of 3.75 lpm and 4.5 A applied current, a current density of 25 mA/cm^2 (Experiments 1 and 3). An additional experiment was conducted at 5 lpm and 6 A current (current density of 22 mA/cm^2) with a 30 second pause between flowing the solution through the electrodialysis unit **501** and flowing the solution through the membrane contactors **502**/**503** (Experiment 10) in order to evaluate the effect of any mixing of the solution coming out from the electrodialysis unit **501** before extracting CO_2 in the membrane contactors **502**/**503**. The objective was also to see the effect of mixing in pH change, if any.

FIG. **5** shows a flow diagram of the combined electrodialysis unit **501** and membrane contactors **502**/**503** but does not show the electrolyte and base tanks for simplicity. The acid tank **505** and the base tank were each filled with 5 L of either "idealized" or "real" seawater solution, depending on the experiment (see Table 1). The electrolyte tank was filled with 5 L of 2M NaOH solution. The seawater solution was then run through the BPMED unit **501**, but not through the membrane contactors **502**/**503**; the vacuum pump **504** was started to record the offset value. The pH of the seawater solution was driven down to approximately pH 4 by running the seawater solution through the BPMED unit **501** for "once-through" time, defined as the time needed to flow the 5 L of seawater solution through the electrodialysis unit **501** exactly once given the volumetric flow rate; this was done by applying the current needed to reach pH 4 in "once-through" time.

The power supply to the electrodialysis unit **501** was disconnected and the solution flow switched to bypass mode immediately after the once-through time without turning off the vacuum pump **504**, thereby diverting the seawater solution to the membrane contactors **502** and **503**. The electrolyte and base flows were also diverted to bypass mode after the once-through time was reached. For Experiment 10 (Table 1), the solution's flow was switched to the membrane contactors **502** and **503** after a pause of 30 seconds after the power supply was stopped; the system was run in bypass mode to let the solution mix properly in the acid tank **505**.

The membrane contactors **502** and **503** were already being pumped by vacuum pump **504** with output through CO_2 flow meter **506**, so all the CO_2 extracted by the membrane contactors **502** and **503** was recorded once the flow was switched to the membrane contactors **502** and **503**. The results of the experiments run on the system shown in FIG. **5** are summarized in Table 2. The entries for Experiment 1 (idealized seawater solution) and Experiment 3 (real seawater solution) show that the difference between idealized and real seawater solutions was not significant.

TABLE 2

Summary of Experiments with Varying Flow Rate, Current, Seawater Solution, and Procedure.

Ex. No.	Flow Rate (lpm)	Current (A)	Current Density (mA/cm^2)	CO_2 (mol)	Energy (kJ/mol)	Efficiency (%)	End pH	CO_2 (lpm)
1	3.75	4.5	25	0.0080	567	70	3.13	0.146
2	3.75	4	22	0.0087	500	76	3.90	0.157
3	3.75	4.5	25	0.0082	616	72	3.41	0.149
4	3	3.5	19	0.0074	621	65	3.55	0.108
5	3	4	22	0.0088	709	77	3.20	0.127
6	4.25	4.5	25	0.0054	882	47	5.37	0.111
7	4.25	5	28	0.0059	941	52	3.55	0.121
8	5	5.5	31	0.0055	877	48	6.58	0.133
9	5	6	33	0.0075	704	65	5.90	0.181
10	5	6	33	0.0078	676	68	3.84	0.189

Different combinations of applied current and flow rates were also investigated (Experiments 2, 4-9). A flow rate of approximately 4 lpm resulted in the highest membrane contactor extraction efficiency. Accordingly, a range of flow rates around 4 lpm—3, 3.75, 4.25, and 5 lpm—was tested, along with corresponding values of applied currents to achieve a pH of around 4 in the acidified solution at the end of the BPMED process. The combination of 3.75 lpm of flow rate and 4 A current (current density of 22 mA/cm^2) (Experiment 2) had the lowest energy consumption—500 kJ/mol—for the electrodialysis process, with an efficiency (percent of CO_2 present in the input solution in the form of HCO_3^- that is extracted as CO_2 gas) of 76%. The conditions used for Experiment 2 also produced an average rate of CO_2 extraction for 5 L of solution in once-through conditions of 0.157 lpm. Experiment 5, which used a flow rate of 3 lpm and a current of 4 A (current density of 22 mA/cm^2), produced slightly higher efficiency in terms of CO_2 extraction (77%), but the total energy consumption was increased (709 kJ/mol) as the once-through time increased due to the lower flow rate. It will be appreciated that the flow rate and current selected for the BPMED of seawater to extract CO_2 need not be 3.75 lpm and 4 A; as the results in Table 2 show, many other combinations of flow rates and currents (including combinations not shown in Table 2) are capable of extracting CO_2 from seawater.

Table 3 summarizes the results of similar experiments conducted using an approximate RO brine solution rather than "idealized" or "real" seawater solution. The approximate RO brine solution was prepared by doubling the concentration of Instant Ocean® salt, as many RO brines have ion concentrations that are approximately double to that seen in seawater.

TABLE 3

Summary of Experiments with Varying Flow Rates for RO Brine Solution.

Ex. No.	Flow Rate (lpm)	Current (A)	Current Density (mA/cm^2)	CO$_2$ (mol)	Energy (kJ/mol)	Efficiency (%)	End pH	CO$_2$ (lpm)
1	3	7	39	0.014	815	62	3.91	0.208
2	3.75	8	44	0.012	1006	52	5.66	0.217
3	4.25	10	56	0.013	1107	57	4.86	0.273
4	5	11	61	0.012	1254	53	4.96	0.296
5	2.5	5.5	31	0.013	753	56	4.61	0.156

As Table 3 shows, in the case of RO brine solution, the system was more efficient while operating at lower flow rates. An efficiency of 62% was found at a flow rate of 3 lpm and a current of 7 A (current density of 39 mA/cm^2). The energy requirement was lowest at a flow rate of 2.5 lpm and a current of 5.5 A (current density of 31 mA/cm^2). Approximately double amplitude of current was needed for titration similar to that seen for seawater solutions (Table 2), and the voltage was increased for RO brine resulting in a higher energy requirement per mole of CO$_2$ extracted than for seawater solution.

Once-Through Experimental Results for an Embodiment Process of Separating CO$_2$ Gas from Process Solutions Using Electrodialysis

To characterize the performance of a system operating in once-through mode, experiments were performed using the following process solutions: "idealized" seawater, prepared using DI water, 0.5M NaCl, and 2.5 mM NaHCO$_3$ but no divalent cations such as Mg^{2+} and Ca^{2+}; "real" seawater, prepared using Instant Ocean® Sea Salt which includes divalent cations like Mg^{2+} and Ca^{2+}; and "real" RO brine, prepared using 2× Instant Ocean® Sea Salt.

For each experiment, an eight-cell two-compartment electrodialysis stack was used of the BPM, AEM, BPM, AEM type with CEM end membranes. The cross-sectional area of each membrane was approximately 180 cm^2. It will be understood that an electrodialysis stack composed of any number n of cells can be used; the eight-cell stack used in these experiments is not the only possible configuration. Further, it will be understood that three-compartment stacks of any number n of cells could alternatively be used, such as the configuration shown in FIG. **4**. It will also be understood that membranes of different cross-sectional areas may be used.

FIG. **6** shows a schematic of the experimental setup used. The system included a BPMED apparatus **601**. The apparatus **601** used titanium electrodes, so an acidic electrode solution **602** (0.1M H$_2$SO$_4$/0.25M Na$_2$SO$_4$) was used. The system used also included two membrane contactors **603** and **604** in series, as well as a CO$_2$ flow meter **605** to monitor the flow of the CO$_2$ gas extracted from the acidified solution, although it will be appreciated that other methods of actively or passively drawing the CO$_2$ out of solution can be used. The system further included an input tank **606** from which the process solution was pumped, and a collection tank **607** to receive the acidified and basified solution output from the BPMED apparatus **601**.

First, idealized seawater was tested. For all experiments, a flow rate of 3.1 lpm was used for the acid solution, and a flow rate of 4.0 lpm was used for the base solution. A higher base solution volumetric flow rate was used in order to equalize the pressures in both solutions, as the membrane contactors cause an extra pressure drop in the acid flow path relative to the base solution flow path. Electrode solution **602** was flowed into the BPMED apparatus **601** at the electrodes, and idealized seawater solution was flowed into the apparatus **601** from the input tank **606**. A vacuum pump (not shown) connected to the membrane contactors **603** and **604** was started in bypass mode and then switched to flow through the flow meter **605**. Power was supplied to the membrane stack of the apparatus **601** manually in constant-current mode.

Steady-state measurements were taken once the pH values were steady, and were made at different constant-current values, keeping all other parameters constant. The results of the experiments are shown in Table 4.

TABLE 4

Summary of Experiments for Idealized Seawater at Different Applied Currents.

Applied Current (A)	Current Density (mA/cm^2)	Voltage (V)	Actual CO$_2$ Flow Rate (lpm)	Energy (kJ/mol)	Acid pH	Base pH
1	6	10.2	0.04	421	6.1	10.2
1.5	8	11.2	0.13	213	5.8	10.5
2	11	12.1	0.14	285	3.5	11.1
3	17	13.8	0.15	456	3.0	11.5
3.5	19	14.5	0.15	559	2.5	11.9
4	22	15.4	0.14	727	2.5	12.0

Through the use of a "once-through" unit, steady-state conditions can be achieved. This facilitates varying the current for a fixed flow rate to adjust the acid pH. In this way the current can be optimized to extract most of the CO$_2$ with the least amount of energy. For example, the results in Table 4 show that at an applied current of 1.5 A (current density of 8 mA/cm^2), 0.13 lpm of CO$_2$ was extracted with an input of 213 kJ/mol CO$_2$; at 2 A (current density of 11 mA/cm^2), 0.14 lpm of CO$_2$ was extracted with an input of 285 kJ/mol CO$_2$.

Next, "real" seawater and RO brine were tested. Three different flow rates were tested. For each flow rate, three different solutions (idealized seawater, real seawater, and RO brine) were titrated to approximate pH values of 4, 5, and 6 by applying the appropriate current for the chosen solution and its flow rate.

The results of the experiments testing "real" seawater are shown in Table 5. FIG. **7** is a graph of the experimental results for "real" seawater showing energy consumption at various acid-solution end-pH values and flow rates.

TABLE 5

Summary of Experiments for "Real" Seawater at Different Flow Rates.

Solution Flow Rate (lpm)	Acid pH	CO$_2$ Flow Rate (lpm)	Energy (kJ/mol)	Efficiency (%)
4.1	6.0	0.10	361	31
4.1	3.7	0.22	284	67
4.1	5.4	0.17	280	52
3.1	3.2	0.16	396	65
3.1	5.0	0.15	241	61
3.1	5.8	0.09	274	37
3.1	3.3	0.17	331	69
3.6	4.0	0.19	256	66
3.6	5.5	0.14	255	49
3.6	4.1	0.17	250	59
3.6	5.6	0.13	236	45

Table 5 and FIG. **7** show the experimental results for experiments with real seawater. FIG. **7** shows that: 1) Within the flow-rate range of 3.1 lpm-4.1 lpm, solution flow rate does not significantly affect the results; and 2) The optimum end pH for minimizing the energy consumed per mol (CO_2) separated is around a pH of 4.5. The optimum in FIG. **7** results from the trade-off between the smaller amount of CO_2 extracted at high pH values (around pH=6) and the diminishing returns in terms of CO_2 extraction for expending the additional energy required to acidify the input seawater to pH 3 at low pH values. This is also illustrated by the efficiency (extracted CO_2 divided by the total CO_2 contained in the input solution) plotted in FIG. **8**.

FIG. **9** shows the efficiency of CO_2 separation for different solutions (idealized seawater, real seawater, and RO brine) for a flow rate of 3.1 lpm. FIG. **9** shows that the efficiency of separation depends on the end pH of the acidic solution, but for a given end pH, the efficiency is approximately the same for idealized seawater, real seawater, and RO brine.

It will be appreciated that variants of the above-disclosed and other features and functions, or alternatives thereof, may be combined into many other different systems or applications. Various presently unforeseen or unanticipated alternatives, modifications, variations, or improvements therein may be subsequently made by those skilled in the art which are also intended to be encompassed by the following claims.

What is claimed is:

1. A method comprising:

flowing a process solution into a BPMED system with a BPMED apparatus having at least two compartments separated by membranes, wherein the process solution is one of a seawater solution, a brine or water that has absorbed gaseous CO_2;

flowing an electrode rinse solution into the BPMED apparatus only across electrodes in the BPMED apparatus;

applying a voltage to the BPMED apparatus and the process solution is acidified and basified, and dissolved CO_2 is generated in the acidified process solution;

flowing the acidified and basified process solution out of the BPMED apparatus;

desorbing the CO_2 out of the acidified process solution;

combining the acidified and basified process solution such that the process solution is approximately neutral pH; and

discharging the process solution from the BPMED system.

2. The method of claim **1** wherein the acidified process solution is flowed out of the BPMED apparatus and through a CO_2 desorption unit before being flowed to an acidified solution tank such that the desorbing occurs at the CO_2 desorption unit.

3. The method of claim **1** wherein the acidified process solution is flowed out of the BPMED apparatus and into an acidified solution tank such that the desorbing occurs at the acidified solution tank.

4. The method of claim **1** further comprising flowing the acidified process solution back through the BPMED apparatus to descale the BPMED apparatus.

5. The method of claim **1** wherein the BPMED apparatus comprises one or more three-compartment BPMED cells such that when the voltage is applied, the process solution is also desalted.

6. The method of claim **1** wherein a flow rate for flowing the process solution into the BPMED apparatus and a current applied by the voltage are selected such that an energy consumption of the BPMED apparatus is minimized.

7. The method of claim **6** wherein the flow rate is approximately 0.3 lpm per cell to 0.7 lpm per cell and the current density is approximately 19 mA/cm^2 to 61 mA/cm^2.

8. The method of claim **7** wherein the flow rate is approximately 0.5 lpm per cell and the current density is approximately 22 mA/cm^2.

9. The method of claim **7** wherein the flow rate is approximately 0.3 lpm per cell and the current is approximately 31 mA/cm^2.

10. The method of claim **1** wherein a current applied by the voltage is selected such that the process solution is acidified to a pH that minimizes an energy consumption of the BPMED apparatus.

11. The method of claim **10** wherein the pH is approximately 3 to 6.

12. The method of claim **11** wherein the pH is approximately 4.5.

13. A method for producing a desalted solution and CO_2 gas comprising:

flowing a process solution comprised of one of seawater, a brine or water, wherein the process solution has absorbed gaseous CO_2 into a BPMED system with a BPMED apparatus, wherein the BPMED apparatus includes a membrane stack comprised of one or more three-compartment cells;

flowing an electrode rinse solution into the BPMED apparatus only across electrodes in the BPMED apparatus, the process solution and the electrode rinse solution being the only solutions used;

applying a voltage to the BPMED apparatus such that the process solution is acidified, basified, and desalted;

flowing the acidified, basified, and desalted process solution out of the BPMED apparatus;

desorbing the CO_2 out of the acidified process solution;

combining the acidified and basified process solution such that the process solution is approximately neutral pH; and

discharging the process solution from the BPMED system.

14. The method of claim **13** wherein the process solution is a seawater solution such that when the process solution is desalted, desalinated water is generated.

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