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(71) Applicant (for all designated States except US): EXXON-

MOBIL UPSTREAM RESEARCH COMPANY

[US/US]; CORP-URC-SW359, P.O. Box 2189, Houston, TX 77252-2189 (US).

(72) Inventors; and

(71) Applicants (for US only): NORTHROP, Paul Scott

[US/US]; 134 W. Stockbridge Landing, Spring, TX 77382

(US). MART, Charles J. [US/US]; 1633 Lichester Drive,

Baton Rouge, LA 70810 (US). CULLINANE, J. Tim

[US/US]; 1155 Spring Road, Easton, PA 18040 (US).

(74) Agents: LOBATO, Ryan L. et al; Exxonmobil Upstream

Research Company, CORP-URC-SW359, P.O. Box 2189,

Houston, TX 77252-2189 (US).

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(54) Title: SEPARATING CARBON DIOXIDE AND HYDROGEN SULFIDE FROM A NATURAL GAS STREAM USING CO-CURRENT CONTACTING SYSTEMS

(57) Abstract: Systems and methods for separating CO₂ and H₂S from a natural gas stream are provided herein. The system includes a first loop of co-current contacting systems configured to remove H₂S and CO₂ from a natural gas stream and a second loop of co-current contacting systems configured to remove the H₂S from the CO₂.



SEPARATING CARBON DIOXIDE AND HYDROGEN SULFIDE FROM A NATURAL GAS STREAM USING CO-CURRENT CONTACTING SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATION

5 This application claims the benefit of U.S. Provisional Patent Application
61/821,618 filed May 9, 2013 entitled SEPARATING CARBON DIOXIDE AND
HYDROGEN SULFIDE FROM A NATURAL GAS STREAM USING CO-CURRENT
CONTACTING SYSTEMS, the entirety of which is incorporated by reference herein.

FIELD OF THE INVENTION

10 [0002] The present techniques provide for the separation of carbon dioxide (CO₂) and hydrogen sulfide (H₂S) from a natural gas stream using co-current contacting systems. More specifically, the present techniques provide for the separation of CO₂ and $\frac{3}{4}$ S from a natural gas stream, as well as the separation of the CO₂ from the H₂S, using a series of co-current contacting systems.

15 BACKGROUND

[0003] This section is intended to introduce various aspects of the art, which may be associated with exemplary embodiments of the present techniques. This description is believed to assist in providing a framework to facilitate a better understanding of particular aspects of the present techniques. Accordingly, it should be understood that this section should be read in this light, and not necessarily as admissions of prior art.

[0004] The production of hydrocarbons from a reservoir oftentimes carries with it the incidental production of non-hydrocarbon gases. Such gases include contaminants such as hydrogen sulfide (H₂S) and carbon dioxide (CO₂). When H₂S or CO₂ are produced as part of a hydrocarbon gas stream, such as methane or ethane, the raw natural gas is sometimes referred to as a "sour" natural gas. The $\frac{3}{4}$ S and CO₂ are often referred to together as "acid gases."

foOOS] Sour natural gas must be treated to remove the H₂S and CO₂ before it can be used as an environmentally-acceptable fuel. As an example, for LNG, the H₂S and CO₂ must be removed to very low levels, e.g., less than about 50 parts per million by volume (ppmv) CO₂ and less than about 4 ppmv H₂S. As another example, for pipeline gas, the H₂S must be removed to a very low level, e.g., less than about 4 ppmv, while the CO₂ may be removed to

a lesser extent.

[0006] Cryogenic gas processes are sometimes used to remove CO₂ from raw natural gas stream to prevent line freezing and orifice plugging. In addition, particularly with $\frac{3}{4}$ S removal, the hydrocarbon fluid stream may be treated with a solvent. Solvents may include
5 chemical solvents such as amines. Examples of amines used in sour gas treatment include monoethanol amine (MEA), diethanol amine (DEA), and methyl diethanol amine (MDEA).

[0007] Physical solvents are sometimes used in lieu of amine solvents. Examples include Selexol[®] and Rectisol[™]. In some instances, hybrid solvents, meaning mixtures of physical and chemical solvents, have been used. An example is Sulfinol[®]. In addition, the use of
10 amine-based acid gas removal solvents is common.

[0008] Amine-based solvents rely on a chemical reaction with the acid gases. The reaction process is sometimes referred to as "gas sweetening." Such chemical reactions are generally more effective than the physical-based solvents, particularly at feed gas pressures below about 300 psia (2.07 MPa). There are instances where special chemical solvents such
15 as Flexsorb[™] are used, particularly for selectively removing H₂S from CCVcontaining gas streams.

[0009] As a result of the gas sweetening process, a treated or "sweetened" gas stream is created. The sweetened gas stream is substantially depleted of H₂S and CO₂. The sweetened gas stream can be further processed for liquids recovery, that is, by condensing out heavier
20 hydrocarbon gases. The sweetened gas stream may be sold into a pipeline or may be used for liquefied natural gas (LNG) feed if the concentrations of $\frac{3}{4}$ S and CO₂ are low enough. In addition, the sweetened gas stream may be used as feedstock for a gas-to-liquids process, and then ultimately used to make waxes, butanes, lubricants, glycols, or other petroleum-based products.

[0010] Known counter-current contactors used for removing $\frac{3}{4}$ S and CO₂ from natural gas streams tend to be large and very heavy. This creates particular difficulty in offshore oil and gas production applications, where smaller equipment is desirable. Further, the transport and set-up of large tower-based facilities is difficult for shale gas production operations that frequently take place in remote locations.

[0011] The removal of H₂S and CO₂ from a natural gas stream produces a rich solvent including the H₂S and CO₂. The rich solvent is sometimes referred to as an absorbent liquid. Following removal of the H₂S and CO₂, a process of regeneration (also called "desorption")

may be employed to separate the $\frac{3}{4}$ S and CO₂ from the active solvent of the absorbent liquid. This produces a lean solvent.

[0012] Regeneration of the lean solvent generates a concentrated mixture of the $\frac{3}{4}$ S and CO₂, typically at around 15 psig. In some cases, this mixture can be sent to a Claus sulfur recovery unit to convert the H₂S to elemental sulfur. However, in many cases, the high ratio of CO₂ to H₂S renders the mixture unsuitable for use as a Claus feed stream. In such cases, the acid gas must be enriched prior to being used as a Claus feed stream. This may be accomplished via a low pressure enrichment process that uses a selective amine to preferentially absorb H₂S. In principle, the remaining gas in this case could be used as a substantially clean (although low pressure) CO₂ stream.

[0013] Alternatively, a "super-selective" H₂S removal process may be used on a sour gas stream to remove substantially all of the H₂S, and to generate a concentrated acid gas stream suitable for Claus feed. This would obviate the need for an acid gas enrichment (AGE) unit, saving substantial costs. A subsequent CO₂ removal process could be used to generate a substantially clean CO₂ stream, as well as sweetened natural gas. The extracted CO₂ may then be sold, or it may be injected into a subterranean reservoir for enhanced oil recovery (EOR) operations.

[0014] U.S. Patent Application Publication No. 2009/0241778 by Lechnick et al. describes a system for removing CO₂ from a feed gas within an absorber unit that contains a solvent, and regenerating the solvent within an eductor. However, because the absorber unit and eductor are likely to be large and very heavy, such a system may be expensive and undesirable, particularly for offshore oil and gas recovery applications.

SUMMARY

[0015] An exemplary embodiment provides a system for separating CO₂ and $\frac{3}{4}$ S from a natural gas stream. The system includes a first loop of co-current contacting systems configured to remove H₂S and CO₂ from a natural gas stream, and a second loop of co-current contacting systems configured to remove the $\frac{3}{4}$ S from the CO₂.

[0016] An exemplary embodiment provides a method for separating CO₂ and $\frac{3}{4}$ S from a natural gas stream. The method includes contacting a sour natural gas stream including CO₂ and $\frac{3}{4}$ S with a lean solvent stream within a first series of co-current contacting systems, generating a sweetened natural gas stream and a rich solvent stream including the CO₂ and the $\frac{3}{4}$ S. The method includes contacting the rich solvent stream with a stripping gas within a

second series of co-current contacting systems, regenerating the lean solvent stream and generating a first gas stream including the CO₂, the H₂S, and the stripping gas, and recirculating the lean solvent stream to the first series of co-current contacting systems. The method also includes contacting the first gas stream with a lean H₂S-selective solvent stream within a third series of co-current contacting systems, generating a rich H₂S-selective solvent stream including the H₂S and a second gas stream including the CO₂ and the stripping gas. The method further includes contacting the rich H₂S-selective solvent stream with a stripping gas within a fourth series of co-current contacting systems, regenerating the lean H₂S-selective solvent stream and generating a third gas stream including the H₂S and the stripping gas, and recirculating the lean H₂S-selective solvent stream to the third series of co-current contacting systems.

[0011] Another exemplary embodiment provides a system for separating CO₂ and H₂S from a natural gas stream. The system includes a first series of co-current contacting systems configured to contact a sour natural gas stream including CO₂ and H₂S with a lean solvent stream to generate a sweetened natural gas stream and a rich solvent stream including the CO₂ and the H₂S. The system includes a second series of co-current contacting systems configured to contact the rich solvent stream with a stripping gas to regenerate the lean solvent stream and generate a first gas stream including the CO₂, the H₂S, and the stripping gas, wherein the lean solvent stream is recirculated to the first series of co-current contacting systems. The system also includes a third series of co-current contacting systems configured to contact the first gas stream with a lean H₂S-selective solvent stream to generate a rich H₂S-selective solvent stream including the H₂S and a second gas stream including the CO₂ and the stripping gas. The system further includes a fourth series of co-current contacting systems configured to contact the rich H₂S-selective solvent stream with a stripping gas to regenerate the lean H₂S-selective solvent stream and generate a third gas stream including the H₂S and the stripping gas, wherein the lean H₂S-selective solvent stream is recirculated to the third series of co-current contacting systems.

[0018] Another exemplary embodiment provides a method for selectively removing one gaseous component from a multi-component gas stream. The method includes flowing a lean solvent stream into a mixer of a co-current contactor via an annular support ring and a number of radial blades extending from the annular support ring, wherein the annular support ring secures the mixer in-line within a pipe. The method also includes flowing a multi-component gas stream including a first gaseous component and a second gaseous component

into the mixer via a central gas entry cone that is supported by the radial blades, wherein a first portion of the multi-component gas stream flows through the central gas entry cone and a second portion of the multi-component gas stream flows around the central gas entry cone between the plurality of radial blades. The method also includes contacting the multi-component gas stream with the lean solvent stream within the mixer and a mass transfer section of the co-current contactor to provide for incorporation of liquid droplets formed from the lean solvent stream into the multi-component gas stream, wherein the liquid droplets include the first gaseous component from the multi-component gas stream. The method further includes separating the liquid droplets from the multi-component gas stream within a separation system, generating a rich solvent stream including the first gaseous component and a gas stream including the second gaseous component.

BRIEF DESCRIPTION OF THE DRAWINGS

- [0019] The advantages of the present techniques are better understood by referring to the following detailed description and the attached drawings, in which:
- 15 j0020] **Fig. 1** is a process flow diagram of a chemical solvent-based gas processing system;
- [0021] **Fig. 2A** is a generalized process flow diagram of a system for recovering carbon dioxide (CO₂) and hydrogen sulfide (H₂S) from a natural gas stream that includes a co-current flow scheme;
- 20 [0022] **Figs. 2B-1** and **2B-2** are a process flow diagram of an exemplary embodiment of the system of **Fig. 2A**;
- [0023] **Fig. 3** is a schematic of a column for separating a feed stream into a gas stream and a liquid stream;
- j0024] **Fig. 4A** is a process flow diagram of a separation system including a number of co-current contacting systems that may be placed in a shell;
- 25 [0025] **Fig. 4B** is a process flow diagram of the separation system of **Fig. 4A** including the co-current contacting systems with the addition of a number of heat exchangers;
- [0026] **Fig. 4C** is a process flow diagram of the separation system of **Fig. 4A** including the co-current contacting systems with the addition of one or more flash drums;
- 30 [0027] **Fig. 5** is a process flow diagram of a gas regeneration system including a number of co-current contacting systems;

- [0028] **Fig. 6** is a process flow diagram of a separation system for preferentially removing one component from a multi-component gas stream;
- [0029] **Fig. 7** is a schematic of a co-current contacting system;
- [0030] **Fig. 8A** is a front view of a mixer;
- 5 [0031] **Fig. 8B** is a side perspective view of the mixer;
- [0032] **Fig. 8C** is a cross-sectional side perspective view of the mixer;
- [0033] **Fig. 8D** is a another cross-sectional side perspective view of the mixer;
- [0034] **Fig. 9** is a process flow diagram of a method for separating CO₂ and H₂S from a natural gas stream; and
- 10 [0035] **Fig. 10** is a process flow diagram of a method for selectively removing one gaseous component from a multi-component gas stream.

DETAILED DESCRIPTION

[0036] In the following detailed description section, specific embodiments of the present techniques are described. However, to the extent that the following description is specific to
15 a particular embodiment or a particular use of the present techniques, this is intended to be for exemplary purposes only and simply provides a description of the exemplary embodiments. Accordingly, the techniques are not limited to the specific embodiments described below, but rather, include all alternatives, modifications, and equivalents falling within the true spirit and scope of the appended claims.

20 [0037] At the outset, for ease of reference, certain terms used in this application and their meanings as used in this context are set forth. To the extent a term used herein is not defined below, it should be given the broadest definition persons in the pertinent art have given that term as reflected in at least one printed publication or issued patent. Further, the present techniques are not limited by the usage of the terms shown below, as all equivalents,
25 synonyms, new developments, and terms or techniques that serve the same or a similar purpose are considered to be within the scope of the present claims.

[0038] "Acid gas" refers to any gas that produces an acidic solution when dissolved in water. Non-limiting examples of acid gases include hydrogen sulfide (H₂S), carbon dioxide (CO₂), sulfur dioxide (SO₂), carbon disulfide (CS₂), carbonyl sulfide (COS), mercaptans, or
30 mixtures thereof.

[0039] "Co-current contactor" refers to a vessel that receives a gas stream and a separate solvent stream in such a manner that the gas stream and the solvent stream contact one another while flowing in generally the same direction. Non-limiting examples include an eductor and a coalescer, or a static mixer plus deliquidizer.

- 5 [0040] The term "co-currently" refers to the internal arrangement of process streams within a unit operation that can be divided into several sub-sections by which the process streams flow in the same direction.

[0041] As used herein, a "column" is a separation vessel in which a counter-current flow is used to isolate materials on the basis of differing properties. In an absorbent column, a
10 liquid solvent is injected into the top, while a mixture of gases to be separated is flowed into the bottom. As the gases flow upwards through the falling stream of absorbent, one gas species is preferentially absorbed, lowering its concentration in the vapor stream exiting the top of the column, while rich liquid is withdrawn from the bottom.

[0042] In a distillation column, liquid and vapor phases are counter-currently contacted to
15 effect separation of a fluid mixture based on boiling points or vapor pressure differences. The high vapor pressure, or lower boiling, component will tend to concentrate in the vapor phase, whereas the low vapor pressure, or higher boiling, component will tend to concentrate in the liquid phase. Cryogenic separation is a separation process carried out in a column at least in part at temperatures at or below 150 degrees Kelvin (K). To enhance the separation,
20 both types of columns may use a series of vertically spaced trays or plates mounted within the column and/or packing elements such as structured or random packing. Columns may often have a recirculated stream at the base to provide heat energy for boiling the fluids, which is generally referred to as "reboiling." Further, a portion of the overhead vapor may be condensed and pumped back into the top of the column as a reflux stream, which can be used
25 to enhance the separation and purity of the overhead product. A bulk liquid stripper is related to a column. However, the bulk liquid stripper functions without the use of a reflux stream and, thus, cannot produce a high-purity overhead product.

[0043] "Dehydrated gas stream" refers to a natural gas stream that has undergone a dehydration process. Typically the dehydrated gas stream has a water content of less than 50
30 ppm, and preferably less than 7 ppm. Any suitable process for dehydrating the natural gas stream can be used. Typical examples of suitable dehydration processes include, but are not limited to, treatment of the natural gas stream with molecular sieves or dehydration using glycol or methanol. Alternatively, the natural gas stream can be dehydrated by formation of

methane hydrates; for example, using a dehydration process as described in WO2004/070297.

[0044] As used herein, the term "dehydration" refers to the pre-treatment of a raw feed gas stream to partially or completely remove water and, optionally, some heavy hydrocarbons. This can be accomplished by means of a pre-cooling cycle, against an external cooling loop or a cold internal process stream, for example. Water may also be removed by means of pre-treatment with molecular sieves, e.g. zeolites, or silica gel or alumina oxide or other drying agents. Water may also be removed by means of washing with glycol, monoethylene glycol (MEG), diethylene glycol (DEG), triethylene glycol (TEG), or glycerol. The amount of water in the gas feed stream is suitably less than 1 volume percent (vol %), preferably less than 0.1 vol %, more preferably less than 0.01 vol %.

[0045] The term "distillation" (or "fractionation") refers to the process of physically separating chemical components into a vapor phase and a liquid phase based on differences in the components' boiling points and vapor pressures at specified temperatures and pressures. Distillation is typically performed in a "distillation column," which includes a series of vertically spaced plates. A feed stream enters the distillation column at a mid-point, dividing the distillation column into two sections. The top section may be referred to as the rectification section, and the bottom section may be referred to as the stripping section. Condensation and vaporization occur on each plate, causing lower boiling point components to rise to the top of the distillation column and higher boiling point components to fall to the bottom. A reboiler is located at the base of the distillation column to add thermal energy. The "bottoms" product is removed from the base of the distillation column. A condenser is located at the top of the distillation column to condense the product emanating from the top of the distillation column, which is called the distillate. A reflux pump is used to maintain flow in the rectification section of the distillation column by pumping a portion of the distillate back into the distillation column.

[0046] The term "enhanced oil recovery" (EOR) refers to processes for enhancing the recovery of hydrocarbons from subterranean reservoirs. Techniques for improving displacement efficiency or sweep efficiency may be used for the exploitation of an oil field by introducing displacing fluids or gas into injection wells to drive oil through the reservoir to producing wells.

[0047] As used herein, the term "fluid" may be used to refer to gases, liquids, combinations of gases and liquids, combinations of gases and solids, or combinations of

liquids and solids.

[0048] The term "flue gas" refers to any gas stream generated as a by-product of hydrocarbon combustion.

[0049] The term "gas" is used interchangeably with "vapor," and is defined as a substance
5 or mixture of substances in the gaseous state as distinguished from the liquid or solid state. Likewise, the term "liquid" means a substance or mixture of substances in the liquid state as distinguished from the gas or solid state.

[0050] A "hydrocarbon" is an organic compound that primarily includes the elements hydrogen and carbon, although nitrogen, sulfur, oxygen, metals, or any number of other
10 elements may be present in small amounts. As used herein, hydrocarbons generally refer to components found in natural gas, oil, or chemical processing facilities.

[0051] With respect to fluid processing equipment, the term "in series" means that two or more devices are placed along a flow line such that a fluid stream undergoing fluid separation moves from one item of equipment to the next while maintaining flow in a substantially
15 constant downstream direction. Similarly, the term "in line" means that two or more components of a fluid mixing and separating device are connected sequentially or, more preferably, are integrated into a single tubular device.

[0052] "Liquefied natural gas" (LNG) is natural gas generally known to include a high percentage of methane. However, LNG may also include trace amounts of other elements or
20 compounds. The other elements or compounds may include, but are not limited to, ethane, propane, butane, CO₂, nitrogen, helium, H₂S, or any combinations thereof, that have been processed to remove one or more components (for instance, helium) or impurities (for instance, water, acid gas, and/or heavy hydrocarbons) and then condensed into a liquid at almost atmospheric pressure by cooling.

[0053] The term "liquid solvent" refers to a fluid in substantially liquid phase that preferentially absorbs one component over another. For example, a liquid solvent may preferentially absorb an acid gas, thereby removing or "scrubbing" at least a portion of the acid gas component from a gas stream or a water stream.
25

[0054] "Natural gas" refers to a multi-component gas obtained from a crude oil well or
30 from a subterranean gas-bearing formation. The composition and pressure of natural gas can vary significantly. A typical natural gas stream contains methane (CH₄) as a major component, i.e., greater than 50 mol % of the natural gas stream is methane. The natural gas

stream can also contain ethane (C₂H₆), higher molecular weight hydrocarbons (e.g., C₃-C₂₀ hydrocarbons), one or more acid gases (e.g., CO₂ or H₂S), or any combinations thereof. The natural gas can also contain minor amounts of contaminants such as water, nitrogen, iron sulfide, wax, crude oil, or any combinations thereof. The natural gas stream may be substantially purified according to embodiments described herein, so as to remove compounds that may act as poisons.

[0055] "Non-absorbing gas" refers to a gas that is not significantly absorbed by a solvent during a gas treating or conditioning process.

[0056] "Solvent" refers to a substance capable at least in part of dissolving or dispersing one or more other substances, such as to provide or form a solution. The solvent may be polar, nonpolar, neutral, protic, aprotic, or the like. The solvent may include any suitable element, molecule, or compound, such as methanol, ethanol, propanol, glycols, ethers, ketones, other alcohols, amines, salt solutions, ionic liquids, or the like. The solvent may include physical solvents, chemical solvents, or the like. The solvent may operate by any suitable mechanism, such as physical absorption, chemical absorption, or the like.

[0057] "Substantial" when used in reference to a quantity or amount of a material, or a specific characteristic thereof, refers to an amount that is sufficient to provide an effect that the material or characteristic was intended to provide. The exact degree of deviation allowable may depend, in some cases, on the specific context.

[0058] The term "sweetened gas stream" refers to a fluid stream in a substantially gaseous phase that has had at least a portion of acid gas components removed.

Overview

[0059] The present techniques provide for the separation of CO₂ and H₂S from a natural gas stream, as well as the separation of the CO₂ from the H₂S, using a series of co-current contacting systems. More specifically, in various embodiments, the CO₂ and H₂S are separated from the natural gas stream by contacting the natural gas stream with a solvent stream within a first series of co-current contacting systems. The resulting sweetened natural gas stream may then be sold into a pipeline or used to produce LNG, for example. The H₂S and CO₂ are then removed from the solvent stream by contacting the solvent stream with a stripping gas within a second series of co-current contacting systems. In addition, the H₂S is removed from the CO₂ by contacting the stripping gas including the H₂S and the CO₂ with an H₂S-selective solvent stream within a third series of co-current contacting systems. Further,

the H_2S is removed from the H_2S -selective solvent stream by contacting the H_2S -selective solvent stream with a stripping gas within a fourth series of co-current contacting systems. The recovered CO_2 may then be sold or injected into a subterranean reservoir for enhanced oil recovery (EOR) operations, and the recovered H_2S may be sent to a Claus sulfur recovery unit to be converted into elemental sulfur, for example.

[0060] The use of a series of co-current contacting systems for natural gas processing and solvent regeneration may allow for a reduction in the size of the overall system as compared to systems that utilize counter-current flow schemes. This may, in turn, reduce the operating costs for the system.

10 Systems for Removing CO_2 and H_2S from Natural Gas

[0061] **Fig. 1** is a process flow diagram of a chemical solvent-based gas processing system **100**. The gas processing system **100** may be used to remove water from a raw natural gas stream **102**, generating a dehydrated natural gas stream **104**. This may be accomplished by flowing the raw natural gas stream **102** into a contactor **106**, which may remove the water from the raw natural gas stream **102**. The dehydrated natural gas stream **104** may then be flowed out of the contactor **106** as an overhead stream. In addition, residual water and acid gas components may be removed in connection with a subsequent process, as described further herein.

[0062] The raw natural gas stream **102** may be obtained from a subsurface reservoir **108** via any suitable type of hydrocarbon recovery operation. The raw natural gas stream **102** may include a non-absorbing gas, such as methane. In addition, the raw natural gas stream **102** may include acid gas, such as H_2S and CO_2 . For example, the raw natural gas stream **102** may include about 0 % to 10 % H_2S and about 0 % to 10 % CO_2 , along with the hydrocarbon gas.

[0063] As shown in **Fig. 1**, the raw natural gas stream **102** may be flowed into an inlet separator **110** upon entry into the gas processing system **100**. When entering the inlet separator **110**, the raw natural gas stream **102** may be under a large amount of pressure. However, the pressure of the raw natural gas stream **102** may vary considerably, depending on the characteristics of the subsurface reservoir **108** from which the gas product is produced. For example, the pressure of the raw natural gas stream **102** may range between atmospheric pressure and several thousand psig. For natural gas treating applications, the pressure of the raw natural gas stream **102** may be boosted to about 100 psig or about 500 psig, or greater, if

desired.

[0064] The inlet separator **110** may clean the raw natural gas stream **102**, for example, to prevent foaming of liquid solvent during a later acid gas treatment process. This may be accomplished by separating the raw natural gas stream into liquid-phase components and gas-phase components. The liquid-phase components may include heavy hydrocarbons, a small portion of water, and impurities such as brine, fracturing fluids, and drilling fluids. Such components may be flowed out of the inlet separator **110** via a bottoms line **114**, and may be sent to an oil recovery system **116**. The gas-phase components may include natural gas and some amount of impurities, such as acid gases and water. Such components may be flowed out of the inlet separator **110** as the overhead natural gas stream **112**.

[0065] From the inlet separator **110**, the natural gas stream **112** may be flowed into the contactor **106**. The contactor **106** may use a desiccant, such as a liquid glycol stream **118**, to absorb water in the natural gas stream **112**. The liquid glycol stream **118** may include various glycols, such as triethylene glycol, among others. The liquid glycol stream **118** may be stored in a glycol tank **120**. A high-pressure pump **122** may force the liquid glycol stream **118** from the glycol tank **120** into the contactor **106** under suitable pressure. For example, the high-pressure pump **122** may boost the pressure of the liquid glycol stream **118** to about 1,500 psig or about 2,500 psig, depending on the pressure of the raw natural gas stream **102**.

[0066] Once inside the contactor **106**, gas within the natural gas stream **112** moves upward through the contactor **106**. Typically, one or more trays **124** or other internals are provided within the contactor **106** to create indirect flow paths for the natural gas stream **112** and to create interfacial area between the gas and liquid phases. At the same time, the liquid from the liquid glycol stream **118** moves downward and across the succession of trays **124** in the contactor **106**. The trays **124** aid in the interaction of the natural gas stream **112** with the liquid glycol stream **118**.

[0067] The contactor **106** operates on the basis of a counter-current flow scheme. In other words, the natural gas stream **112** is directed through the contactor **106** in one direction, while the liquid glycol stream **118** is directed through the contactor **106** in the opposite direction. As the two fluid materials interact, the down-flowing liquid glycol stream **118** absorbs water from the up-flowing natural gas stream **112** to produce the dehydrated natural gas stream **104**.

[0068] Upon exiting the contactor **106**, the dehydrated natural gas stream **104** can be

flowed through an outlet separator **126**. The outlet separator **126**, also referred to as a scrubber, may allow any liquid glycol carried over from the contactor **106** to fall out of the dehydrated natural gas stream **104**. A final dehydrated natural gas stream **128** may be flowed out of the outlet separator **126** via an overhead line **130**. Any residual liquid glycol **132** may drop out through a bottoms line **134**.

[0069] A spent desiccant stream **136** may flow out of the bottom of the contactor **106**. The spent desiccant stream **136** may be a glycol solution that is rich in the absorbed water. The spent desiccant stream **136** may be at a relatively high temperature, such as about 90 °F to about 102 °F, or higher. In various embodiments, the gas processing system **100** includes equipment for regenerating the liquid glycol stream **118** from the spent desiccant stream **136**, as described further herein.

[0070] From the contactor **106**, the spent desiccant stream **136** may be heated within a heat exchanger **138** and then flowed into a regenerator **144**. The regenerator **144** may be used to regenerate the liquid glycol stream **118** from the spent desiccant stream **136**. The regenerator **144** may be a large pressure vessel, or interconnected series of pressure vessels, that operates at about 15 psig to about 25 psig, for example. The regenerator may include a reboiler **140** that is coupled to a distillation column **142**.

[0071] The spent desiccant stream **136** can be flowed through a tube bundle **146** in the top of the distillation column **142**. High-temperature water vapor and off-gases **148** being released from the distillation column **142** may preheat the spent desiccant stream **136** as it flows through the tube bundle **146**, before the water vapor and off-gases **148** are released via an overhead line **150**.

[0072] After being preheated within the distillation column **142**, the spent desiccant stream **136** may be released from the tube bundle **146** as a warmed glycol stream **152**. The warmed glycol stream **152** may be flowed into a flash drum **154**. The flash drum **154** may operate at a pressure of about 50 psig to about 100 psig, for example. The flash drum **154** may have internal parts that create a mixing effect or a tortuous flow path for the glycol stream **152**.

[0073] Residual gases **156**, such as methane, H₂S, and CO₂, may be flashed out of the flash drum **154** via an overhead line **158**. The residual gases **156** captured in the overhead line **158** may be reduced to an acid gas content of about 100 ppm if contacted with an amine. This concentration of acid gases is small enough that the residual gases **156** can be used as

fuel gas for the gas processing system **100**.

[0074] In addition, any entrained heavier hydrocarbons, such as hexane or benzene, within the glycol stream **152** may be separated within the flash drum **154** as a liquid of lesser density than the glycol. The resulting hydrocarbon stream **160** may be flowed out of the flash
5 drum **154** via a bottoms line **162**.

[0075] Further, as the temperature and pressure of the glycol stream **152** drops within the flash drum **154**, the hydrocarbons within the glycol stream **152** are separated out, producing a partially-purified glycol stream **164**. The partially-purified glycol stream **164** may then be released from the flash drum **154**. The partially-purified glycol stream **164** may be flowed
10 through a filter **166**, such as a mechanical filter or carbon filter, for particle filtration.

[0076] The resulting filtered glycol stream **168** may then be flowed through a heat exchanger **170**. Within the heat exchanger **170**, the filtered glycol stream **168** may be heated via heat exchange with the liquid glycol stream **118**. The resulting high-temperature glycol stream **174** may be flowed into the distillation column **142** of the regenerator **144**. As the
15 high-temperature glycol stream **174** travels through the distillation column **142**, water vapor and off-gases **148**, such as H₂S and CO₂, may be removed from the high-temperature glycol stream **174**.

[0077] The high-temperature glycol stream **174** may be flowed out of the bottom of the distillation column **142** and into the reboiler **140**. In addition, the reboiler **140** may boil off
20 residual water vapor and off-gases **148** from the high-temperature glycol stream **174**. The components that are boiled off may travel upward through the distillation column **142** and be removed as the water vapor and off-gases **148** in the overhead line **150**.

[0078] The regenerator **144** may also include a separate stripping section **176** fed from the liquid pool in the reboiler **140**. The stripping section **176** may include packing that
25 promotes further distillation, as well as dry stripping gas, e.g., cryogenically-generated nitrogen. Any remaining impurities, such as water, H₂S, and/or CO₂, boil off and join the water vapor and off-gases **148** in the overhead line **150**. The high-temperature glycol stream **174** may then be flowed into a surge tank **178**, from which it may be released as the liquid glycol stream **118**.

[0079] The regenerated liquid glycol stream **118** may be pumped out of the surge tank **178** via a booster pump **180**. The booster pump **180** may increase the pressure of the liquid glycol stream **118** to about 50 psig, for example.

[0080] The liquid glycol stream **118** may then be flowed through the heat exchanger **170**, in which the liquid glycol stream **118** may be partially cooled via heat exchange with the filtered glycol stream **168**. The liquid glycol stream **118** may be stored in the glycol tank **120**. The high-pressure pump **122** may then force the liquid glycol stream **118** from the glycol tank **120** through a cooler **182** prior to being returned to the contactor **106**. The cooler **182** may cool the liquid glycol stream **118** to ensure that the glycol will absorb water when it is returned to the contactor **106**. For example, the cooler **182** may chill the liquid glycol stream **118** to about **100 °F** or **125 °F**.

[0081] The process flow diagram of **Fig. 1** is not intended to indicate that the gas processing system **100** is to include all of the components shown in **Fig. 1**. Further, any number of additional components may be included within the gas processing system **100**, depending on the details of the specific implementation. For example, additional heat may be provided to the reboiler **140** to assist in flashing off the water. Further, the gas processing system **100** may include any suitable types of heaters, chillers, condensers, liquid pumps, gas compressors, blowers, bypass lines, other types of separation and/or fractionation equipment, valves, switches, controllers, and pressure-measuring devices, temperature-measuring devices, level-measuring devices, or flow-measuring devices, among others.

[0082] **Fig. 1** demonstrates the use of a known contactor **106** in the context of a gas dehydration process. However, the gas processing system **100** is also substantially representative of a sour gas removal operation. In that instance, the liquid stream **118** includes a chemical solvent, such as a primary amine, a secondary amine, or a tertiary amine. The liquid stream **118** may also be an ionic liquid or a blend of a physical solvent with an amine. For purposes of discussion, the liquid stream **118** may be interchangeably referred to herein as an amine, a chemical solvent, or an absorbent liquid.

[0083] In some embodiments, a solvent that preferentially removes H_2S molecules over CO_2 molecules may be used. For example, a tertiary amine typically does not effectively strip out CO_2 as quickly as H_2S . Therefore, two separate gas processing systems **100** may be sequentially operated, with one configured to strip out primarily H_2S , and the other configured to strip out primarily CO_2 . A separate CO_2 stream that is substantially free of H_2S may also be generated.

[0084] Regardless of the application and the solvent used, the disadvantage of gas processing systems that include counter-current flow schemes, such as the gas processing system **100** of **Fig. 1**, is that comparatively low velocities are required to avoid entrainment

of the down-flowing liquid solvent in the natural gas stream **102**. Also, relatively long distances are required for disengagement of the liquid droplets from the natural gas stream **102**. Depending on the flow rate of the natural gas stream **102**, the contactor **106** can be greater than 15 feet in diameter, and more than 100 feet tall. For high-pressure applications, the vessel has thick, metal walls. Consequently, counter-current contactor vessels can be large and very heavy. This is generally undesirable, particularly for offshore oil and gas recovery applications.

[0085] In the gas processing system **100** of **Fig. 1**, the contactor **106** includes a single contacting tower. However, in some applications, more than one contacting tower may be used. In addition, very large contactors may be used for high-volume, high-pressure applications. In the case of low-pressure applications, such as CO₂ removal from flue gas at a power generation plant, it is estimated that a 50 foot by 50 foot duct contactor would be used for a relatively small, 500 megawatt power plant flue gas application. Many hundreds of gallons per minute of solvent would also be flowed through the contactor. Thus, such operations may become very costly.

[0086] Further, the internals of the tower **106** can make it susceptible to wave motion in an offshore environment. Therefore, it may be desirable to have a mass transfer process that does not rely on conventional tower internals. For example, it may be desirable to utilize a series of low pressure-drop, small contacting devices to remove CO₂ and H₂S from flash-gas streams.

[0087] Embodiments described herein utilize a co-current flow scheme as an alternative to the counter-current flow scheme demonstrated in the contactor **106** of **Fig. 1**. The co-current flow scheme utilizes one or more co-current contacting systems connected in series within a pipe. A natural gas stream and a liquid solvent may move together, i.e., co-currently, within the co-current contacting systems. In some embodiments, the natural gas stream and the liquid solvent move together generally along the longitudinal axis of the respective co-current contacting system. In general, co-current contactors can operate at much higher fluid velocities than counter-current contactors. As a result, co-current contactors tend to be smaller than counter-current contactors that utilize standard packed or trayed towers.

[0088] **Fig. 2A** is a generalized process flow diagram of a system **200** for separating CO₂ and H₂S from a natural gas stream that includes a co-current flow scheme. The system **200** may function as an all-in-one gas processing system, solvent regeneration system, and acid

gas recovery system. Moreover, the system **200** may be an alternative to the gas processing system **100** described with respect to **Fig. 1**.

[0089] The system **200** may employ a number of co-current contacting systems (CCCS's). Specifically, the system **200** may employ a first series of co-current contacting systems **202A**, a second series of co-current contacting systems **202B**, a third series of co-current contacting systems **202C**, and a fourth series of co-current contacting systems **202D**. Moreover, it is to be understood that the system **200** is not limited to the series of co-current contacting systems **202A-D** shown in **Fig. 2**. For example, in some embodiments, the system **200** may only include the first and second series of co-current contacting systems **202A** and **202B**, or may only include the first, second, and third series of co-current contacting systems **202A-C**, depending on the details of the specific implementation. In other embodiments, the system **200** may include any number of additional series of co-current contacting systems not shown in **Fig. 2**.

[0090] Each co-current contacting system within the series of co-current contacting systems **202A-D** includes a co-current contactor upstream of a separation system. In addition, each series of co-current contacting systems **202A-D** may include any number of co-current contacting systems connected in series. Further, in some embodiments, one or more of the series of co-current contacting systems **202A-D** may include only one co-current contacting system.

[0091] According to the embodiment shown in **Fig. 2A**, the first series of co-current contacting systems **202A** contacts a sour natural gas stream **204** from a hydrocarbon production operation, for example, with a lean solvent stream **206**, producing a sweetened natural gas stream **208** and a rich solvent stream **210** including CO₂ and H₂S. In various embodiments, the sweetened natural gas stream **208** is then sold into a pipeline or used to produce LNG.

[0092] From the first series of co-current contacting systems **202A**, the rich solvent stream **210** is flowed into the second series of co-current contacting systems **202B**, along with a stripping gas **212**. The second series of co-current contacting systems **202B** contact the rich solvent stream **210** with the stripping gas **212**, regenerating the lean solvent stream **206** and producing a gas stream **214** including the stripping gas, CO₂, and H₂S. In various embodiments, the lean solvent stream **206** is then recirculated to the first series of co-current contacting systems **202A**.

[0093] From the second series of co-current contacting systems **202B**, the gas stream **214** including the stripping gas, CO₂, and H₂S is flowed into the third series of co-current contacting systems **202C**, along with a lean H²S-selective solvent stream **216**. The third series of co-current contacting systems **202C** contacts the gas stream **214** with the H₂S-selective solvent stream **216**, producing a gas stream **218** that includes the CO₂ and the stripping gas, as well as a rich H₂S-selective solvent stream **220** that includes the H₂S. In some embodiments, the CO₂ within the gas stream **218** is then sold or injected into a subterranean reservoir for enhanced oil recovery (EOR) operations.

[0094] From the third series of co-current contacting systems **202C**, the rich H₂S-selective solvent stream **220** is flowed into the fourth series of co-current contacting systems **202D**, along with a stripping gas **222**. The fourth series of co-current contacting systems **202D** contact the rich H²S-selective solvent stream **220** with the stripping gas **222**, regenerating the lean H²S-selective solvent stream **216** and producing a gas stream **224** including the H₂S and the stripping gas. In various embodiments, the lean H²S-selective solvent stream **216** is then recirculated to the third series of co-current contacting systems **202C**. In addition, in some embodiments, the H₂S within the gas stream **224** is then sent to a Claus sulfur recovery unit to be converted into elemental sulfur.

[0095] **Figs. 2B-1 and 2B-2** are a process flow diagram of an exemplary embodiment of the system **200** of **Fig. 2A**. Like numbered items are as described with respect to **Fig. 2A**. The sour natural gas stream **204** may be flowed through an inlet separator **226**. The inlet separator **226** may be used to clean the sour natural gas stream **204** by filtering out impurities, such as brine and drilling fluids. Some particle filtration may also take place. The cleaning of the sour natural gas stream **204** can prevent foaming of solvent during the acid gas treatment process.

[0096] In some embodiments, the sour natural gas stream **204** may also be pretreated upstream of the inlet separator **226** or the first series of co-current contacting systems **202A**. For example, the sour natural gas stream **204** may undergo a water wash to remove glycol or other chemical additives. This may be accomplished via a separate processing loop (not shown) wherein water is introduced to the gas, such as via an additional co-current contacting system. Water has an affinity for glycol and will pull the glycol out of the sour natural gas stream **204**. This, in turn, will help control foaming within the first series of co-current contacting systems **202A**. In the case of flue gas applications, corrosion inhibitors may be added to the solvent to retard the reaction of O₂ with the steel in the processes.

[0097] From the inlet separator **226**, the sour natural gas stream **204** may be flowed into the first series of co-current contacting systems **202A**, where it is mixed with the lean solvent stream **206**. The solvent stream **206** may include an amine solution, such as monoethanol amine (MEA), diethanol amine (DEA), or methyldiethanol amine (MDEA). Other solvents, such as physical solvents, alkaline salts solutions, or ionic liquids, may also be used for H₂S removal. In various embodiments, the lean solvent stream **206** is a solvent stream that has undergone a desorption process for the removal of acid gas impurities. Specifically, the lean solvent stream **206** introduced into the first series of co-current contacting systems **202A** includes lean solvent that has been regenerated via the second series of co-current contacting systems **202B**.

[0098] The first series of co-current contacting systems **202A** may include six co-current contacting systems **228A-F** connected in series. Each co-current contacting system **228A-F** removes a portion of the acid gas content, i.e., the CO₂ and H₂S, from the natural gas stream **204**, thereby releasing a progressively sweetened natural gas stream in a downstream direction. The final co-current contacting system **228F** provides the final sweetened natural gas stream **208**.

[0099] The sour natural gas stream **204** is flowed into the first co-current contacting system **228A** within the first series of co-current contacting systems **202A**. In addition, a first partially-loaded, or "rich," solvent stream **230A** is flowed from the second co-current contacting system **228B** into the first co-current contacting system **228A**. Once inside the first co-current contacting system **228A**, the sour natural gas stream **204** and the first partially-loaded solvent stream **230A** move along the longitudinal axis of the first co-current contacting system **228A**. As they travel, the first partially-loaded solvent stream **230A** interacts with the CO₂ and H₂S in the sour natural gas stream **204**, causing the CO₂ and H₂S to chemically attach to or be absorbed by the amine molecules of the first partially-loaded solvent stream **230A**. The rich solvent stream **210** may then be flowed out of the first co-current contacting system **228A**. In addition, a first partially-sweetened natural gas stream **232A** may be flowed out of the first co-current contacting system **228A** and into a second co-current contacting system **228B**.

[0100] A third co-current contacting system **228C** may be provided after the second co-current contacting system **228B**, and a fourth co-current contacting system **228D** may be provided after the third co-current contacting system **228C**. In addition, a fifth co-current contacting system **228E** may be provided after the fourth co-current contacting system **228D**,

and a final co-current contacting system **228F** may be provided after the fifth co-current contacting system **228E**. Each of the second, third, fourth, and fifth co-current contacting systems **228B**, **228C**, **228D**, and **228E** may generate a respective partially-sweetened natural gas stream **232B**, **232C**, **232D**, and **232E**. In addition, each of the third, fourth, fifth, and
5 final co-current contacting systems **228C**, **228D**, **228E**, and **228F** may generate respective partially-loaded solvent stream **230B**, **230C**, **230D**, and **230E**. If an amine is used as the solvent stream **206**, the partially-loaded solvent stream **230A-E** may include rich amine solutions.

[0101] As the progressively-sweetened natural gas streams **232A-E** are generated, the gas
10 pressure in the system **200** will gradually decrease. As this occurs, the liquid pressure of the progressively-richer solvent streams **230A-E** may be correspondingly increased. This may be accomplished by placing one or more booster pumps (not shown) between each co-current contacting system **228A-F** to boost liquid pressure in the system **200**.

[0102] The rich solvent stream **210** exiting the first series of co-current contacting
15 systems **202A** is flowed through a flash drum **234**. Absorbed natural gas **236** may be flashed from the rich solvent stream **210** within the flash drum **234**, and may be flowed out of the flash drum **234** via an overhead line **238**.

[0103] The rich solvent stream **226** is then flowed from the flash drum **234** to the second series of co-current contacting systems **202B**. The second series of co-current contacting
20 systems **202B** may include six co-current contacting systems **240A-F** connected in series. Each co-current contacting system **240A-F** removes a portion of the CO₂ and H₂S from the rich solvent stream **210**, thereby releasing the lean solvent stream **206** and the gas stream **214** including the stripping gas, CO₂, and H₂S. The lean solvent stream **206** may then be recirculated to the first series of co-current contacting systems **202A**, while the gas stream
25 **214** may be flowed into the third series of co-current contacting systems **202C**.

[0104] In various embodiments, the stripping gas **212** is flowed into the first co-current contacting system **240A** within the second series of co-current contacting systems **202B**. In addition, a first partially-unloaded, or "lean," solvent stream **242A** is flowed from the second co-current contacting system **240B** into the first co-current contacting system **240A**. Once
30 inside the first co-current contacting system **240A**, the stripping gas **212** and the first partially-unloaded solvent stream **242A** move along the longitudinal axis of the first co-current contacting system **240A**. As they travel, the first partially-unloaded solvent stream **242A** interacts with the stripping gas **212**, causing any remaining CO₂ and H₂S within the

first partially-unloaded solvent stream **242A** to chemically detach or desorb from the amine molecules to the stripping gas **212**. The resulting lean solvent stream **206** may then be flowed out of the first co-current contacting system **240A** within the second series of co-current contacting systems **202B**, and may be recirculated to the first series of co-current contacting systems **202A**. In addition, a first gas mixture **244A** including the stripping gas, the CO₂, and the H₂S may be flowed out the first co-current contacting system **240A** and into a second co-current contacting system **240B**.

[0105] A third co-current contacting system **240C** may be provided after the second co-current contacting system **240B**, and a fourth co-current contacting system **240D** may be provided after the third co-current contacting system **240C**. In addition, a fifth co-current contacting system **240E** may be provided after the fourth co-current contacting system **240D**, and a final co-current contacting system **240F** may be provided after the fifth co-current contacting system **240E**. Each of the second, third, fourth, and fifth co-current contacting systems **240B**, **240C**, **240D**, and **240E** may generate a respective gas mixture **244B**, **244C**, **244D**, and **244E** including CO₂ and H₂S. In addition, each of the third, fourth, fifth, and final co-current contacting systems **240C**, **240D**, **240E**, and **240F** may generate respective partially-unloaded solvent stream **242B**, **242C**, **242D**, and **242E**.

[0106] From the second series of co-current contacting systems **202B**, the resulting gas stream **214** including the stripping gas, CO₂, and H₂S is flowed into the third series of co-current contacting systems **202C**. The third series of co-current contacting systems **202C** may include six co-current contacting systems **246A-F** connected in series. Each co-current contacting system **246A-F** removes a portion of the H₂S from the gas stream **214**, thereby releasing the rich H₂S-selective solvent stream **220** including the H₂S and the gas stream **218** including the CO₂ and the stripping gas. The CO₂ within the gas stream **218** may then be used as part of a miscible EOR operation to recover oil, for example. In addition, the rich H₂S-selective solvent stream **220** may be flowed into the fourth series of co-current contacting systems **202D** for the removal of the H₂S.

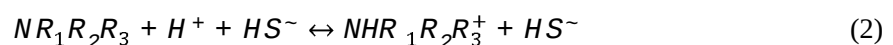
[0107] In various embodiments, the gas stream **214** including the stripping gas, CO₂, and H₂S is flowed into the first co-current contacting system **246A** within the third series of co-current contacting systems **202C**. In addition, a first partially-loaded, or "rich," H₂S-selective solvent stream **248A** including some amount of H₂S is flowed from the second co-current contacting system **246B** into the first co-current contacting system **246A**. Once inside the first co-current contacting system **246A**, the gas stream **214** and the partially-loaded H₂S-

selective solvent stream **248A** move along the longitudinal axis of the first co-current contacting system **246A**. As they travel, the first partially-loaded H⁺S-selective solvent stream **248A** interacts with the $\frac{1}{4}$ S within the gas stream **214**, causing the $\frac{1}{4}$ S to chemically attach to or be absorbed by the molecules of the first partially-loaded H⁺S-selective solvent stream **248A**. The resulting rich H⁺S-selective solvent stream **220** including the $\frac{1}{4}$ S may then be flowed out of the third series of co-current contacting systems **202C** and into the fourth series of co-current contacting systems **202D**. In addition, a first gas mixture **250A** including the stripping gas and the CO₂, as well as a decreased amount of the H₂S, may be flowed out of the first co-current contacting system **246A** and into a second co-current contacting system **246B**.

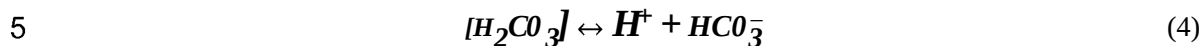
[0108] A third co-current contacting system **246C** may be provided after the second co-current contacting system **246B**, and a fourth co-current contacting system **246D** may be provided after the third co-current contacting system **246C**. In addition, a fifth co-current contacting system **246E** may be provided after the fourth co-current contacting system **246D**, and a final co-current contacting system **246F** may be provided after the fifth co-current contacting system **246E**. Each of the second, third, fourth, and fifth co-current contacting systems **246B**, **246C**, **246D**, and **246E** may generate a respective gas mixture **250B**, **250C**, **250D**, and **250E** including the stripping gas and the CO₂, as well as progressively decreasing amount of $\frac{1}{4}$ S. In addition, each of the third, fourth, fifth, and final co-current contacting systems **246C**, **246D**, **246E**, and **246F** may generate respective partially-loaded H₂S-selective solvent streams **248B**, **248C**, **248D**, and **248E**.

[0109] In various embodiments, the H⁺S-selective solvent stream that is used within the third series of co-current contacting systems **202C** is a specially-designed solvent that enhances the selectivity of $\frac{1}{4}$ S over CO₂ within the co-current contacting systems **246A-F**. Acid gases react reversibly with solvents via different routes. For example, in the case of physical solvents such as methanol, absorption occurs due to van der Waals attraction for the polar H₂S and polarizable CO₂ molecules. As another example, in the case of chemical solvents such as amines, the reaction is chemical in nature.

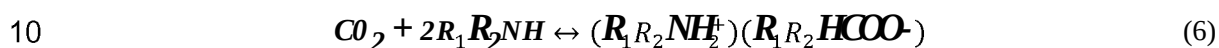
[0110] Specifically, for $\frac{1}{4}$ S, the only route is an acid-base reaction, as shown below in Eqs. (1) and (2).



In Eq. (2), R_1 , R_2 , and R_3 represent organic substituents attached to the nitrogen atom of the tertiary amine. With tertiary amines, CO_2 can react only via the acid-base route, as shown below in Eqs. (3)-(5).



If the amine is a secondary amine that includes one hydrogen atom attached to the nitrogen atom, or a primary amine that includes two hydrogen atoms attached to the nitrogen atom, CO_2 can react to form a carbamate, as shown below in Eq. (6).



[0111] Because CO_2 and H_2S react with chemical solvents via such different routes, the use of a specially-designed solvent within the co-current contacting systems described herein may allow for the selective removal of H_2S from a gas stream that includes both H_2S and CO_2 . In various embodiments, the specially-designed solvent is a tertiary amine. However, it is to be understood that the specially-designed may also be any other suitable solvent that is capable of selectively absorbing H_2S over CO_2 , such as sterically-hindered amines.

[0112] Because the H_2S reaction is almost instantaneous relative to the CO_2 reaction, lowering the residence time of the gas stream **214** and the H^+S -selective solvent stream within each co-current contacting systems **246A-F** may enhance the selective removal of H_2S from the gas stream **214**. Therefore, the co-current contacting systems **246A-F** may be designed such that the residence time is relatively short.

[0113] The rich H^+S -selective solvent stream **220** including the H_2S may be flowed from the third series of co-current contacting systems **202C** into the fourth series of co-current contacting systems **202D** for the recovery of the H_2S and regeneration of the lean H_2S -selective solvent stream **216**. The fourth series of co-current contacting systems **202D** may include six co-current contacting systems **252A-F** connected in series. Each co-current contacting system **252A-F** removes a portion of the H_2S from the rich H^+S -selective solvent stream **220**, thereby releasing the lean H^+S -selective solvent stream **216** and the gas stream **224** including the H_2S and the stripping gas. The lean H^+S -selective solvent stream **216** may then be recirculated to the third series of co-current contacting systems **202C**. In addition, the H_2S within the gas stream **224** may then be converted into elemental sulfur using a Claus

sulfur recovery unit.

[0114] In various embodiments, the stripping gas **222** is flowed into the first co-current contacting system **252A** within the fourth series of co-current contacting systems **202D**. In addition, a first partially-unloaded, or "lean," H₂S-selective solvent stream **254A** is flowed
 5 from the second co-current contacting system **252B** into the first co-current contacting system **252A**. Once inside the first co-current contacting system **252A**, the stripping gas **222** and the first partially-unloaded H₂S-selective solvent stream **254A** move along the longitudinal axis of the first co-current contacting system **252A**. As they travel, the first partially-unloaded s
 H₂S-selective solvent stream **254A** interacts with the stripping gas **222**, causing any
 10 remaining H₂S within the first partially-unloaded H₂S-selective solvent stream **254A** to chemically detach or desorb from the amine molecules of the stripping gas **222**. The resulting lean H₂S-selective solvent stream **216** may then be flowed out of the fourth series of co-current contacting systems **202D**, and may be recirculated to the third series of co-current contacting systems **202C**. In addition, a first gas mixture **256A** including the stripping gas
 15 and the H₂S may be flowed out of the first co-current contacting system **252A** and into a second co-current contacting system **252B**.

[0115] A third co-current contacting system **252C** may be provided after the second co-current contacting system **252B**, and a fourth co-current contacting system **252D** may be provided after the third co-current contacting system **252C**. In addition, a fifth co-current
 20 contacting system **252E** may be provided after the fourth co-current contacting system **252D**, and a final co-current contacting system **252F** may be provided after the fifth co-current contacting system **252E**. Each of the second, third, fourth, and fifth co-current contacting systems **252B**, **252C**, **252D**, and **252E** may generate a respective gas mixture **256B**, **256C**, **256D**, and **256E** including the stripping gas and an increasing amount of H₂S. In addition,
 25 each of the third, fourth, fifth, and final co-current contacting systems **252C**, **252D**, **252E**, and **252F** may generate respective partially-unloaded H₂S-selective solvent stream **254B**, **254C**, **254D**, and **254E**.

[0116] The process flow diagrams of **Figs. 2A, 2B-1, and 2B-2** are not intended to indicate that the system **200** is to include all of the components shown in **Figs. 2A, 2B-1, and**
 30 **2B-2**. Further, any number of additional components may be included within the system **200**, depending on the details of the specific implementation. For example, the system **200** may include any suitable types of heaters, chillers, condensers, liquid pumps, gas compressors, blowers, bypass lines, other types of separation and/or fractionation equipment, valves,

switches, controllers, and pressure-measuring devices, temperature-measuring devices, level-measuring devices, or flow-measuring devices, among others.

[0117] **Fig. 3** is a schematic of a column **300** for separating a feed stream **302** into a gas stream **304** and a liquid stream **306**. The feed stream **302** may be a gas stream that includes two or more different components with different boiling points and vapor pressures, such as an absorbent solvent and a gas contaminant. The column **300** may be similar to the columns used in the regeneration system described with respect to **Fig. 1**.

[0118] The column **300** may include a number of trays **308** or other internals that create indirect flow paths for the feed stream **302** and create interfacial area between the gas and liquid phases. The feed stream **302** may be injected into an upper or middle portion of the column **300**, between trays **308**. The gas within the feed stream **302** moves upward through the column **300**. At the same time, any liquid within the column **300** moves downward and across the succession of trays **308** in the column **300**. In addition, the liquid may include a reflux stream **310** that is reinjected into the top portion of the column **300**, as described further herein.

[0119] The column **300** may utilize a variety of separation technologies, depending on the species in the feed stream **302**. For example, the column may be a distillation column, a countercurrent separation column, or a regeneration column, among others.

[0120] For a distillation column, the feed stream **302** may include a mixture of liquids with slightly different boiling points. In this case, the column **302** is a distillation column that functions to separate the species by the differences in boiling point. The trays **308** determine the number of theoretical plates, and, thus, the separation efficiency of the column **300**.

[0121] In a countercurrent column, the feed stream **302** may include a mixture of gases, such as methane and H_2O or H_2S . As the gases flow upwards through the falling stream of liquid, one gas species is preferentially absorbed by the liquid, lowering its concentration in the gas rising to the top of the column **300**. In some embodiments, the liquid includes a physical solvent (not shown) that is injected into a top portion of the column **300**. More specifically, the liquid and vapor phases may be counter-currently contacted to effect separation of a fluid mixture based on chemical affinities, boiling point difference, or vapor pressure differences, or combinations thereof.

[0122] In a regeneration column, the feed stream includes a liquid that contains a dissolved or adsorbed gas. As the liquid falls through the column **300**, the gas is released and

exits through the top of the column **300**.

[0123] The component that concentrates in the gas phase may be flowed out of the top of the column **300** as an overhead gas stream **312**, while the component that concentrates in the liquid phase may be flowed out of the bottom of the column **300** as a bottoms liquid stream **314**. In addition, some amount of liquid **316** may be allowed to collect in the bottom of the column **300** before being flowed out of the column **300** in order to provide for increased separation of the gas phase from the liquid phase.

[0124] The bottoms liquid stream **314** may be flowed through a reboiler **318**. The reboiler **318** may increase the temperature of the bottoms liquid stream **314**, vaporizing a portion of the bottoms liquid stream **314**, which may include components in the liquid, or a portion of the liquid itself. The resulting stream **320** may be flowed back into the bottom portion of the column **300** to provide heat to the liquids **316** collecting in the bottom of the column **300**.

[0125] A portion of the overhead gas stream **312** may be cooled and at least partially condensed within a heat exchanger **322**. The cooled gas stream **324** may then be separated into the gas stream **304** and a liquid stream **326** within a separation vessel **328**. The liquid stream **326** may be pumped back into the top portion of the column **300** as the reflux stream **310**. Within the column **300**, the reflux stream **310** may be used to enhance the performance of the column **300** by increasing the degree of separation between the liquid phase and the gas phase.

[0126] In practice, the column **300** may be very large and heavy. This may create difficulty in many applications, such as offshore oil and gas production applications. Therefore, the co-current contacting system described herein may provide a desirable alternative to the column **300**.

[0127] **Fig. 4A** is a process flow diagram of a separation system **400** including a number of co-current contacting systems **402A-C** that may be placed in a shell **403**. In this embodiment, the separation system **400** may be analogous to a separation column, for example, as described with respect to **Fig. 3**, in which each of the co-current contacting systems **402A-C** are acting as bed packing. In some embodiments, the shell **403** is a permanent, climate-controlled structure. In other embodiments, the shell **403** is a temporary or portable structure. In other embodiments, the shell **403** is an insulated jacket. In various embodiments, the separation system **400** is implemented as part of the system **200** described

with respect to Fig. 2A, 2B-1, and 2B-2. For example, the separation system 400 may be one of the series of co-current contacting systems 202A-D within the system 200 of Figs. 2A, 2B-1, and 2B-2. In the illustrative arrangement shown in Fig. 4A, a first co-current contacting system 402A, a second co-current contacting system 402B, and a third co-current contacting system 402C are provided, each residing within the single shell 403.

[0128] In various embodiments, due to the pump requirements on the liquid streams, the inter-stage liquid streams may be flowed through the shell 403. The shell 403 may be designed to keep the equipment and the solvent streams flowing therein cool. This may be done through climate control within the shell 403 or through the circulation of a cooling medium adjacent to the shell 403.

[0129] A first gas stream 404 may be flowed into the first co-current contacting system 402A. The first co-current contacting system 402A may generate a first partially purified gas stream 406A, which may be flowed from the first co-current contacting system 402A to the second co-current contacting system 402B. The second co-current contacting system 402B may then generate a second partially purified gas stream 406B, which may be flowed from the second co-current contacting system 402B to the third co-current contacting system 402C. In some embodiments, the third co-current contacting system 402C generates a final purified gas stream 408.

[0130] Each of the first, second, and third co-current contacting systems 402A-C also generates a respective rich solvent stream 410A, 410B, and 410C. The third rich solvent stream 410C may be directed back to the second co-current contacting system 402B, and the second rich solvent stream 410B may be directed back to the first co-current contacting system 402A. In addition, the third co-current contacting system 402C may receive a lean (or semi-lean) solvent stream 410D from another source. Further, the first rich solvent stream 410A may be sent another separation system, e.g., another series of co-current contacting systems, for regeneration, as described with respect to Figs. 2A, 2B-1, and 2B-2, or may serve as a liquid solvent for a preceding co-current contacting system (not shown).

[0131] Fig. 4B is a process flow diagram of the separation system 400 of Fig. 4A including the co-current contacting systems 402A, 402B, and 402C with the addition of a number of heat exchangers 412A and 412B. The heat exchangers 412A and 412B may be used to cool the rich solvent streams 410B and 410C. In some embodiments, the heat exchangers 412A and 412B are used as an alternative to the use of the shell 403.

[0132] **Fig. 4C** is a process flow diagram of the separation system **400** of **Fig. 4A** including the co-current contacting systems **402A**, **402B**, and **402C** with the addition of one or more flash drums **414**. In the embodiment shown in **Fig. 4C**, the second rich solvent stream **410B** may be flowed through the flash drum **414**. A flash line **416** may be provided coming off the top of the flash drum **414**. The flash drum **414** and associated flash line **416** may permit methane and any CO₂ absorbed in the second rich solvent stream **410B** to be flashed out before the second rich solvent stream **410B** is flowed into the first co-current contacting system **402A**. H₂O in vapor form may also be vented from the flash line **416**. In various embodiments, flashing the second rich solvent stream **410B** creates a semi-lean solvent stream. The use of a semi-lean solvent stream in the first co-current contacting system **402A** may improve the efficiency of the first co-current contacting system **402A** and reduce the load on the regenerator. Further, in some embodiments, any of the other solvent streams **410A**, **410C**, or **410D** may also be flowed through a flash drum that is similar to the flash drum **414**. In some embodiments, gas, e.g., methane, CO₂, and H₂O, flashing out of the flash line **416** is merged with gas flashing out of flash lines associated with any number of other flash drums within the gas processing system.

[0133] As shown in **Fig. 4C**, the second solvent stream **410B** may also be flowed through a pump **418** after it exits the flash drum **414**. The pump **418** may increase the pressure of the second solvent stream **410B**, to treat the high pressure gas and to overcome the effect of the pressure drop that occurs within the co-current contacting systems **402A-C**. Increasing the pressure of the second solvent stream **410B** may also allow the second solvent stream **410B** to more effectively entrain the acid gases within the gas stream **404**.

[0134] It is to be understood that the separation system **400** is not limited to the number of co-current contacting systems shown in **Figs. 4A-C**. Rather, the separation system **400** may include any suitable number of co-current contacting systems, depending on the details of the specific implementation. Further, the interconnections within the separation system **400** do not have to be arranged as shown in **Figs. 4A-C**. Rather, any suitable variations or alternatives to the interconnections shown in **Figs. 4A-C** may be present within the separation system **400**, depending on the details of the specific implementation.

[0135] **Fig. 5** is a process flow diagram of a gas regeneration system **500** including a number of co-current contacting systems **502A-C**. The co-current contacting systems **502A-C** may be used for the removal of CO₂ and H₂S from a rich solvent stream **504**. For example, in some embodiments, the gas regeneration system **500** may be implemented as the second

series of co-current contacting systems **202B** within the system **200** of **Fig. 2A**.

[0136] As shown in **Fig. 5**, a stripping gas **506** may be flowed into a first co-current contacting system **502A**. The stripping gas **506** may be nitrogen, steam, or any other suitable type of stripping gas. If the stripping gas **506** is steam, the spent stream may be condensed,
5 and the remaining vapor may be sent to a sulfur recovery unit or acid gas injection unit. In addition, the stripping gas **506** may be gas generated by boiling the liquid discharge from a third co-current contacting system **502C**, analogous to using a reboiler in a regular separation column.

[0137] In addition, a first partially-unloaded, or "lean," solvent stream **508A** may be
10 heated within a first heat exchanger **510** and then flowed into the first co-current contacting system **502A**. Once inside the first co-current contacting system **502A**, the stripping gas **506** and the first partially -unloaded solvent stream **508A** move along the longitudinal axis of the first co-current contacting system **502A**. As they travel, the first partially-unloaded solvent stream **508A** interacts with the stripping gas **506**, causing any remaining CO_2 and H_2S within
15 the first partially -unloaded solvent stream **508A** to chemically attach to or be absorbed by the amine molecules of the stripping gas **506**. The resulting lean solvent stream **512** may then be flowed out of the gas regeneration facility **500**. In some embodiments, the lean solvent stream **512** is flowed into another series of co-current contacting systems for the processing of a natural gas stream, as described with respect to the system **200** of **Figs. 2A, 2B-1, and**
20 **2B-2**. Further, in some embodiments, a portion of the lean solvent stream **512** is boiled to generate the stripping gas **506**.

[0138] A first gas mixture **514A** including the stripping gas and a portion of the CO_2 and H_2S may be flowed from the first co-current contacting system **502A** to a second co-current contacting system **502B**. In addition, a second partially-unloaded solvent stream **508B** may
25 be heated within a second heat exchanger **516** and then flowed into the second co-current contacting system **502B**. Once inside the second co-current contacting system **502B**, the first gas mixture **514A** and the second partially-unloaded solvent stream **508B** move along the longitudinal axis of the second co-current contacting system **502B**. As they travel, the second partially-unloaded solvent stream **508B** interacts with the first gas mixture **514A**, causing a
30 portion of the CO_2 and H_2S within the second partially-unloaded solvent stream **508B** to chemically attach to or be absorbed by the amine molecules within the first gas mixture **514A**. The resulting first partially-unloaded solvent stream **508A** may then be flowed from the second co-current contacting system **502B** to the first co-current contacting system **502A**.

[0139] A second gas mixture **514B** including the stripping gas and a larger portion of the CO₂ and H₂S may be flowed from the second co-current contacting system **502B** to a third co-current contacting system **502C**. In addition, the rich solvent stream **504** may be flowed into the third co-current contacting system **502C**. In various embodiments, the rich solvent stream **504** may be warm due to the exothermic chemical reaction involved in an earlier CO₂ and H₂S removal process, as well as possible pre-heating with an outside source.

[0140] Once inside the third co-current contacting system **502C**, the second gas mixture **514B** and the rich solvent stream **504** move along the longitudinal axis of the third co-current contacting system **502C**. As they travel, the rich solvent stream **504** interacts with the second gas mixture **514B**, causing a portion of the CO₂ and H₂S within the rich solvent stream **504** to chemically attach to or be absorbed by the amine molecules within the second gas mixture **514B**. The resulting second partially-unloaded solvent stream **508B** may then be flowed from the third co-current contacting system **502C** to the second co-current contacting system **502B**. In addition, a gas stream **518** including the CO₂, H₂S, and stripping gas may be flowed out of the gas regeneration facility **500**. In various embodiments, the CO₂ within the gas stream **518** may be recovered within another series of co-current contacting systems, and the H₂S may be recovered within yet another series of co-current contacting systems, as described with respect to the system **200** of Figs. 2A, 2B-1, and 2B-2.

[0141] It is to be understood that the gas regeneration system **500** is not limited to the number of co-current contacting systems shown in Fig. 5. Rather, the gas regeneration system **500** may include any suitable number of co-current contacting systems, depending on the details of the specific implementation. Further, the interconnections within the gas regeneration system **500** do not have to be arranged as shown in Fig. 5. Rather, any suitable variations or alternatives to the interconnections shown in Fig. 5 may be present within the gas regeneration system **500**, depending on the details of the specific implementation.

[0142] Fig. 6 is a process flow diagram of a separation system **600** for preferentially removing one component from a multi-component gas stream. More specifically, the separation system **600** may be used to remove one gaseous component, referred to herein as "gas A," from a multi-component gas stream **602** including gas A and another gaseous component, referred to herein as "gas B." According to embodiments described herein, gas A may be H₂S, and gas B may be CO₂. However, it is to be understood that gas A and gas B may also be any other types of gas that are to be separated from one another via the separation system **600**.

[0143] The separation system **600** may include a number of co-current contacting systems **604A-C** connected in series. Each co-current contacting system **604A-C** removes a portion of gas A from the multi-component gas stream **602** using a lean gas A-selective solvent stream **606** that preferentially absorbs gas A over gas B. This may result in the generation of a rich gas A-selective solvent stream **608** including gas A, as well as a separate gas stream **610** including primarily gas B.

[0144] In various embodiments, the multi-component gas stream **602** including gas A and gas B is flowed into the first co-current contacting system **604A**. In addition, a first partially-loaded, or "rich," gas A-selective solvent stream **612A** including some amount of gas A is flowed from the second co-current contacting system **604B** into the first co-current contacting system **604A**. Once inside the first co-current contacting system **604A**, the multi-component gas stream **602** and the first partially-loaded gas A-selective solvent stream **612A** move along the longitudinal axis of the first co-current contacting system **604A**. As they travel, the first partially-loaded gas A-selective solvent stream **612A** interacts with gas A within the multi-component gas stream **602**, causing the molecules of gas A to chemically attach to or be absorbed by the molecules of the first partially-loaded gas A-selective solvent stream **612A**. This may result in the generation of a first gas mixture **614A** including gas B and some amount of gas A, as well as the rich gas A-selective solvent stream **608** including gas A. The rich gas A-selective solvent stream **608** may then be flowed out of the separation system **600**.

[0145] In various embodiments, the first gas mixture **614A** is flowed out of the first co-current contacting system **604A** and into a second co-current contacting system **604B**. In addition, a second partially-loaded gas A-selective solvent stream **612B** is flowed from a third co-current contacting system **604C** into the second co-current contacting system **604B**. Once inside the second co-current contacting system **604B**, the first gas mixture **614A** and the second partially-loaded gas A-selective solvent stream **612B** move along the longitudinal axis of the second co-current contacting system **604B**. As they travel, the second partially-loaded gas A-selective solvent stream **612B** interacts with gas A within the first gas mixture **614A**, causing the molecules of gas A to chemically attach to or be absorbed by the molecules of the second partially-loaded gas A-selective solvent stream **612B**. The resulting first partially-loaded gas A-selective solvent stream **612A** may then be flowed from the second co-current contacting system **604B** into the first co-current contacting system **604A**. In addition, the resulting second gas mixture **614B**, which includes a lower amount of gas A than the first gas mixture **614A**, may be flowed out of the second co-current contacting

system **604B** and into the third co-current contacting system **604C**.

[0146] In addition to the second gas mixture **614B**, the lean gas A-selective solvent stream **606** may be flowed into the third co-current contacting system **604C** from another source. The second gas mixture **614B** and the lean gas A-selective solvent stream **606** may
 5 move along the longitudinal axis of the third co-current contacting system **604C**. As they travel, the lean gas A-selective solvent stream **606** interacts with any remaining gas A within the second gas mixture **614B**, causing the remaining molecules of gas A to chemically attach to or be absorbed by the molecules of the lean gas A-selective solvent stream **606**. The resulting second partially-loaded gas A-selective solvent stream **612B** may then be flowed
 10 from the third co-current contacting system **604C** into the second co-current contacting system **604B**. In addition, the resulting gas stream **610** that includes primarily gas B may be flowed out of the separation system **600**.

[0147] In various embodiments, the gas A-selective solvent stream is a specially-designed solvent that preferentially absorbs gas A, i.e., species "A," over gas B, i.e., species
 15 "B." The rate of absorption (R_A) of A may be as shown below in Eq. (7).

$$R_A = K_{ogA} a \Delta P_{lmA} \quad (7)$$

In Eq. (7), K_{ogA} is the overall mass transfer coefficient of A lumped on the gas side, a is the specific surface area, and ΔP_{lm} is the log mean driving force. The driving force is the difference in the partial pressure of A in the gas phase minus the equilibrium vapor pressure
 20 of A above the solvent. Similarly, the rate of absorption (R_B) of B may be as shown below in Eq. (8).

$$R_B = K_{ogB} a \Delta P_{lmB} \quad (8)$$

Therefore, the rate of absorption of B over A may be as shown below in Eq. (9).

$$\frac{R_A}{R_B} = \left(\frac{K_{ogA}}{K_{ogB}} \right) \left(\frac{\Delta P_{lmA}}{\Delta P_{lmB}} \right) \quad (9)$$

[0148] In some embodiments, altering the characteristics of the solvent stream may improve the ratio of K_{ogA} to K_{ogB} . For example, the addition of solvent molecules that increase the rate of reaction of A and decrease the rate of reaction of B will likely improve the ratio. Alternatively, certain additives that interfere with the reaction of B with the solvent stream may be included within the solvent stream, thereby increasing the ratio of K_{ogA} to
 30 K_{ogB} .

[0149] It is to be understood that the separation system **600** is not limited to the number of co-current contacting systems shown in **Fig. 6**. Rather, the separation system **600** may include any suitable number of co-current contacting systems, depending on the details of the specific implementation. Further, the interconnections within the separation system **600** do not have to be arranged as shown in **Fig. 6**. Rather, any suitable variations or alternatives to the interconnections shown in **Fig. 6** may be present within the separation system **600**, depending on the details of the specific implementation.

Co-Current Contacting System

[0150] **Fig. 7** is a schematic of a co-current contacting system **700**. The co-current contacting system **700** may provide for the separation of components within a gas stream. The co-current contacting system **700** may include a co-current contactor **702** that is positioned in-line within a pipe **704**. The co-current contactor **702** may include a number of components that provide for the efficient contacting of a liquid droplet stream with a flowing gas stream **706**. The liquid droplet stream can be used for the separation of impurities, such as **H₂O**, **H₂S**, or **CO₂**, from a gas stream **706**.

[0151] In various embodiments, the co-current contactor **702** includes a mixer **708** and a mass transfer section **710**. As shown in **Fig. 7**, the gas stream **706** may be flowed through the pipe **704** and into the mixer **708**. A liquid stream **712** may also be flowed into the mixer **708**, for example, through a hollow space **714** coupled to flow channels **716** in the mixer **708**. The liquid stream **712** may include any type of treating liquid, e.g., solvent, that is capable of removing the impurities from the gas stream **706**.

[0152] From the flow channels **716**, the liquid stream **712** is released into the gas stream **706** as fine droplets through injection orifices **718**, and is then flowed into the mass transfer section **710**. This may result in the generation of a treated gas stream **720** within the mass transfer section **710**. The treated gas stream **720** may include small liquid droplets dispersed in a gas phase. The liquid droplets may include impurities from the gas stream **706** that were adsorbed or dissolved into the liquid stream **712**.

[0153] The treated gas stream **720** may be flowed from the mass transfer section **710** to a separation system **722**, such as a cyclonic separator, a mesh screen, or a settling vessel. The separation system **722** removes the liquid droplets from the gas phase. The liquid droplets may include the original liquid stream with the incorporated impurities **724**, and the gas phase may include a purified gas stream **726**. In various embodiments, the purified gas

stream **726** is a gas stream that has been purified via the removal of H_2S and CO_2 .

[0154] **Fig. 8A** is a front view of a mixer **800**. The mixer **800** is implemented within a co-current contactor, such as the co-current contactor **702** described with respect to the co-current contacting system **700** of **Fig. 7**. The mixer **800** may be an axial, in-line co-current contactor located within a pipe. The front view of the mixer **800** represents an upstream view of the mixer **800**.

[0155] The mixer **800** may include an outer annular support ring **802**, a number of radial blades **804** extending from the annular support ring **802**, and a central gas entry cone **806**. The annular support ring **802** may secure the mixer **800** in-line within the pipe. In addition, the radial blades **804** may provide support for the central gas entry cone **806**.

[0156] The annular support ring **802** may be designed as a flanged connection, or as a removable or fixed sleeve inside the pipe. In addition, the annular support ring **802** may include a liquid feed system and a hollow channel described further with respect to **Figs. 7, 8C and 8D**. A liquid stream may be fed to the mixer **800** via the hollow channel in the annular support ring **802**. The hollow channel may allow equal distribution of the liquid stream along the perimeter of the mixer **800**.

[0157] Small liquid channels within the annular support ring **802** may provide a flow path for the liquid stream to flow through injection orifices **808** within the radial blades **804**. The liquid injection orifices **808** may be located on or near the leading edge of each radial blade **804**. Placement of the liquid injection orifices **808** on the radial blades **804** may allow the liquid stream to be uniformly distributed in a gas stream that is directed between the radial blades **804**. Specifically, the liquid stream may be contacted by the gas stream flowing through the gaps between the radial blades **804**, and may be sheared into small droplets and entrained in the gas phase.

[0158] The gas stream may also be flowed into the central gas entry cone **806** through a gas inlet **812**. The central gas entry cone **806** may block a cross-sectional portion of the pipe. The radial blades **804** include gas exit slots **810** that allow the gas stream to be flowed out of the central gas entry cone **806**. This may increase the velocity of the gas stream as it flows through the pipe. The central gas entry cone **806** may direct a predetermined amount of the gas stream to the gas exit slots **810** on the radial blades **804**.

[0159] Some of the liquid stream injected through the radial blades **804** may be deposited on the surface of the radial blades **804** as a liquid film. As the gas stream flows through the

central gas entry cone **806** and is directed out of the gas exit slots **810** on the radial blades **804**, the gas stream may sweep, or blow, much of the liquid film off the radial blades **804**. This may enhance the dispersion of the liquid stream into the gas phase. Further, the obstruction to the flow of the gas stream and the shear edges created by the central gas entry cone **806** may provide a zone with an increased turbulent dissipation rate. The may result in the generation of smaller droplets that enhance the mass transfer rate of the liquid stream and the gas stream.

[0160] The size of the mixer **800** may be adjusted such that the gas stream flows at a high velocity. This may be accomplished via either a sudden reduction in the diameter of the annular support ring **802** or a gradual reduction in the diameter of the annular support ring **802**. The outer wall of the mixer **800** may be slightly converging in shape, terminating at the point where the gas stream and the liquid stream are discharged into the downstream pipe. This may allow for the shearing and re-entrainment of any liquid film that is removed from the mixer **800**. Further, a radial inward ring, grooved surface, or other suitable equipment may be included on the outer diameter of the mixer **800** near the point where the gas stream and the liquid stream are discharged into the downstream pipe. This may enhance the degree of liquid entrainment within the gas phase.

[0161] The downstream end of the mixer **800** may discharge into a section of pipe (not shown). The section of pipe may be a straight section of pipe, or a concentric expansion section of pipe. In some embodiments, the central gas entry cone **806** terminates with a blunt ended cone or a tapered ended cone. In other embodiments, the central gas entry cone **806** terminates with a ridged cone, which may include multiple concentric ridges along the cone that provide multiple locations for droplet generation. In addition, any number of gas exit slots **810** may be provided on the cone itself to allow for the removal of the liquid film from the mixer **800**.

[0162] **Fig. 8B** is a side perspective view of the mixer **800**. Like numbered items are as described with respect to **Fig. 8A**. As shown in **Fig. 8B**, the upstream portion of the central gas entry cone **806** may extend further into the pipe than the annular support ring **802** and the radial blades **804** in the upstream direction. The downstream portion of the central gas entry cone **806** may also extend further into the pipe than the annular support ring **802** and the radial blades **804** in the downstream direction. The length of the central gas entry cone **806** in the downstream direction depends on the type of cone at the end of the central gas entry cone **806**, as described further with respect to **Figs. 8C** and **8D**.

[0163] **Fig. 8C** is a cross-sectional side perspective view of the mixer **800**. Like numbered items are as described with respect to **Figs. 8A** and **8B**. According to the embodiment shown in **Fig. 8C**, the central gas entry cone **806** of the mixer **800** terminates with a tapered ended cone **814**. Terminating the central gas entry cone **806** with a tapered ended cone **814** may reduce the overall pressure drop in the pipe caused by the mixer **800**.

[0164] **Fig. 8D** is another cross-sectional side perspective view of the mixer **800**. Like numbered items are as described with respect to **Figs. 8A-C**. According to the embodiment shown in **Fig. 8D**, the central gas entry cone **806** of the mixer **800** terminates with a blunt ended cone **816**. Terminating the central gas entry cone **806** with a blunt ended cone **816** may encourage droplet formation in the center of the pipe.

Method for Separating CO₂ and H₂S from a Natural Gas Stream

[0165] **Fig. 9** is a process flow diagram of a method **900** for separating CO₂ and H₂S from a natural gas stream. Specifically, the method **900** may provide for the removal of CO₂ and FLS from the natural gas stream, as well as the recovery of separate CO₂ and FLS streams. According to embodiments described herein, the method **900** is implemented by a number of co-current contacting systems. For example, the method **900** may be implemented by the series of co-current contacting systems **202A-D** described with respect to the system **200** of **Figs. 2A, 2B-1, and 2B-2**.

[0166] The method begins at block **902**, at which a sour natural gas stream including CO₂ and FLS is contacted with a lean solvent stream within a first series of co-current contacting systems, resulting in the generation of a sweetened natural gas stream and a rich solvent stream including the CO₂ and the FLS. More specifically, the sour natural gas stream is progressively sweetened via contact with the solvent stream within each of a number of co-current contacting systems connected in series. In some embodiments, the resulting sweetened natural gas stream is used to produce LNG.

[0167] At block **904**, the rich solvent stream is contacted with a stripping gas within a second series of co-current contacting systems, resulting in the regeneration of the lean solvent stream and the generation of a first gas stream including the CO₂, the FLS, and the stripping gas. More specifically, the CO₂ and the FLS are progressively removed from the rich solvent stream via contact with the stripping gas within each of a number of co-current contacting systems connected in series. Further, at block **906**, the lean solvent stream is recirculated to the first series of co-current contacting systems.

[0168] At block **908**, the first gas stream is contacted with a lean H₂S-selective solvent stream within a third series of co-current contacting systems, resulting in the generation of a rich H₂S-selective solvent stream including the H₂S and a second gas stream including the CO₂ and the stripping gas. More specifically, the $\frac{3}{4}$ S is progressively removed from the first gas stream via contact with the H[^]S-selective solvent stream within each of a number of co-current contacting systems connected in series. In various embodiments, the CO₂ is removed from the second gas stream to recover a final CO₂ product. The resulting stripping gas may then be recirculated to the second series of co-current contacting systems. In addition, in some embodiments, the final CO₂ product is injected into a subterranean reservoir for enhanced oil recovery (EOR) operations.

[0169] At block **910**, the rich H₂S-selective solvent stream is contacted with a stripping gas within a fourth series of co-current contacting systems, resulting in the regeneration of the lean H[^]S-selective solvent stream and the generation of a third gas stream including the H₂S and the stripping gas. More specifically, the $\frac{1}{4}$ S is progressively removed from the rich H₂S-selective solvent stream via contact with the stripping gas within each of a number of co-current contacting systems connected in series. In various embodiments, the H₂S is removed from the third gas stream to recover a final H₂S product. The resulting stripping gas may then be recirculated to the fourth series of co-current contacting systems. In addition, in some embodiments, elemental sulfur is recovered from the final H₂S product within a Claus sulfur recovery unit. Furthermore, at block **912**, the lean H[^]S-selective solvent stream is recirculated to the third series of co-current contacting systems.

[0170] The process flow diagram of **Fig. 9** is not intended to indicate that the blocks of the method **900** are to be executed in any particular order, or that all of the blocks of the method **900** are to be included in every case. Further, any number of additional blocks not shown in **Fig. 9** may be included within the method **900**, depending on the details of the specific implementation.

Method for Selectively Removing One Gaseous Component from a Multi-Component Gas Stream

[0171] **Fig. 10** is a process flow diagram of a method **1000** for selectively removing one gaseous component from a multi-component gas stream. According to embodiments described herein, the method **1000** is implemented by a number of co-current contacting systems connected in series. For example, the method **1000** may be implemented by the co-current contacting systems **604A-C** described with respect to the separation system **600** of

Fig. 6.

[0172] The method begins at block **1002**, at which a lean solvent stream is flowed into a mixer of a co-current contactor via an annular support ring and a number of radial blades extending from the annular support ring. The annular support ring secures the mixer in-line
5 within a pipe.

[0173] At block **1004**, a multi-component gas stream including a first gaseous component and a second gaseous component is flowed into the mixer via a central gas entry cone that is supported by the radial blades. More specifically, a first portion of the multi-component gas stream flows through the central gas entry cone, and a second portion of the multi-component
10 gas stream flows around the central gas entry cone between the radial blades. In some embodiments, the first gaseous component is H_2S , the second gaseous component is CO_2 , and the solvent stream is an $H^A S$ -selective solvent stream. For example, the solvent stream may be a tertiary amine.

[0174] At block **1006**, the multi-component gas stream is contacted with the lean solvent stream within the mixer and a mass transfer section of the co-current contactor to provide for incorporation of liquid droplets formed from the lean solvent stream into the multi-component gas stream. According to embodiments described herein, the solvent stream is a specially-designed solvent that preferentially absorbs the first gaseous component over the second gaseous component. Therefore, the liquid droplets include the first gaseous
15 component from the multi-component gas stream.

[0175] At block **1008**, the liquid droplets are separated from the multi-component gas stream within a separation system, resulting in the generation of a rich solvent stream including the first gaseous component and a gas stream including the second gaseous component. Accordingly, the method **1000** provides for the selective removal of the first
25 gaseous component from the multi-component gas stream using the specially-designed solvent.

[0176] The process flow diagram of **Fig. 10** is not intended to indicate that the blocks of the method **1000** are to be executed in any particular order, or that all of the blocks of the method **1000** are to be included in every case. Further, any number of additional blocks not
30 shown in **Fig. 10** may be included within the method **1000**, depending on the details of the specific implementation. For example, in some embodiments, the multi-component gas stream is flowed through a number of co-current contactors and corresponding separation

systems connected in series within the pipe. In such embodiments, the first gaseous component is progressively removed from the multi-component gas stream within each co-current contactor and corresponding separation system. Further, in some embodiments, the lean solvent stream is regenerated from the rich solvent stream within a separate co-current
5 contactor and corresponding separation system, or separate series of co-current contactors and corresponding separation systems connected in series within the pipe.

CLAIMS

What is claimed is:

1. A system for separating H_2S and CO_2 from a natural gas stream, including:
 - a first loop of co-current contacting systems configured to remove H_2S and CO_2 from
5 a natural gas stream; and
 - a second loop of co-current contacting systems configured to remove the H_2S from
the CO_2 .
2. The system of claim 1, wherein the first loop of co-current contacting systems
includes:
 - 10 a first series of co-current contacting systems configured to remove the H_2S and the
 CO_2 from the natural gas stream by contacting the natural gas stream with a solvent stream,
providing for incorporation of the H_2S and the CO_2 from the natural gas stream into the
solvent stream;
 - a second series of co-current contacting systems configured to remove the H_2S and
15 the CO_2 from the solvent stream, wherein the solvent stream is recirculated to the first series
of co-current contacting systems.
3. The system of claim 2, wherein the second loop of co-current contacting systems
includes:
 - a third series of co-current contacting systems configured to remove the H_2S from the
20 CO_2 by contacting the H_2S and the CO_2 with an H_2S -selective solvent stream, providing for
incorporation of the H_2S into the H_2S -selective solvent stream; and
 - a fourth series of co-current contacting systems configured to remove the H_2S from
the H_2S -selective solvent stream, wherein the H_2S -selective solvent stream is recirculated to
the third series of co-current contacting systems.
- 25 4. A method for separating CO_2 and H_2S from a natural gas stream, including:
 - contacting a sour natural gas stream including CO_2 and H_2S with a lean solvent stream
within a first series of co-current contacting systems, generating a sweetened natural gas
stream and a rich solvent stream including the CO_2 and the H_2S ;
 - contacting the rich solvent stream with a stripping gas within a second series of co-
30 current contacting systems, regenerating the lean solvent stream and generating a first gas

stream including the CO₂, the H₂S, and the stripping gas;

recirculating the lean solvent stream to the first series of co-current contacting systems;

5 contacting the first gas stream with a lean EbS-selective solvent stream within a third series of co-current contacting systems, generating a rich H₂S-selective solvent stream including the H₂S and a second gas stream including the CO₂ and the stripping gas;

contacting the rich H₂S-selective solvent stream with a stripping gas within a fourth series of co-current contacting systems, regenerating the lean H₂S-selective solvent stream and generating a third gas stream including the H₂S and the stripping gas; and

10 recirculating the lean EbS-selective solvent stream to the third series of co-current contacting systems.

5. The method of claim 4, including producing liquefied natural gas (LNG) from the sweetened natural gas stream.

6. The method of any of claims 4 and 5, including removing the CO₂ from the second
15 gas stream to recover a final CO₂ product.

7. The method of claim 6, including recirculating the stripping gas from the second gas stream to the second series of co-current contacting systems.

8. The method of any of claims 6 and 7, including injecting the final CO₂ product into a subterranean reservoir for enhanced oil recovery (EOR) operations.

20 9. The method of any of claims 4-6, including removing the H₂S from the third gas stream to recover a final H₂S product.

10. The method of claim 9, including recirculating the stripping gas from the third gas stream to the fourth series of co-current contacting systems.

11. The method of any of claims 9 and 10, including recovering elemental sulfur from the
25 final H₂S product within a Claus sulfur recovery unit.

12. The method of any of claims 4-6 and 9, wherein contacting the sour natural gas stream with the lean solvent stream within a first series of co-current contacting systems includes progressively sweetening the sour natural gas stream via contact with the lean solvent stream within each of a number of co-current contacting systems connected in series.

30 13. The method of any of claims 4-6, 9, and 12, wherein contacting the rich solvent

stream with the stripping gas within the second series of co-current contacting systems includes progressively removing the CO_2 and the H_2S from the rich solvent stream via contact with the stripping gas within each of a number of co-current contacting systems connected in series.

5 14. The method of any of claims 4-6, 9, 12, and 13, wherein contacting the first gas stream with the lean $\text{H}^{\wedge}\text{S}$ -selective solvent stream within the third series of co-current contacting systems includes progressively removing the $\frac{3}{4}$ S from the first gas stream via contact with the lean $\text{H}^{\wedge}\text{S}$ -selective solvent stream within each of a number of co-current contacting systems connected in series.

10 15. The method of any of claims 4-6, 9, and 12-14, wherein contacting the rich $\text{I}\frac{3}{4}\text{S}$ -selective solvent stream with the stripping gas within the fourth series of co-current contacting systems includes progressively removing the H_2S from the rich H_2S -selective solvent stream via contact with the stripping gas within each of a number of co-current contacting systems connected in series.

15 16. A system for separating CO_2 and H_2S from a natural gas stream, including:

a first series of co-current contacting systems configured to contact a sour natural gas stream including CO_2 and H_2S with a lean solvent stream to generate a sweetened natural gas stream and a rich solvent stream including the CO_2 and the H_2S ;

20 a second series of co-current contacting systems configured to contact the rich solvent stream with a stripping gas to regenerate the lean solvent stream and generate a first gas stream including the CO_2 , the H_2S , and the stripping gas, wherein the lean solvent stream is recirculated to the first series of co-current contacting systems;

25 a third series of co-current contacting systems configured to contact the first gas stream with a lean $\text{H}^{\wedge}\text{S}$ -selective solvent stream to generate a rich $\text{H}^{\wedge}\text{S}$ -selective solvent stream including the $\text{I}\frac{3}{4}\text{S}$ and a second gas stream including the CO_2 and the stripping gas; and

30 a fourth series of co-current contacting systems configured to contact the rich H_2S -selective solvent stream with a stripping gas to regenerate the lean $\text{H}^{\wedge}\text{S}$ -selective solvent stream and generate a third gas stream including the H_2S and the stripping gas, wherein the lean $\text{H}^{\wedge}\text{S}$ -selective solvent stream is recirculated to the third series of co-current contacting systems.

17. The system of claim 16, wherein each of the first series of co-current contacting

systems, the second series of co-current contacting systems, the third series of co-current contacting systems, and the fourth series of co-current contacting systems includes a number of co-current contacting systems connected in series.

18. The system of claim 17, wherein each of the number of co-current contacting systems
5 includes:

a co-current contactor located in-line within a pipe, the co-current contactor including:

a mixer, including:

an annular support ring configured to maintain the mixer within the
pipe;

10 a number of radial blades configured to allow a liquid stream to flow
into the mixer; and

a central gas entry cone configured to allow a gas stream to flow
through a hollow section within the mixer; and

a mass transfer section downstream of the mixer;

15 wherein the mixer and the mass transfer section provide for efficient
incorporation of liquid droplets formed from the liquid stream into the gas stream; and
a separation system configured to remove the liquid droplets from the gas stream.

19. The system of claim 18, wherein the separation system includes a cyclonic separator.

20. The system of any of claims 18 and 19, wherein a downstream portion of the central
20 gas entry cone includes a blunt ended cone.

21. The system of any of claims 18-20, wherein a downstream portion of the central gas
entry cone includes a tapered ended cone.

22. The system of any of claims 16 and 17, wherein the H²S-selective solvent stream
includes a tertiary amine.

25 23. The system of any of claims 16, 17, and 22, wherein the H₂S-selective solvent stream
includes a sterically-hindered amine.

24. The system of any of claims 16, 17, 22, and 23, wherein the stripping gas includes
nitrogen.

25. The system of any of claims 16, 17, and 22-24, wherein the system includes a CO₂

separation system configured to remove the CO₂ from the second gas stream to recover a final CO₂ product.

26. The system of claim 25, wherein the stripping gas from the second gas stream is recirculated to the second series of co-current contacting systems.

5 27. The system of any of claims 16, 17, and 22-25, wherein the system includes a H₂S separation system configured to remove the H₂S from the third gas stream to recover a final H₂S product.

28. The system of claim 27, wherein the stripping gas from the third gas stream is recirculated to the fourth series of co-current contacting systems.

10 29. A method for selectively removing one gaseous component from a multi-component gas stream, including:

flowing a lean solvent stream into a mixer of a co-current contactor via an annular support ring and a number of radial blades extending from the annular support ring, wherein the annular support ring secures the mixer in-line within a pipe;

15 flowing a multi-component gas stream including a first gaseous component and a second gaseous component into the mixer via a central gas entry cone that is supported by the number of radial blades, wherein a first portion of the multi-component gas stream flows through the central gas entry cone and a second portion of the multi-component gas stream flows around the central gas entry cone between the number of radial blades;

20 contacting the multi-component gas stream with the lean solvent stream within the mixer and a mass transfer section of the co-current contactor to provide for incorporation of liquid droplets formed from the lean solvent stream into the multi-component gas stream, wherein the liquid droplets include the first gaseous component from the multi-component gas stream; and

25 separating the liquid droplets from the multi-component gas stream within a separation system, generating a rich solvent stream including the first gaseous component and a gas stream including the second gaseous component.

30 30. The method of claim 29, wherein the first gaseous component includes H₂S, the second gaseous component includes CO₂, and the solvent stream includes an H₂S-selective solvent stream.

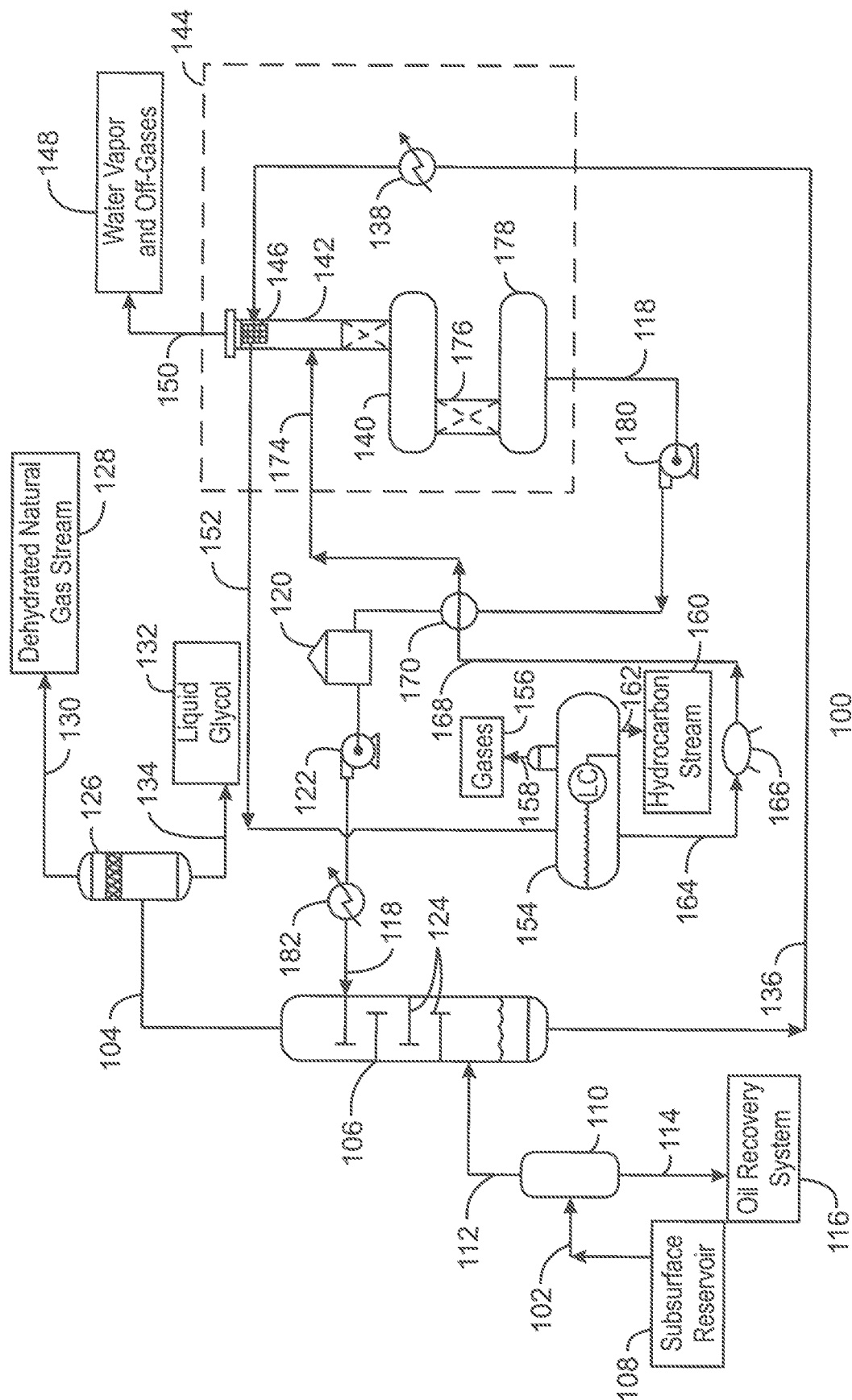
31. The method of claim 30, wherein the H₂S-selective solvent stream includes a tertiary

amine.

32. The method of any of claims 30 and 31, wherein the H²S-selective solvent stream includes a sterically-hindered amine.

33. The method of any of claims 29 and 30, including flowing the multi-component gas
5 stream through a number of co-current contactors and corresponding separation systems connected in series within the pipe.

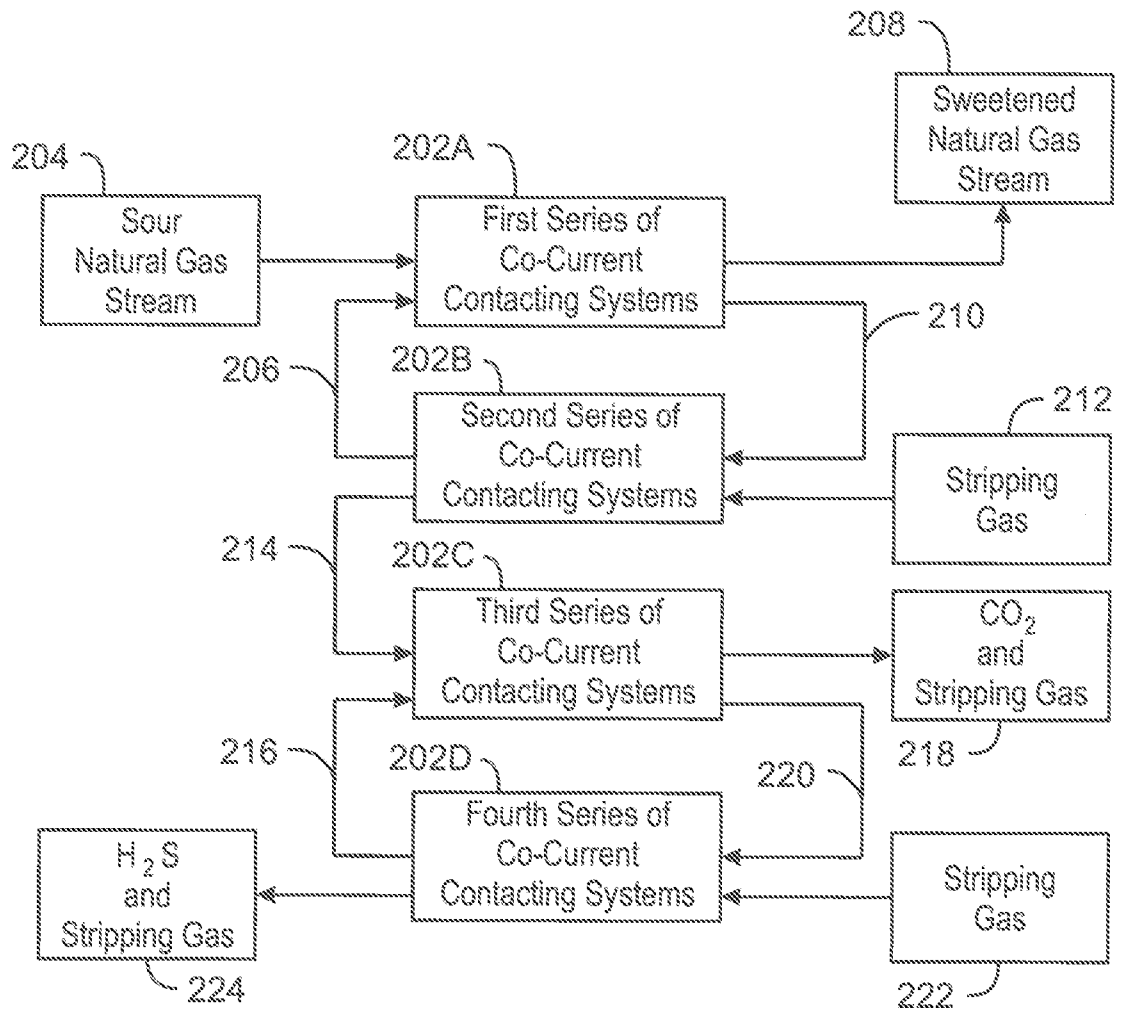
34. The method of any of claims 29, 30, and 33, including regenerating the lean solvent stream from the rich solvent stream within a separate co-current contactor and corresponding separation system.



Prior Art

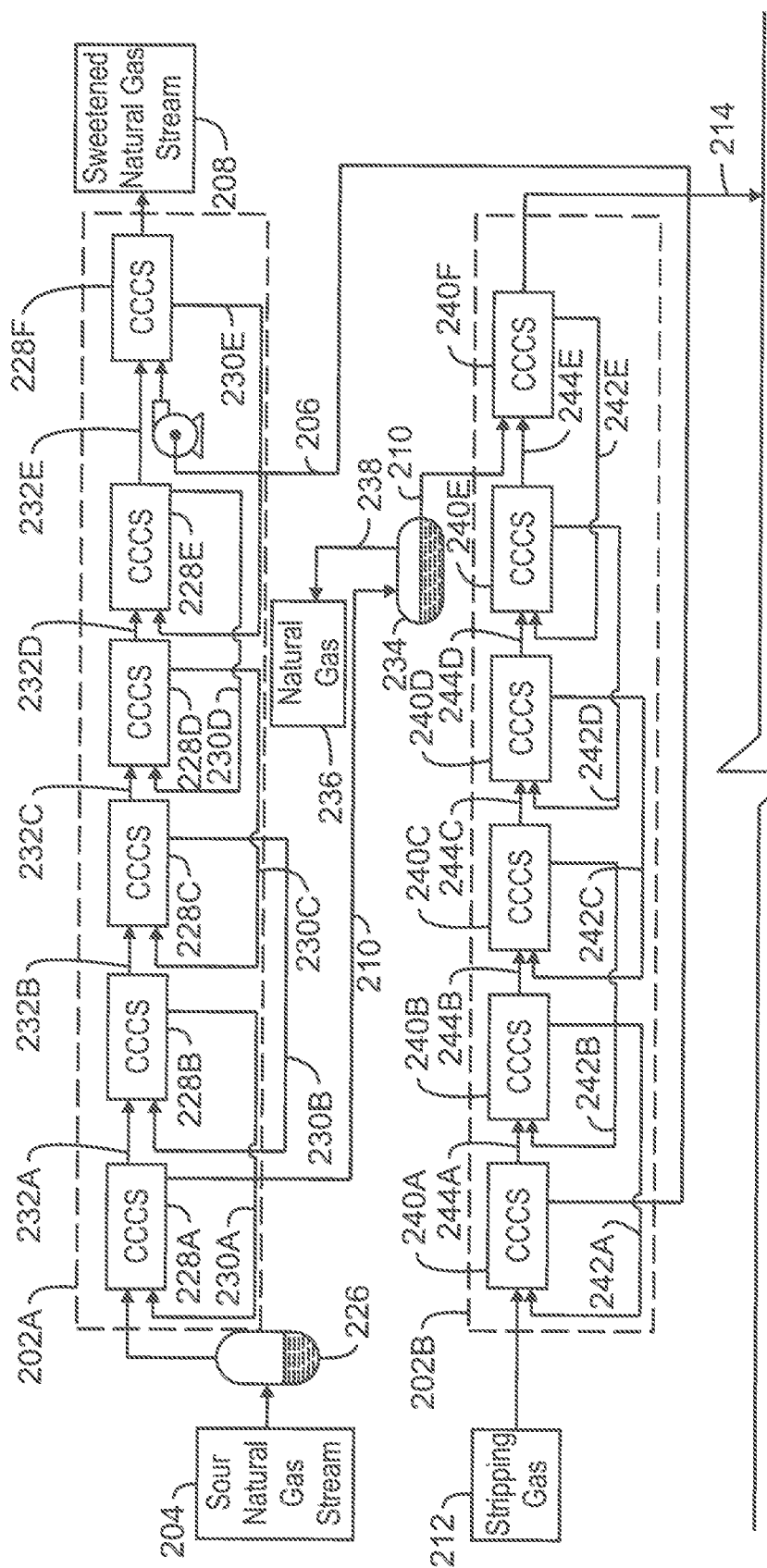
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200
FIG. 2A

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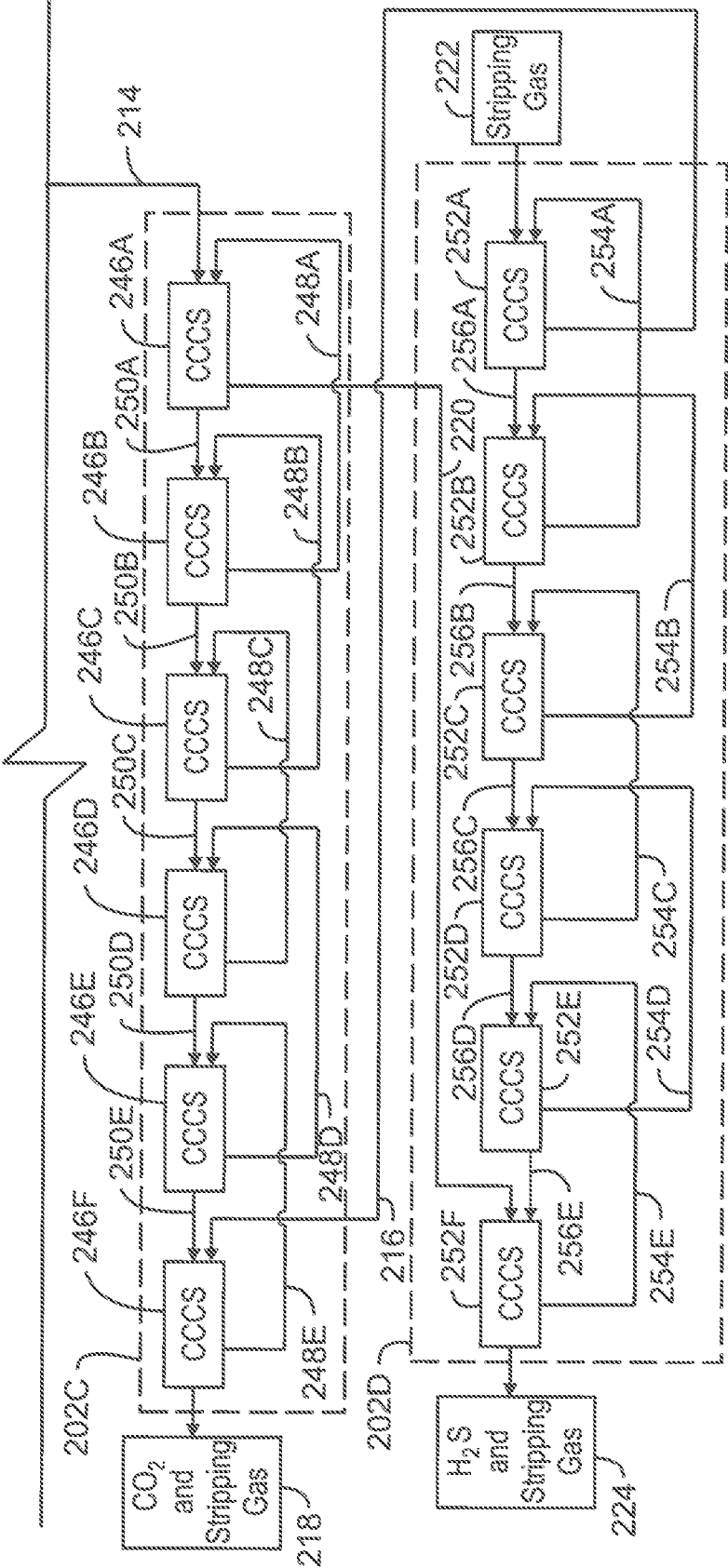


Continued on FIG. 2B-2

200

FIG. 2B-1

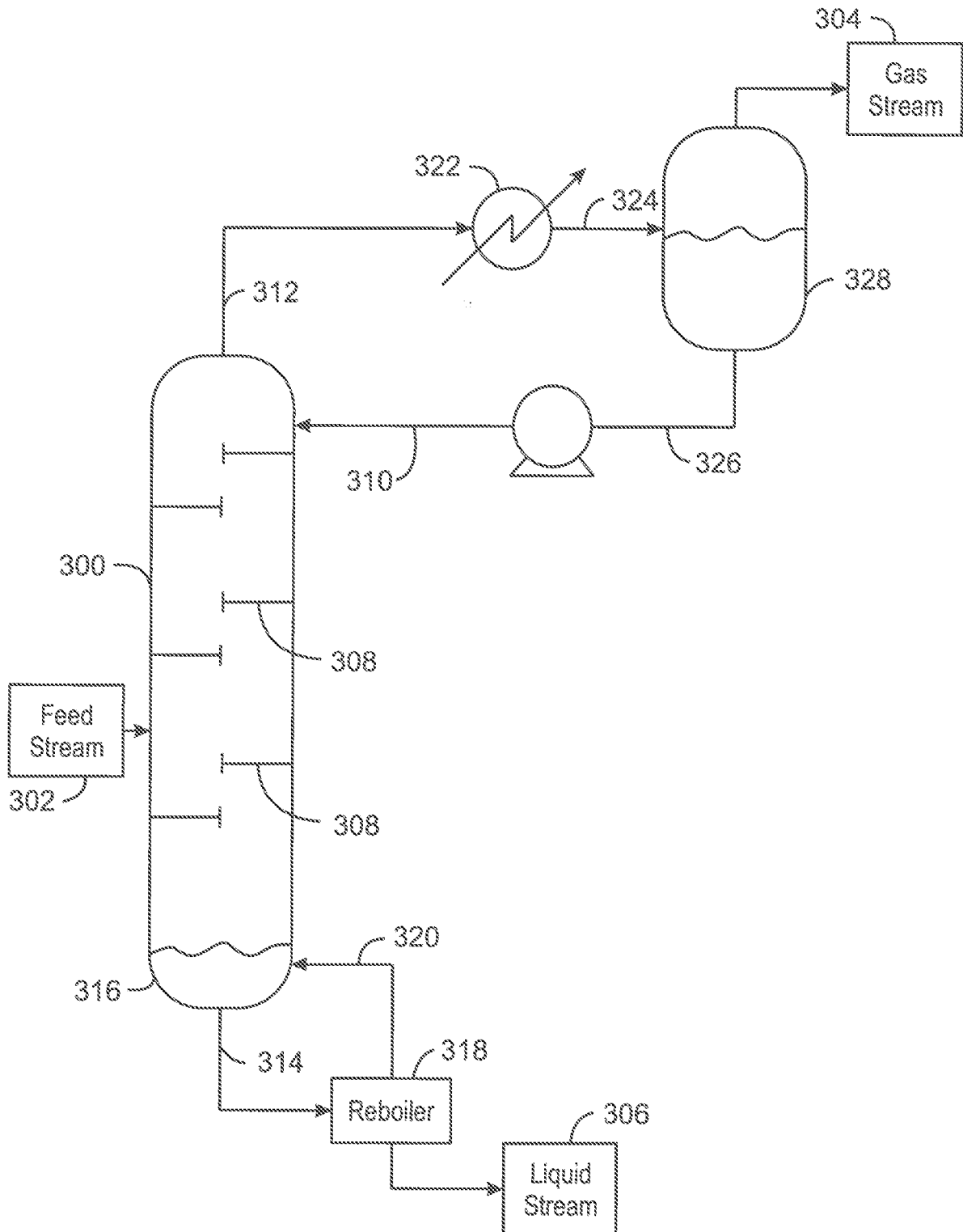
Continued on FIG. 2B-1



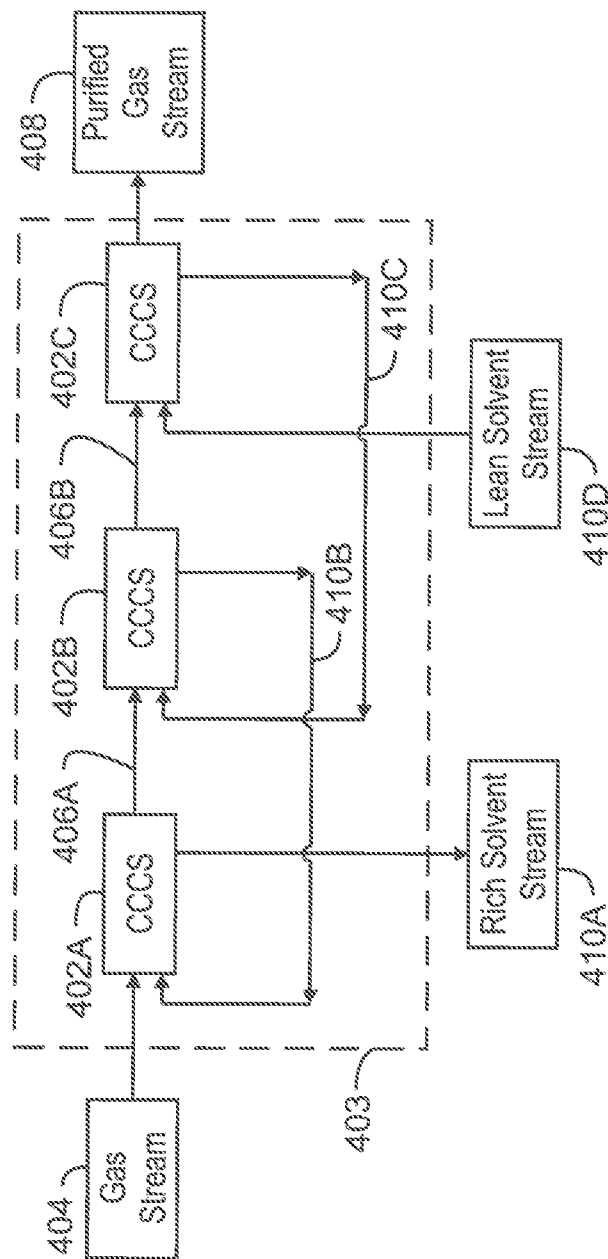
200

FIG. 2B-2

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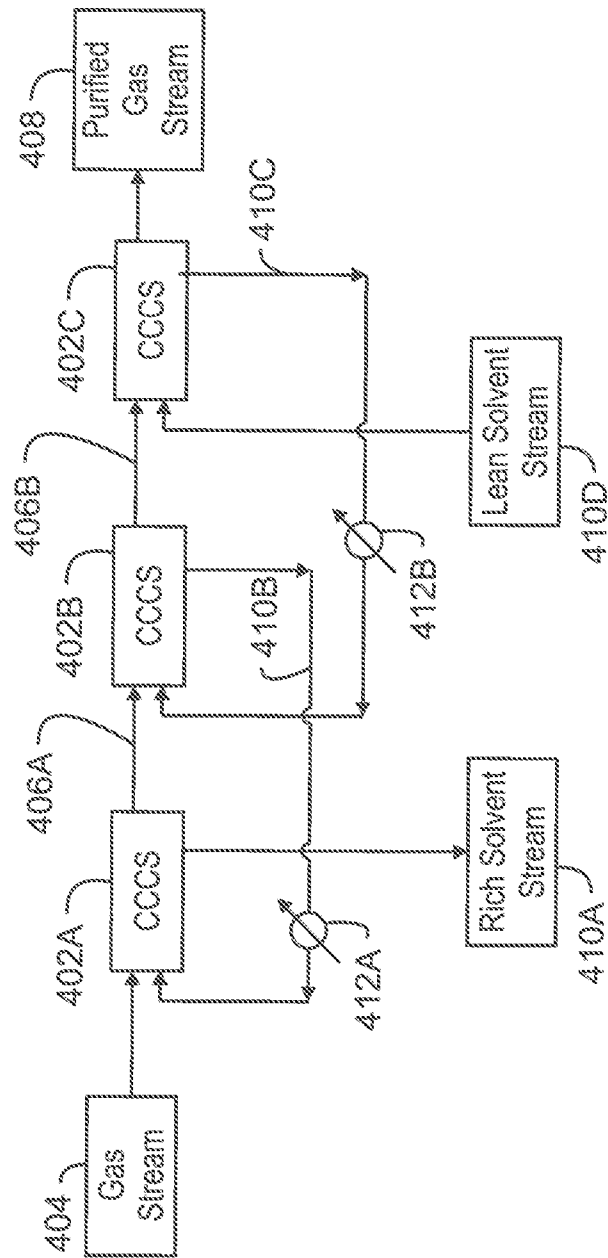


[Prior Art]
FIG. 3

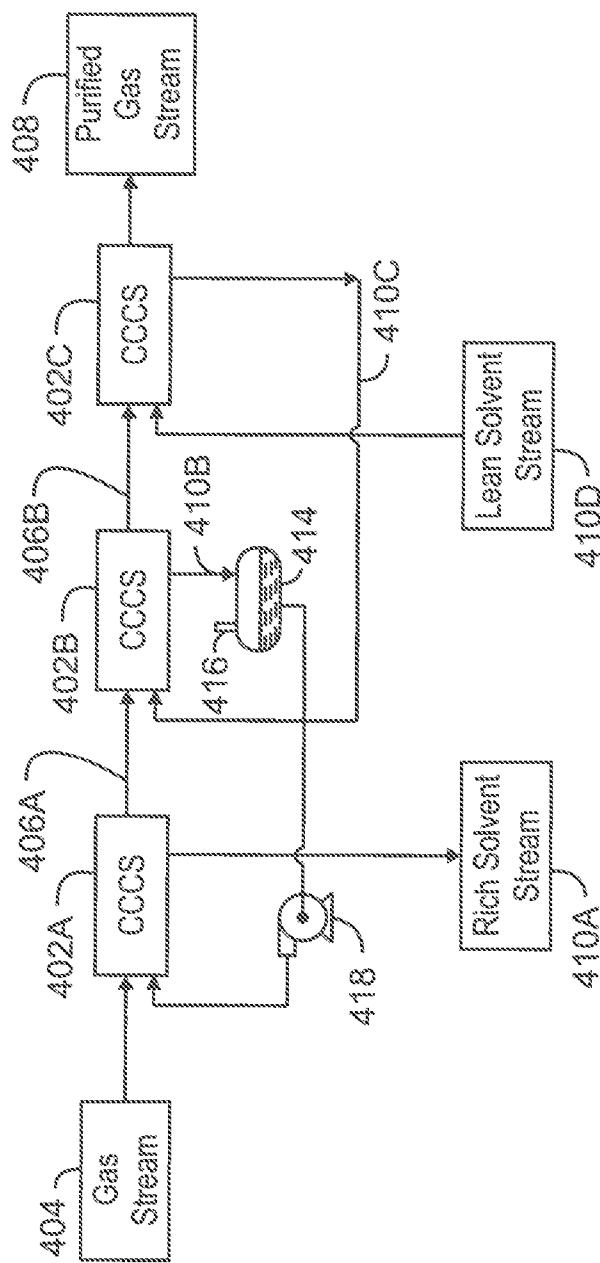


400
FIG. 4A

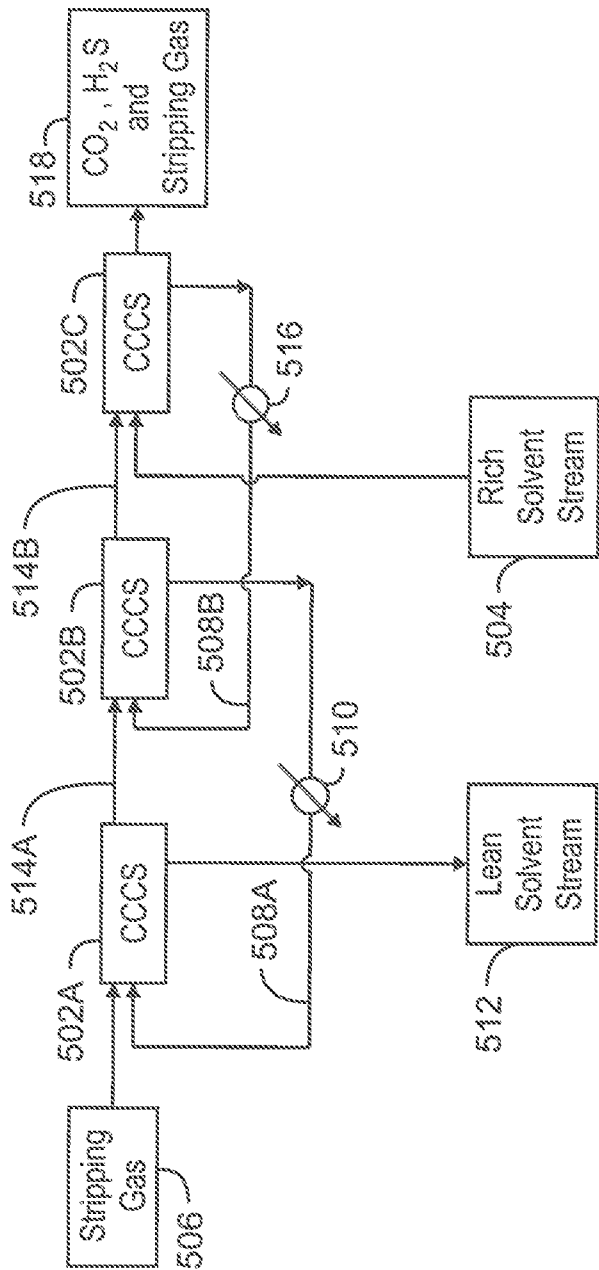
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400
FIG. 4B

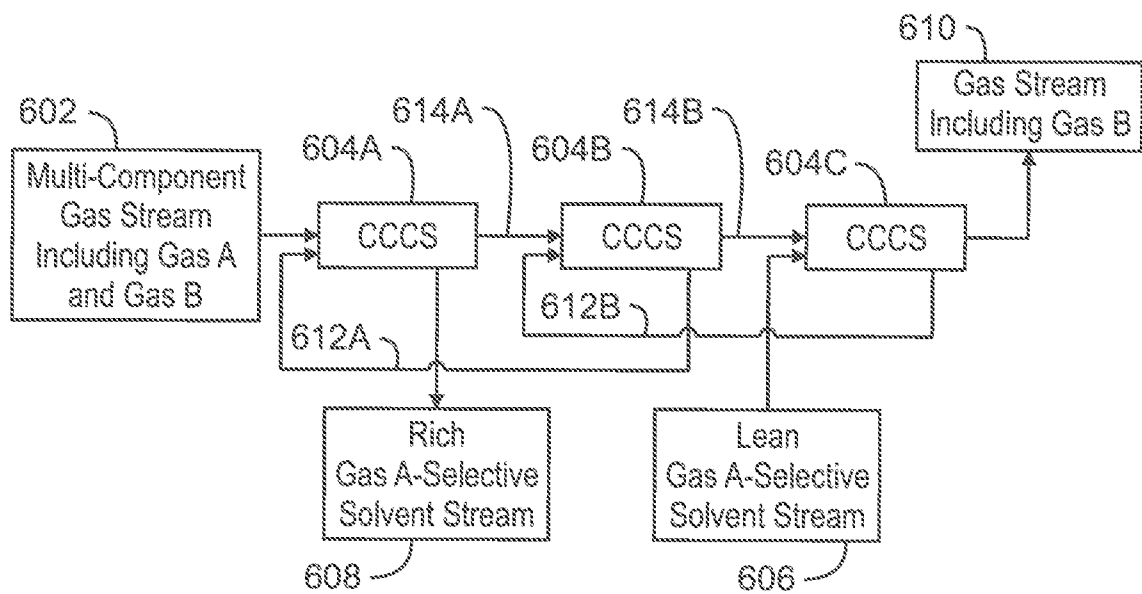


400
FIG. 4C



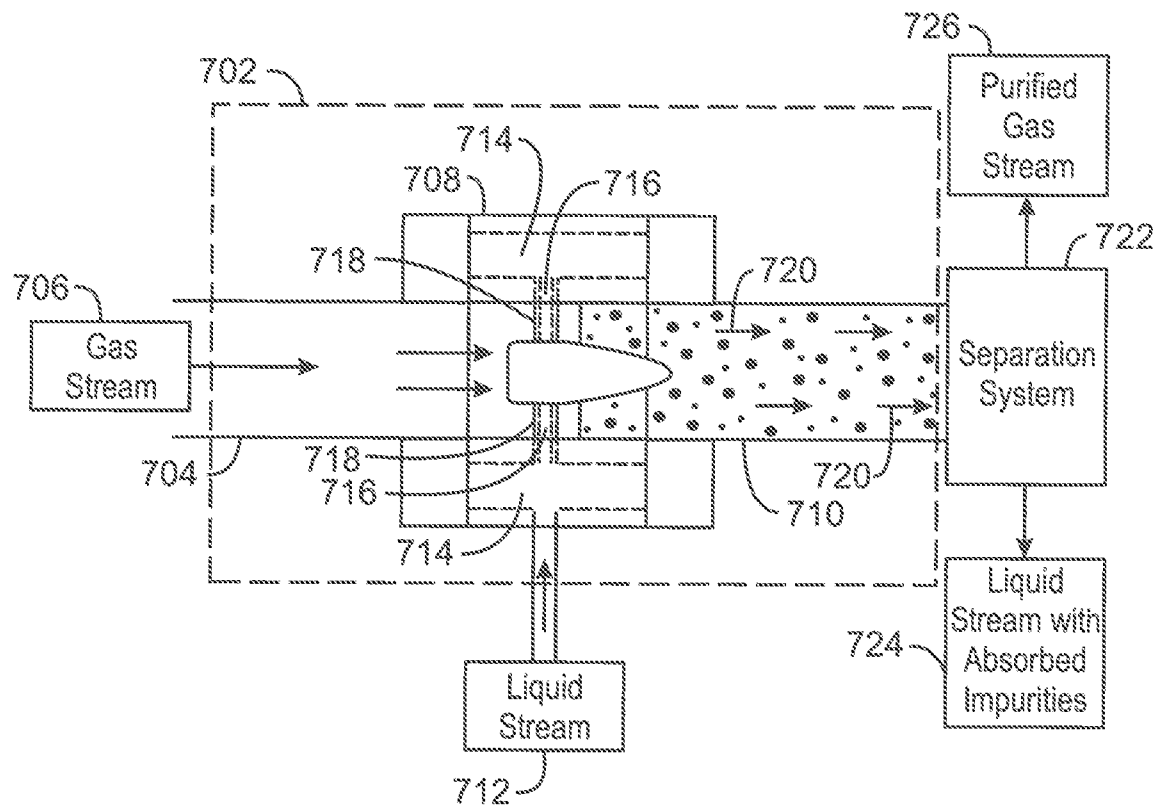
500
FIG. 5

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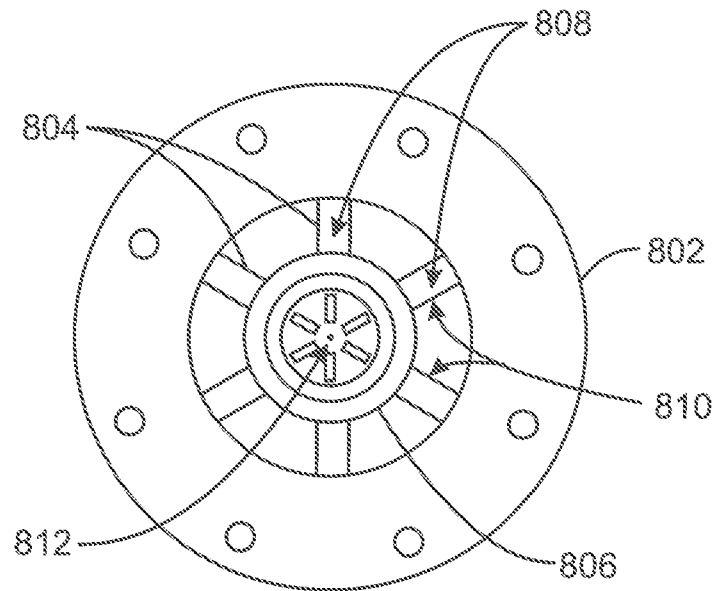
600
FIG. 6

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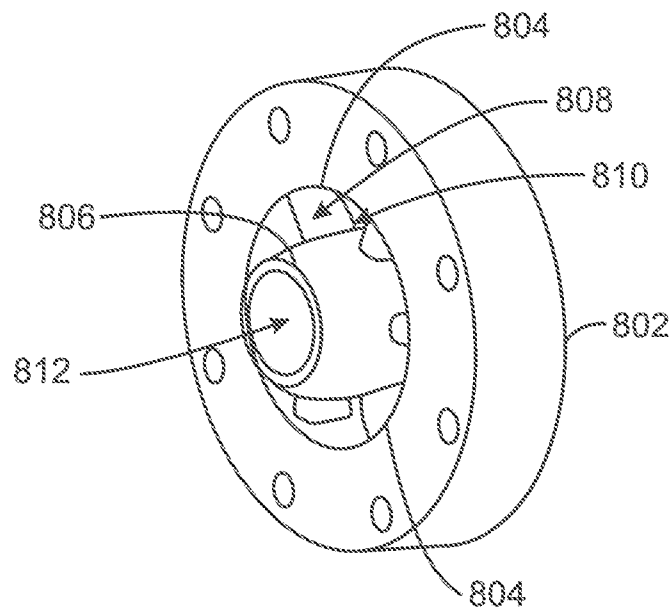


700
FIG. 7

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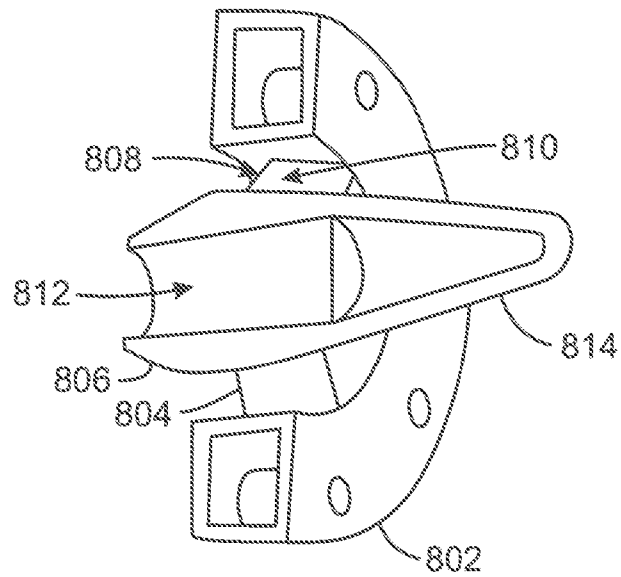


800
FIG. 8A

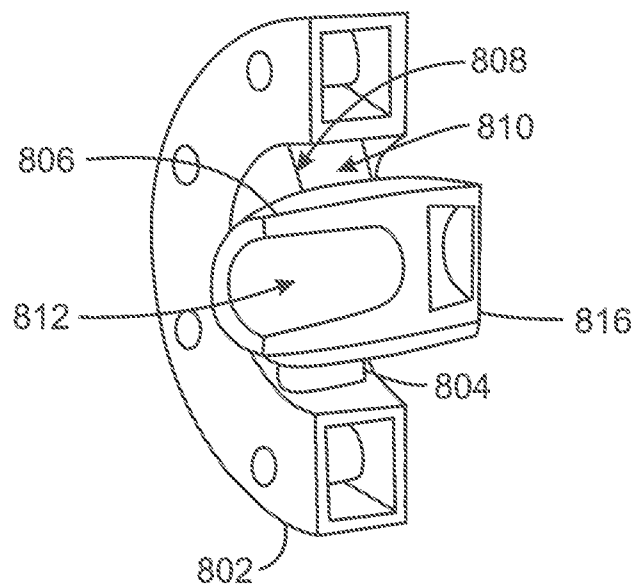


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FIG. 8B

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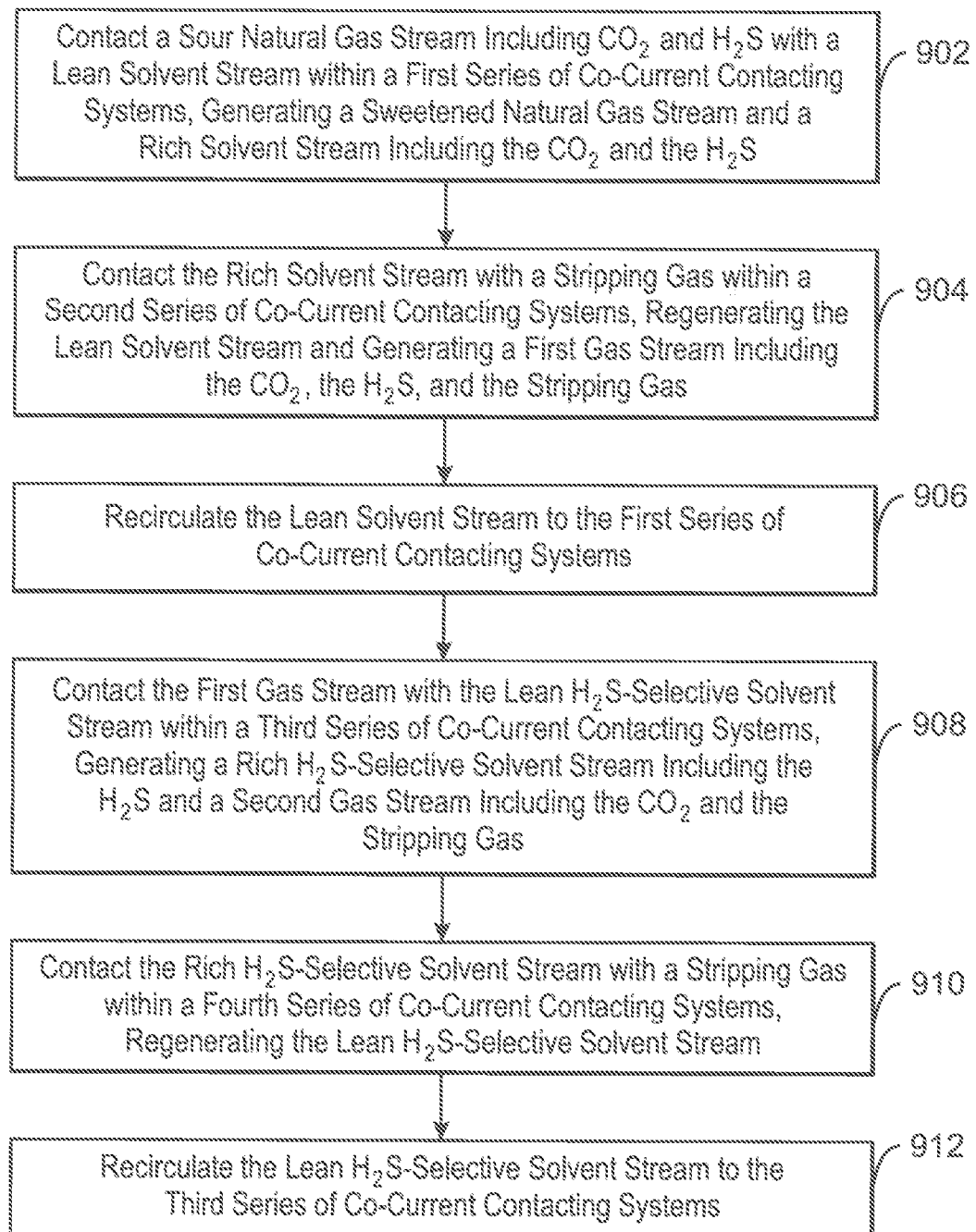


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FIG. 8C



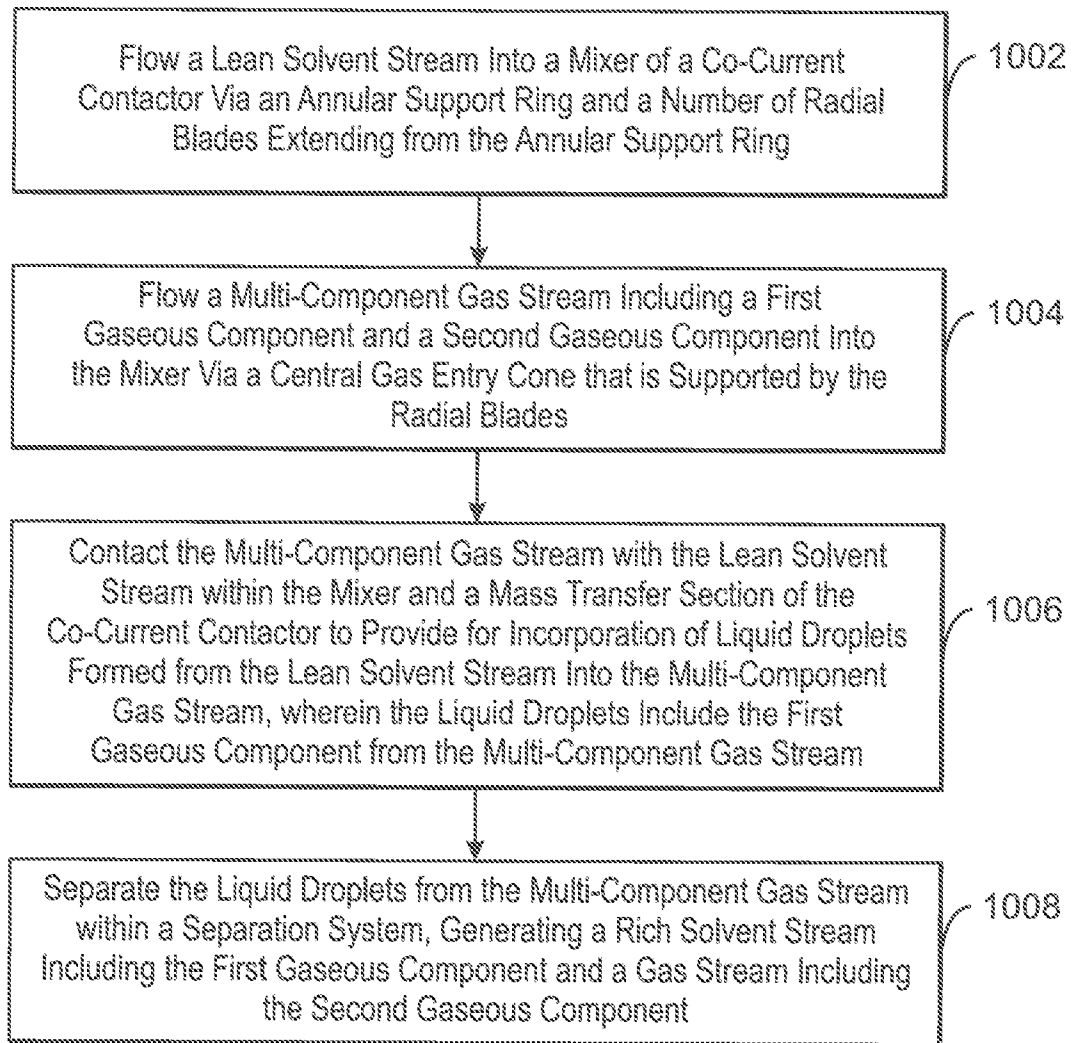
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FIG. 8D

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900
FIG. 9

15/15



1000
FIG. 10