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Kolodji

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(54) **APPARATUS AND METHOD FOR OXYGEN AND CARBON DIOXIDE ENRICHMENT OF ATMOSPHERIC AIR**

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(51) **Int. Cl.**
B01D 53/22 (2006.01)
B01D 53/26 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC **B01D 53/226** (2013.01); **B01D 53/261** (2013.01); **B01D 53/265** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC .. B01D 53/226; B01D 53/261; B01D 53/265;
B01D 53/62; B01D 53/85; B01D 63/043;
(Continued)

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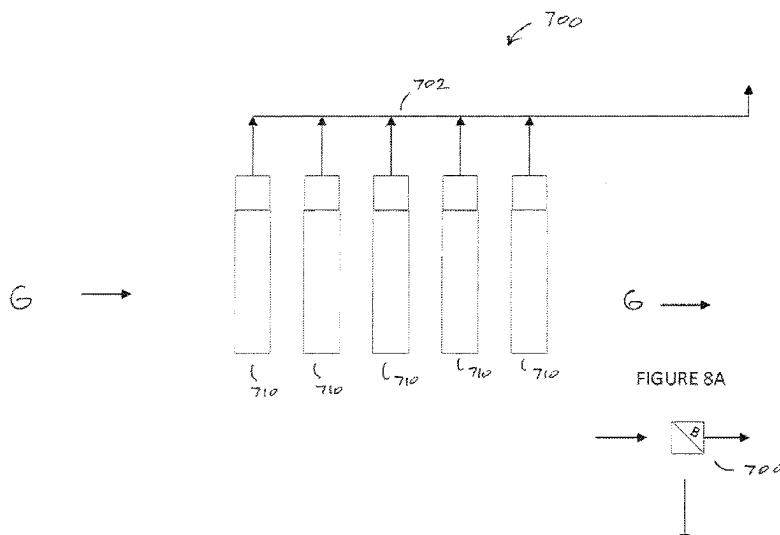
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(57) **ABSTRACT**

An apparatus utilizes a membrane unit to capture components from atmospheric air, including oxygen and carbon dioxide, resulting in a permeate stream having an enriched concentration of oxygen and carbon dioxide. Alternatively, the membrane unit may be utilized to form a permeate stream having a permeate of enriched fast gas components. The permeate stream is thereafter directed to a permeate processing facility which may include a second stage of permeate enrichment, a flue gas generator, or a carbon dioxide sequestration facility for processing of an enriched stream of carbon dioxide. Among other carbon dioxide sequestration facilities, the carbon dioxide may be biologically sequestered by a facility of photosynthetic organisms, such as trees in an orchard, crops, or the like. The membrane unit may be shell-less and utilize a vacuum or positive pressure to facilitate the flow of fast gas components through a selective barrier of the membrane.

19 Claims, 27 Drawing Sheets



- (51) **Int. Cl.**
B01D 53/62 (2006.01)
B01D 53/85 (2006.01)
B01D 63/04 (2006.01)
B01D 63/10 (2006.01)
- (52) **U.S. Cl.**
CPC **B01D 53/62** (2013.01); **B01D 53/85** (2013.01); **B01D 63/043** (2013.01); **B01D 63/107** (2022.08); **B01D 2053/224** (2013.01); **B01D 2251/95** (2013.01); **B01D 2257/504** (2013.01); **B01D 2313/24** (2013.01); **B01D 2317/02** (2013.01)
- (58) **Field of Classification Search**
CPC B01D 2053/224; B01D 2251/95; B01D 2257/504; B01D 2313/24; B01D 2317/02; B01D 53/225; B01D 2256/12; B01D 2257/102; B01D 2258/06; B01D 53/228; B01D 63/02; B01D 63/10; B01D 63/12
See application file for complete search history.
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FIGURE 1

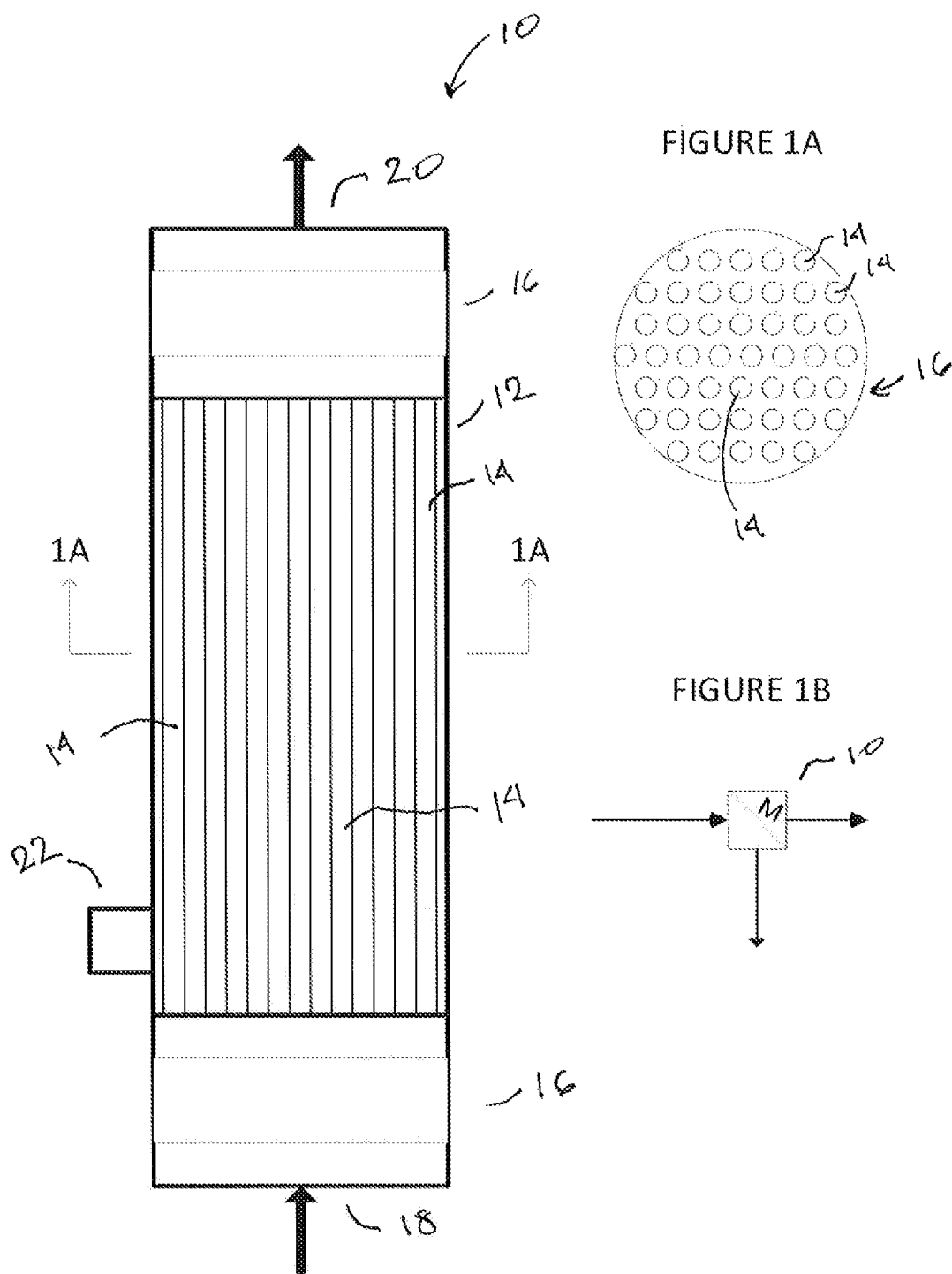


FIGURE 2

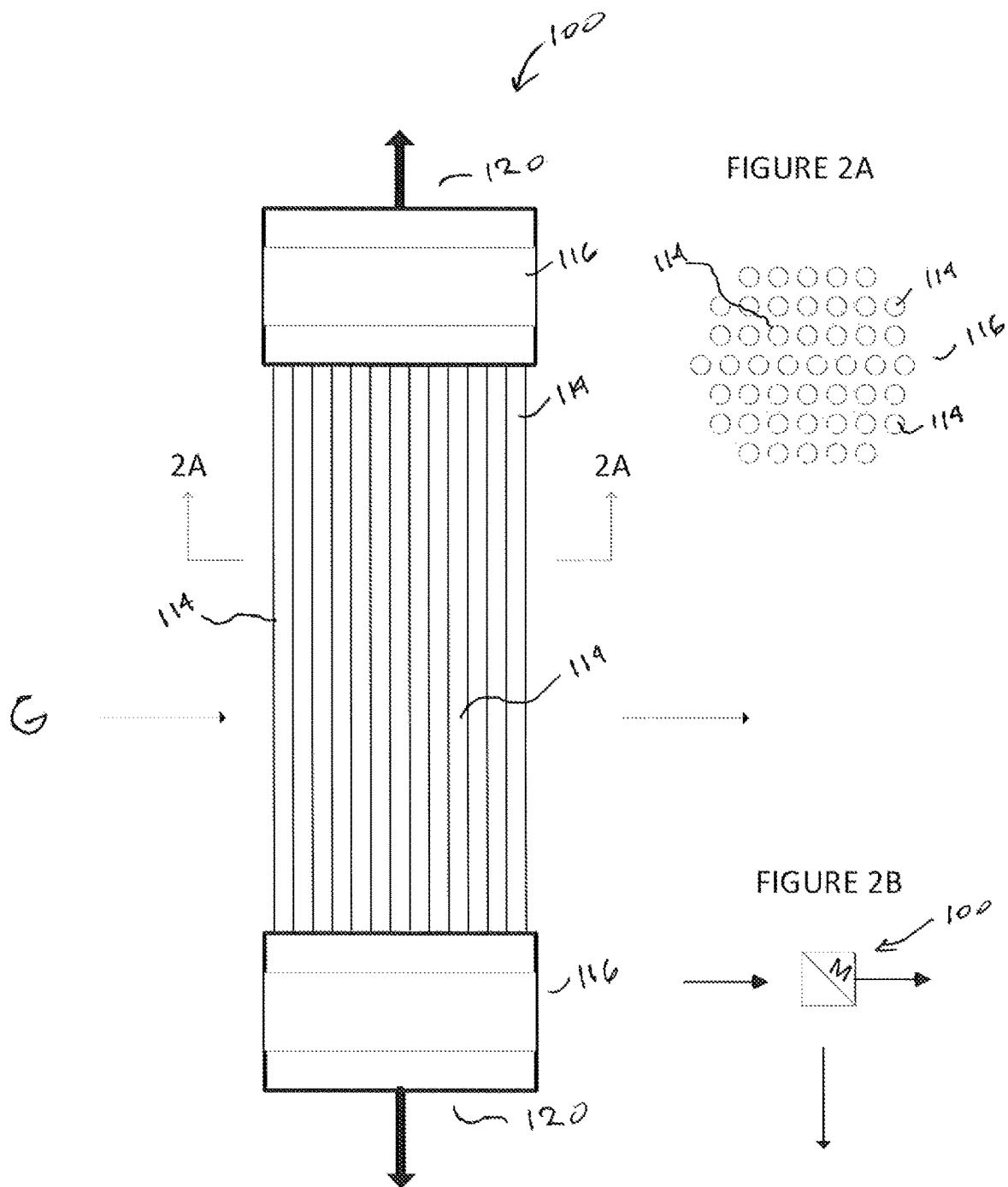


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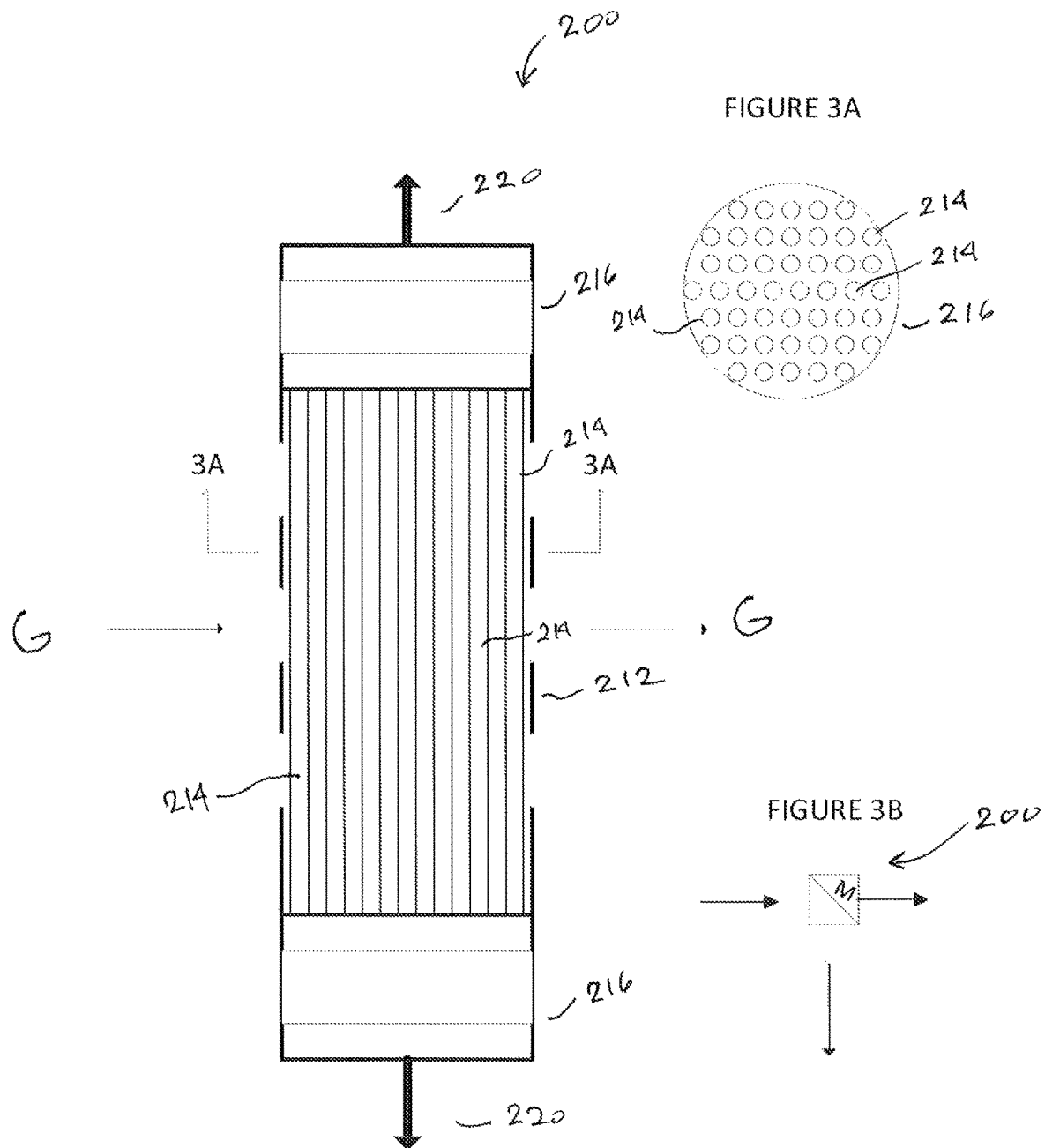


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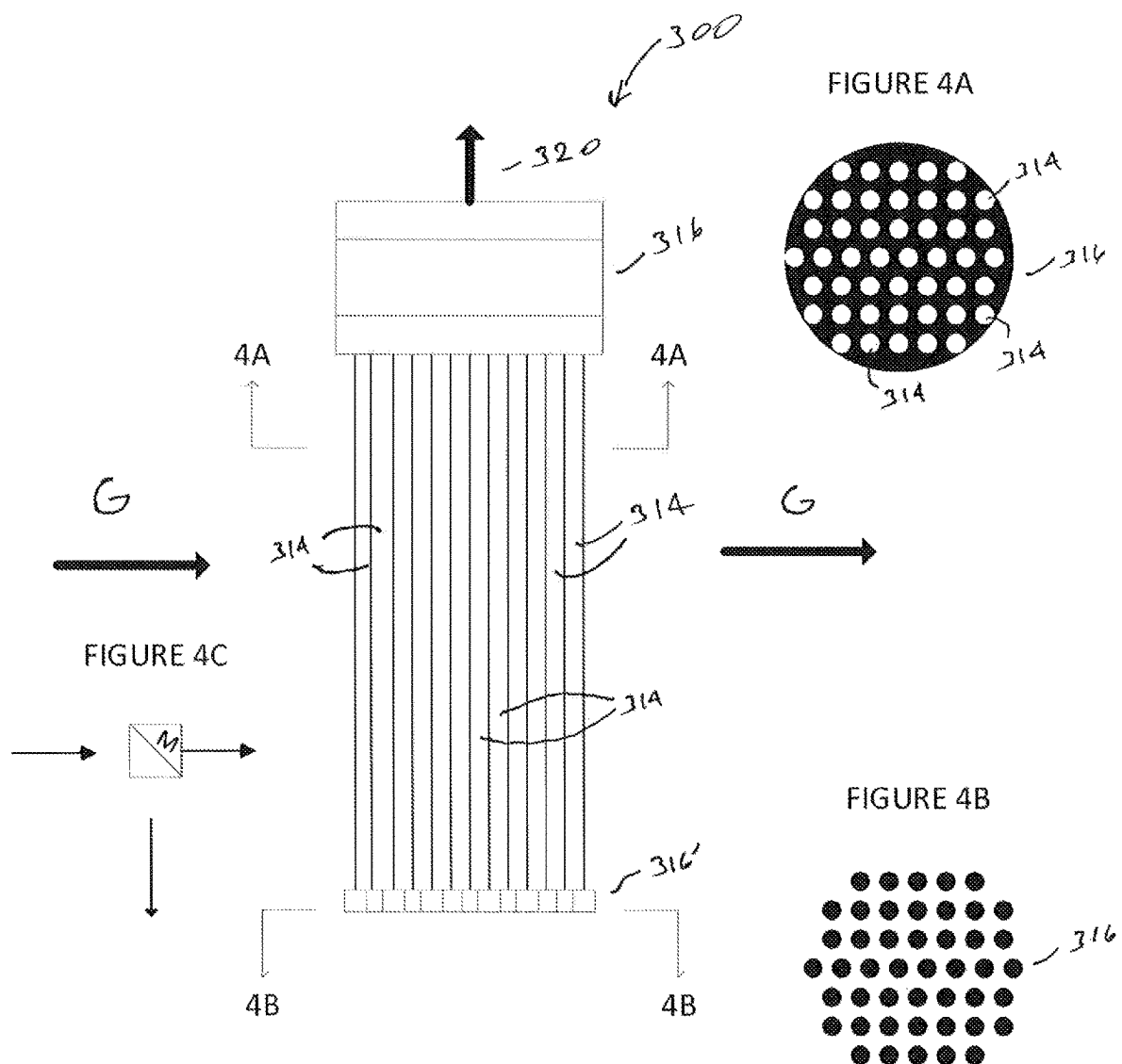


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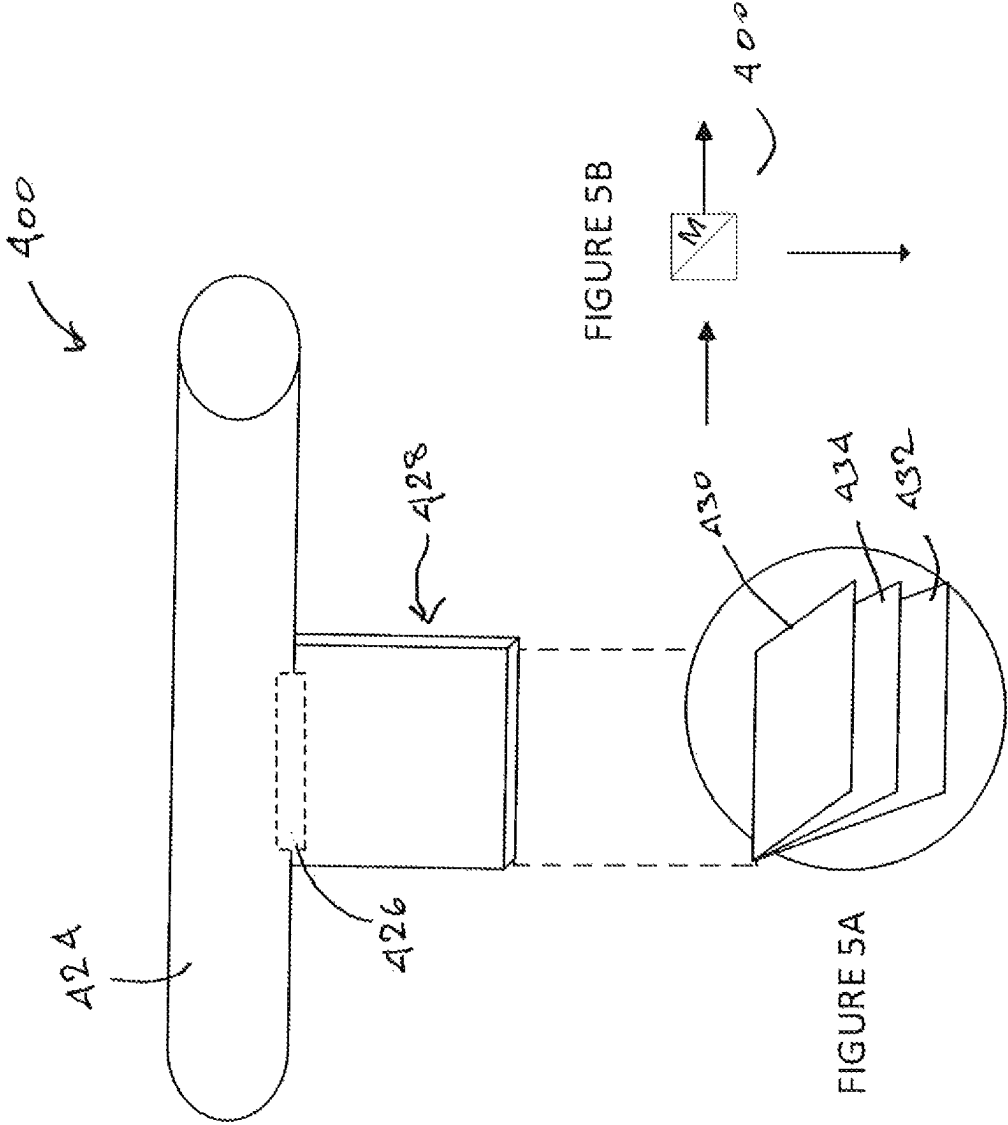


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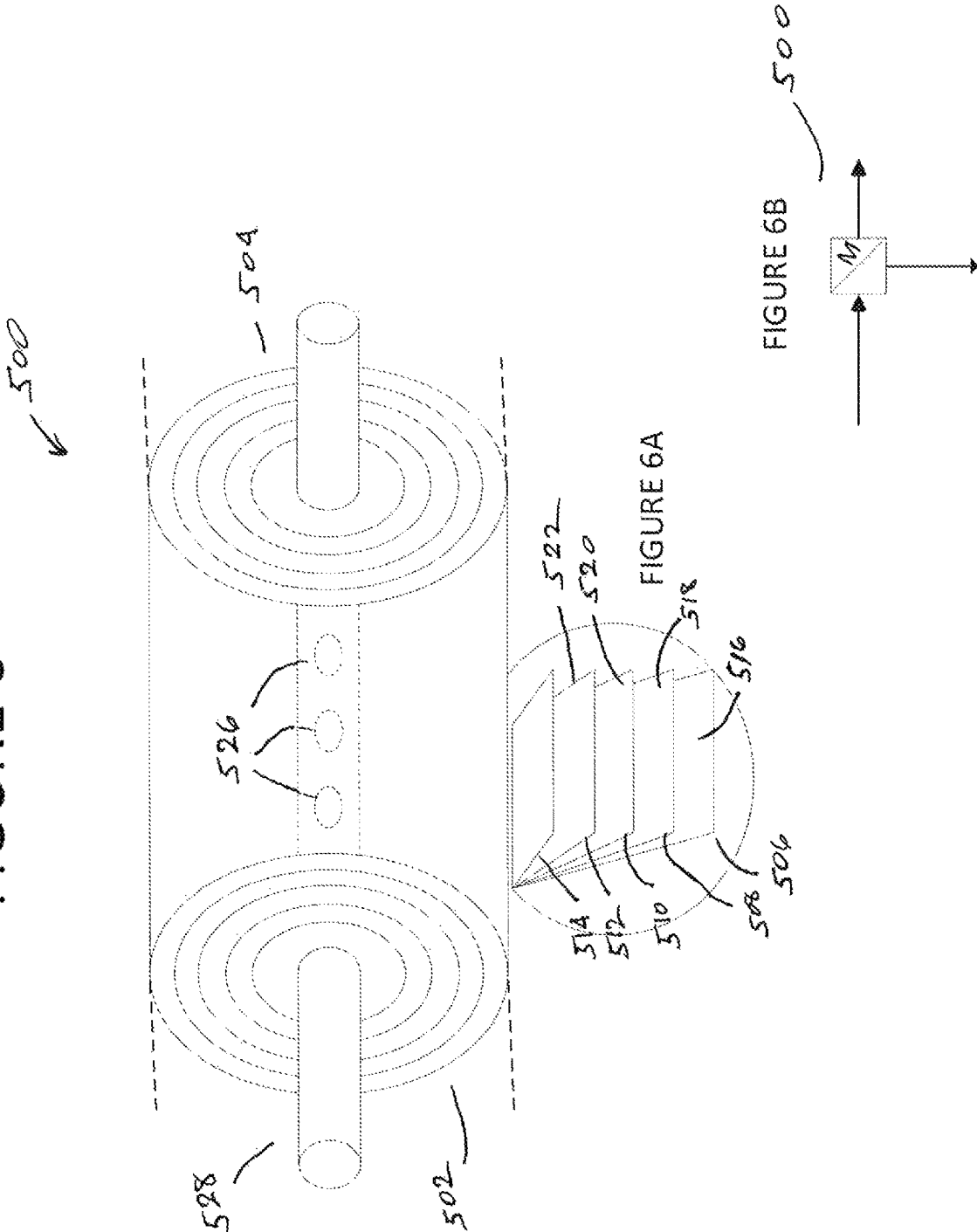


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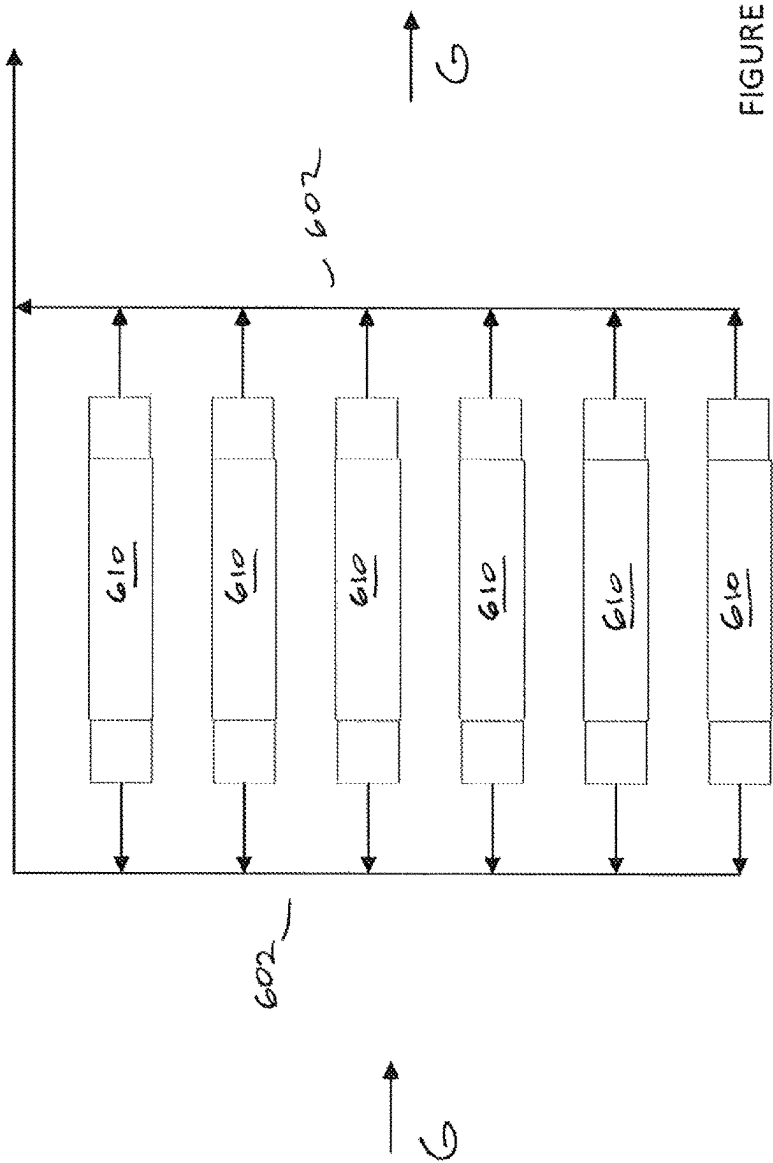


FIGURE 7A

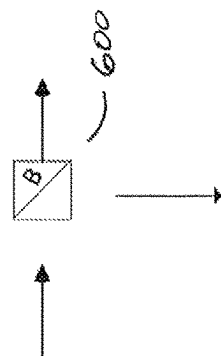


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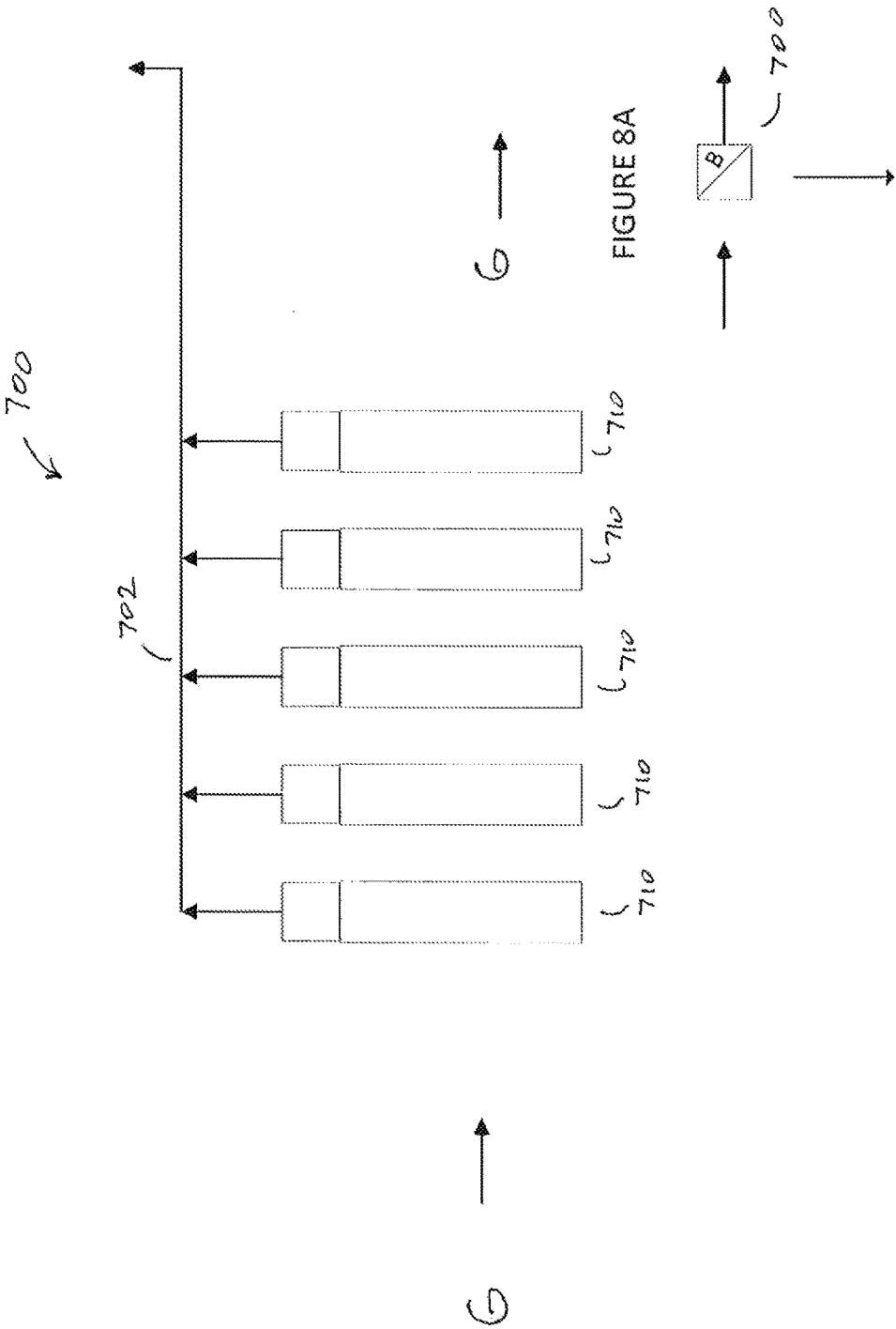


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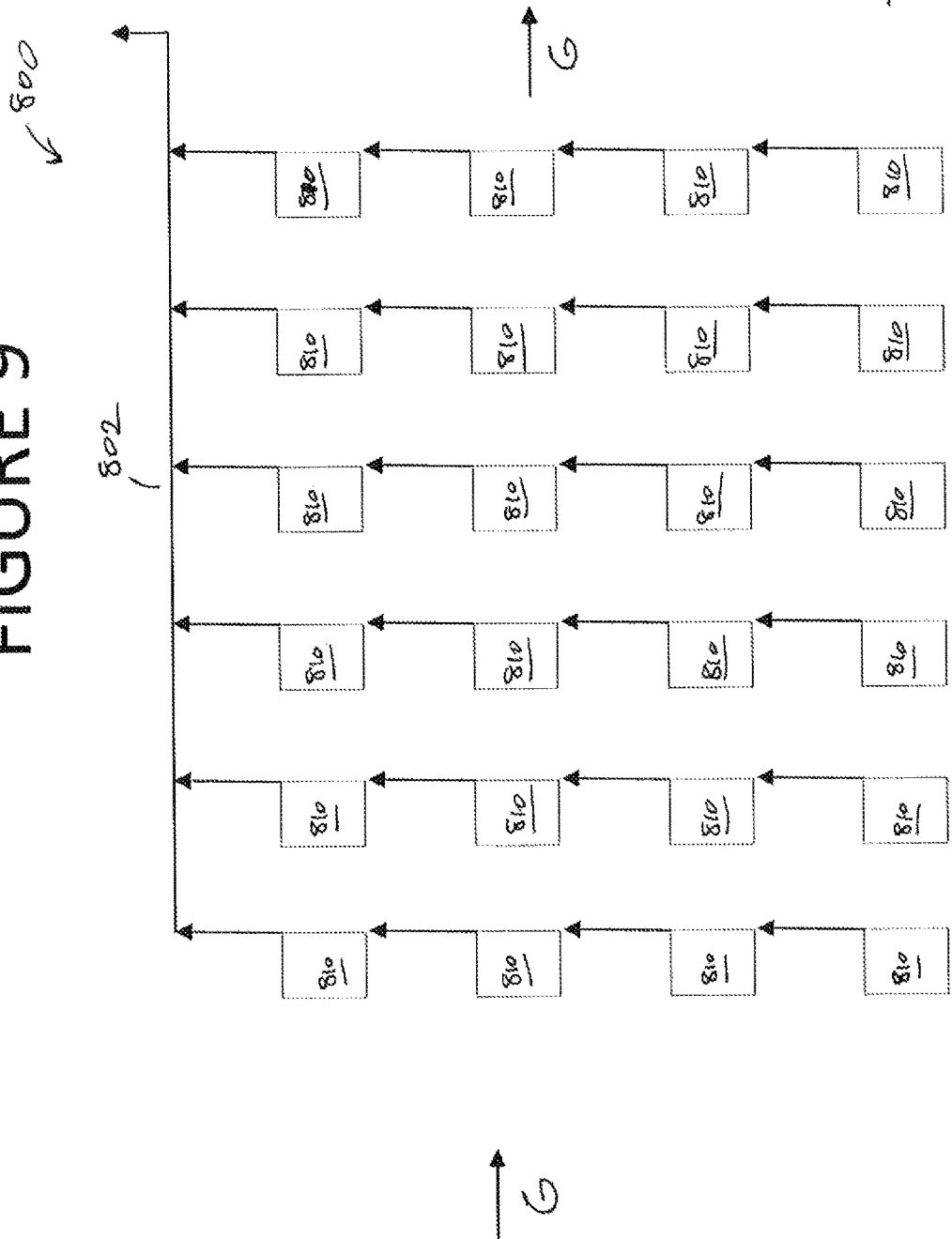


FIGURE 9A

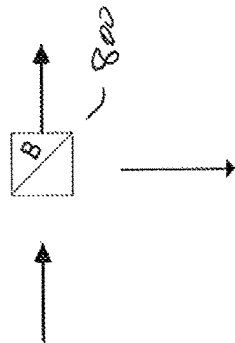


FIGURE 10

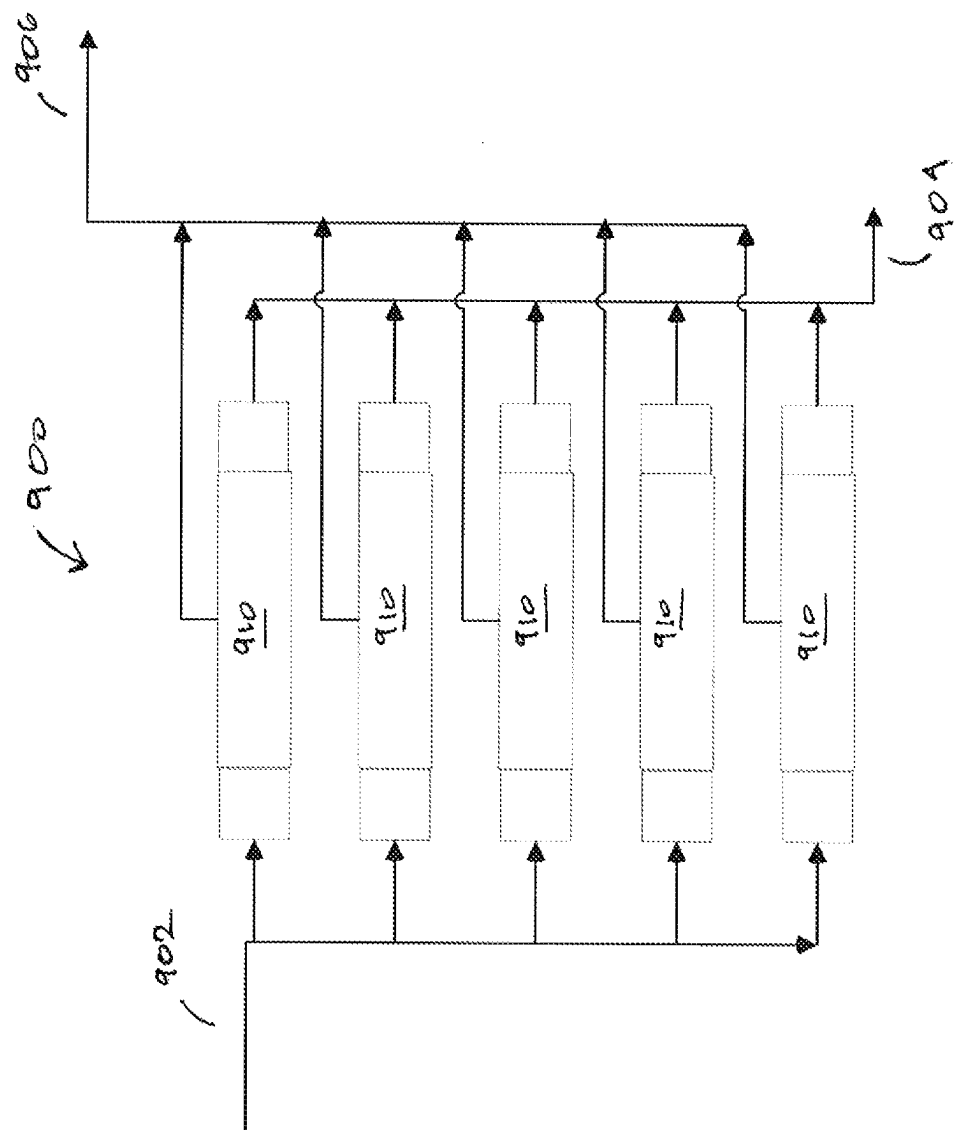


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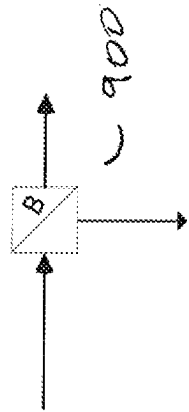


FIGURE 11

FIGURE 11A

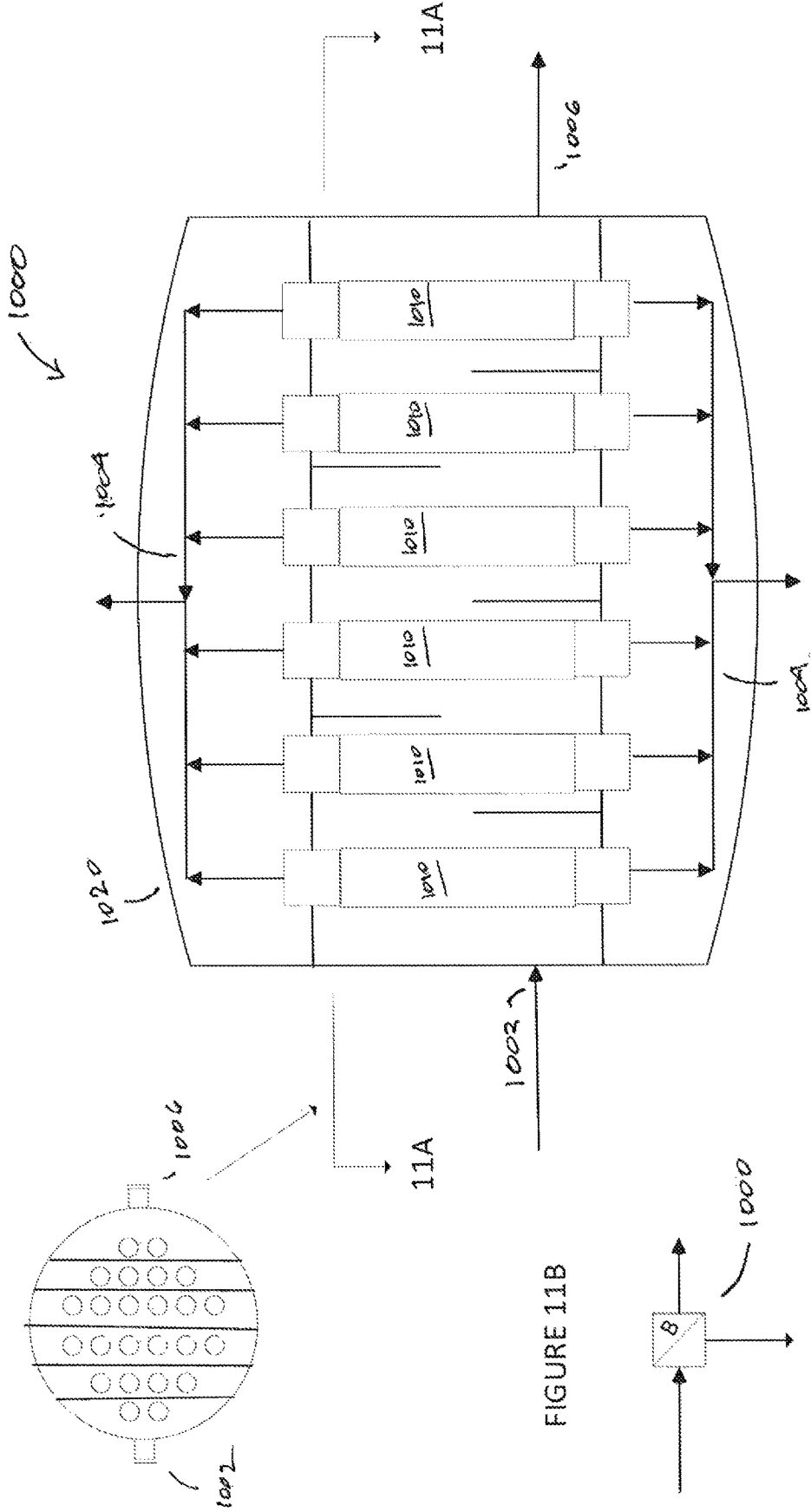
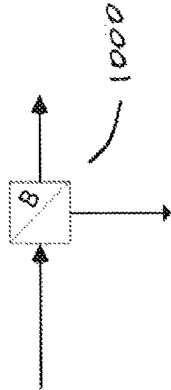
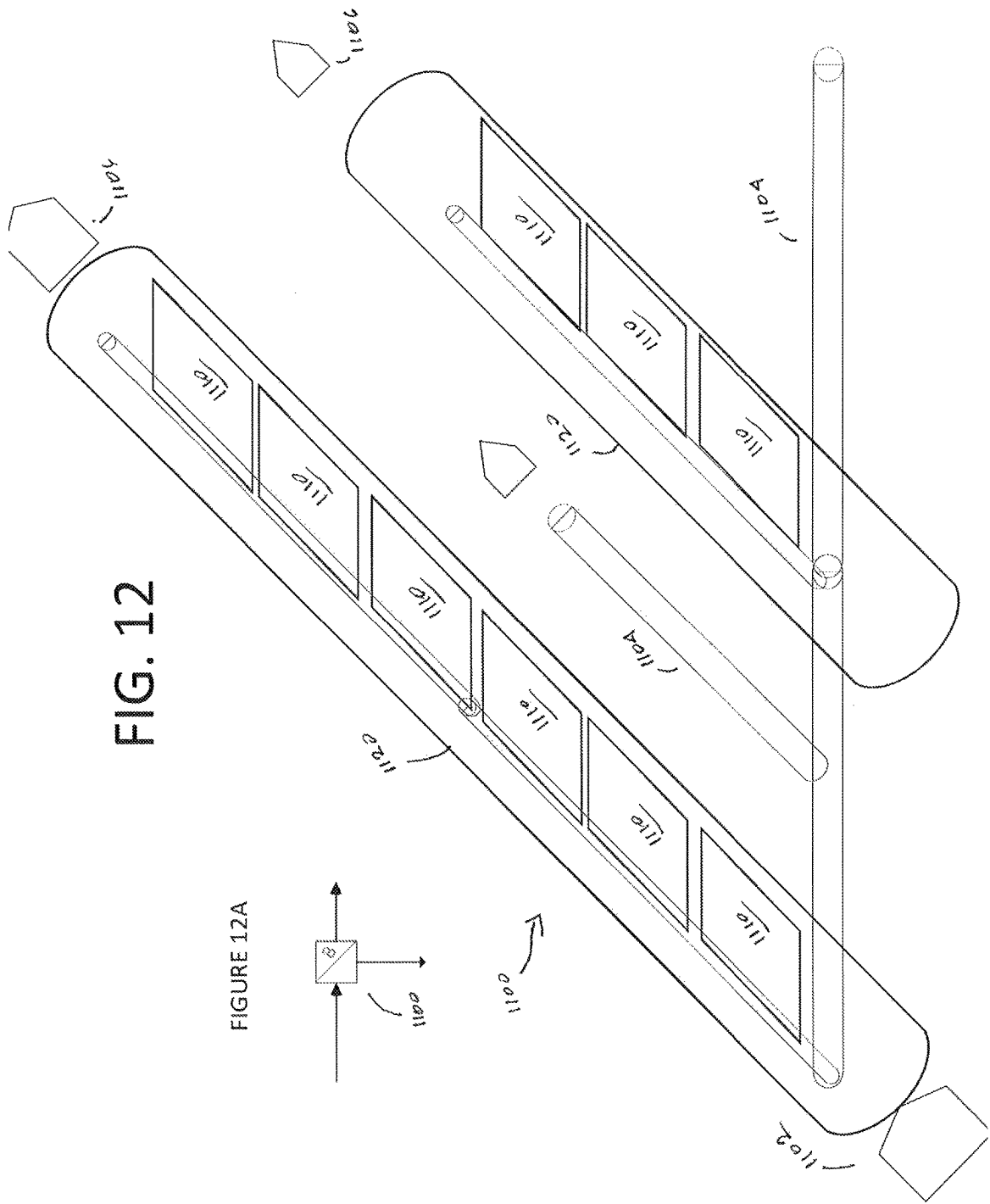


FIGURE 11B





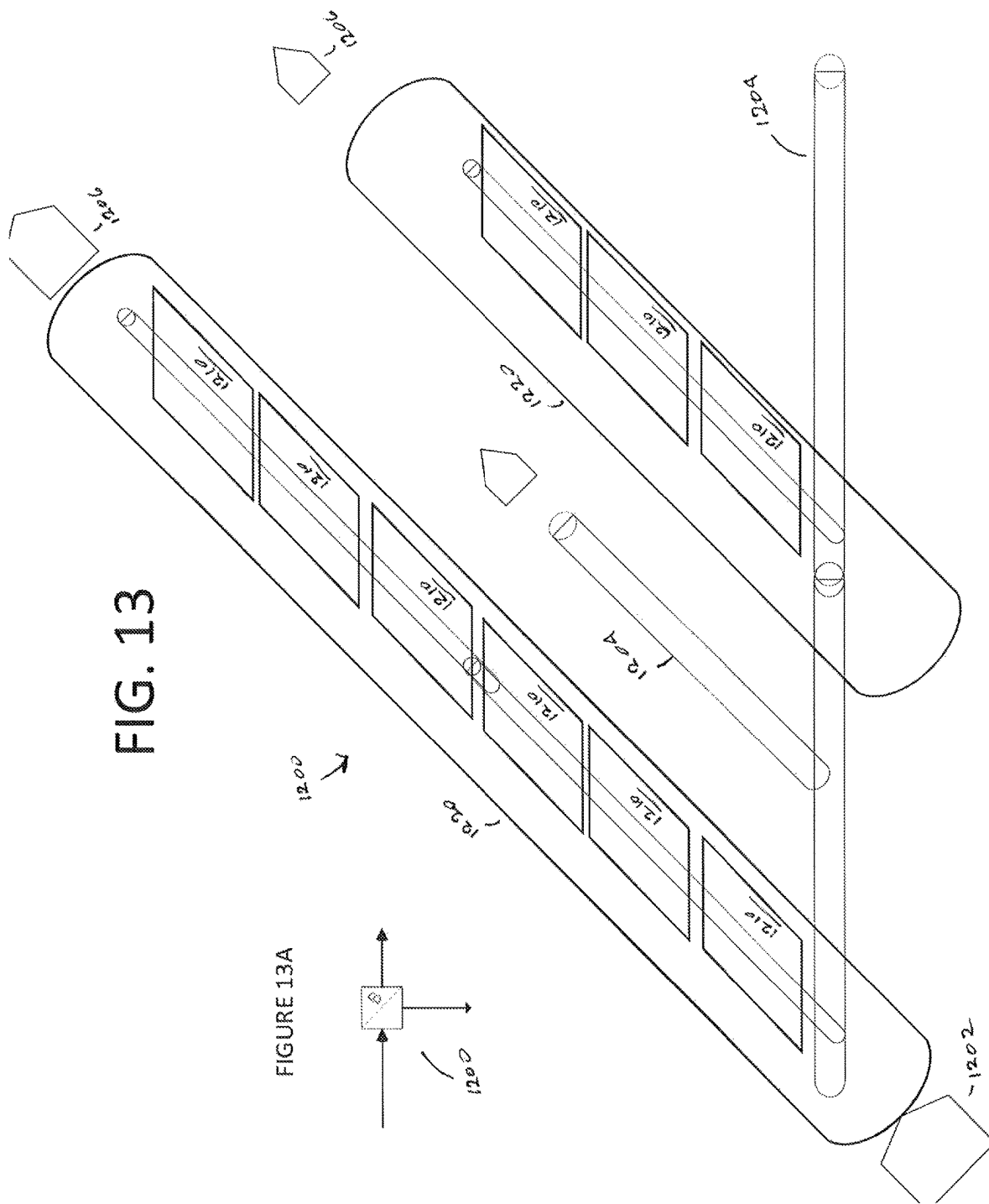
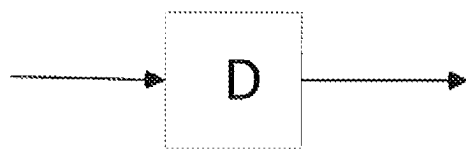


FIGURE 14



1300

FIGURE 14A

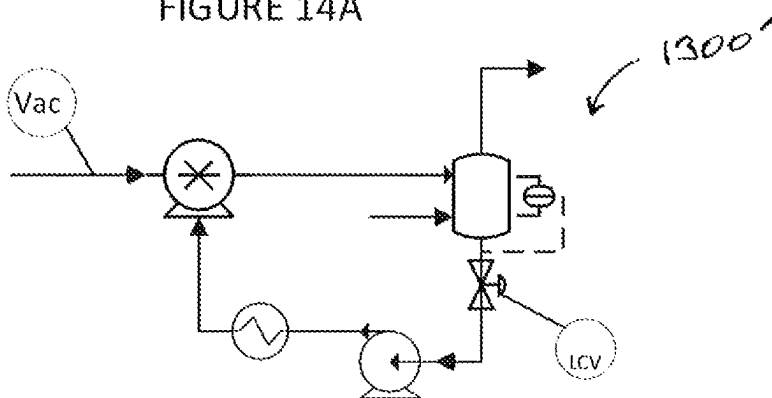
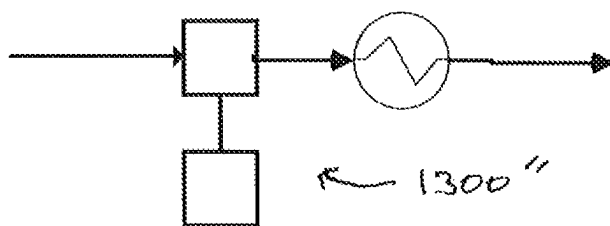
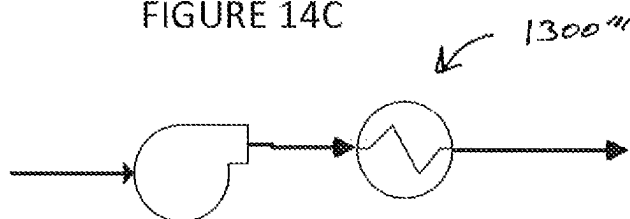


FIGURE 14B



1300''

FIGURE 14C



1300'''

FIGURE 15

FIGURE 15A

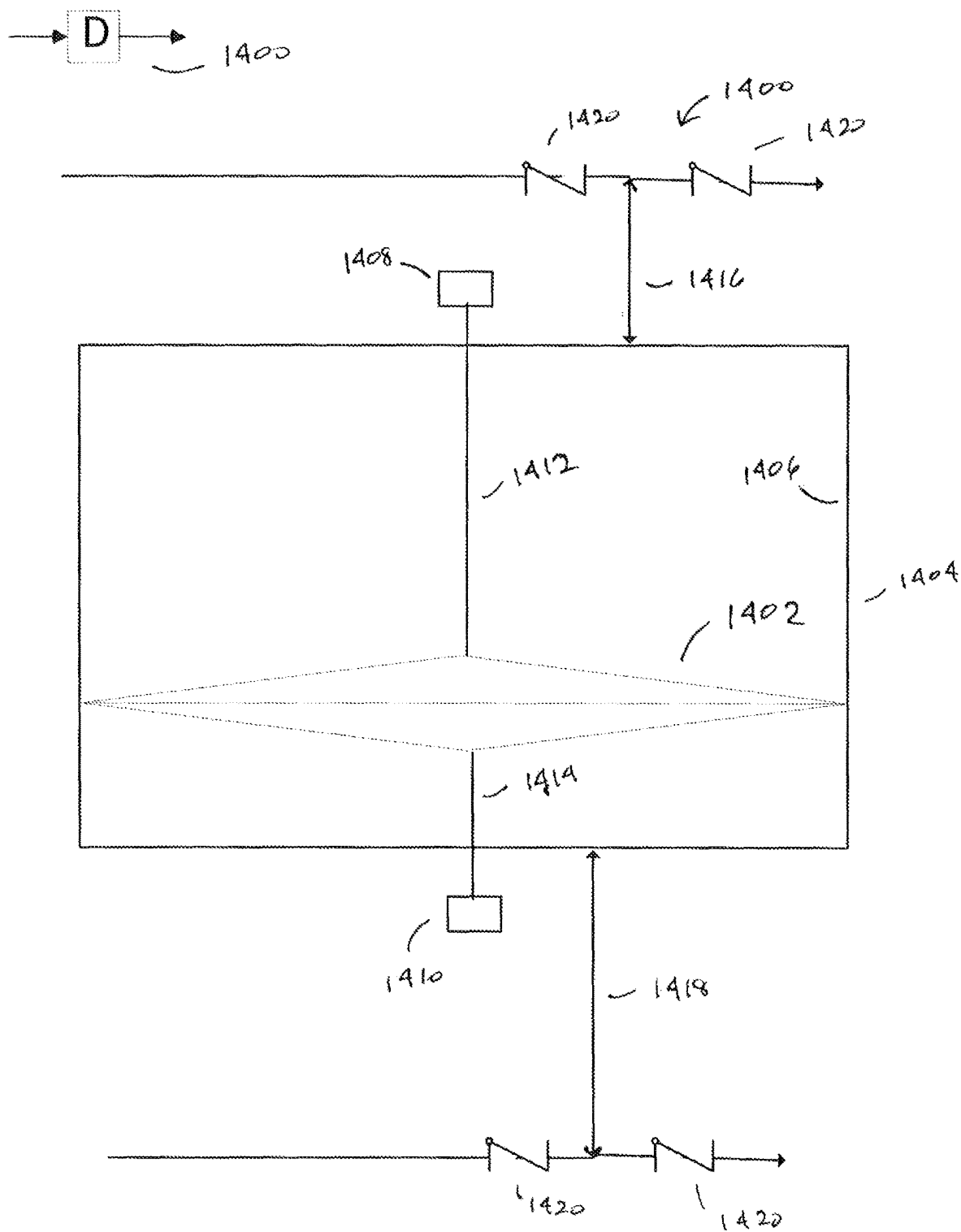


FIGURE 16

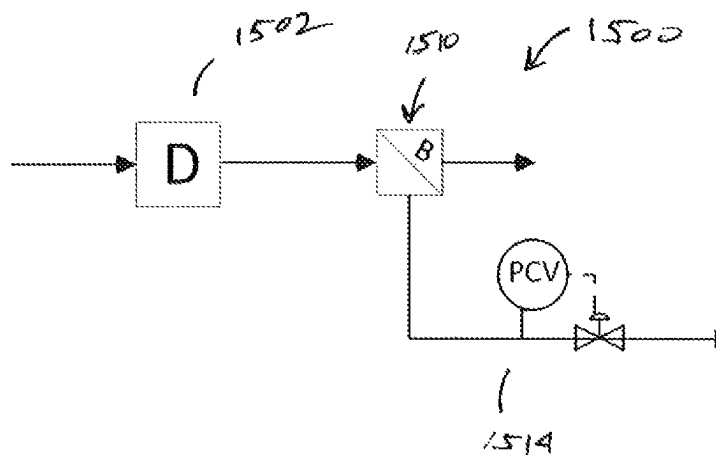


FIGURE 17

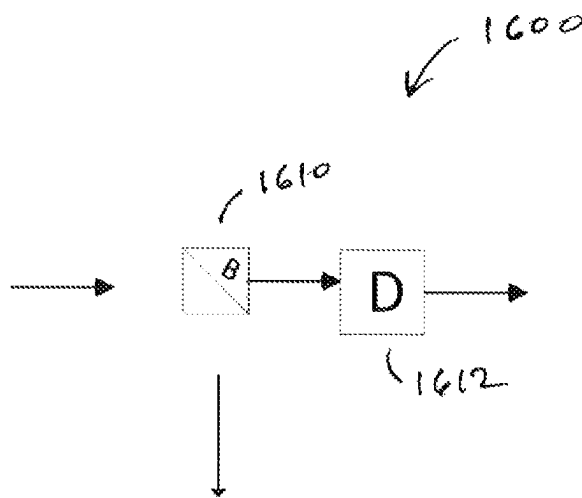


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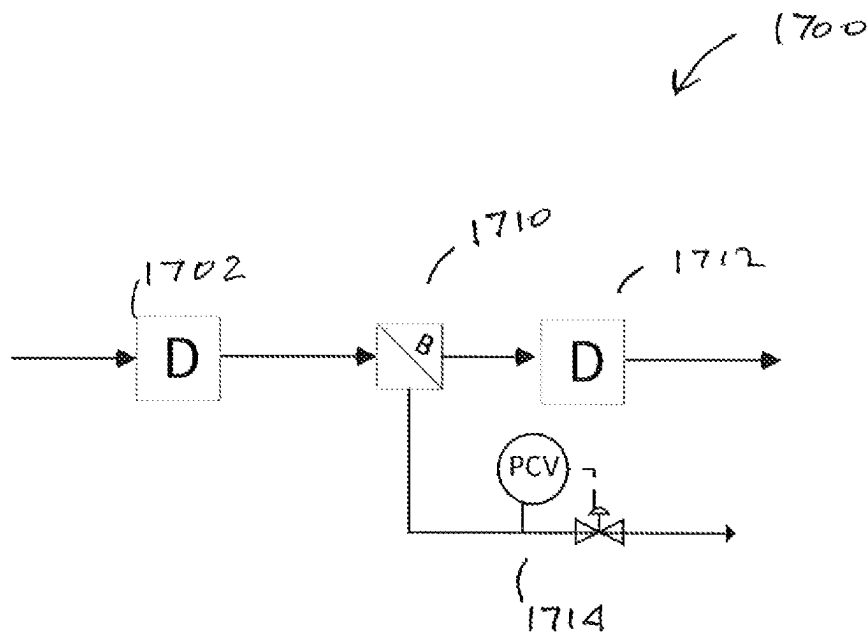


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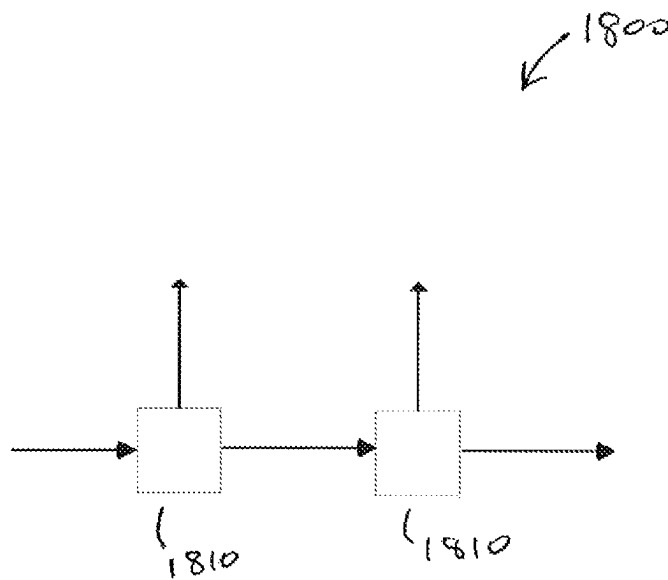


FIGURE 20

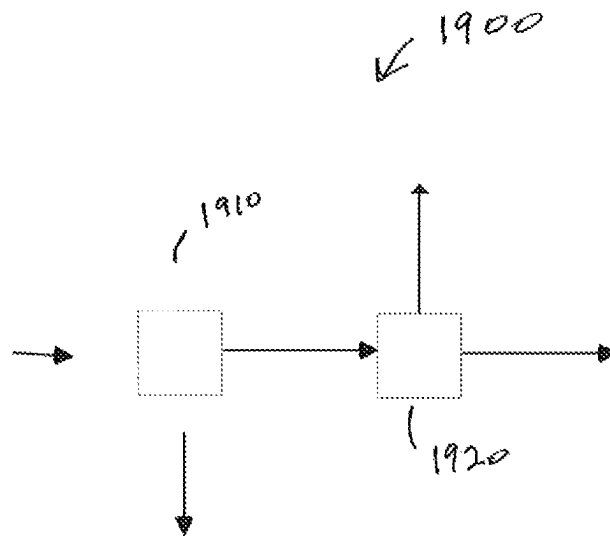


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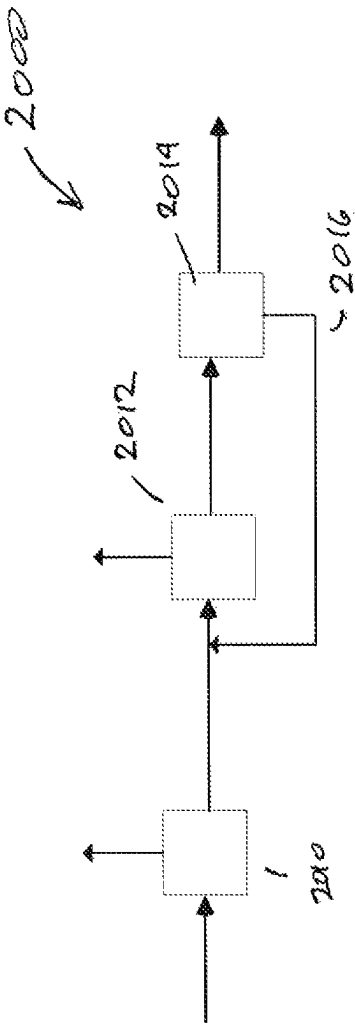


FIGURE 21A

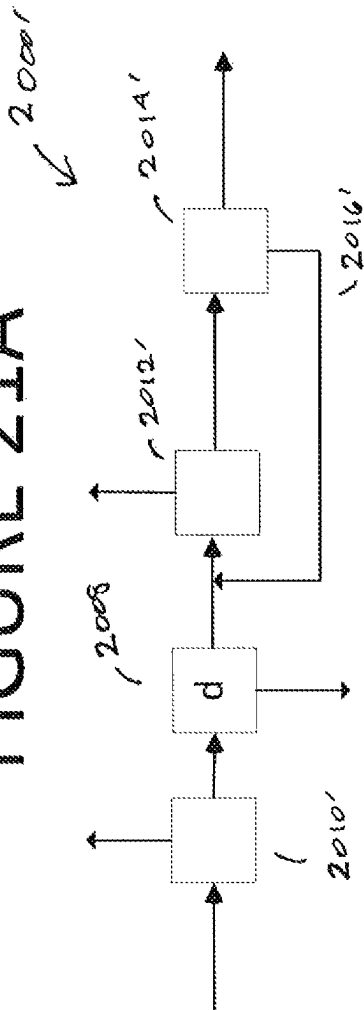


FIGURE 22

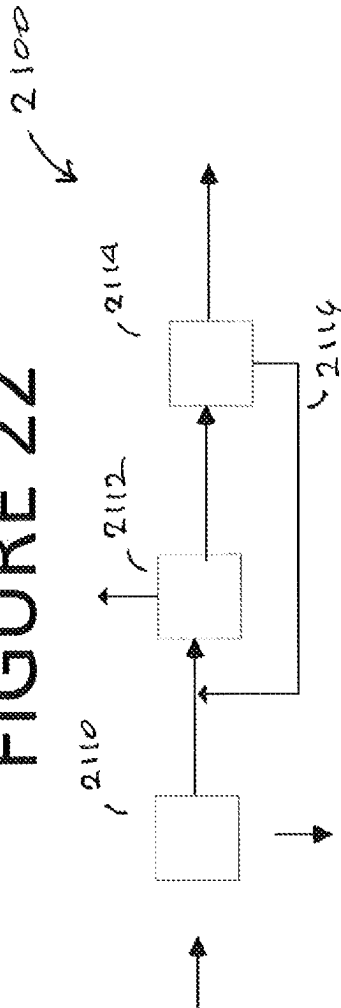


FIGURE 22A

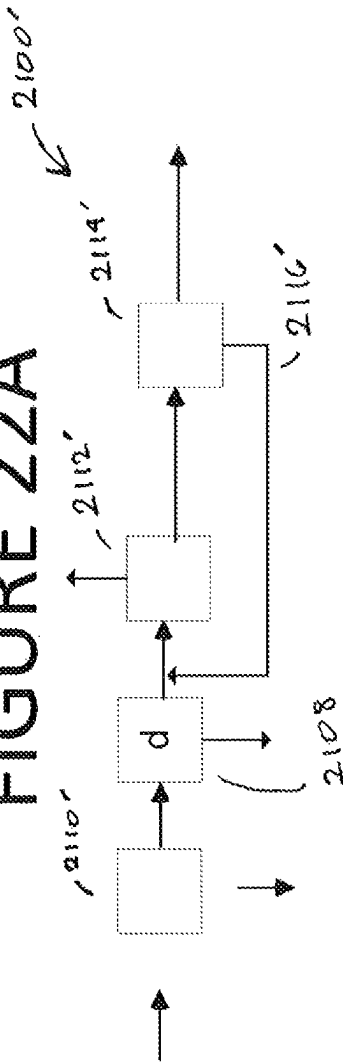


FIGURE 23

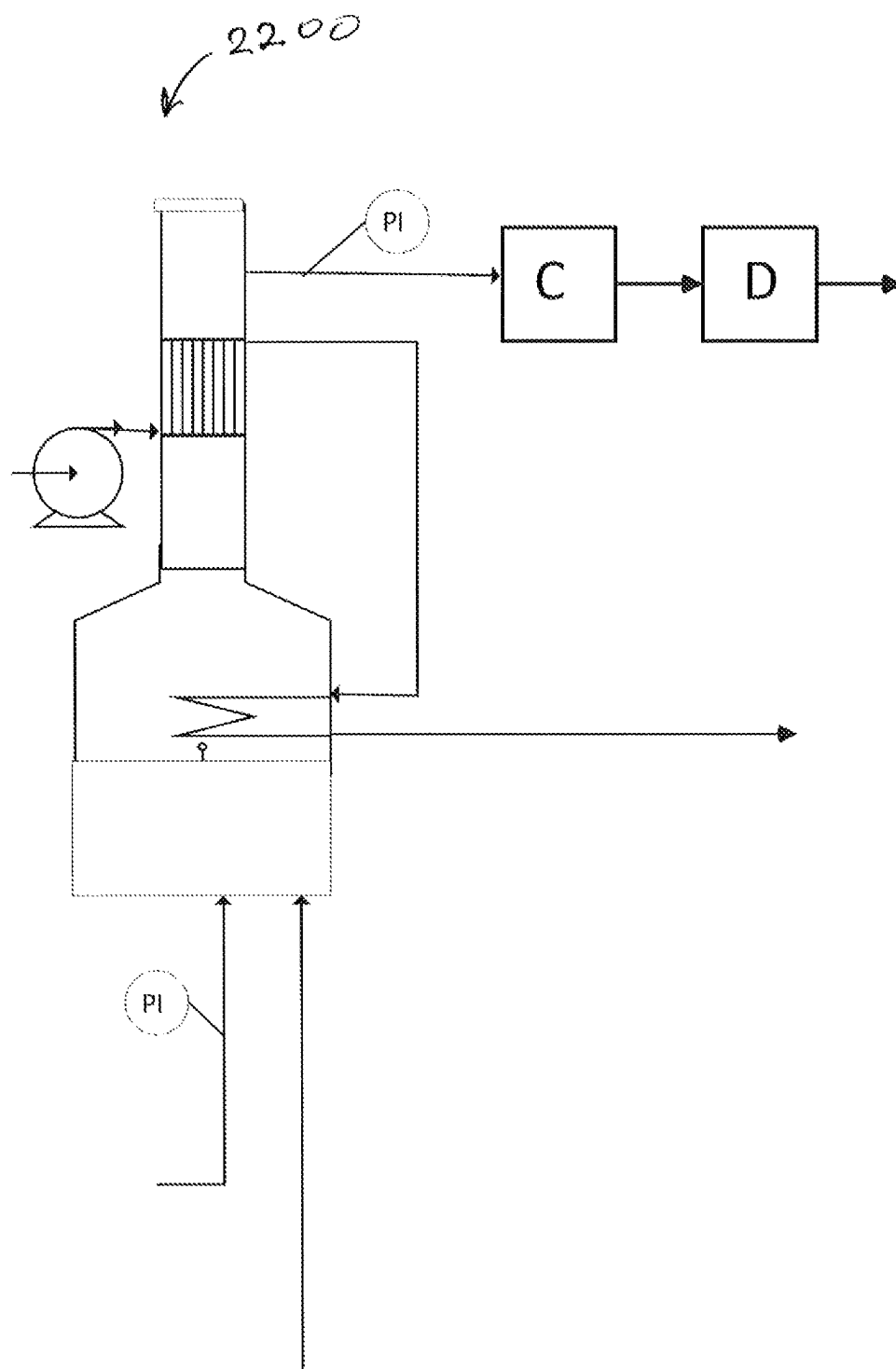


FIGURE 24

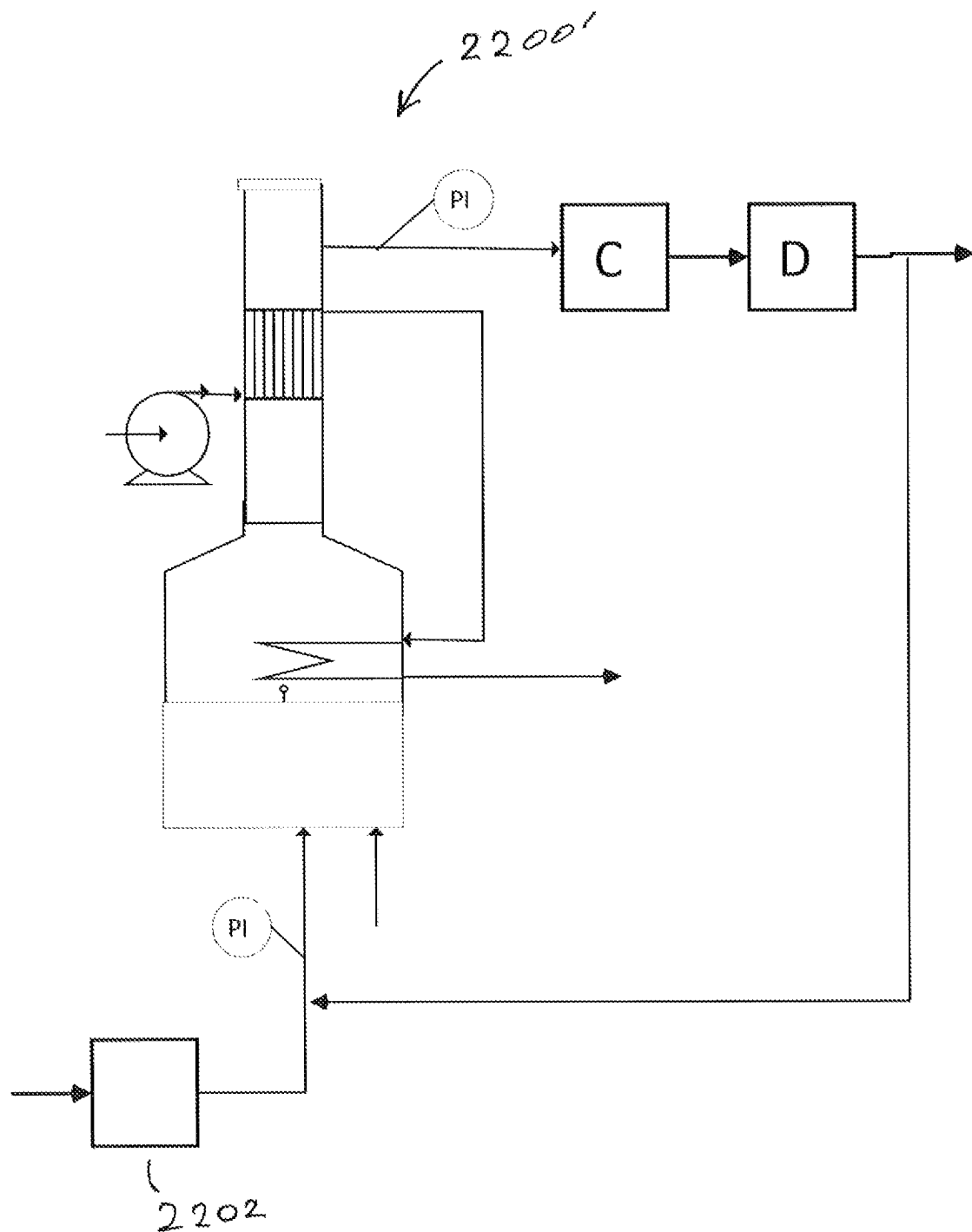


FIGURE 25

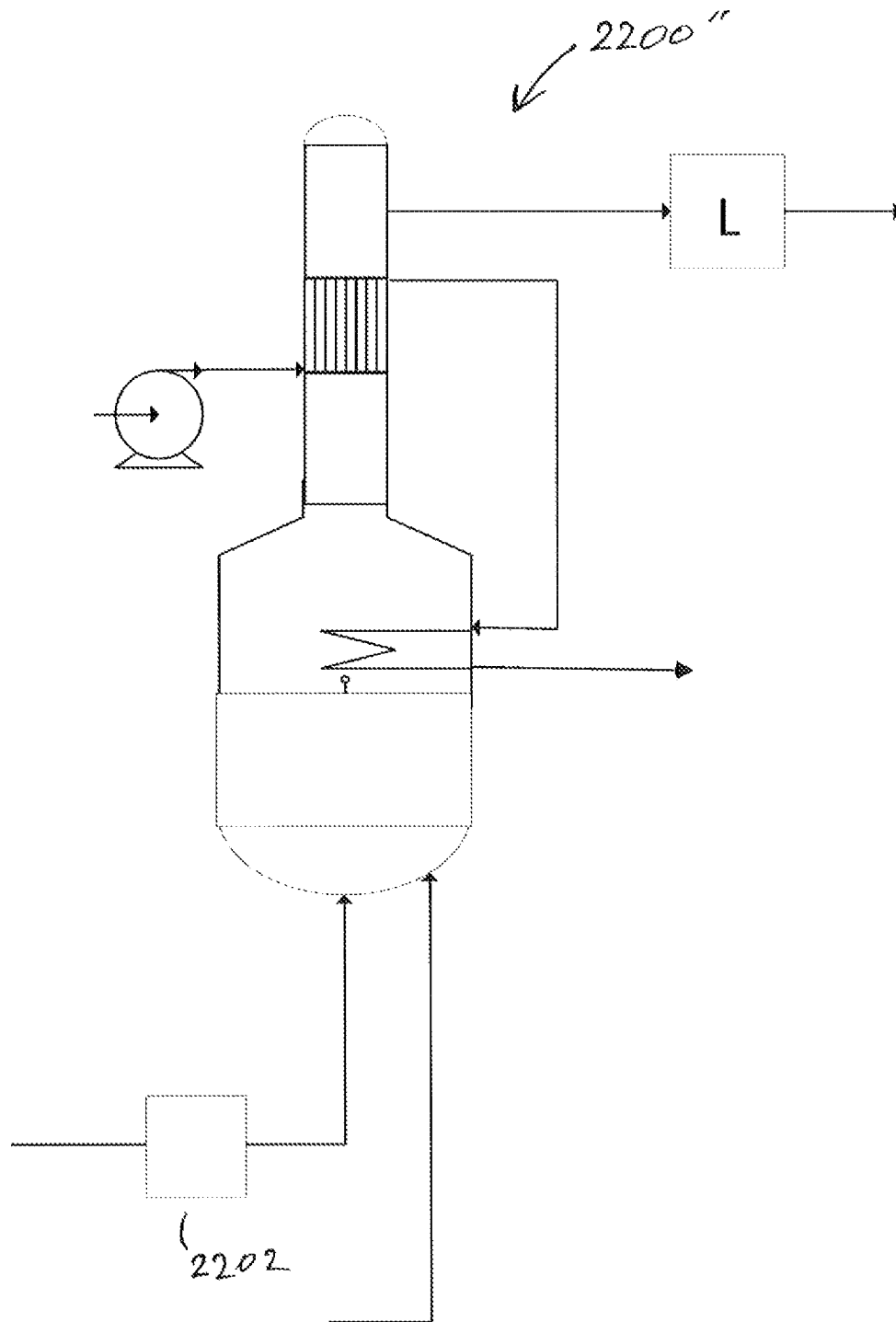


FIGURE 26

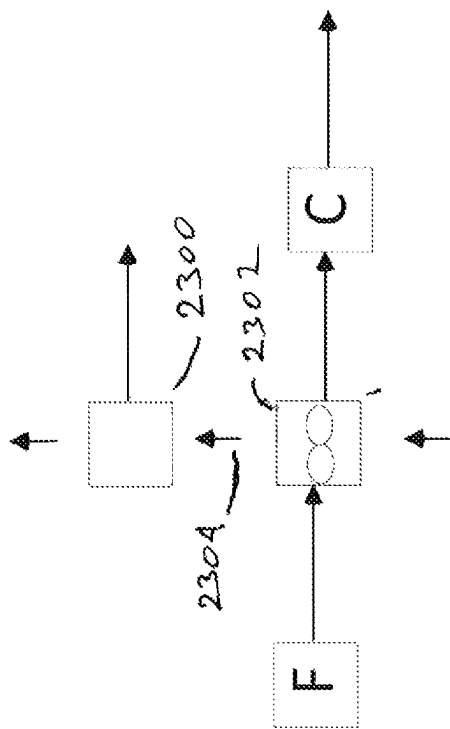
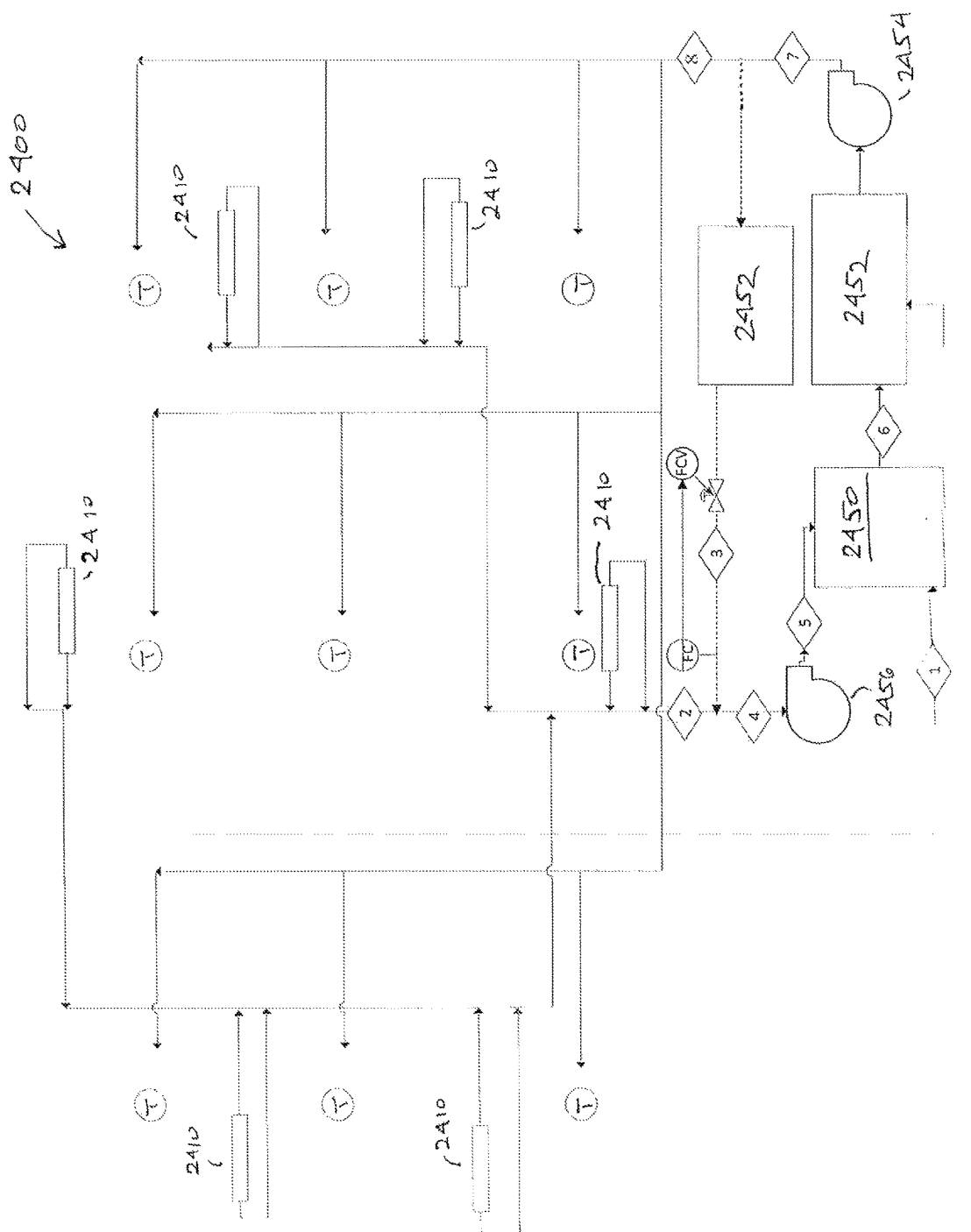


FIGURE 27



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APPARATUS AND METHOD FOR OXYGEN AND CARBON DIOXIDE ENRICHMENT OF ATMOSPHERIC AIR

BACKGROUND OF THE INVENTION

This invention relates to enriching (increasing) the oxygen and carbon dioxide components into a permeate as generated from an atmospheric air stream as processed through a membrane configuration operating under an internally applied vacuum. Embodiments of the present invention may utilize what the inventor herein refers to as a “wig” configuration. This title refers to a membrane construction comprising a plurality of individual hollow fiber membrane elements which all pass a gas permeate into a collection member commonly, but not necessarily, at a common end of the membrane elements, which loosely approximates the configuration of individual strands of hair attached to a wig cap or caps.

It is known that carbon dioxide is a major contributor to global warming. Global warming is a result of increasing concentrations of greenhouse gases (“GHG”) in the atmosphere. Industrial facilities, power plants, and transportation are the primary greenhouse gas (CO₂) contributors accounting for over 80% of greenhouse gas production in the world. Carbon dioxide is the primary anthropogenic (i.e., man-made) GHG, accounting for a substantial portion of the human contribution to the greenhouse effect in recent (under 200) years.

A carbon dioxide enriched product produced by use of this membrane configuration may be forwarded to a sequestration facility to prevent release of the carbon dioxide into the atmosphere. Embodiments of this membrane configuration may be utilized to reduce the overall concentration of carbon dioxide in the atmosphere by direct removal of the CO₂ from the air, also known as Direct Air Capture. Embodiments of this membrane configuration may also be utilized to reduce CO₂ added to the atmosphere generated by energy consumed during a process, for example by reducing the consumption of non-renewable fuel utilized to power a process or fuel combusted within the process. The term “sequestration facility” is defined herein as anyone of a variety of mechanisms which sequester the carbon dioxide thereby preventing immediate release back into the atmosphere. The term may include systems which utilize bio-sequestration, such as orchards, crops, forests, and other photosynthetic organisms which either convert carbon dioxide utilizing photosynthesis or store the carbon dioxide in the organism. The sequestration facility may also include manufacturing processes which utilize or make a product with carbon dioxide, including production of dry ice utilized for preserving items requiring cold storage during transport such as various foods and medicines. The sequestration facility may also include a system which injects carbon dioxide into petroleum reservoirs for purposes of enhanced oil recovery such as miscible flooding.

A process of the presently disclosed invention utilizes membranes to provide an enriched oxygen stream—as opposed to the commonly used air feed stream—to a flue gas generator, or other devices which use air or oxygen in a reaction process to produce a product, (sometimes collectively referred to herein as “oxygen reaction devices”) to decrease the energy demand and/or increase the capacity of such oxygen reaction devices. The use of the enriched oxygen stream realized through the membrane configurations disclosed herein may thereby decrease non-renewable fuel (natural gas, gasoline, coal) consumption and thereby

2

reduce the production of green house (CO₂) gas emissions. As well, the CO₂ in the flue gas of an oxygen enriched flue gas generator is more highly concentrated, making the CO₂ more economically capturable.

For purposes of this disclosure, the term “flue gas generator” is defined as a stationary (non-mobile) or mobile device which normally emits elevated concentrations of carbon dioxide to atmosphere within an emitted gas stream. Examples of stationary flue gas generators are industrial steam generators, biogas/natural gas/coal fired power plants, ethanol plants, amine regenerators, cement manufacturing kilns, fermenters, water heaters and heater furnaces. Examples of mobile flue gas generators are automobiles, trains, and air planes with internal combustion or jet engines. Examples of other “oxygen reaction devices” include activated sludge reactors producing biogas, sulfur recovery units making sulfur from a refinery or gas plant acid gases, ethylene oxide production units, syngas plants, and apparatus utilized in pyrolysis processes and glass manufacturing.

In the case of stationary flue gas generators, the flue gas with highly enriched CO₂, can be captured and thus utilized for various commercial uses, which may include enhanced oil recovery operations, agricultural use, medical applications, and other known commercial applications.

There is an ongoing and critical need for additional mechanisms and methods for reducing consumption of non-renewable fuels and reducing energy’s contribution to atmospheric carbon dioxide, also known as energy carbon management.

SUMMARY OF THE INVENTION

Embodiments of the present invention exploit the unique property of membranes to economically achieve direct air capture and/or produce an enriched carbon dioxide stream from atmospheric air (i.e., having an approximate normal air dry composition of 20.9% Oxygen, 78.05% Nitrogen, and 0.04% or 400 ppm CO₂ by volume). Water composition in air varies more than other components and is significant depending on ambient temperature. Water vapor concentration in normal air can be as high as 4% at 120 F, and for example, at -40 F can be as low as 0.2%. Carbon dioxide, oxygen, and water vapor is separated from nitrogen in the air feed stream by the disclosed membrane configuration to produce a permeate or product stream comprising enriched (higher than normal air) concentration of carbon dioxide, oxygen and water, and a separate residue or biproduct stream with enriched nitrogen.

Processes utilizing the membrane configurations disclosed herein are distinguishable from other known processes which yield only highly purified (90%+) concentrations of carbon dioxide, nitrogen, and oxygen, such as cryogenic air separation units (ASUs) or Vacuum Pressure Swing Absorption (VPSA). ASU systems require significantly higher capital expense and significantly higher operating costs. Moreover, these systems may present significantly higher operational risks because of high operating pressures and/or sub-freezing operating temperatures. VPSA and conventional multiple stage prior art hollow fiber require higher feed and operating pressures. In comparison, embodiments of the present invention operate at low pressure and near ambient temperature. In the case of conventional membranes, the air is pressurized at conventionally 120 to 150 psig into the tube side channels, tube-sheets and through the internal bore of the hollow fiber tubes, and the

3

permeate passes through the pressurized tube inner wall to pass into the shell enclosed side encasing the bundle of membrane tubes.

In contrast, embodiments of the presently disclosed membrane units drive the feed not by pressurizing the much higher capacity feed stream, but by pulling a vacuum on the relatively smaller product permeate stream into the bore side of the tubes, a stream with $\frac{1}{3}$ to $\frac{1}{2}$ the total volume of the feed gas, thus requires $\frac{1}{3}$ to $\frac{1}{2}$ the energy required for conventional membrane. The performance of the membranes of the present invention is also approximately 30% higher than for conventional air separation membranes, because there is no pressure drop on the residue side, and the membranes of the present invention have air first contact with the hollow fiber tube on the exterior wall of the tube, which has inherently high area per tube than the conventional membrane's air first contact of the inner bore wall. Performance is further enhanced by the lack of any pressure drop on the residue side, and higher volume flow rates allowed on the "shell-less shell side." The commercial manufacturing cost of the membranes of the present invention may be significantly reduced, as embodiments of the membranes of the present invention can be produced with a single tube sheet instead of two tube-sheets and does not need a shell enclosure.

Embodiments of the present invention may further have a desiccant system on the 1st stage permeate, which potentially saves approximately 40% on the downstream stage energy in comparison to conventional membrane processes. It is noted that the materials and technology utilized in the field of membranes take advantage of an aspect not available to the cryogenic or specifically more competitive VPSA adsorption materials and technology. Specifically, a membrane can equally process CO₂ and oxygen in a vacuum as it can under pressure. Membranes perform based on Fick's law and the higher the partial pressure differential between the permeate and the feed, the primary process control parameter driving "flux" or a component's flowrate through the membrane to the permeate side of a specific material, the better the separation performance of the membrane. Thus, if the partial pressure drop is caused by a difference between two positive partial pressures or a negative or vacuum based partial pressure and positive partial pressure are equal, the performance of the membrane is the same, all else being equal. Not so for adsorbents. Adsorbent performance is based on the Langmuir isotherm where the fraction adsorbed varies linearly with partial pressure. Thus if the absolute partial pressure increases, then adsorption increases, and vice versa, thus this is why regeneration or desorption can occur in a vacuum.

Embodiments of the presently disclosed membrane units may be configured in with a primary (single stage) unit producing a mild or moderate increase (enrichment) in concentration of oxygen (up to 50%), water, and carbon dioxide (up to 1200 ppm) in a product stream which is achieved by utilizing the membrane unit to separate out nitrogen from normal ambient atmospheric air. When utilized for oxygen enrichment of the combustion air with a flue gas generator the resulting concentration of CO₂ emitted from the flue generator may be over 20%, and 33% when water is removed. The resulting permeate stream does not have to be highly purified in carbon dioxide or oxygen or water to attain significant benefits, although the resulting permeate may be further processed with embodiments of this invention to produce highly purified oxygen with a secondary and/or tertiary (2nd and/or 3rd stage) membrane or other form of enrichment, and highly purified CO₂ (up to

4

90% requires at least a third stage.) By capturing and removing water from the flue gas of a highly oxygen (up to 90%) enriched combustion oxygen fed stationary flue gas generator, a very highly purified (99%+- potable) water as removed from the CO₂ bearing flue gas of a flue gas generator with embodiments of the present invention can be achieved.

Embodiments of the presently disclosed membrane units may utilize membrane materials having properties similar to those of the cellulose acetate based sheet membrane units of the flat or spiral wound type such as used in the Separex™ membrane product as manufactured by Honeywell/UOP, or other polymeric based membrane materials such as used in "plate and frame" type Polaris™ membranes units as manufactured by MTR, Inc., or used in hollow fiber type membrane units such as Cynara™ membranes manufactured by Schlumberger, or PRISM™ membranes as manufactured by Air Products, or Nitrox™ membranes systems as manufactured by Generon. However, these known conventional membrane devices have significant supporting structure and require multiple blowers or compressors for operation of the systems as compared to the processes required for membranes having the wig configuration disclosed herein.

Membranes configured from the above listed membrane materials and products may be utilized to enrich the oxygen, water, and carbon dioxide concentrations of a gas stream processed through the membrane units. Carbon dioxide, water, and oxygen pass or permeate more rapidly through the membrane relative to nitrogen, thereby forming a permeate stream which is more concentrated or enriched in oxygen, water, and carbon dioxide than the "feed" stream. It is noted that the term "feed" is used somewhat loosely for purposes of this disclosure and does not refer to a stream delivered to the membrane via a compressor or blower and with an intake or similar structure. With embodiments of the presently disclosed wig membrane configuration, a "feed" side of the membrane unit is simply the air exposed exterior sides of a collection of membrane hollow fiber tubes, which are suspended on one or both ends by a tubesheet(s), where a gas (i.e., air) flows or blows against the exterior outside walls of the deployed tubes. The air can blow as wind naturally, or warm air under (150 F) can be force drafted, such as from the discharged air of an air-cooling unit, across the external wall of the membrane tubes. It may be noted that for this embodiment of the invention, providing a higher velocity air passing over the exposed hollow fiber tubes, and/or a higher temperature over the exposed hollow fiber tubes further improves the performance (energy savings and enrichment) of the wig membrane unit above the conventional prior art hollow fiber membrane units (CHFMU).

Other significant benefits of the "wig" membrane units over conventional membrane units, especially CHFMU, is the lower fabrication cost of the membranes having the wig configuration. As indicated above, these savings are due in part due to an embodiment of the primary wig membrane unit having only a single outlet tube sheet—as all CHFMU used for oxygen enrichment from air have two tube sheets, an inlet tube sheet and an outlet tubesheet. Further, all embodiments of the primary wig membrane unit have no shell unlike all CHFMU. Another benefit of the wig configuration over CHFMU is lower energy consumption due to lower pressure drop, higher performance (i.e., capable of producing higher concentrations of oxygen due to the lower pressure drop), and pliability of the membrane allowing better fit into secondary membrane structures as needed for other membrane configurations.

The permeate—nitrogen depleted air—is brought into the interior (bore) of each membrane tube by a vacuum applied to the open end or ends of each membrane tube at the outlet tubesheet(s). Gas components, predominantly nitrogen, which pass relatively slowly through the membrane in comparison to oxygen, carbon dioxide and water, remain mostly on the outside of the membrane tubes, and pass over the tubes remaining in the atmosphere. The permeate is collected through tubesheet(s) into a permeate conduit or channel, such as ducting, which collects the permeate from one or more of the wig membrane units and forwards the permeate as desired.

In one embodiment of the invention, a stationary flue gas generator may be disposed between a primary membrane unit and a sequestration facility as defined above. The oxygen reaction processes utilized in flue gas generators conventionally use atmospheric air that produce a wet (meaning concentration with water) flue gas that contains lower nitrogen concentrations (65 to 74%) and much higher carbon dioxide concentrations (5 to 11%) with respect to that found in wet atmospheric air (approximately 78% and 0.04%, respectively.) As indicated above, the flue gas produced by introducing the permeate stream generated from the disclosed membrane units in place of conventional atmospheric air, can have a lower yet (almost half) the concentration of nitrogen (down to 40%) and higher yet concentration (almost double) of over 20% carbon dioxide in the flue gas, thus a flue gas significantly more dilute in the component nitrogen and much more significantly higher in concentration of the component carbon dioxide than in atmospheric air or than in the flue gas exhaust from a conventional flue gas generator using atmospheric air for combustion. This carbon dioxide in the flue gas can be even more concentrated in CO₂ (up to 80%) when a secondary membrane unit is added, and the bulk component of water is removed (in a usable and pure form as a separate product) thus making the flue gas itself actually a highly concentrated CO₂ product that can be more economically transported, processed and capturable as may then be utilized in more of the types of sequestration facilities discussed above.

Further, these lower concentrations of nitrogen produced in the oxygen feed replacing combustion air to the flue gas generator contribute to decreasing the volume of gas processed through the flue gas generator, and thus allows for increased capacity and thermal efficiency (due to the thermal properties of CO₂ versus nitrogen) of the flue gas generator, providing fuel savings while lowering NO_x production and concentration in the flue gas emissions. Further, the higher firing temperature in the flue gas generator because of reduced nitrogen concentration, allows for low heat value fuels, such as renewable biogas, to be used without requiring supplemental feed of high heat value non-renewable fuels, such as natural gas. The higher firing temperature also produces a more valuable and recoverable waste heat, adding further to the thermal efficiency and fuel savings. In some embodiments of the invention the flue gas generator may be pressurized thereby eliminating the need for downstream cooling/pressurization of the flue gas prior to being processed for sequestration.

For higher than 90% concentration of oxygen, especially useful in other devices which use air or oxygen in a reaction process to produce a product other than flue gas generators, embodiments of the present invention may also comprise a secondary (or tertiary) enrichment system which utilizes the permeate from a primary or first stage membrane unit as a feed for secondary membrane units contained within enclosures such as conduit or piping or as feed for a cryogenic air

separation unit (ASU), or a vacuum pressure swing adsorption unit (VPSA), or a temperature swing absorption unit (TSA) or other forms of oxygen separation such as ion transport membranes (ITM). In the case of using 90% oxygen in a flue gas generator, the flue gas can have dry concentrations of CO₂ that exceeds 90%. Another benefit of using primary enrichment is the significant reduction in capital and operating cost of the secondary enrichment system.

A further benefit of another embodiment of the invention is the use of a recycle stream of cooled flue gas to the combustion zone (oxygen enriched feed location) to mitigate higher firing temperatures produced when oxygen enrichment to a flue gas generator is used, also known conventionally as oxy-combustion. This requires a larger vacuum device at the outlet tubesheet if only a primary wig membrane unit is used, or larger vacuum or blower device at the outlet of a secondary enrichment system when a secondary enrichment system is used. Secondary oxygen enrichment with recycle allows for even higher concentrations to be produced in the dried flue gas (over 90% CO₂.) Specifically, when high oxygen concentrations (higher than 35%) oxygen is processed conventionally in a flue gas generator, costly modifications to the furnace refractory and burner are conventionally required. With the disclosed embodiment of the recycle stream, plug and play is allowed with higher concentrations of oxygen enrichment. Plug and play is defined as no modifications being required of the existing burner or refractory of the flue gas generator, because the higher combustion temperature found in conventional oxygen enrichment combustion is mitigated or brought back to conventional air fired combustion temperatures with the cooled and recycled flue gas. Thus, the additional benefit of the recycle stream, that being plug and play, also provides significant savings of capital cost and schedule time due to simplicity of implementation of the embodiment of the invention. A unique vacuum system may be utilized for application of vacuum to the primary and secondary membrane units. The disclosed bellows system is relatively simple and requires low power input to generate the vacuum necessary to process a feed gas through the disclosed membrane units.

Methods of direct air capture of carbon dioxide utilizing membrane members under vacuum is also disclosed.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 depicts a prior art pressurized hollow fiber membrane unit with air “pressurized” into the feed tube sheet end of the membrane unit wherein the membrane tubes are fully enclosed (set) within a shell, with permeate flow to the shell nozzle of the membrane unit, for primary (first), secondary (second), or later (third, fourth, etc.) stage(s) bank(s) of an embodiment of a gas phase single or multistage bank(s) enrichment system of the present invention.

FIG. 1A is a sectional view along line 1A-1A of FIG. 1. FIG. 1B is a schematic depiction of a “pressurized” membrane unit including the membrane unit depicted in FIG. 1 which is utilized in other embodiments and figures of the present disclosure.

FIG. 2 depicts an embodiment of an ambient air/residue exposed or draft or pressurized hollow fiber membrane unit wherein there is no shell enclosure, having a “wig” configuration having permeate flowing to both hollow fiber membrane tube sheets of the hollow fiber wig draft membrane unit for primary (first) stage draft bank only, or any (primary,

7

secondary, etc.) stage pressurized bank embodiment of a gas phase single or multistage bank(s) enrichment system of the present invention.

FIG. 2A is a sectional view along line 2A-2A of FIG. 2.

FIG. 2B is a schematic depiction of a generalized embodiment of a draft membrane unit which includes the embodiment of the draft hollow fiber wig membrane unit depicted in FIG. 2.

FIG. 3 depicts an embodiment of a draft or pressurized hollow fiber wig membrane unit having a wig configuration having permeate flowing to both hollow fiber membrane tube sheets, wherein the membrane tubes are set within a perforated shell of the hollow fiber wig membrane unit for primary (first) stage draft bank only, and/or any (primary, secondary, etc.) stage pressurized bank embodiment of a gas phase single or multistage bank(s) enrichment system of the present invention.

FIG. 3A is a sectional view along line 3A-3A of FIG. 3.

FIG. 3B is a schematic depiction of a generalized embodiment of a draft membrane unit which includes the embodiment of the draft (only) hollow fiber wig membrane unit depicted in FIG. 3.

FIG. 4 depicts an embodiment of a draft (only) hollow fiber wig membrane unit wherein there is no shell enclosure having permeate flowing to a single tube sheet having a wig configuration having the tubes blocked on one end of the hollow fiber wig membrane unit for primary (first) stage draft bank only, and/or any (primary, secondary, etc.) stage pressurized bank embodiment of a gas phase single or multistage bank(s) enrichment system of the present invention.

FIG. 4A is a sectional view along line 4A-4A of FIG. 4.

FIG. 4B is a sectional view along line 4B-4B of FIG. 4.

FIG. 4C is a schematic depiction of a generalized embodiment of a draft membrane unit which includes the embodiment of the draft hollow fiber wig membrane unit depicted in FIG. 4.

FIG. 5 depicts an embodiment of a draft or pressurized sheet membrane unit having permeate flowing into slotted or perforated pipe from permeate channels of the sheet membrane unit for primary (first) stage draft bank only, and/or any (primary, secondary, etc.) stage pressurized bank which may be utilized in single or multistage pressurized bank(s) embodiment of a gas phase enrichment system of the present invention.

FIG. 5A is a schematic depiction of the individual membrane and spacer sheets of the sheet membrane unit of FIG. 5.

FIG. 5B is a schematic depiction of a generalized embodiment of a draft membrane unit which includes the embodiment of the draft (only) sheet membrane unit depicted in FIG. 5.

FIG. 6 depicts an embodiment of a pressurized spiral wound (sheet) membrane unit having permeate flowing into a central slotted or perforated pipe from permeate channels of the pressurized spiral wound (sheet) membrane unit for any (primary, secondary, etc.) stage pressurized bank which may be utilized in single or multistage pressurized bank(s) of an embodiment of a gas phase enrichment system of the present invention.

FIG. 6A schematically depicts the individual membrane and spacer sheets of the pressurized spiral wound (sheet) membrane unit of FIG. 6.

FIG. 6B is a schematic depiction of a generalized embodiment of a pressurized membrane unit which includes the embodiment of the pressurized spiral wound (sheet) membrane unit depicted in FIG. 6.

8

FIG. 7 depicts an embodiment of a draft membrane bank of draft (only) membrane units having the general configuration of the draft (only) membrane units depicted in FIGS. 2 and/or 3 herein for a primary (first) stage draft bank only of a gas phase single or multistage bank(s) enrichment system of the present invention.

FIG. 7A is a schematic depiction of a generalized embodiment of a draft (only) membrane bank including the embodiment of the draft membrane bank depicted in FIG. 7.

FIG. 8 depicts an embodiment of a draft membrane bank of draft (only) membrane units having the general configuration of the draft membrane units depicted in FIGS. 4 and/or 5 herein for a primary (first) stage draft bank only of a gas phase single or multistage bank(s) enrichment system of the present invention.

FIG. 8A is a schematic depiction of a generalized embodiment of a draft membrane bank including the embodiment of the draft membrane bank depicted in FIG. 8.

FIG. 9 depicts an embodiment of a draft membrane bank of draft (only) membrane units having the general configuration of the draft membrane units depicted in FIGS. 2 and/or 3 and/or 4, and/or 5 herein for a primary (first) stage draft bank only of a gas phase single or multistage bank(s) enrichment system of the present invention.

FIG. 9A is a schematic depiction of a generalized embodiment of a draft membrane bank including the embodiment of the draft membrane bank depicted in FIG. 9.

FIG. 10 depicts an embodiment of a pressurized membrane bank of membrane units utilized in any stage of a gas phase single or multistage bank(s) enrichment system, the pressurized membrane units including the embodiment of the pressurized membrane unit depicted in FIG. 1.

FIG. 10A is a schematic depiction of a generalized embodiment of a pressurized membrane bank including the embodiment of the pressurized membrane bank depicted in FIG. 10.

FIG. 11 depicts an embodiment of a pressurized membrane bank of membrane units utilized in any stage of a gas phase single or multistage bank(s) of an enrichment system, the pressurized membrane units including the embodiments of pressurized membrane units (only) depicted in FIGS. 2 and 3.

FIG. 11A is a sectional view taken along line 11A-11A of FIG. 11.

FIG. 11B is a schematic depiction of a generalized embodiment of a pressurized membrane bank including the embodiment of the pressurized membrane bank depicted in FIG. 11.

FIG. 12 depicts an embodiment of a pressurized membrane bank of membrane units utilized in any stage of a gas phase single or multistage bank(s) of an enrichment system, the pressurized membrane unit including the embodiment of pressurized membrane units (only) depicted in FIG. 5.

FIG. 12A is a schematic depiction of a generalized embodiment of a pressurized membrane bank including the embodiment of the pressurized membrane bank depicted in FIG. 12.

FIG. 13 depicts an embodiment of a pressurized membrane bank of pressurized membrane units utilized in any stage of a gas phase single or multistage bank(s) of an enrichment system, the pressurized membrane unit including the embodiment of pressurized membrane units depicted in FIG. 6.

FIG. 14 schematically depicts a generalized pressure differential apparatus which may be utilized in embodiments of the disclosed system and process.

FIG. 14A depicts an embodiment a liquid ring vacuum pump system which may be utilized as a pressure differential apparatus in embodiments of the disclosed system and process to apply a vacuum.

FIG. 14B schematically depicts a reciprocating compressor which may be utilized as a pressure differential apparatus in embodiments of the disclosed system and process to apply a positive pressure.

FIG. 14C schematically depicts a centrifugal blower which may be utilized as a pressure differential apparatus in embodiments of the disclosed system and process to apply a positive pressure.

FIG. 15 depicts another embodiment of a pressure differential apparatus (bellows tank) which may be utilized in embodiments of the disclosed system and process.

FIG. 15A is a schematic depiction of a generalized pressure differential apparatus which includes the embodiment depicted bellows tank in FIG. 15.

FIG. 16 schematically depicts a pressurized primary (1st stage) membrane bank system which may utilize membrane banks as depicted in FIGS. 10 through 13, the system having a pressure differential apparatus upstream of the pressurized membrane bank, the pressurized membrane bank system also having a pressure control apparatus on the residue stream.

FIG. 17 schematically depicts a draft membrane bank system which may utilize membrane banks as depicted in FIGS. 7 through 9, the system having a pressure differential apparatus as depicted in FIGS. 14 through 15 downstream of the draft membrane bank.

FIG. 18 schematically depicts a membrane bank as depicted in FIGS. 10 through 13 having a pressure differential apparatus on both the upstream and downstream sides of the membrane bank, the membrane bank further comprising a pressure controlled residue stream.

FIG. 19 schematically depicts a two stages enrichment system with both stages having pressurized membrane banks as depicted in any of FIGS. 10 through 13 configured as pressurized membrane bank systems depicted in either FIG. 16 or 18.

FIG. 20 schematically depicts a two stages enrichment system with the first stage system configured as a draft membrane bank system as depicted in FIG. 17 and the second stage configured as a pressurized membrane bank system from in either FIG. 16 or 18.

FIG. 21 schematically depicts three stages of an enrichment system with the first two stages configured as in FIG. 19 with the third stage comprising a recycled residue stream to the intake of the second stage.

FIG. 21A schematically depicts the three stages of an enrichment system depicted in FIG. 21, but also comprising a dessicant or refrigeration apparatus between the first and second stage configured to provide water removal from the gas prior to entry into the second stage as well as provide a pressure driver for an optional outlet stream of permeate.

FIG. 22 schematically depicts three stages of an enrichment system with the first two stages configured as the system depicted in FIG. 20, with the third stage comprising a pressurized membrane bank system as depicted in FIG. 16 or 18 comprising a recycled residue stream to the intake of the second stage.

FIG. 22A schematically depicts the three stages of an enrichment system depicted in FIG. 22, but also comprising a dessicant or refrigeration gas drying apparatus between the first and second stage configured to provide water removal

from the gas prior to entry into the second stage as well as provide a pressure driver for an optional outlet stream of permeate.

FIG. 23 schematically depicts a flue gas generator with conventional combustion air feed and fuel gas, having a cooling apparatus and a gas driver apparatus on the flue gas.

FIG. 24 schematically depicts the flue gas generator of FIG. 23 to which any of the systems depicted in FIGS. 16 through 22 may be utilized to enrich the combustion air to the burner.

FIG. 25 schematically depicts a pressurized flue gas generator with recycled and cooled flue gas to flue gas feed to which any of the systems depicted in FIGS. 16 through 22 may be utilized to enrich the combustion air to the burner.

FIG. 26 schematically depicts a draft membrane bank disposed at an air cooler fan discharge for improving draft membrane unit performance, the draft membrane bank unit being any those as depicted in FIGS. 7 through 9.

FIG. 27 depicts a membrane system with a flue gas generator (mobile or stationary) which may be utilized in providing an enriched stream of carbon dioxide in an agricultural application.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Referring now to the Figures, FIGS. 1, 1A and 1B depict a prior art configuration of a hollow fiber membrane unit 10. Membrane unit 10 has a membrane housing 12 comprising a plurality of hollow fiber membrane tubes 14, where the wall of each of the hollow fiber membrane tubes is a selective barrier through which certain components readily pass through and other components do not. The membrane unit 10 has tube sheets 16 at each of the ends of the membrane unit, which bind the outer walls of the hollow fiber tubes to each other and support the tube bundle within the membrane housing 12. An inlet 18 is at one end of the membrane unit 14 and an outlet 20 is at the other end.

Gas having an initial composition comprising both fast gas components and slow gas components enters the membrane unit 10 through inlet 18, with the fast gas components permeating the selective barrier of the tube walls more readily than the slow gas components. A residue gas exits the membrane unit 14 through outlet 20 and a permeate stream exists the membrane unit through permeate nozzle 22. The residue gas has, on a per volume basis, a reduced concentration of the faster gas components and an enriched concentration of the slower gas components. Likewise, the permeate stream has, on a per volume basis, a reduced concentration of the slower gas components and an increased concentration of fast gas components. This configuration of a hollow fiber membrane unit 10 receives the gas through the inlet 18 under pressure and membrane housing (or shell) 12 is necessary to contain the pressurized gas and to support the membrane tubes 14. It is to be appreciated that housing 12 is relatively heavy and it adds to the weight and expense of the membrane unit 10.

FIGS. 2, 2A and 2B depict a membrane unit 100 of the present invention having a "wig" configuration which may be utilized in an open air (i.e., "draft") application. As discussed above, "wig" configuration refers to a construction comprising a plurality of individual hollow fiber membrane elements 114 which all pass a gas permeate into a collection member commonly, but not necessarily, at a common end of the membrane elements. Membrane unit 100 has the same hollow fiber membrane tubes 114, such that the fast gas components passing more readily through

11

the selective barrier of the walls of tubes **114** than the slow gas components. In contrast to the prior art membrane unit **10**, membrane unit **100** has no housing **12** and does not have a discrete inlet comparable to that of inlet **18** of the prior art membrane unit **10**. Instead, the exteriors of tubes **114** are exposed to gas G of an ambient environment. In one of the embodiments of the present invention fast gas components preferentially flow through the selective barrier of each membrane tube **114**, with permeate gas flowing out through permeate outlets **120**. Gas components making up a “residue” stream simply comprise those components which do not pass through the walls of the membrane tubes **114** flowing past the membrane unit **100**. Membrane unit **100** comprises tubesheets **116**, which will be substantially lighter than tube sheets **16** of the prior art membrane unit **10** thereby saving on weight and expense.

Gas G may comprise ambient air having a concentration of oxygen, nitrogen, carbon dioxide and water vapor. For the selective barrier of the hollow fiber membrane elements of the present invention, oxygen, carbon dioxide and water vapor are considered to be “fast gas” components and nitrogen is a “slow gas” component. Thus, in one embodiment of the invention, a membrane unit **100** disposed in an environment of ambient air will produce a permeate having an enriched concentration of oxygen, carbon dioxide and water vapor where the permeate will also have a depleted concentration of nitrogen.

FIGS. **3**, **3A**, **3B** depict a membrane unit **200** of the present invention depicts an embodiment of a draft or pressurized hollow fiber wig membrane unit having a wig configuration having permeate flowing to both hollow fiber membrane tube sheets **216**. Similar to membrane unit **100**, membrane unit **200** comprises a plurality of hollow fiber membrane tubes **214** with each tube having a selective barrier wall which, in some embodiments of the invention, passes fast gas components to the interior of each tube more readily than slow gas components. The resulting permeate having a higher concentration of fast gas components than the ambient gas G flows to the outlets **220** adjacent tube sheets **216**. However, in contrast to the embodiments of the membrane unit depicted in FIGS. **2** and **2A**, membrane unit **200** is set within a perforated shell **212**, thereby providing additional support and containment for the hollow fiber membrane tubes **214**.

FIGS. **4**, **4A** and **4B** depict an embodiment of a draft (only) hollow fiber wig membrane unit **300** having no shell or enclosure and having permeate flowing to a single tube sheet **316**. In this embodiment of the membrane unit **300**, hollow fiber tubes **314** have one end of each of the hollow fiber tubes **314** blocked with plug sheet **316'** which collectively blocks all of the tubes or each tube may be individually plugged or capped. Similar to membrane units **100** and **200**, membrane unit **300** comprises a plurality of hollow fiber membrane tubes **314** with each tube having a selective barrier wall which, in some embodiments of the invention, passes fast gas components to the interior of each tube more readily than slow gas components. The resulting permeate has a higher concentration of fast gas components than the ambient gas G flows to the outlet **320** adjacent the tube sheet **316**.

FIGS. **5**, **5A** and **5B** depict an embodiment of a draft or pressurized sheet membrane unit **400** having permeate flowing into slotted or perforated pipe from permeate channels of the sheet membrane unit for primary (first) stage draft bank only, and/or any (primary, secondary, etc.) stage pressurized bank which may be utilized in single or multistage pressurized bank(s) embodiment of a gas phase enrichment system

12

of the present invention. Membrane unit **400** has a slotted collection pipe **424** having a permeate collection pipe slot **426**. A sheet membrane element **428** may have a top membrane sheet **430** and a bottom membrane sheet **432** glued only on three sides to a ribbed sheet **434**, where a top permeate channel is defined between the top membrane sheet **430** and the ribbed sheet **434** and a bottom permeate channel is defined between the bottom membrane sheet **432** and the ribbed sheet **434**. The fourth side of sheet membrane element is not glued comprising open ends of top and bottom membrane elements which extend over the permeate collection pipe slot **426**.

FIGS. **6**, **6A** and **6B** depict an embodiment of a pressurized spiral wound (sheet) membrane unit **500**. In this embodiment of the membrane unit **50** feed enters into the front face **502** of each unit and the residue stream leaves the rear face **504** of each unit. Spiral wound membrane unit **500** is fabricated from alternating sheets of membrane sheets, each comprising a selective barrier, and spacer sheets. FIG. **6A** shows an expanded detail of an unwound membrane unit, where the spiral membrane unit has the following elements: (1) a bottom feed/residue spacer **506**; (2) a bottom membrane sheet **508**; (3) a permeate spacer **510**; (4) a top membrane sheet **512**; (5) a top feed/residue spacer **514**; (6) a bottom feed/residue channel **516**; (7) a bottom feed permeate channel **518**; (8) a top permeate channel **520**; and (9) a top feed/residue channel **522**. The membrane sheet layers **508**, **512** are glued to the feed/residue spacers **506**, **514** at the front edges only and glued to the permeate spacer **510** at the front and the side edges. The open ends of permeate channels **518**, **520** are attached over perforations **526** in a permeate collection pipe **528**. The top feed/residue spacer **514** is longitudinally ribbed on the bottom of the spacer and the bottom feed/residue spacer **506** is longitudinally ribbed on the top of the spacer. Permeate spacer **510** is laterally ribbed on the top and bottom of the spacer.

Gas flows in a spiral pattern through the spiral wound membrane unit **500** with the permeate received by permeate collection pipe **528**. The ends of permeate collection pipe **528** may be threaded so that the spiral wound membrane units **500** may be attached in end-to-end configuration for collection of the permeate. An assembly of multiple spiral wound membrane units **500** may be connected to a permeate collection header.

FIGS. **7**, **7A** depict an embodiment of a draft membrane bank **600** of draft (only) membrane units **610** having the general configuration of the membrane units **100**, **200** described above and depicted in FIGS. **2** and/or **3** or the like. Draft membrane bank **600** is utilized as a primary (first) stage draft bank only of a gas phase single or multistage bank(s) enrichment system of the present invention. The exteriors of the banked membrane units **610** are exposed to gas G of an ambient environment. Fast gas components preferentially flow through the selective barrier of each membrane unit with permeate gas flowing out and collected through permeate headers **602** and directed to a permeate processing facility, which may include a second stage of enrichment, a flue gas generator or to a carbon dioxide sequestering facility.

FIGS. **8**, **8A** depict an embodiment of a draft membrane bank **700** of draft (only) membrane units **710**, which may include membrane units **300**, **400** described above and depicted in FIGS. **4** and/or **5** or the like. Draft membrane bank **700** is utilized for a primary (first) stage draft bank only of a gas phase single or multistage bank(s) enrichment system of the present invention. The exteriors of the banked membrane units **710** are exposed to gas G of an ambient

13

environment. Fast gas components preferentially flow through the selective barrier of each membrane unit **710** with permeate gas flowing out and collected through permeate header **702** and directed to a permeate processing facility, which may include a second stage of enrichment, a flue gas generator or to a carbon dioxide sequestering facility.

FIGS. **9**, **9A** depict an embodiment of a draft membrane bank **800** of draft (only) membrane units **810**, which may include membrane units **100**, **200**, **300**, **400** described above and depicted in FIGS. **2** and/or **3** and/or **4**, and/or **5** or the like. Draft membrane bank **800** is utilized for a primary (first) stage draft bank only of a gas phase single or multistage bank(s) enrichment system of the present invention. The exteriors of the banked membrane units **810** are exposed to gas **G** of an ambient environment. Fast gas components preferentially flow through the selective barrier of each membrane unit **810** with permeate gas flowing out and collected through permeate header **802** and directed to a permeate processing facility, which may include a second stage of enrichment, a flue gas generator or to a carbon dioxide sequestering facility.

FIGS. **10**, **10A** depict an embodiment of a pressurized membrane bank **900** of pressurized membrane units **910** utilized in any stage of a gas phase single or multistage bank(s) enrichment system. The pressurized membrane units **910** may include embodiments of the pressurized membrane unit **10** depicted in FIG. **1**. Pressurized bank **900** receives a stream of gas through inlet header **902** and may discharge the resulting permeate gas through permeate outlet header **904** and may discharge residual gas through residual outlet header **906**. Permeate outlet header **904** may direct the permeate to a permeate processing facility, which may include a further stage of enrichment, a flue gas generator or to a carbon dioxide sequestering facility. Residual outlet header **906** may appropriately discharge or recycle the residual gas stream.

FIGS. **11**, **11A**, **11B** depicts an embodiment of a pressurized membrane bank **1000** of membrane units **1010**. Membrane units **1010** utilized in pressurized membrane bank **1000** may include embodiments of the membrane units **100**, **200** described above and depicted in FIGS. **2** and **3**. Pressurized membrane bank receives a stream of gas through inlet **1002** and may discharge the resulting permeate gas through permeate outlet headers **1004** and may discharge residual gas through outlet **1006**. Permeate outlet headers **1004** may direct the permeate to a permeate processing facility, which may include a further stage of enrichment, a flue gas generator or to a carbon dioxide sequestering facility. Outlet **1006** may appropriately discharge or recycle the residual gas stream. Membrane units **1010** are contained within a shell **1020**. Pressurized membrane bank **1000** may be utilized in any stage of a gas phase single or multistage bank(s) of an enrichment system.

FIGS. **12**, **12A** depict an embodiment of a pressurized membrane bank **1100** of membrane units **1110**. Membrane units **1110** utilized in pressurized membrane bank **1100** may include embodiments of the membrane units **400** described above and depicted in FIG. **5**. Pressurized membrane bank **1100** receives a stream of gas through inlet **1102** and may discharge the resulting permeate gas through permeate outlet headers **1104** and may discharge residual gas through residual outlets **1106**. Permeate outlet headers **1104** may direct the permeate to a permeate processing facility, which may include a further stage of enrichment, a flue gas generator or to a carbon dioxide sequestering facility. Residual outlets **1106** may appropriately discharge or

14

recycle the residual gas stream. Membrane units **1110** are contained within a shell **1120** which may include low pressure ducting. Pressurized membrane bank **1100** may be utilized in any stage of a gas phase single or multistage bank(s) of an enrichment system.

FIGS. **13**, **13A** depict an embodiment of a pressurized membrane bank **1200** of membrane units **1210**. Membrane units **1210** utilized in pressurized membrane bank **1200** may include embodiments of the membrane units **500** described above and depicted in FIG. **6**. Pressurized membrane bank **1200** receives a stream of gas through inlet **1202** and may discharge the resulting permeate gas through permeate outlet headers **1204** and may discharge residual gas through residual outlets **1206**. Permeate outlet headers **1204** may direct the permeate to a permeate processing facility, which may include a further stage of enrichment, a flue gas generator or to a carbon dioxide sequestering facility. Residual outlets **1206** may appropriately discharge or recycle the residual gas stream. Membrane units **1210** are contained within a shell **1220** which may include low pressure ducting. Pressurized membrane bank **1200** may be utilized in any stage of a gas phase single or multistage bank(s) of an enrichment system.

FIG. **14** schematically depicts a generalized pressure differential apparatus **1300**, which may be utilized in embodiments of the disclosed system and process to provide pressure or vacuum to the selective barriers of the various disclosed membrane units discussed above. FIG. **14A** schematically depicts a pressure differential apparatus **1300'** comprising a liquid ring vacuum pump system which is one embodiment of differential pressure apparatus which may be utilized, comprising a liquid ring vacuum pump system. FIG. **14B** schematically depicts a pressure differential apparatus **1300''** comprising a reciprocating compressor system which may be utilized as a pressure differential apparatus in embodiments of the disclosed system and process to apply a positive pressure. FIG. **14C** schematically depicts a pressure differential apparatus **1300'** comprising a centrifugal blower system which may be utilized as a pressure differential apparatus in embodiments of the disclosed system and process to apply a positive pressure.

Another embodiment of a pressure differential apparatus is depicted in FIGS. **15**, **15A**. This embodiment of pressure differential apparatus comprises a bellows tank **1400**. Bellows tank **1400** may have a double-acting piston **1402** set within a large cylinder **1404**. Piston **1402** may have graphite rings and/or the cylinder walls **1406** may comprise graphite. Actuation devices **1408**, **1410** respectively utilize connectors **1412**, **1414** to actuate piston **1402** in either direction within the cylinder **1404**. It is to be appreciated that large cylinder **1404** need not be a pressure vessel and that actuation devices **1408**, **1410** may be small winches driven by small motors and connectors **1412**, **1414** may be light rods or small diameter cables. Double-acting piston **1402** may be diamond-shaped to provide additional structural integrity under vacuum conditions. Bellows tank **1400** applies vacuum to a connected membrane unit on each upstroke, relative to the position of intake/discharge lines **1416**, **1418** which are connected to the membrane units, with an upstroke causing permeate to be pulled into cylinder **1404** through the intake/discharge line receiving vacuum on the upstroke. On each downstroke permeate is pushed out of the cylinder **1404** through intake/discharge lines **1416**, **1418**, with the flow direction controlled by the action of check valves **1420**.

FIG. **16** schematically depicts a pressurized primary (1st stage) membrane bank system **1500** comprising a pressur-

15

ized membrane bank **1510**. The pressurized membrane bank **1510** may comprise embodiments of pressurized membrane banks **900**, **1000**, **1100**, **1200** described above and depicted in FIGS. **10** through **13**. Membrane bank system **1500** has a pressure differential apparatus **1502** upstream of the pressurized membrane bank, where the pressure differential apparatus may comprise the various embodiments depicted in FIG. **14** (including **14A**, **14B** and **14C**) and the bellows tank **1400** depicted in FIG. **15**. The pressurized membrane bank **1500** may also have a pressure control apparatus **1514** on the residue stream.

FIG. **17** schematically depicts a draft membrane bank **1600** system comprising a membrane bank **1610**. Membrane bank **1610** may comprise membrane banks **600**, **700**, and **800** described above and depicted in FIGS. **7** through **9**. Membrane bank system **1600** has a pressure differential apparatus **1612** downstream of the pressurized membrane bank **1610**, where the pressure differential apparatus may comprise the various embodiments depicted in FIG. **14** (including **14A**, **14B** and **14C**) and the bellows tank **1400** depicted in FIG. **15**.

FIG. **18** schematically depicts a pressurized primary (1st stage) membrane bank system **1700** comprising a pressurized membrane bank **1710**. The pressurized membrane bank **1710** may comprise embodiments of pressurized membrane banks **900**, **1000**, **1100**, **1200** described above and depicted in FIGS. **10** through **13**. Membrane bank system **1700** has a pressure differential apparatus **1702** upstream of the pressurized membrane bank, where the pressure differential apparatus may comprise the various embodiments depicted in FIG. **14** (including **14A**, **14B** and **14C**) and the bellows tank **1400** depicted in FIG. **15**. Membrane bank system **1700** also has a pressure differential apparatus **1712** downstream of the pressurized membrane bank **1710**, where the pressure differential apparatus may again comprise the various embodiments depicted in FIG. **14** (including **14A**, **14B** and **14C**) and the bellows tank **1400** depicted in FIG. **15**. The pressurized membrane bank **1700** may also have a pressure control apparatus **1714** on the residue stream.

FIG. **19** schematically depicts a two stages enrichment system **1800** with both stages having pressurized membrane banks **1810**. Membrane banks **1810** may comprises membrane banks **900**, **1000**, **1100**, **1200** described above and as depicted in any of FIGS. **10** through **13** and configured as pressurized membrane bank systems **1500**, **1700** as described above and depicted in either FIG. **16** or **18**.

FIG. **20** schematically depicts a two stages enrichment system **1900** with a first stage system **1910** which may be configured utilizing draft membrane system **1600** as described above and depicted in FIG. **17**. Second stage **1920** may be configured as a pressurized membrane bank system utilizing pressurized bank systems **1500**, **1700** as as described above and depicted in FIG. **16** or **18**.

FIG. **21** schematically depicts a three stage of an enrichment system **2000** comprising a first stage **2010**, a second stage **2012** and a third stage **2014**. First stage first **2010** and the second stage **2012** may utilize a two-stage enrichment system utilizing the configuration of two stage system **1800** described above and as depicted in FIG. **19**. Third stage **2014** comprises a conduit **2016** which provides a recycled residue stream to the intake of the second stage **2012**.

FIG. **21A** schematically depicts a three stage of an enrichment system **2000'** comprising a first stage **2010'**, a second stage **2012'** and a third stage **2014'**. First stage first **2010'** and the second stage **2012'** may utilize a two-stage enrichment system utilizing the configuration of two stage system **1800** described above and as depicted in FIG. **19**. Third stage

16

2014' comprises a conduit **2016'** which provides a recycled residue stream to the intake of the second stage **2012'**. However enrichment system **2000'** further comprises a desiccant or refrigeration apparatus **2008** between the first stage **2010'** and the second stage **2012'** configured to provide water removal from the gas prior to entry into the second stage as well as provide an optional outlet stream of water.

FIG. **22** schematically depicts a three stage enrichment system **2100** comprising a first stage **2110**, a second stage **2112** and a third stage **2114**. First stage first **2110** and second stage **2112** may a two-stage enrichment system utilizing the configuration of two stage system **1900** described above and as depicted in FIG. **20**. Third stage **2114** comprises a conduit **2116** which provides a recycled residue stream to the intake of the second stage **2112**.

FIG. **22A** schematically depicts a three stage of an enrichment system **2100'** comprising a first stage **2110'**, a second stage **2112'** and a third stage **2114'**. First stage first **2110'** and the second stage **2112'** may utilize a two-stage enrichment system utilizing the configuration of two stage system **1900** described above and as depicted in FIG. **20**. Third stage **2114'** comprises a conduit **2116'** which provides a recycled residue stream to the intake of the second stage **2112'**. However enrichment system **2100'** further comprises a desiccant or refrigeration apparatus **2108** between the first stage **2110'** and the second stage **2112'** configured to provide water removal from the gas prior to entry into the second stage as well as provide an optional outlet stream of water.

FIG. **23** schematically depicts a flue gas generator **2200** with conventional combustion air feed and fuel gas, having a cooling apparatus C and a gas driver apparatus D on the flue gas. FIG. **24** schematically depicts a flue gas generator **2200'** similar to that depicted in FIG. **23** but further comprising a combustion air enrichment apparatus **2202**. Air enrichment apparatus may include in of the systems **1500**, **1600**, **1700**, **1800**, **1900**, **2000** and **2100** described above and as depicted in FIGS. **16** through **22** to enrich the combustion air to the burner. FIG. **25** schematically depicts a pressurized flue gas generator **2200"** having a liquid water removal apparatus L on the flue gas discharge and a combustion air enrichment apparatus **2202** with recycled and cooled flue gas to flue gas feed. Air enrichment apparatus may include in of the systems **1500**, **1600**, **1700**, **1800**, **1900**, **2000** and **2100** described above and as depicted in FIGS. **16** through **22** to enrich the combustion air to the burner.

FIG. **26** schematically depicts a flue gas generator F having flue gas discharged to an air cooler fan **2302** and processed through cooling apparatus C. A draft membrane bank **2300** is disposed at the air cooler fan discharge **2304** for improving draft membrane unit performance, where the draft membrane banks may comprise draft membrane banks **600**, **700** and **800** as described above and depicted in FIGS. **7** through **9**.

FIG. **27** depicts an enrichment system **2400** deployed within an orchard comprising trees T. It is to be appreciated that a tree orchard may be utilized as a sequestering facility which utilizes photosynthetic organisms (trees) to sequester carbon dioxide. Enrichment system **2400** may comprise a plurality of membrane units **2410** as disclosed herein. Membrane units **2410** may capture and enrich carbon dioxide in the vicinity of the trees T. Membrane units **2410** may also be disposed around the perimeter of the orchard to capture "fugitive" carbon dioxide which has not been utilized in photosynthesis. Moreover, for orchards utilizing carbon dioxide emitting mechanisms, such as flue gas generators, for support purposes, the enrichment system may be utilized to both make those flue gas generators more fuel efficient by

17

increasing oxygen concentration in the intake air and to also capture carbon dioxide in the exhaust and enrich and cool it for application to the orchard. Thus, enrichment system **2400** may further comprise a stationary or mobile flue gas generator **2450**. Flue gas generator **2450** may have an economizer (not shown). Membrane units **2410** may also be utilized to provide oxygen enriched air to the intake of the flue gas generator **2450**. Flue gas generator **2450** may provide a flue gas having elevated level of carbon dioxide which may be enriched with membrane units **24** an enriched stream of carbon dioxide in an agricultural application. Flue gas generator **2450** may send hot gas to one or more cooling devices **2452** which may comprise a dry ice containment or a quench column device. Discharge from cooling devices **2452** will have an enriched carbon dioxide concentration which may be pressurized by a blower **2454** for further distribution for either distribution to trees **T** or to provide additional cooling for the air intake of the flue gas generator **2450**. A vacuum pump **2456** may be utilized to provide vacuum to the various membrane units **2410**.

18

As indicated, FIG. **27** depicts the following flow streams for five different cases

- 1—fuel gas to the flue gas generator
- 2—enriched O₂/CO₂ from the membrane permeate header to vacuum pump **2456**.
- 3.—dried CO₂ recirculated for cooling.
- 4.—intake at vacuum pump **2456**.
- 5.—vacuum pump discharge for cooling into the flue gas generator economizer.
- 6.—hot exhaust from the flue gas generator **2450**.
- 7.—cooled gas discharge from blower **2454**.
- 8.—intake to second cooling device **2454**.
- 9.—enriched CO₂ stream for orchard distribution.

The tables presented below provide examples of the heat and material balances which may be realized utilizing a system as shown in FIG. **27** for five different scenarios utilizing the presently disclosed Membrane Air Enrichment (“MAE”) process in a ten tree orchard utilized as a sequestration facility.

TABLE 1

for Case 1: Simplified Heat and Material Balance for MAE Process								
Air Feed Case (20.8% O ₂)								
BASIS: 50 Tons CO ₂ /Y for 10 almond trees, Quench Makes 35 Tons Water/Y								
Process Parameters/Stream Names	Stream Numbers							
	1	2	3	4	5	6	7	8
	Fuel****	Air	Dry Recirc	Vac Suct	Vac Disch	Flue Gas	Cool FG	Crop Carbon
Absolute Pressure, psia	25	14.7	N/A	N/A	N/A	14.7	15	15
Temperature F. **	Ambient	Ambient				350	90	90
Gas Standard Volumetric Rate, SCFM	6.32	60.70				67.02	55.83	55.83
Total Molar Flow Rate- LbMole/Hr)	1	9.602				10.602	8.831288	8.831287082
Mole Balance, lb mols/hr								
Methane (CH ₄ — LbMole/Hr)	1	0				0	0	0
Oxygen (O ₂ — LbMole/Hr)	0	2				0	0	0
Nitrogen (N ₂ — LbMole/Hr)	0	7.4				7.4	7.4	7.4
Water (H ₂ O— LbMole/Hr)	0	0.196				2.196	0.41957	0.4195703
Carbon Dioxide (CO ₂ — LbMole/Hr)	0	0.006				1.006	1.006	1.006
Mole Percent								
Methane (CH ₄ — Mole Percent)	100.0	0.0				0.0	0.0	0.0
Oxygen (O ₂ — Mole Percent)	0.0	20.8				0.0	0.0	0.0
Nitrogen (N ₂ — Mole Percent)	0.0	77.1				69.8	83.8	83.8
Water (H ₂ O— Mole Percent)	0.0	2.0				20.7	4.8	4.8
Carbon Dioxide (CO ₂ — Mole Percent)	0.0	0.0625				9.5	11.4	11.4
Total	100.0	100.0				100.0	100.0	100.0
Mass Balance, Tons/yr								
Methane (CH ₄ — Tons/yr)	17.5	0.0				0.0	0.0	0.0
Oxygen (O ₂ — Tons/yr)	0.0	70.1				0.0	0.0	0.0
Nitrogen (N ₂ — Tons/yr)	0.0	226.9				226.9	226.9	226.9
Water (H ₂ O— Tons/yr)	0.0	3.9				43.3	8.3	8.3
Carbon Dioxide (CO ₂ —Tons/yr)	0.0	0.3				48.5	48.5	48.5
Total, Tons/yr	17.5	301.1				318.6	283.6	283.6

for Case 2 Simplified Heat and Material Balance for MAE Process
33% O₂ Enrich Feed Case
BASIS: 50 Tons CO₂/Y for 10 almond trees, Quench Makes 35 Tons Water/Y
Gross 30% Increase in Duty of Steam/Power Generation- Net 20% Increase with vacuum pump deduct

TABLE 3

Heat and Material Balances for New MAE Process: BASIS 50 Tons/Year CO₂ for 10 almond trees Using Quench
40% Increase in Duty of Existing Steam/Power Generation Device

[illegible]

TABLE 3-continued

for Case 3 Heat and Material Balances for New MAE Process: BASIS 50 Tons/Year CO2 for 10 almond trees Using Quench 40% Increase in Duty of Existing Steam/Power Generation Device								
Process Parameters/Stream Names	Stream Numbers							
	1 Fuel****	2 Comb O2	3 Dry Recirc	4 Vac Suct	5 Vac Disch	6 Flue Gas	7 Cool FG	8 Crop Carbon
Mass Balance, Tons/yr ***								
Methane (CH4— Tons/yr)	17.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oxygen (O2— Tons/yr)	0.0	70.1	0.0	70.1	70.1	0.0	0.0	0.0
Nitrogen (N2— Tons/yr)	0.0	61.3	30.7	92.0	92.0	92.0	92.0	61.3
Water (H2O— Tons/yr)	0.0	1.6	0.0	1.6	1.6	41.0	0.0	0.0
Carbon Dioxide (CO2—Tons/yr)	0.0	0.1	25.4	25.5	25.5	73.7	76.1	50.7
Total, Tons/yr	17.5	133.1	56.0	189.2	189.2	206.7	168.1	112.1

TABLE 4

for Case 4								
Heat and Material Balances for New MAE	Basis 50 T 50% O2		/Year Enrich	CO2 Without		Recirc		
60% Increase in Duty of New Steam/Power Generation								
	Stream Numbers							
Process Parameters/Stream Names	1 Fuel****	2 Comb O2	3 Dry Recirc	4 Vac Suct	5 Vac Disch	6 Flue Gas	7 Cool FG	8 Crop Carbon
Absolute Pressure, psia	25	3.8			16		16	15
Temperature F. **	Ambient	Ambient		Ambient	200		170	60
Gas Standard Volumetric Rate, SCFM	6.32	25.81			25.81	32.13	19.30	19.30
Total Molar Flow Rate- LbMole/Hr)	1	4.083			4.083	5.083	3.053	3.053
Mole Balance, lb mols/hr								
Methane (CH4— LbMole/Hr)	1	0	0	0	0	0	0	0
Oxygen (O2— LbMole/Hr)	0	2	0	2	2	0	0	0
Nitrogen (N2— LbMole/Hr)	0	2	0	2	2	2	2	2
Water (H2O— LbMole/Hr)	0	0.08	0	0.08	0.08	2.08	0	0
Carbon Dioxide (CO2— LbMole/Hr)	0	0.003	0	0.003	0.003	1.003	1.053	1.053
Mole Percent								
Methane (CH4— Mole Fraction)	100.0	0.0	0	0.0	0.0	0.0	0.0	0.0
Oxygen (O2— Mole Fraction)	0.0	49.0	0	49.0	49.0	0.0	0.0	0.0
Nitrogen (N2— Mole Fraction)	0.0	49.0	0	49.0	49.0	39.3	65.5	65.5
Water (H2O— Mole Fraction)	0.0	2.0	0	2.0	2.0	40.9	0.0	0.0
Carbon Dioxide (CO2— Mole Fraction)	0.0	0.07	0	0.1	0.1	19.7	34.5	34.5
Total	100.0	100.0	0	100.0	100.0	100.0	100.0	100.0
Mass Balance, Tons/yr ***								
Methane (CH4— Tons/yr)	17.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oxygen (O2— Tons/yr)	0.0	70.1	0.0	70.1	70.1	0.0	0.0	0.0
Nitrogen (N2— Tons/yr)	0.0	61.3	0.0	61.3	61.3	61.3	61.3	61.3
Water (H2O— Tons/yr)	0.0	1.6	0.0	1.6	1.6	41.0	0.0	0.0
Carbon Dioxide (CO2—Tons/yr)	0.0	0.1	0.0	0.1	0.1	48.3	50.7	50.7
Total, Tons/yr	17.5	133.1	0.0	133.1	133.1	150.6	112.1	112.1

TABLE 5

for Case 5								
Heat and Material Balances for New MAE Process: BASIS 80 Tons/Year CO ₂ for 10 almond trees Using 9.6 Tons/Yr Dry Ice Standard Air to Bio Gas Supplemented with Natural Gas								
Process Parameters/Stream Names	Stream Numbers							
	1	2	3	4	5A	6	7	8
	Fuel	Comb O ₂	Dry Recirc	Vac Suct	Air	Flue Gas	Cool FG	Crop Carbon
Absolute Pressure, psia	25	3.8	3.8	3.8	14.7	15	16	15
Temperature F, **	Ambient	Ambient	50	Ambient	Ambient	350	170	60
Gas Standard Volumetric Rate, SCFM	9.17	0.00	0.00	0.00	60.69	69.85	57.24	57.24
Total Molar Flow Rate- LbMole/Hr)	1.45	0	0	0	9.6	11.05	9.054	9.054
Mole Balance, lb mols/hr								
Methane (CH ₄ — LbMole/Hr)	1	0	0	0	0	0	0	0
Oxygen (O ₂ — LbMole/Hr)	0	0	0	0	2	0	0	0
Nitrogen (N ₂ — LbMole/Hr)	0	0	0	0	7.4	7.4	7.4	7.4
Water (H ₂ O— LbMole/Hr)	0	0	0	0	0.196	2.196	0	0
Carbon Dioxide(CO ₂ — LbMole/Hr)	0.45	0	0	0	0.004	1.454	1.654	1.654
Mole Percent								
Methane (CH ₄ — Mole Fraction)	69.0	0.0	0	0.0	0.0	0.0	0.0	0.0
Oxygen (O ₂ — Mole Fraction)	0.0	0.0	0	0.0	20.8	0.0	0.0	0.0
Nitrogen (N ₂ — Mole Fraction)	0.0	0.0	0	0.0	77.1	67.0	81.7	81.7
Water (H ₂ O— Mole Fraction)	0.0	0.0	0	0.0	2.0	19.9	0.0	0.0
Carbon Dioxide (CO ₂ — Mole Fraction)	31.0	0.00	0	0.0	0.0	13.2	18.3	18.3
Total	100.0	0.0	0.0	0.0	100.0	100.0	100.0	100.0
Mass Balance, Tons/yr ***								
Methane (CH ₄ — Tons/yr)	17.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oxygen (O ₂ — Tons/yr)	0.0	0.0	0.0	0.0	70.1	0.0	0.0	0.0
Nitrogen (N ₂ — Tons/yr)	0.0	0.0	0.0	0.0	226.9	226.9	226.9	226.9
Water (H ₂ O— Tons/yr)	0.0	0.0	0.0	0.0	3.9	43.3	0.0	0.0
Carbon Dioxide (CO ₂ —Tons/yr)	21.7	0.0	0.0	0.0	0.2	70.1	79.7	79.7
Total, Tons/yr	39.2	0.0	0.0	0.0	301.0	340.2	306.6	306.6

While the above is a description of various embodiments of the present invention, further modifications may be employed without departing from the spirit and scope of the present invention. Thus the scope of the invention should not be limited according to these factors, but according to the claims of the forthcoming non-provisional patent application.

What is claimed is:

1. An apparatus for direct air capture of gas components from an ambient environment at atmospheric pressure, wherein the ambient environment comprises a first concentration of fast gas components and a first concentration of slow gas components, the apparatus comprising:

a shell-less membrane unit comprising a selective barrier and a permeate channel wherein the selective barrier is exposed to the first concentration of fast gas components at atmospheric pressure and the selective barrier is exposed to the first concentration of slow gas components at atmospheric pressure, wherein a portion of fast gas components and a portion of slow gas components flow through the selective barrier surface to the permeate channel as a result of a pressure differential across the selective barrier;

a pressure differential device which applies the pressure differential across the selective barrier of the shell-less membrane unit, the pressure differential device selected from the group consisting of a liquid ring vacuum system, a reciprocating compressor system, a centrifugal blower system, and a bellows tank;

a conduit connecting the permeate channel to a permeate processing facility, wherein as the pressure differential is applied across the barrier of the shell-less membrane unit, a first permeate stream forms in the permeate channel, wherein the first permeate stream comprises a second concentration of fast gas components and a second concentration of slow gas components, wherein the second concentration of fast gas components is greater than the first concentration of fast gas components and the second concentration of slow gas components is less than the first concentration of slow gas components; and

wherein at least a portion of the first permeate stream is delivered through the conduit to the permeate processing facility.

2. The apparatus of claim 1 comprising a plurality of shell-less membrane units configured into a membrane bank.

3. The apparatus of claim 1 wherein the pressure differential applied to the shell-less-membrane unit comprises a vacuum produced with the pressure differential device disposed between the shell-less membrane unit and the permeate processing facility.

4. The apparatus of claim 1 wherein the permeate processing facility comprises a second stage apparatus which processes the at least a portion of the first permeate stream into a second permeate stream having a third concentration of fast gas components and a third concentration of slow gas components, wherein the third concentration of fast gas components is greater than the second concentration of fast

25

gas components and the third concentration of slow gas components is less than the second concentration of slow gas components, and at least a portion of the second permeate stream is delivered to a second permeate processing facility.

5. The apparatus of claim 4 wherein the second stage apparatus comprises a plurality of shell-less membrane units configured into a membrane bank, wherein the membrane bank has been disposed within a shell connected to the conduit, the shell comprising a second conduit for delivery of the at least a portion of the second permeate stream to the second permeate processing facility.

6. The apparatus of claim 4 further comprising a gas drying device which receives the at least a portion of the first permeate stream prior to entry into the second stage apparatus wherein the gas drying device is selected from the group consisting of a dessicant apparatus and a refrigeration apparatus.

7. The apparatus of claim 1 wherein the permeate processing facility comprises a flue gas generator.

8. The apparatus of claim 7 wherein at least a portion of a flue gas produced by the flue gas generator is recycled through a conduit to a gas intake of the flue gas generator.

9. The apparatus of claim 1 wherein the permeate processing facility comprises a sequestration facility.

10. The apparatus of claim 9 wherein the sequestration facility comprises a plurality of photosynthetic organisms.

11. An apparatus for direct air capture of components of ambient air at atmospheric pressure, where the ambient air comprises a first concentration of oxygen, a first concentration of nitrogen, and a first concentration of carbon dioxide:

a hollow fiber membrane unit comprising a first selective barrier surface directly exposed to the ambient air at atmospheric pressure, the hollow fiber membrane unit further comprising a first permeate channel configured to receive a flow of oxygen, nitrogen and carbon dioxide from the selective barrier surface;

a vacuum applying apparatus which applies a vacuum to the hollow fiber membrane unit wherein the vacuum applying apparatus is selected from the group consisting of a vacuum pump, a liquid ring vacuum pump system and a bellows system;

a conduit connecting the permeate channel to a permeate processing facility;

wherein, as the vacuum is applied to the hollow fiber membrane unit, a permeate forms in the permeate channel, wherein the permeate comprises a second concentration of oxygen, a second concentration of nitrogen and a second concentration of carbon dioxide; wherein the second concentration of oxygen is greater than the first concentration of oxygen, the second concentration of carbon dioxide is greater than the first concentration of carbon dioxide, and the second concentration of nitrogen is less than the first concentration of nitrogen; and

wherein at least a portion of the permeate is delivered through the conduit to the permeate processing facility.

12. The apparatus of claim 11 wherein the hollow fiber membrane unit is not contained within an outer shell.

13. The apparatus of claim 11 wherein a plurality of the hollow fiber membrane units are configured into a membrane bank.

26

14. The apparatus of claim 13 wherein the membrane bank is disposed within a shell.

15. An apparatus for direct air capture of gas components from an ambient environment at atmospheric pressure, wherein the ambient environment comprises a first concentration of fast gas components at atmospheric pressure and a first concentration of slow gas components at atmospheric pressure, the apparatus comprising:

a spiral wound sheet membrane unit comprising a selective barrier exposed to the first concentration of fast gas components at atmospheric pressure and the selective barrier is exposed to the first concentration of slow gas components at atmospheric pressure, and a permeate channel configured to receive a flow of fast gas components and slow gas components through the selective barrier;

a conduit connecting the permeate channel to a permeate processing facility;

a pressure differential device which applies a pressure differential across the selective barrier, the pressure differential device located within a portion of the conduit connecting the permeate channel to the permeate processing facility, the pressure differential device selected from the group consisting of a liquid ring vacuum system, a reciprocating compressor system, a centrifugal blower system and a bellows tank;

wherein as the pressure differential is applied across the selective barrier, a permeate forms in the permeate channel, wherein the permeate comprises a second concentration of fast gas components and a second concentration of slow gas components,

wherein the second concentration of fast gas components is greater than the first concentration of fast gas components and the second concentration of slow gas components is less than the first concentration of slow gas components; and

wherein at least a portion of the permeate is delivered through the conduit to the permeate processing facility.

16. The apparatus of claim 15 wherein the spiral wound sheet membrane unit is not contained within an outer shell.

17. The apparatus of claim 15 wherein comprising a plurality of spiral wound membrane units configured into a membrane bank.

18. The apparatus of claim 15 wherein the permeate processing facility comprises a second stage apparatus which processes the at least a portion of the first permeate stream into a second permeate stream having a third concentration of fast gas components and a third concentration of slow gas components, wherein the third concentration of fast gas components is greater than the second concentration of fast gas components and the third concentration of slow gas components is less than the second concentration of slow gas components, and at least a portion of the second permeate stream is delivered to a second permeate processing facility.

19. The apparatus of claim 18 wherein the second stage apparatus comprises a plurality of shell-less spiral wound sheet membrane units configured into a membrane bank, wherein the membrane bank has been disposed within a shell connected to the conduit, the shell comprising a second conduit for delivery of at least a portion of the second permeate stream to a second permeate processing facility.

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