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(54) Titre : SEPARATION DES IMPURETES D'UN FLUX GAZEUX A L'AIDE D'UN SYSTEME DE MISE EN CONTACT A COCOURANT ORIENTE VERTICALEMENT

(54) Title: SEPARATING IMPURITIES FROM A GAS STREAM USING A VERTICALLY ORIENTED CO-CURRENT CONTACTING SYSTEM

(57) Abrégé/Abstract:
A vertically oriented co-current contacting system and methods for separating impurities from a gas stream including a vertically oriented co-current contactor (VOCC) located in-line within a pipe, a vertically oriented mixer (VOM) including an annular support ring configured to maintain the VOM within the pipe, a number of radial blades configured to allow a liquid stream to flow into the VOM, and a central gas entry cone configured to allow a gas stream to flow through a hollow section within the VOM, a vertically oriented mass transfer section downstream of the VOM. The VOM and the vertically oriented mass transfer section provide for efficient incorporation of liquid droplets including impurities from the gas stream formed from the liquid stream into the gas stream. The vertically oriented co-current contacting system also includes a separation system configured to remove the liquid droplets.

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(54) **Title**: SEPARATING IMPURITIES FROM A GAS STREAM USING A VERTICALLY ORIENTED CO-CURRENT CONTACTING SYSTEM

(57) **Abstract**: A vertically oriented co-current contacting system and methods for separating impurities from a gas stream including a vertically oriented co-current contactor (VOCC) located in-line within a pipe, a vertically oriented mixer (VOM) including an annular support ring configured to maintain the VOM within the pipe, a number of radial blades configured to allow a liquid stream to flow into the VOM, and a central gas entry cone configured to allow a gas stream to flow through a hollow section within the VOM, a vertically oriented mass transfer section downstream of the VOM. The VOM and the vertically oriented mass transfer section provide for efficient incorporation of liquid droplets including impurities from the gas stream formed from the liquid stream into the gas stream. The vertically oriented co-current contacting system also includes a separation system configured to remove the liquid droplets.

SEPARATING IMPURITIES FROM A GAS STREAM USING A VERTICALLY ORIENTED CO-CURRENT CONTACTING SYSTEM

FIELD

[0002] The present techniques provide for the separation of impurities from a gas stream using a vertically oriented co-current contacting system. More specifically, the present techniques provide for the incorporation of liquid droplets formed from a liquid stream into a gas stream to effect the removal of impurities from the gas stream using a vertically oriented co-current contacting system.

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 discussion 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 (H_2S), carbon dioxide (CO_2), and water. When H_2S or CO_2 are produced as part of a hydrocarbon gas stream, such as methane or ethane, the raw gas stream is sometimes referred to as "sour gas." The H_2S and CO_2 are often referred to together as "acid gases."

[0005] In addition to hydrocarbon production streams, acid gases may be associated with synthesis gas streams, or with refinery gas streams. Acid gases may also be present within so-called flash gas streams in gas processing facilities. Further, acid gases may be generated by the combustion of coal, natural gas, or other carbonaceous fuels.

[0006] Natural gas streams may contain not only H_2S or CO_2, but may also contain other "acidic" impurities. These include mercaptans and other trace sulfur compounds (SO_x). In

addition, natural gas streams may contain water. Such impurities are often removed prior to industrial or residential use.

[0007] Processes have been devised to remove contaminants from a raw natural gas stream. In the case of acid gases, cryogenic gas processing is sometimes used, particularly to remove CO_2 to prevent line freezing and orifice plugging. In other instances, particularly with H_2S removal, the hydrocarbon fluid stream is treated with a solvent. Solvents may include 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).

[0008] 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 amine-based acid gas removal solvents is common.

[0009] 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 as Flexsorb™ are used, particularly for selectively removing H_2S from CO_2-containing gas streams.

[0010] As a result of the gas sweetening process, a treated or "sweetened" gas stream is created. The sweetened gas stream is substantially depleted of H_2S and/or CO_2 components. The sweetened gas stream can be further processed for liquids recovery, that is, by condensing out heavier hydrocarbon gases. The sweetened gas stream may be sold into a pipeline or may be used for liquefied natural gas (LNG) feed if the CO_2 concentration is less than, for example, about 50 ppm. 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. The extracted CO_2 may be sold, or may be injected into a subterranean reservoir for enhanced oil recovery (EOR) operations.

[0011] When a natural gas stream contains water, a dehydration process is usually undertaken before acid gas removal. This is done through the use of glycol or other desiccant in a water separator. The dehydration of natural gas is performed to control the formation of gas hydrates and to prevent corrosion of distribution pipelines. The formation of gas hydrates

and the corrosion of distribution pipelines can cause a decrease in flow volume as well as frozen control valves, plugged orifices, and other operating problems.

[0012] Traditionally, the removal of acid gases or water from a raw natural gas stream using a chemical solvent (or desiccant) involves counter-currently contacting the raw natural gas stream with the chemical solvent. The raw natural gas stream is introduced into the bottom section of a contacting tower. At the same time, the chemical solvent is directed into a top section of the tower. The tower has trays, packing, or other "internals." As the chemical solvent cascades through the internals, it absorbs the undesirable components, carrying them away through the bottom of the contacting tower as part of a "rich" solvent solution. At the same time, gaseous fluid that is largely depleted of the undesirable components exits at the top of the tower.

[0013] The rich solvent or rich glycol that exits the contactor is sometimes referred to as an absorbent liquid. Following absorption, a process of regeneration (also called "desorption") may be employed to separate contaminants from the active solvent of the absorbent liquid. This produces a "lean" solvent or a "lean" glycol that is then typically recycled into the contacting tower for further absorption.

[0014] Known counter-current contactors used for dehydration or for H_2S and CO_2 absorption tend to be very large and 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.

SUMMARY

[0015] An exemplary embodiment provides a vertically oriented co-current contacting system for separating impurities from a gas stream. The vertically oriented co-current contacting system includes a vertically oriented co-current contactor located in-line within a pipe. The vertically oriented co-current contactor includes a vertically oriented mixer including an annular support ring configured to maintain the vertically oriented mixer within the pipe, a number of radial blades configured to allow a liquid stream to flow into the vertically oriented mixer, and a central gas entry cone configured to allow a gas stream to flow through a hollow section within the vertically oriented mixer. The vertically oriented co-current contactor also includes a vertically oriented mass transfer section downstream of the vertically oriented mixer. The vertically oriented mixer and the vertically oriented mass

transfer section provide for efficient incorporation of liquid droplets formed from the liquid stream into the gas stream. The liquid droplets include impurities from the gas stream. The vertically oriented co-current contacting system also includes a separation system configured to remove the liquid droplets including the impurities from the gas stream.

[0016] Another exemplary embodiment provides a method for separating impurities from a gas stream. The method includes flowing a liquid stream into a vertically oriented mixer of a vertically oriented 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 vertically oriented mixer in-line within a pipe. The method also includes flowing a gas stream into the vertically oriented mixer via a central gas entry cone that is supported by the radial blades, wherein a first portion of the gas stream flows through the central gas entry cone and a second portion of the gas stream flows around the central gas entry cone between the radial blades. The method also includes contacting the gas stream with the liquid stream within the vertically oriented mixer and a vertically oriented mass transfer section of the vertically oriented co-current contactor to provide for incorporation of liquid droplets formed from the liquid stream into the gas stream, wherein the liquid droplets include impurities from the gas stream. The method further includes separating the liquid droplets including the impurities from the gas stream within a separation system.

[0017] Another exemplary embodiment provides a method for separating impurities from a natural gas stream. The method includes flowing a semi-lean solvent stream into a first vertically oriented co-current contactor of a vertically oriented co-current contacting system and flowing a natural gas stream into the first vertically oriented co-current contactor. The method includes contacting the natural gas stream with the semi-lean solvent stream within the first vertically oriented co-current contactor to provide a first multi-phase stream, wherein the first multi-phase stream includes the natural gas stream with incorporated liquid droplets formed from the semi-lean solvent stream that include impurities from the natural gas stream. The method also includes flowing the first multi-phase stream into a second vertically oriented co-current contactor of the vertically oriented co-current contacting system and flowing a lean solvent stream into the second vertically oriented co-current contactor. The method also includes contacting the first multi-phase stream with the lean solvent stream within the second vertically oriented co-current contactor to provide a second multi-phase stream, wherein the second multi-phase stream includes the natural gas stream with additional incorporated liquid droplets formed from the lean solvent stream that include

residual impurities from the natural gas stream. The method further includes separating the second multi-phase stream into a purified natural gas stream and a rich solvent stream within a separation system of the vertically oriented co-current contacting system.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] The advantages of the present techniques are better understood by referring to the following detailed description and the attached drawings, in which:

[0019] Fig. 1 is a process flow diagram of a chemical solvent-based gas processing system;

[0020] Fig. 2A is a process flow diagram of a gas processing system that includes a vertically oriented co-current flow scheme;

[0021] Fig. 2B is a process flow diagram of another gas processing system that includes a vertically oriented co-current flow scheme;

[0022] Fig. 3 is a schematic of a column for separating a feed stream into a gas stream and a liquid stream;

[0023] Fig. 4A is a process flow diagram of a separation system including a number of vertically oriented co-current contacting systems that may be placed in a shell;

[0024] Fig. 4B is a process flow diagram of the separation system of Fig. 4A including the vertically oriented co-current contacting systems with the addition of a number of heat exchangers;

[0025] Fig. 5 is a process flow diagram of a number of vertically oriented co-current contacting systems that operate in connection with one or more flash drums;

[0026] Fig. 6 is a process flow diagram of a gas regeneration facility including a number of vertically oriented co-current contacting systems;

[0027] Fig. 7A is a process flow diagram of a vertically oriented co-current contacting system including a vertically oriented co-current contactor and a vertically oriented separation system;

[0028] Fig. 7B is a process flow diagram of the vertically oriented co-current contacting system of Fig. 7A including the vertically oriented co-current contactor and a horizontally oriented separation system;

[0029] Fig. 7C is a process flow diagram of the vertically oriented co-current contacting

system of Fig. 7A including a number of vertically oriented co-current contactors connected in series upstream of the vertically oriented separation system;

[0030] Fig. 8 is a process flow diagram of a vertically oriented co-current contacting system including a number of vertically oriented co-current contactors and a vertically oriented separation system that may be used to purify a natural gas stream;

[0031] Fig. 9 is a schematic of a vertically oriented co-current contacting system;

[0032] Fig. 10A is a top view of a vertically oriented mixer;

[0033] Fig. 10B is a top perspective view of the vertically oriented mixer of Fig. 10A;

[0034] Fig. 10C is a cross-sectional side perspective view of the vertically oriented mixer of Figs. 10A and 10B;

[0035] Fig. 10D is another cross-sectional side perspective view of the vertically oriented mixer of Figs. 10A-C;

[0036] Fig. 11 is a process flow diagram of a method for separating impurities from a gas stream; and

[0037] Fig. 12 is a process flow diagram of a method for separating impurities from a natural gas stream using a vertically-oriented co-current contacting system that includes multiple vertically-oriented co-current contactors upstream of a single separation system.

DETAILED DESCRIPTION

[0038] 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 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.

[0039] 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, 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.

[0040] "Acid gas" refers to any gas that produces an acidic solution when dissolved in water. Non-limiting examples of acid gases include hydrogen sulfide (H_2S), carbon dioxide (CO_2), sulfur dioxide (SO_2), carbon disulfide (CS_2), carbonyl sulfide (COS), mercaptans, or mixtures thereof.

[0041] "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.

[0042] 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.

[0043] 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 solvent is injected into the top, while a mixture of gases to be separated is flowed through the bottom. As the gases flow upwards through the falling stream of solvent, one gas species is preferentially absorbed, lowering its concentration in the vapor stream exiting the top of the column.

[0044] In a distillation column, liquid and vapor phases are counter-currently contacted to 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, 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 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.

[0045] "Dehydrated gas stream" refers to a natural gas stream that has undergone a dehydration process to remove at least a portion of the water from the natural gas stream. 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 WO 2004/070297.

[0046] 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.

[0047] 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.

[0048] 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.

[0049] 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.

[0050] The term “flue gas” refers to any gas stream generated as a by-product of hydrocarbon combustion.

[0051] The term "gas" is used interchangeably with "vapor," and is defined as a substance 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.

[0052] A “hydrocarbon” is an organic compound that primarily includes the elements hydrogen and carbon, although nitrogen, sulfur, oxygen, metals, or any number of other elements may be present in small amounts. As used herein, hydrocarbons generally refer to components found in natural gas, oil, or chemical processing facilities.

[0053] 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 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.

[0054] The term “industrial plant” refers to any plant that generates a gas stream containing at least one hydrocarbon or an acid gas. One non-limiting example is a coal-powered electrical generation plant. Another example is a cement plant that emits CO_2 at low pressures.

[0055] "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 compounds. The other elements or compounds may include, but are not limited to, ethane, propane, butane, carbon dioxide, nitrogen, helium, hydrogen sulfide, 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.

[0056] 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.

[0057] "Natural gas" refers to a multi-component gas obtained from a crude oil well or from a subterranean gas-bearing formation. The composition and pressure of natural gas can vary significantly. A typical natural gas stream contains methane (CH_4) 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 (C_2H_6), higher molecular weight hydrocarbons (e.g., C_3-C_{20} hydrocarbons), one or more acid gases (e.g., carbon dioxide or hydrogen sulfide), 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 prior to use in embodiments, so as to remove compounds that may act as poisons.

[0058] "Non-absorbing gas" refers to a gas that is not significantly absorbed by a solvent during a gas treating or conditioning process.

[0059] "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, 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, chemisorption, physisorption, adsorption, pressure swing adsorption, temperature swing adsorption, or the like.

[0060] "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.

[0061] 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

[0062] The present techniques provide for the removal of impurities from a gas stream using a vertically oriented co-current contacting system. More specifically, the present

techniques provide for the incorporation of liquid droplets formed from a liquid stream into a gas stream to effect the removal of impurities from the gas stream using a vertically oriented co-current contacting system. The vertically oriented co-current contacting system includes a co-current contactor including a mixer and a mass transfer section, as well as a separation system. In various embodiments, the mixer and mass transfer section of the co-current contactor and, optionally, the separation system are vertically oriented.

[0063] In various embodiments, the vertically oriented co-current contacting system contacts a gas stream, e.g., a natural gas stream, including impurities with a liquid stream, e.g., a lean or semi-lean solvent stream, by injecting the liquid stream into the gas stream as a fine mist of droplets within the mixer of the co-current contactor. The mist provides a high surface area for the incorporation of the impurities into the liquid stream, for example, by adsorption, dissolution, reaction, and the like, within the mass transfer section of the co-current contactor. A purified gas stream may then be generated by separating the gas stream from the liquid stream including the incorporated impurities within the separation system. In addition, in some embodiments, a co-current contacting system including a number of vertically oriented co-current contactors and corresponding separations systems may be employed to progressively purify the gas stream. Further, in some embodiments, a co-current contacting system including a number of vertically oriented co-current contactors upstream of a single separation system may be employed to purify the gas stream.

[0064] Existing co-current contacting systems for removing impurities from gas streams are typically oriented horizontally. Therefore, gravity acts on the liquid stream including the incorporated impurities, causing the liquid stream to accumulate at the bottom of the contacting system. More specifically, gravity may cause the liquid droplets to coalesce into larger liquid droplets, and may drive the larger liquid droplets to create a film on the bottom walls of the piping. This may reduce the area of the mass transfer section that is available for incorporation of the liquid droplets into the gas stream and, thus, reduce the degree of separation of the impurities from the gas stream.

[0065] Accordingly, embodiments described herein provide for the separation of impurities from a gas stream using a vertically oriented co-current contacting system. More specifically, the mixer and mass transfer section of the co-current contactor and, optionally, the separation system are oriented vertically according to embodiments described herein. Vertical orientation of the co-current contacting system reduces the influence of gravity on the liquid droplets that have been incorporated into the gas stream. Therefore, the fraction of

liquid flowing on the walls of the piping is reduced, and the liquid droplet sizes are reduced through the mass transfer section of the co-current contactor due to less coalescence of the liquid droplets. This may increase the area of the mass transfer section that is available for incorporation of the liquid droplets into the gas stream and, thus, increase the degree of separation of impurities from the gas stream. In addition, vertical orientation of the co-current contacting system reduces the footprint of the co-current contracting system, particularly in the case of off-shore applications, by making the co-current contacting system more compact. Furthermore, vertical orientation of the co-current contacting system may allow the co-current contacting system to be conformed to a wide variety of limited space configurations. The ability to conform the co-current contacting system to such a wide variety of limited space configurations may be desirable for many different applications.

[0066] As discussed above, in some embodiments, a co-current contacting system including a number of vertically oriented co-current contactors upstream of a single separation system may be employed to purify a gas stream. In various embodiments, each vertically oriented co-current contacting system includes a vertically oriented mixer and a vertically oriented mass transfer section. The separation system may be either vertically or horizontally oriented, depending on the details of the specific implementation. Moreover, in some embodiments, different solvent streams may be injected into each co-current contactor. For example, a semi-lean solvent stream may be injected into the mixer of the first co-current contactor, and a lean solvent stream may be injected into the mixer of the second co-current contactor. The injection of a fresh or lean solvent stream into the second co-current contactor may reduce the concentration of the impurities within the vertically oriented co-current contacting system and increase the driving force for the incorporation of the liquid droplets into the gas stream. Therefore, the degree of separation of the impurities from the gas stream may be increased. In some embodiments that use multiple co-current contactors in sequence, lean solvent streams may be alternately injected between solvent streams that have various levels of absorbed acid gases.

Gas Processing System

[0067] 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 discussed further herein.

[0068] 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 an acid gas, such as H_2S or 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.

[0069] 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.

[0070] 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**.

[0071] 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 pump **122** may force the liquid glycol stream **118** from the glycol tank **120** into the contactor **106** under suitable pressure. For example, the pump **122**

may boost the pressure of the liquid glycol stream **118** to about 1,000 psig or higher, depending on the pressure of the raw natural gas stream **102**.

[0072] 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**.

[0073] 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**.

[0074] 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**. The outlet separator **126** may also be used as a water wash vessel to capture vapor-phase solvent. 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**.

[0075] 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 low 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 discussed further herein.

[0076] From the contactor **106**, the spent desiccant stream **136** may be flowed into a regenerator **138**. Specifically, the spent desiccant stream **136** can be flowed through a tube bundle **140** in the top of a distillation column **142** of the regenerator **138**. 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 **140**, before the water vapor and off-gases **148** are released via an overhead line **150**.

[0077] In various embodiments, the regenerator **138** may be used to regenerate the liquid glycol stream **118** from the spent desiccant stream **136**. The regenerator **138** may be a large pressure vessel, or interconnected series of pressure vessels, that operates at about 15 psig to about 25 psig, for example.

[0078] After being preheated within the distillation column **142**, the spent desiccant stream **136** may be released from the tube bundle **140** 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**.

[0079] Residual gases **156**, such as methane, H_2S, or CO_2, 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**.

[0080] In addition, any entrained heavier hydrocarbons, such as ethane or propane, within the glycol stream **152** may be captured within the flash drum **154**. The resulting hydrocarbon stream **160** may be flowed out of the flash drum **154** via a bottoms line **162**.

[0081] 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 through a filter **166**, such as a carbon filter, for particle filtration.

[0082] 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 **172** may be flowed into the distillation column **142** of the regenerator **138**. As the high-temperature glycol stream **172** travels through the distillation column **142**, water vapor and off-gases **148**, such as H_2S and CO_2, may be removed from the high-temperature glycol stream **172**.

[0083] The high-temperature glycol stream **172** may be flowed out of the bottom of the distillation column **142** and into a reboiler **174** within the regenerator **138**. The reboiler **174** may increase the temperature of the high-temperature glycol stream **172** using heat provided by a heat exchanger **175**. In addition, the reboiler **174** may boil off residual water vapor and off-gases **148** from the high-temperature glycol stream **172**. 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**.

[0084] The regenerator **138** may also include a separate stripping section **176** fed from the liquid pool in the reboiler **174**. The stripping section **176** may include packing that promotes further distillation. Any remaining impurities, such as water, H_2S, or CO_2, boil off and join the water vapor and off-gases **148** in the overhead line **150**. The high-temperature glycol stream **172** may then be flowed into a surge tank **178**, from which it may be released as the liquid glycol stream **118**.

[0085] The regenerated liquid glycol stream **118** may be pumped out of the surge tank **178** via a pump **180**. The pump **180** may increase the pressure of the liquid glycol stream **118** to about 1,500 psig or about 2,500 psig, for example.

[0086] 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**. In addition, the liquid glycol stream **118** may be flowed 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 liquid glycol stream **118** is not flashing 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.

[0087] 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 **174** 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.

[0088] 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 glycol stream **118** includes a chemical solvent, such as a primary amine, a secondary amine, or a tertiary amine. The liquid glycol stream **118** may also be an ionic liquid or a blend of a physical solvent with an amine. For purposes of discussion, the liquid glycol stream **118** may be interchangeably referred to herein as an amine, a chemical solvent, or an absorbent liquid.

[0089] 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 absorb CO_2 as quickly as H_2S. Therefore, two separate gas processing systems **100** may be sequentially operated, with one configured to absorb primarily H_2S, and the other configured to absorb primarily CO_2. A separate CO_2 stream that is substantially free of H_2S may also be generated.

[0090] 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.

[0091] 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 CO_2 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.

[0092] 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 CO_2 or H_2S from flash-gas streams.

[0093] Embodiments described herein utilize a vertically oriented co-current flow scheme as an alternative to the counter-current flow scheme demonstrated in the contactor **106** of Fig. 1. The vertically oriented co-current flow scheme utilizes one or more vertically oriented 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 vertically oriented 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 vertically oriented 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.

[0094] Fig. 2A is a process flow diagram of a gas processing system **200** that includes a vertically oriented co-current flow scheme. The gas processing system **200** may be an alternative to the gas processing system **100** discussed with respect to Fig. 1. The gas processing system **200** may be used for the removal of H_2S or other acid gas components from a gas stream **202**. In addition, in some embodiments, the gas processing system **200** may be used for the removal of water or other impurities from the gas stream **202**.

[0095] The gas processing system **200** may employ a number of vertically oriented co-current contacting systems **204A-F**. In some embodiments, each vertically oriented co-current contacting system **204A-F** includes vertically oriented co-current contactor upstream of a separation system. In other embodiments, each vertically oriented co-current contacting system **204A-F** includes a number of vertically oriented co-current contactors upstream of a single separation system. In both embodiments, the separation system may be either vertically oriented or horizontally oriented, depending on the details of the specific implementation.

[0096] The gas stream **202** may be a natural gas stream from a hydrocarbon production operation. For example, the gas stream **202** may be a flue gas stream from a power plant, or a synthesis gas (syn-gas) stream. If the natural gas stream **202** is a syn-gas stream, the gas stream **202** may be cooled and filtered before being introduced into the gas processing system **200**. The gas stream **202** may also be a flash gas stream taken from a flash drum in a gas processing system itself. In addition, the gas stream **202** may be a tail gas stream from a

Claus sulfur recovery process or an impurities stream from a regenerator. Furthermore, the gas stream **202** may be an exhaust emission from a cement plant or other industrial plant. In this instance, CO_2 may be absorbed from excess air or from a nitrogen-containing flue gas.

[0097] The gas stream **202** may include a non-absorbing gas, such as methane, and one or more impurities, such as an acid gas. For example, the gas stream **202** may include CO_2 or H_2S. The gas processing system **200** may convert the gas stream **202** into a sweetened gas stream **206** by removing the acid gases.

[0098] In operation, the gas stream **202** may be flowed into a first vertically oriented co-current contacting system **204A**, where it is mixed with a solvent stream **208**. If the gas processing system **200** is to be used for the removal of H_2S, or other sulfur compounds, the solvent stream **208** 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 H_2S removal. In embodiments used for other purposes, such as dehydration or reactions, other solvents or reactants, such as glycols, may be used. The solvent stream **208** may include a lean solvent that has undergone a desorption process for the removal of acid gas impurities. For example, in the gas processing system **200** shown in Fig. 2A, the solvent stream **208** introduced into the first vertically oriented co-current contacting system **204A** includes a semi-lean solvent that is taken from a central portion of a regenerator **210**. A lean solvent stream **212** taken from the regenerator **210** may also be directed into a final vertically oriented co-current contacting system **204F**.

[0099] In various embodiments, the gas processing system **200** employs a series of vertically oriented co-current contacting systems **204A-F**. Each vertically oriented co-current contacting system **204A-F** removes a portion of the acid gas content from the natural gas stream **202**, thereby releasing a progressively sweetened natural gas stream in a downstream direction. The final vertically oriented co-current contacting system **204F** provides the final sweetened natural gas stream **206**.

[0100] Before entering the first vertically oriented co-current contacting system **204A**, the natural gas stream **202** may pass through an inlet separator **214**. The inlet separator **214** may be used to clean the natural gas stream **202** by filtering out impurities, such as brine and drilling fluids. Some particle filtration may also take place. The cleaning of the natural gas stream **202** can prevent foaming of solvent during the acid gas treatment process.

[0101] As shown in Fig. 2A, the solvent stream **208** is flowed into the first vertically oriented co-current contacting system **204A**. Movement of the semi-lean solvent stream **208** into the first vertically oriented co-current contacting system **204A** may be aided by a pump **216**. The pump **216** may cause the semi-lean solvent stream **208** to flow into the first vertically oriented co-current contacting system **204A** at a suitable pressure, for example, of about 15 psig to about 1,500 psig.

[0102] Once inside the first vertically oriented co-current contacting system **204A**, the natural gas stream **202** and the solvent stream **208** move along the longitudinal axis of the first vertically oriented co-current contacting system **204A**. As they travel, the solvent stream **208** interacts with the H_2S, H_2O, and/or other impurities in the natural gas stream **202**, causing the H_2S, H_2O, and/or other impurities to chemically attach to or be absorbed by the amine molecules. A first partially-loaded, or "rich," gas treating solution **218A** may be flowed out of the first vertically oriented co-current contacting system **204A**. In addition, a first partially-sweetened natural gas stream **220A** may be flowed out of a bottom portion of the first vertically oriented co-current contacting system **204A** and into a second vertically oriented co-current contacting system **204B**.

[0103] As shown in the example illustrated in Fig. 2A, a third vertically oriented co-current contacting system **204C** may be provided after the second vertically oriented co-current contacting system **204B**, and a fourth vertically oriented co-current contacting system **204D** may be provided after the third vertically oriented co-current contacting system **204C**. In addition, a fifth vertically oriented co-current contacting system **204E** may be provided after the fourth vertically oriented co-current contacting system **204D**, and a final vertically oriented co-current contacting system **204F** may be provided after the fifth vertically oriented co-current contacting system **204E**. Each of the second, third, fourth, and fifth vertically oriented co-current contacting systems **204B**, **204C**, **204D**, and **204E** may generate a respective partially-sweetened natural gas stream **220B**, **220C**, **220D**, and **220E**. In addition, each of the second, third, fourth, fifth, and final vertically oriented co-current contacting systems **204B**, **204C**, **204D**, **204E**, and **204F** may generate respective partially-loaded gas treating solution **218B**, **218C**, **218D**, **218E**, and **218F**. If an amine is used as the solvent stream **208**, the partially-loaded gas treating solutions **218A-F** may include rich amine solutions. In the gas processing system **200**, the second loaded gas treating solution **218B** merges with the rich gas treating solution **218A** and goes through a regeneration process in the regenerator **210**.

[0104] As the progressively-sweetened natural gas streams **220A-E** are generated, the gas pressure in the gas processing system **200** will gradually decrease. As this occurs, the liquid pressure of the progressively-richer gas treating solutions **218A-F** may be correspondingly increased. This may be accomplished by placing one or more booster pumps (not shown) between each vertically oriented co-current contacting system **204A-F** to boost liquid pressure in the gas processing system **200**.

[0105] In the gas processing system **200**, solvent streams may be regenerated by flowing the partially-loaded gas treating solutions **218A** and **218B** through a flash drum **221**. Absorbed natural gas **222** may be flashed from the partially-loaded gas treating solutions **218A** and **218B** within the flash drum **221**, and may be flowed out of the flash drum **221** via an overhead line **224**.

[0106] The resulting rich solvent stream **226** may be flowed from the flash drum **221** to the regenerator **210**. The rich solvent stream **226** may be introduced into the regenerator **210** for desorption. The regenerator **210** may include a stripper portion **228** including trays or other internals (not shown). The stripper portion **228** may be located directly above a reboiler portion **230**. A heat source **232** may be provided with the reboiler **230** to generate heat. The regenerator **210** produces the regenerated, lean solvent stream **212** that is recycled for re-use in the final vertically oriented co-current contacting system **204F**. Stripped overhead gas from the regenerator **210**, which may include concentrated H_2S (or CO_2), may be flowed out of the regenerator **210** as an overhead impurities stream **234**.

[0107] The overhead impurities stream **234** may be flowed into a condenser **236**, which may cool the overhead impurities stream **234**. The resulting cooled impurities stream **238** may be flowed through a reflux accumulator **240**. The reflux accumulator **240** may separate any remaining liquid, such as condensed water, from the impurities stream **238**. This may result in the generation of a substantially pure acid gas stream **242**, which may be flowed out of the reflux accumulator **240** via an overhead line **244**.

[0108] In some embodiments, if the initial natural gas stream **202** includes CO_2, and a CO_2-selective solvent stream **208** is used, the acid gas stream **242** includes primarily CO_2. The CO_2-rich acid gas stream **242** may be used as part of a miscible EOR operation to recover oil. If the oil reservoir to be flooded does not contain a significant amount of H_2S or other sulfur compounds, the CO_2 to be used for the EOR operation may not contain significant H_2S or other sulfur compounds. However, concentrated CO_2 streams from oil and gas production operations may be contaminated with small amounts of H_2S. Thus, it may be

desirable to remove the H_2S from the CO_2, unless the acid gas stream 202 is to be injected purely for geologic sequestration.

[0109] In some embodiments, if the initial natural gas stream **202** includes H_2S, an H_2S-selective solvent stream **208** may be used to capture the H_2S. The H_2S may then be converted into elemental sulfur using a sulfur recovery unit (not shown). The sulfur recovery unit may be a so-called Claus unit. Those of ordinary skill in the art will understand that a "Claus process" is a process that is sometimes used by the natural gas and refinery industries to recover elemental sulfur from H_2S-containing gas streams.

[0110] In practice, the "tail gas" from the Claus process, which may include H_2S, SO_2, CO_2, N_2, and water vapor, can be reacted to convert the SO_2 to H_2S via hydrogenation. The hydrogenated tail gas stream has a high partial pressure, a large amount of CO_2, e.g., more than 50%, and a small amount of H_2S, e.g., a few percent or less. This type of gas stream, which is typically near atmospheric pressure, is amenable to selective H_2S removal. The recovered H_2S may be recycled to the front of the Claus unit, or may be sequestered downstream. Alternatively, a direct oxidation of the H_2S to elemental sulfur may be performed using various processes known in the field of gas separation.

[0111] Because the H_2S reaction is instantaneous relative to the CO_2 reactions, lowering the residence time, i.e., the contact time between the vapor and liquid phases, will result in less CO_2 being absorbed into the solvent. The design of the vertically oriented co-current contacting systems **204A-F** enhances selective H_2S removal due to the short contact time inherent in the equipment design.

[0112] As shown in Fig. 2A, a residual liquid stream **246** may be flowed out of the bottom of the reflux accumulator **240**. The residual liquid stream **246** may be flowed through a reflux pump **248**, which may boost the pressure of the residual liquid stream **246** and pump the residual liquid stream **246** into the regenerator **210**. The residual liquid stream **246** may be flowed out of the regenerator **210**, for example, from the bottom of the reboiler portion **230** as part of the lean solvent stream **212**. Some water may be added to the lean solvent stream **212** to balance the loss of water vapor to the partially sweetened natural gas streams **220A-E**. This water may be added at an intake or suction of the reflux pump **248**.

[0113] The lean solvent stream **212** may be at a low pressure. Accordingly, the lean solvent stream **212** may be passed through a pressure boosting pump **250**. From the pressure boosting pump **250**, the lean solvent stream **212** may be flowed through a cooler **254**. The

cooler **254** may cool the lean solvent stream **212** to ensure that the lean solvent stream **212** will absorb acid gases effectively. The resulting chilled lean solvent stream **256** is then used as the solvent stream for the final vertically oriented co-current contacting system **204F**.

[0114] In some embodiments, a solvent tank **258** is provided proximate the final vertically oriented co-current contacting system **204F**. The chilled lean solvent stream **256** may be flowed from the solvent tank **258**. In other embodiments, the solvent tank **258** is off-line and provides a reservoir for the lean solvent stream **256**.

[0115] The process flow diagram of Fig. 2A is not intended to indicate that the gas processing system **200** is to include all of the components shown in Fig. 2A. Further, any number of additional components may be included within the gas processing system **200**, depending on the details of the specific implementation. For example, the gas processing 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.

[0116] Fig. 2B is a process flow diagram of another gas processing system **260** that includes a vertically oriented co-current flow scheme. Like numbered items are as described with respect to Fig. 2A. Operation of the gas processing system **260** of Fig. 2B is similar to that of the gas processing system **200** of Fig. 2A. However, in the gas processing system **260**, the first vertically oriented co-current contacting system **204A** receives the partially-loaded gas treating solution **218B** from the second vertically oriented co-current contacting system **204B**. Therefore, the gas processing system **260** does not include the semi-lean solvent stream **208**. In this example, the series of vertically oriented co-current contacting systems **204A-F** acts like a separation column, for example, wherein each stage corresponds to a packed stage.

[0117] Because the partially-loaded gas treating solution **218B** received by the first vertically oriented co-current contacting system **204A** in Fig. 2B has already been processed through the second vertically oriented co-current contacting system **204B**, the partially-loaded gas treating solution **218B** may be very rich. For this reason, it may be desirable to provide some level of intermediate processing of the partially-loaded gas treating solution **218B**.

[0118] Alternatively, a semi-lean liquid stream could be taken from other sweetening

operations in the gas processing system **260** and used, at least in part, as an amine solution for the first or second vertically oriented co-current contacting system **204A** or **204B**. In this respect, there are situations in which a single type of solvent is used for more than one service in the gas processing system **260**. This is referred to as integrated gas treatment. For example, MDEA may be used both for high-pressure, H_2S-selective acid gas removal, as well as in a Claus tail gas treating (TGT) process. The rich amine stream from the TGT process is not heavily loaded with H_2S and CO_2, owing to the low pressure of the process. Thus, in some embodiments, the rich amine stream from the TGT process is used as a semi-lean stream for the first or second vertically oriented co-current contacting system **204A** or **204B**. The semi-lean stream (not shown) may be pumped to a suitable pressure and injected into the first or second vertically oriented co-current contacting system **204A** or **204B**, possibly along with the partially-loaded gas treating solution from the succeeding vertically oriented co-current contacting system.

[0119] Further, in the gas processing system **260** of Fig. 2B, the first partially-loaded solvent solution **218A** is flowed through a heat exchanger **262** after being flowed through the flash drum **221**. Within the heat exchanger **262**, the temperature of the first partially-loaded solvent solution **218A** is increased via heat exchange with the lean solvent **212** taken from the regenerator **210**. This serves to heat the first partially-loaded solvent solution **218A** before introduction into the regenerator **210**, while cooling the lean solvent stream **212**.

[0120] The process flow diagram of Fig. 2B is not intended to indicate that the gas processing system **260** is to include all of the components shown in Fig. 2B. Further, any number of additional components may be included within the gas processing system **260**, depending on the details of the specific implementation.

[0121] 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 a solvent and a gas contaminant. The column **300** may be similar to the columns used in the regenerators **138** and **210** discussed with respect to Figs 1, 2A, and 2B.

[0122] 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 **136**.

[0123] The feed stream **302** may be injected into a lower 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 re-injected into the top portion of the column **300**, as discussed further herein.

[0124] 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.

[0125] 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**.

[0126] 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 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.

[0127] 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**.

[0128] 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.

[0129] 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 potion of the column **300** to provide heat to the liquids **316** collecting in the bottom of the column **300**.

[0130] 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 column **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.

[0131] 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 vertically oriented co-current contacting system described herein may provide a desirable alternative to the column **300**.

[0132] Fig. 4A is a process flow diagram of a separation system **400** including a number of vertically oriented 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 discussed with respect to Fig. 3, in which each of the vertically oriented 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. The separation system **400** may be implemented as part of a gas processing system, such as the gas processing system **200** or **260** discussed with respect to Fig. 2A or 2B. The gas processing system may utilize a number of vertically oriented co-current contacting systems **402A-C** connected in series, such as the vertically oriented co-current contacting systems **204A-F** discussed with respect to Figs. 2A and 2B. In the illustrative arrangement shown in Fig. 4A, a first vertically oriented co-current contacting system **402A**, a second vertically oriented co-current contacting system **402B**, and a third vertically oriented co-current contacting system **402C** are provided, each residing within the single shell **403**.

[0133] 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 solutions 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**.

[0134] A first gas stream **404** may be flowed into the first vertically oriented co-current contacting system **402A**. The first vertically oriented co-current contacting system **402A** may generate a first partially purified gas stream **406A**, which may be flowed from the first vertically oriented co-current contacting system **402A** to the second vertically oriented co-current contacting system **402B**. The second vertically oriented co-current contacting system **402B** may then generate a second partially purified gas stream **406B**, which may be flowed from the second vertically oriented co-current contacting system **402B** to the third vertically oriented co-current contacting system **402C**. In some embodiments, the third vertically oriented co-current contacting system **402C** generates a final purified gas stream **408**.

[0135] Each of the first, second, and third vertically oriented co-current contacting systems **402A-C** also generates a respective rich gas treating solutions **410A**, **410B**, and **410C**. The third rich gas treating solution **410C** may be directed back to the second vertically oriented co-current contacting system **402B** as a liquid solvent, and the second rich gas treating solution **410B** may be directed back to the first vertically oriented co-current contacting system **402A**. In addition, the third vertically oriented co-current contacting system **402C** may receive a gas treating solution **410D** from another source. In various embodiments, the gas treating solution **410D** received by the third vertically oriented co-current contacting system **402C** is a lean or semi-lean liquid solvent. Further, the first rich gas treating solution **410A** may be returned to a regenerator (not shown), such as the regenerator **210** discussed with respect to Figs. 2A and 2B, or may serve as a liquid solvent for a preceding co-current contacting system (not shown).

[0136] The number of vertically oriented co-current contacting systems is not limited to that shown. Further, the interconnections do not have to be arranged as shown. In other applications, the vertically oriented co-current contacting systems **402A-C** may be used as reactors, for example, by including a reactant in the first gas stream **404**, and injecting a second reactant in the respective rich gas treating solutions **410A**, **410B**, and **410C**.

[0137] Fig. 4B is a process flow diagram of the separation system **400** of Fig. 4A including the vertically oriented 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 gas treating solutions **410B** and **410C**. In some embodiments, the heat exchangers **412A** and **412B** are used as an alternative to the use of the shell **403**.

[0138] Fig. 5 is a process flow diagram of a number of vertically oriented co-current contacting systems **500A-C** that operate in connection with one or more flash drums **502**. The vertically oriented co-current contacting systems **500A-C** may be implemented as part of a gas processing system, such as the gas processing systems **200** or **260** discussed with respect to Fig. 2A or 2B. The vertically oriented co-current contacting systems **500A-C** may be connected in series, similarly to the vertically oriented co-current contacting systems **204A-F** discussed with respect to Figs. 2A and 2B. In the illustrative arrangement shown in Fig. 5, a first vertically oriented co-current contacting system **500A**, a second vertically oriented co-current contacting system **500B**, and a third vertically oriented co-current contacting system **500C** are provided.

[0139] A first gas stream **504** may be flowed into the first vertically oriented co-current contacting system **500A**. The first vertically oriented co-current contacting system **500A** may generate a first partially purified gas stream **506A**, which may be flowed from the first vertically oriented co-current contacting system **500A** to the second vertically oriented co-current contacting system **500B**. The second vertically oriented co-current contacting system **500B** may then generate a second partially purified gas stream **506B**, which may be flowed from the second vertically oriented co-current contacting system **500B** to the third vertically oriented co-current contacting system **500C**. In some embodiments, the third vertically oriented co-current contacting system **500C** generates a final purified gas stream **508**.

[0140] Each of the first, second, and third vertically oriented co-current contacting systems **500A**, **500B**, and **500C** also generates a respective rich gas treating solution **510A**, **510B**, and **510C**. The third rich gas treating solution **510C** may be directed back to the second vertically oriented co-current contacting system **500B** as a liquid solvent, and the second rich gas treating solution **510B** may be directed back to the first vertically oriented co-current contacting system **510A** as a liquid solvent. In addition, the third vertically oriented co-current contacting system **500C** may receive a gas treating solution **510D** from another source. In various embodiments, the gas treating solution **510D** received by the third vertically oriented co-current contacting system **500C** is a lean or semi-lean liquid solvent. Further, the first rich gas treating solution **510A** may be returned to a regenerator (not shown), such as the regenerator **210** discussed with respect to Figs. 2A and 2B, or may serve as a liquid solvent for a preceding co-current contacting system (not shown).

[0141] As shown in Fig. 5, the second rich gas treating solution **510B** may be flowed through the flash drum **502**. A flash line **512** may be provided coming off the top of the flash

drum **502**. The flash drum **502** and associated flash line **512** may permit methane and any CO_2 absorbed in the second rich gas treating solution **510B** to be flashed out before the second rich gas treating solution **510B** is flowed into the first vertically oriented co-current contacting system **500A**. H_2O in vapor form may also be vented from the flash line **512**. In various embodiments, flashing the second rich gas treating solution **510B** creates a semi-lean solvent solution. The use of a semi-lean solvent solution in the first vertically oriented co-current contacting system **500A** may improve the efficiency of the first vertically oriented co-current contacting system **500A** and reduce the load on the regenerator. Further, in some embodiments, any of the other gas treating solutions **510A**, **510C**, or **510D** may also be flowed through a flash drum that is similar to the flash drum **502**.

[0142] In some embodiments, gas, e.g., methane, CO_2, and H_2O, flashing out of the flash line **512** is merged with gas flashing out of flash lines associated with any number of other flash drums within the gas processing system. For example, for the gas processing system **200** discussed with respect to Fig. 2A, the gas flashing out of the flash line **512** may be merged with the natural gas **222** flashing out of the flash drum **221**. The pressure of the gas flashing out of the flash line **512** may correspond to the pressure of the natural gas **222** flashing out of the flash drum **221**.

[0143] As shown in Fig. 5, the second gas treating solution **510B** may also be flowed through a pump **514** after it exits the flash drum **502**. The pump **514** may increase the pressure of the second gas treating solution **510B**, which may help to overcome the effect of the pressure drop that occurs within the vertically oriented co-current contacting systems **500A-C**. Increasing the pressure of the second gas treating solution **510B** may also allow the second gas treating solution **510B** to more effectively entrain the acid gases within the gas stream **504**.

[0144] The use of multiple vertically oriented co-current contacting systems in series has been described herein in connection with the removal of acid gases from a gas stream. For example, Figs. 2A and 2B show applications wherein the concentration of H_2S (or any other type of acid gas) within the gas stream is sequentially lowered through the use of a number of vertically oriented co-current contacting systems. However, the gas processing systems **200** and **260**, as well any other type of gas processing system that includes a number of vertically oriented co-current contacting systems connected in series, may also be used for a variety of other applications. For example, in some embodiments, the vertically oriented co-current contacting systems described herein are used for the dehydration of natural gas. Raw natural

gas is often saturated with water. The water is typically removed to avoid the formation of natural gas hydrates and to prevent corrosion in pipelines.

[0145] In known operations, dehydration is commonly accomplished by contacting the wet gas stream with a glycol solvent. The glycol solvent is typically triethylene glycol (TEG). Contacting takes place in a trayed tower or a packed absorber. In operation, lean TEG, e.g., TEG that is substantially free of water, enters the top of the contactor, while the wet gas enters near the bottom of the tower. The two fluid streams flow counter-currently through the column. The downward-flowing TEG absorbs water from the upward-flowing natural gas. The natural gas exits the top of the column substantially dry, while the rich TEG exits the bottom of the column, containing the absorbed water.

[0146] One or more vertically oriented co-current contacting systems, such as the vertically oriented co-current contacting systems discussed with respect to Figs. 2A, 2B, 4A, 4B, and 5, may be used in place of the trayed tower or packed absorber for rapidly contacting a desiccant with wet gas. In addition, higher pressure drops may be used to disperse the liquid solvent in the vapor phase and improve the efficiency of the vertically oriented co-current contacting systems.

[0147] Fig. 6 is a process flow diagram of a gas regeneration facility **600** including a number of vertically oriented co-current contacting systems **602A-C**. The vertically oriented co-current contacting systems **602A-C** may be used for the removal of acid gas **604** from a rich solvent solution **606**. The rich solvent solution **606** may be warm due to the exothermic chemical reaction involved in an earlier CO_2 or H_2S removal process, as well as possible pre-heating with an outside source.

[0148] As shown in Fig. 6, a stripping gas **608** may be flowed into a first vertically oriented co-current contacting system **602A**. In addition, a first partially-unloaded, or "lean," solvent stream **610A** may be heated within a first heat exchanger **612** and then flowed into the first vertically oriented co-current contacting system **602A**. Once inside the first vertically oriented co-current contacting system **602A**, the stripping gas **608** and the first partially-unloaded solvent stream **610A** move along the longitudinal axis of the first vertically oriented co-current contacting system **602A**. As they travel, the first partially-unloaded solvent stream **610A** interacts with the stripping gas **608**, causing any remaining acid gas within the first partially-unloaded solvent stream **610A** to chemically attach to or be absorbed by the amine molecules of the stripping gas **608**. The resulting lean solvent stream **614** may then be flowed out of the gas regeneration facility **600**. In some embodiments, the

lean solvent solution **614** is introduced into a vertically oriented co-current contacting system of a gas processing system, such as the gas processing system **200** or **260** of Fig. 2A or 2B. Further, in some embodiments, a portion of the lean solvent solution **614** is boiled to generate the stripping gas **608**.

[0149] A first gas mixture **616A** including the stripping gas and a portion of the acid gas may be flowed out of a bottom portion of the first vertically oriented co-current contacting system **602A** and into a second vertically oriented co-current contacting system **602B**. In addition, a second partially-unloaded solvent stream **610B** may be heated within a second heat exchanger **618** and then flowed into the second vertically oriented co-current contacting system **602B**. Once inside the second vertically oriented co-current contacting system **602B**, the first gas mixture **616A** and the second partially-unloaded solvent stream **610B** move along the longitudinal axis of the second vertically oriented co-current contacting system **602B**. As they travel, the second partially-unloaded solvent stream **610B** interacts with the first gas mixture **616A**, causing a portion of the acid gas within the second partially-unloaded solvent stream **610B** to chemically attach to or be absorbed by the amine molecules within the first gas mixture **610A**. The resulting first partially-unloaded solvent stream **610A** may then be flowed from the second vertically oriented co-current contacting system **602B** to the first vertically oriented co-current contacting system **602A**.

[0150] A second gas mixture **616B** including the stripping gas and a larger portion of the acid gas may be flowed out of a bottom portion of the second vertically oriented co-current contacting system **602B** and into a third vertically oriented co-current contacting system **602C**. In addition, the rich solvent stream **606** may be flowed into the third vertically oriented co-current contacting system **602C**. Once inside the third vertically oriented co-current contacting system **602C**, the second gas mixture **616B** and the rich solvent stream **606** move along the longitudinal axis of the third vertically oriented co-current contacting system **602C**. As they travel, the rich solvent stream **606** interacts with the second gas mixture **616B**, causing a portion of the acid gas within the rich solvent stream **606** to chemically attach to or be absorbed by the amine molecules within the second gas mixture **616B.** The resulting second partially-unloaded solvent stream **610B** may then be flowed from the third vertically oriented co-current contacting system **602C** to the second vertically oriented co-current contacting system **602B**. In addition, the acid gas **604** (and stripping gas) may be flowed out of the gas regeneration facility **600**.

[0151] In some embodiments, the rich solvent solution **606** may include water instead of

acid gas. In such embodiments, the water may be removed from the rich solvent solution **606** using the vertically oriented co-current contacting systems **602A-C**.

[0152] In various embodiments, a number of vertically oriented co-current contacting systems connected in series are used for the distillation of hydrocarbon mixtures or crude oil into near pure components. In such embodiments, the solvent may be steam or heated kerosene, and the gas phase may be methane and/or ethane. In addition, the hydrocarbon mixture may be heated to facilitate phase separation across the vertically oriented co-current contacting systems.

[0153] A number of vertically oriented co-current contacting systems connected in series may also be used for flash gas conditioning. In high-pressure gas purification processes, e.g. acid gas removal processes and dehydration processes, the rich solvent is often flashed into a vessel at a pressure in the range of 100 psig to 150 psig, for example. This flash stage releases much of the physically absorbed methane, but also releases some of the absorbed contaminants, such as H_2S, CO_2, and water vapor. To meet fuel gas specifications, this stream is often re-contacted with a small slip-stream of lean solvent.

[0154] To remove impurities from the gas, a number of vertically oriented co-current contacting systems connected in series may be employed as absorbers. Only two or three stages may be used to remove the impurities, as the H_2S specification for flash gas is generally not as stringent as that for pipeline gas. The flash gas may be used as fuel gas within a gas processing system, such as the gas processing system **200** or **260** of Fig. 2A or 2B, instead of being sold commercially.

[0155] In some embodiments, the gas stream represents gas from a catalytic hydro-desulfurization process (CHDS). In oil refineries, CHDS is sometimes used to convert mercaptans, sulfides, thiophenes, and other sulfur-containing compounds to H_2S. As an incidental byproduct of the CHDS, light hydrocarbons may be produced. It is possible to treat this gas to remove the H_2S, and then use the treated gas as fuel, for example. Such treatment may be accomplished using a series of vertically oriented co-current contacting systems, such as the vertically oriented co-current contacting systems discussed with respect to Figs. 2A, 2B, 4A, 4B, 5, and 6.

[0156] A number of techniques have been demonstrated herein for sequentially removing acid gases from a raw gas stream by using two or more vertically oriented co-current contacting systems connected in series. Some of the techniques described herein involve the

removal of acid gases, either partially or completely, and either selectively or non-selectively, from hydrocarbon gas streams. The gas stream may be a natural gas stream, a combustion exhaust gas stream, or a refining gas stream, for example. The absorbent liquid may include an absorption solution including at least one chemical compound such as monoethanolamine (MEA), diglycolamine (DGA), diethanolamine (DEA), methyldiethanolamine (MDEA), 2-amino-2-methyl-l-propanol (AMP), piperazine (PZ), ammonia, amines, alkanolamines, their derivatives, and other chemical solvents and/or mixtures thereof. The absorbent liquid may also include at least one chemical component such as kinetic enhancers, corrosion inhibitors, anti-foam chemicals, oxygen scavengers, salts, neutralizers, anti-fouling chemicals, and anti-degradation chemicals.

[0157] The absorbent liquid may include at least one chemical component selected for absorbing, assimilating, or otherwise reacting with a gas, such as CO_2, H_2S, SO_2, and NO_x. Alternatively, the absorbent liquid may include a desiccating liquid including at least one chemical compound such as monoethylene glycol (MEG), diethylene glycol (DEG), or triethylene glycol (TEG).

Co-Current Contacting System

[0158] Fig. 7A is a process flow diagram of a vertically oriented co-current contacting system **700** including a vertically oriented co-current contactor **702** and a vertically oriented separation system **704**. The co-current contacting system **700** may be used as any of the units labeled "CCCS" in Figs. 2, 4, 5, or 6. As shown in Fig. 7A, the vertically oriented co-current contactor **702** includes a vertically oriented mixer **706** and a vertically oriented mass transfer section **708**. In various embodiments, a gas stream **710**, such as a natural gas stream, and a gas treating solution **712**, such as a lean or semi-lean solvent solution, are injected into the vertically oriented mixer **706**. As the gas stream **710** and the gas treating solution **712** are flowed downwards through the vertically oriented mixer **706** and the vertically oriented mass transfer section **708**, the gas stream **710** is contacted with the gas treating solution **712**. As a result, liquid droplets formed from the gas treating solution **712** are incorporated into the gas stream **710**. In addition, in various embodiments, impurities from the gas stream **710** are incorporated into the liquid droplets formed from the gas treating solution **712**.

[0159] The gas stream **710** with the incorporated liquid droplets is then flowed downwards into the vertically oriented separation system **704**. Within the vertically oriented separation system **704**, the liquid droplets including the impurities are separated from the gas stream **710**, resulting in the generation of a purified gas stream **714** and a rich gas treating

solution **716**.

[0160] In various embodiments, vertical orientation of the mixer **706** and the mass transfer section **708** of the vertically oriented co-current contacting system **700** reduces the influence of gravity on the liquid droplets that have been incorporated into the gas stream **710**. Therefore, the fraction of liquid flowing on the walls of the piping is reduced, and the liquid droplet sizes are reduced through the vertically oriented mass transfer section 708 due to less coalescence of the liquid droplets. This may increase the area of the vertically oriented mass transfer section **708** that is available for incorporation of the liquid droplets into the gas stream **710** and, thus, increase the degree of separation of impurities from the gas stream **710**. In addition, vertical orientation of the mixer **706**, the mass transfer section **708**, and the separation system **704** of the vertically oriented co-current contacting system **700** reduces the footprint of the vertically oriented co-current contracting system **700**, particularly in the case of off-shore applications, by making the vertically oriented co-current contacting system **700** more compact. Furthermore, vertical orientation of the mixer **706**, the mass transfer section **708**, and the separation system **704** of the vertically oriented co-current contacting system **700** may allow the system to be conformed to a wide variety of limited space configurations.

[0161] Fig. 7B is a process flow diagram of the vertically oriented co-current contacting system **700** of Fig. 7A including the vertically oriented co-current contactor **702** and a horizontally oriented separation system **718**. Like numbered items are as described with respect to Fig. 7A. According to the embodiment shown in Fig. 7B, the gas stream **710** with the incorporated liquid droplets is flowed into the horizontally oriented separation system **718** via a line **720** including an angle, such as a 90° bend. In some embodiments, the horizontally oriented separation system **718** is included within the vertically oriented co-current contacting system **700** rather than the vertically oriented separation system **704** to allow the vertically oriented co-current contacting system **700** to conform to specific limited space configurations.

[0162] Fig. 7C is a process flow diagram of the vertically oriented co-current contacting system **700** of Fig. 7A including a number of vertically oriented co-current contactors **702** and **703** connected in series upstream of the vertically oriented separation system **704**. Like numbered items are as described with respect to Fig. 7A. According to the embodiment shown in Fig. 7C, the vertically oriented co-current contacting system **700** includes two vertically oriented co-current contactors **702** and **703** upstream of a single separation system

704. The separation system **704** may be either vertically or horizontally oriented, depending on the details of the specific implementation. Moreover, while only two vertically oriented co-current contactors **702** and **703** are shown in Fig. 7C, it is to be understood that the vertically oriented co-current contacting system **700** may include any number of additional vertically oriented co-current contactors, depending on the details of the specific implementation. In various embodiments, the presence of two or more vertically oriented co-current contactors **702** and **703** within the vertically oriented co-current contacting system **700** increases the area that is available for incorporation of the liquid droplets into the gas stream **710** and, thus, increases the degree of separation of impurities from the gas stream **710**.

[0163] In some embodiments, different gas treating solutions **712A** and **712B** may be injected into each vertically oriented co-current contactor **702** and **703**. For example, the gas treating solution **712A** that is injected into the vertically oriented mixer **706A** of the first vertically oriented co-current contactor **702** may be a semi-lean solvent stream, while the gas treating solution **712B** that is injected into the vertically oriented mixer **706B** of the second vertically oriented co-current contactor **703** may be a lean solvent stream. The injection of a fresh or lean solvent stream into the second vertically oriented co-current contactor **703** may reduce the concentration of the impurities within the vertically oriented co-current contacting system **700** and increase the driving force for the incorporation of the liquid droplets into the gas stream **710**. Therefore, the degree of separation of the impurities from the gas stream **710** may be increased.

[0164] The process flow diagrams of Figs. 7A, 7B, and 7C are not intended to indicate that the vertically oriented co-current contacting system **700** is to include all of the components shown in Figs. 7A, 7B, and 7C. Further, the vertically oriented co-current contacting system **700** may include any number of additional components not shown in Figs. 7A, 7B, or 7C, depending on the details of the specific implementation. For example, in some embodiments, the mixer **706** or the mass transfer section **708** may be horizontally oriented rather than vertically oriented. The orientation of each component of the vertically oriented co-current contacting system **700** may be chosen for each implementation based on the amount of incorporation of the liquid droplets into the gas stream **710** that is desired, as well as the specific dimensions of the space in which the vertically oriented co-current contacting system **700** is to be placed.

[0165] Fig. 8 is a process flow diagram of a vertically oriented co-current contacting

system **800** including a number of vertically oriented co-current contactors **801**, **802**, and **803** and a vertically oriented separation system **804** that may be used to purify a natural gas stream **806**. Each vertically oriented co-current contactor **801**, **802**, and **803** includes a vertically oriented mixer **808A-C** and a vertically oriented mass transfer section **810A-C**.

[0166] In various embodiments, the natural gas stream **806** and a semi-lean solvent stream **812** are injected into the vertically oriented mixer **808A** of the first vertically oriented co-current contactor **801**. As the natural gas stream **806** and the semi-lean solvent stream **812** are flowed downwards through the vertically oriented mixer **808A** and the vertically oriented mass transfer section **810A** of the first vertically oriented co-current contactor 801, the natural gas stream **806** is contacted with the semi-lean solvent stream **812**. As a result, liquid droplets formed from the semi-lean solvent stream **812** are incorporated into the natural gas stream **806**. In addition, impurities from the natural gas stream **806** are incorporated into the liquid droplets formed from the semi-lean solvent stream **812**.

[0167] From the first vertically oriented co-current contacting system **801**, the natural gas stream **806** with the incorporated liquid droplets is flowed downwards into the vertically oriented mixer **808B** of the second vertically oriented co-current contactor **802**. In addition, a lean solvent stream **814** is injected into the vertically oriented mixer **808B** of the second vertically oriented co-current contactor **802**. As the natural gas stream **806** including the incorporated liquid droplets and the lean solvent stream **814** are flowed downwards through the vertically oriented mixer **808B** and the vertically oriented mass transfer section **810B** of the second vertically oriented co-current contactor **802**, the natural gas stream **806** including the incorporated liquid droplets is contacted with the lean solvent stream **814**. As a result, additional liquid droplets formed from the lean solvent stream **814** are incorporated into the natural gas stream **806**. The liquid droplets formed from the lean solvent stream **814** may include additional impurities from the natural gas stream **806**.

[0168] From the second vertically oriented co-current contacting system **802**, the natural gas stream **806** with the incorporated liquid droplets is flowed downwards into the vertically oriented mixer **808C** of the third vertically oriented co-current contactor **803**. In addition, another lean solvent stream **816** is injected into the vertically oriented mixer **808C** of the third vertically oriented co-current contactor **803**. As the natural gas stream **806** including the incorporated liquid droplets and the lean solvent stream **816** are flowed downwards through the vertically oriented mixer **808C** and the vertically oriented mass transfer section **810C** of the third vertically oriented co-current contactor **803**, the natural gas stream **806**

including the incorporated liquid droplets is contacted with the lean solvent stream **816**. As a result, additional liquid droplets formed from the lean solvent stream **816** are incorporated into the natural gas stream **806**. The liquid droplets formed from the lean solvent stream **816** may include residual impurities from the natural gas stream **806**.

[0169] The natural gas stream **806** with the incorporated liquid droplets is then flowed downwards into the vertically oriented separation system **804**. Within the vertically oriented separation system **804**, the liquid droplets including the impurities are separated from the natural gas stream **806**, resulting in the generation of a purified gas stream **818** and a rich solvent stream **820**.

[0170] The process flow diagram of Fig. 8 is not intended to indicate that the vertically oriented co-current contacting system **800** is to include all of the components shown in Fig. 8. Further, the vertically oriented co-current contacting system **800** may include any number of additional components not shown in Fig. 8, depending on the details of the specific implementation. For example, while the mixers **808A-C** and the mass transfer sections **810A-C** of the co-current contactors **801**, **802**, and **803** are described as being vertically oriented, in some embodiments, the mixers **808A-C** or mass transfer sections **810A-C** may be horizontally oriented. Moreover, while the separation system **804** is described as being vertically oriented, in some embodiments, the separation system **804** may be horizontally oriented. The orientation of each component of the vertically oriented co-current contacting system **800** may be chosen for each implementation based on the amount of incorporation of the liquid droplets into the natural gas stream **806** that is desired, as well as the specific dimensions of the space in which the vertically oriented co-current contacting system **800** is to be placed.

[0171] Fig. 9 is a schematic of a vertically oriented co-current contacting system **900**. The vertically oriented co-current contacting system **900** may provide for the separation of components within a gas stream. In addition, the vertically oriented co-current contacting system **900** may aid in the implementation of various gas processing systems, such as the gas processing systems **200** and **260** of Figs. 2A and 2B, where the rapid separation of components is desired. In some embodiments, the vertically oriented co-current contacting system **900** is one of the vertically oriented co-current contacting systems **204A-F, 402A-C**, **500A-C**, **602A-C**, **700**, or **800** discussed with respect to Figs. 2A, 2B, 4A, 4B, 5, 6, 7A-C, or 8, respectively.

[0172] The vertically oriented co-current contacting system **900** may include a vertically

oriented co-current contactor **902** that is positioned in-line within a pipe **904**. The vertically oriented co-current contactor **902** may include a number of components that provide for the efficient contacting of a liquid droplet stream with a flowing gas stream **906**. The liquid droplet stream can be used for the separation of impurities, such as H_2O, H_2S, or CO_2, from the gas stream **906**.

[0173] In various embodiments, the vertically oriented co-current contactor **902** includes a vertically oriented mixer **908** and a vertically oriented mass transfer section **910**. As shown in Fig. 9, the gas stream **906** may be flowed through the pipe **904** and into the vertically oriented mixer **908**. A liquid stream **912** may also be flowed into the vertically oriented mixer **908**, for example, through a hollow space **914** coupled to flow channels **916** in the vertically oriented mixer **908**. The liquid stream **912** may include any type of treating liquid, e.g., solvent, that is capable of removing the impurities from the gas stream **906**.

[0174] From the flow channels **916**, the liquid stream **912** is released into the gas stream **906** as fine droplets through injection orifices **918**, and is then flowed into the vertically oriented mass transfer section **910**. This may result in the generation of a treated gas stream **920** within the vertically oriented mass transfer section **910**. The treated gas stream **920** may include small liquid droplets dispersed in a gas phase. The liquid droplets may include impurities from the gas stream **906** that were adsorbed or dissolved into the liquid stream **912**.

[0175] The treated gas stream **920** may be flowed from the vertically oriented mass transfer section **910** to a separation system **922**, such as a cyclonic separator, a mesh screen, or a settling vessel. The separation system **922** may be either vertically oriented or horizontally oriented, depending on the details of the specific implementation. The separation system **922** removes the liquid droplets from the gas phase. The liquid droplets may include the original liquid stream with the incorporated impurities **924**, and the gas phase may include a purified gas stream **926**. In some embodiments, the purified gas stream **926** is a dehydrated gas stream that has been purified via the removal of H_2O. In other embodiments, the purified gas stream **926** is a purified gas stream that has been purified via the removal of H_2S and/or CO_2, for example.

[0176] Fig. 10A is a top view of a vertically oriented mixer **1000**. The vertically oriented mixer **1000** is implemented within a vertically oriented co-current contactor, such as the vertically oriented co-current contactor **902** described with respect to the vertically oriented co-current contacting system **900** of Fig. 9. The vertically oriented mixer **1000** may be an

axial, in-line mixer located within a pipe. The top view of the vertically oriented mixer **1000** represents an upstream view of the vertically oriented mixer **1000**.

[0177] The vertically oriented mixer **1000** may include an outer annular support ring **1002**, a number of radial blades **1004** extending from the annular support ring **1002**, and a central gas entry cone **1006**. The annular support ring **1002** may secure the vertically oriented mixer **1000** in-line within the pipe. In addition, the radial blades **1004** may provide support for the central gas entry cone **1006**.

[0178] The annular support ring **1002** may be designed as a flanged connection, or as a removable or fixed sleeve inside the pipe. In addition, the annular support ring **1002** may include a liquid feed system and a hollow channel discussed further with respect to Figs 9, 10C and 10D. A liquid stream may be fed to the vertically oriented mixer **1000** via the hollow channel in the annular support ring **1002**. The hollow channel may allow equal distribution of the liquid stream along the perimeter of the vertically oriented mixer **1000**.

[0179] Small liquid channels within the annular support ring **1002** may provide a flow path for the liquid stream to flow through injection orifices **1008** within the radial blades **1004**. The liquid injection orifices **1008** may be located on or near the leading edge of each radial blade **1004**. Placement of the liquid injection orifices **1008** on the radial blades **1004** may allow the liquid stream to be uniformly distributed in a gas stream that is directed between the radial blades **1004**. Specifically, the liquid stream may be contacted by the gas stream flowing through the gaps between the radial blades **1004**, and may be sheared into small droplets and entrained in the gas phase.

[0180] The gas stream may also be flowed into the central gas entry cone **1006** through a gas inlet **1012**. The central gas entry cone **1006** may block a cross-sectional portion of the pipe. The radial blades **1004** include gas exit slots **1010** that allow the gas stream to be flowed out of the central gas entry cone **1006**. This may increase the velocity of the gas stream as it flows through the pipe. The central gas entry cone **1006** may direct a predetermined amount of the gas stream to the gas exit slots **1010** on the radial blades **1004**.

[0181] Some of the liquid stream injected through the radial blades **1004** may be deposited on the surface of the radial blades **1004** as a liquid film. As the gas stream flows through the central gas entry cone **1006** and is directed out of the gas exit slots **1010** on the radial blades **1004**, the gas stream may sweep, or blow, much of the liquid film off the radial blades **1004**. 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 **1006** 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.

[0182] The size of the vertically oriented mixer **1000** 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 **1002** or a gradual reduction in the diameter of the annular support ring **1002**. The outer wall of the vertically oriented mixer **1000** may be slightly converging in shape, terminating at the point where the gas stream and the liquid stream are discharged into the downstream vertically oriented mass transfer section. This may allow for the shearing and re-entrainment of any liquid film that is removed from the vertically oriented mixer **1000**. Further, a radial inward ring, grooved surface, or other suitable equipment may be included on the outer diameter of the vertically oriented mixer **1000** near the point where the gas stream and the liquid stream are discharged into the downstream vertically oriented mass transfer section. This may enhance the degree of liquid entrainment within the gas phase.

[0183] The downstream end of the vertically oriented mixer **1000** may discharge into a vertically oriented mass transfer section (not shown). The vertically oriented mass transfer section may be a straight section of pipe, or a concentric expansion section of pipe. In some embodiments, the central gas entry cone **1006** terminates with a blunt ended cone or a tapered ended cone. In other embodiments, the central gas entry cone **1006** 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 **1010** may be provided on the cone itself to allow for the removal of the liquid film from the vertically oriented mixer **1000**.

[0184] Fig. 10B is a top perspective view of the vertically oriented mixer **1000** of Fig. 10A. Like numbered items are as described with respect to Fig. 10A. As shown in Fig. 10B, the upstream portion of the central gas entry cone **1006** may extend further into the pipe than the annular support ring **1002** and the radial blades **1004** in the upstream direction. The downstream portion of the central gas entry cone **1006** may also extend further into the pipe than the annular support ring **1002** and the radial blades **1004** in the downstream direction. The length of the central gas entry cone **1006** in the downstream direction depends on the type of cone at the end of the central gas entry cone **1006**, as discussed further with respect to

Figs. 10C and 10D.

[0185] Fig. 10C is a cross-sectional side perspective view of the vertically oriented mixer **1000** of Figs. 10A and 10B. Like numbered items are as described with respect to Figs. 10A and 10B. According to the embodiment shown in Fig. 10C, the central gas entry cone **1006** of the vertically oriented mixer **1000** terminates with a tapered ended cone **1014**. Terminating the central gas entry cone **1006** with a tapered ended cone **1014** may reduce the overall pressure drop in the pipe caused by the vertically oriented mixer **1000**.

[0186] Fig. 10D is another cross-sectional side perspective view of the vertically oriented mixer **1000** of Figs. 10A-C. Like numbered items are as described with respect to Figs. 10A-C. According to the embodiment shown in Fig. 10D, the central gas entry cone **1006** of the vertically oriented mixer **1000** terminates with a blunt ended cone **1016**. Terminating the central gas entry cone **1006** with a blunt ended cone **1016** may encourage droplet formation in the center of the pipe.

Method for Separating Impurities from a Gas Stream

[0187] Fig. 11 is a process flow diagram of a method **1100** for separating impurities from a gas stream. The method **1100** is implemented by one or more vertically oriented co-current contacting systems within a gas processing system. The method begins at block **1102**, at which a liquid stream is flowed into a vertically oriented co-current contactor. More specifically, the liquid stream is flowed into a vertically oriented mixer of the vertically oriented co-current contactor. The liquid stream may be flowed into the vertically oriented mixer via an annular support ring and a number of radial blades extending from the annular support ring. The annular support ring may secure the vertically oriented mixer in-line within a pipe. The liquid stream may be any suitable type of absorbent liquid stream, for example.

[0188] At block **1104**, a gas stream is flowed into the vertically oriented co-current contactor. More specifically, the gas stream is flowed into the vertically oriented mixer of the vertically oriented co-current contactor. The gas stream may be flowed into the vertically oriented mixer via a central gas entry cone that is supported by the radial blades. The gas stream may be a natural gas stream, for example.

[0189] At block **1106**, the gas stream is contacted with the liquid stream within the vertically oriented co-current contactor to provide for incorporation of liquid droplets formed from the liquid stream into the gas stream. More specifically, the gas stream is contacted with the liquid stream within the vertically oriented mixer and a vertically oriented mass

transfer section of the vertically oriented co-current contactor. In various embodiments, impurities within the gas stream are incorporated into the liquid droplets. Such impurities may include water or acid gas, such as H_2S or CO_2, for example.

[0190] In some embodiments, the central gas entry cone increases the turbulence of the gas flow by partially obstructing the gas flow. Such an increase in turbulence may result in an increase in the amount of dispersion of the liquid droplets within the gas stream. In addition, shearing forces created by the shape of the vertically oriented co-current contactor may aid in the dispersion of the liquid droplets within the gas stream.

[0191] At block **1108**, the liquid droplets are separated from the gas stream within a separation system. The separation system may be a cyclonic separator or a separation column, for example. Moreover, the separation system may be either vertically oriented or horizontally oriented, depending on the details of the specific implementation. In various embodiments, impurities that have been incorporated into the liquid droplets are also separated from the gas stream along with the liquid droplets. This may result in the generation of a purified gas stream. For example, if the gas stream is a natural gas stream, and the impurities include water, the natural gas stream may be dehydrated via the removal of the water. As another example, if the gas stream is a natural gas stream, and the impurities include acid gas, the natural gas stream may be sweetened via the removal of the acid gas.

[0192] The process flow diagram of Fig. 11 is not intended to indicate that the blocks of the method **1100** are to be executed in any particular order, or that all of the blocks of the method **1100** are to be included in every case. Further, any number of additional blocks not shown in Fig. 11 may be included within the method **1100**, depending on the details of the specific implementation. For example, the gas stream may be flowed through any number of additional vertically oriented co-current contacting systems connected in series within the pipe. In some embodiments, the vertically oriented co-current contacting systems progressively purify the gas stream by removing residual impurities. Further, in some embodiments, the impurities are removed from the liquid stream downstream of the separation system. The liquid stream may then be recycled to the vertically oriented co-current contacting system, or may be flowed into another vertically oriented co-current contacting system.

[0193] In various embodiments, a single vertically oriented co-current contacting system includes a series of vertically oriented co-current contactors upstream of a separation system. In such embodiments, the gas stream is contacted with the liquid stream within each

vertically oriented co-current contactor to provide for incorporation of liquid droplets formed from the liquid stream into the gas stream, and the liquid droplets are then separated from the gas stream within the downstream separation system. This embodiment is described further with respect to Fig. 12.

[0194] In some embodiments, the method **1100** may be used for quench applications. For example, the method **1100** may be used for injection of cooling water or direct injection of hot oil for ethylene quenching applications. In addition, the method **1100** may be used for water wash applications, such as water wash applications including an acid gas absorber overhead stream.

[0195] Fig. 12 is a process flow diagram of a method **1200** for separating impurities from a natural gas stream using a vertically-oriented co-current contacting system that includes multiple vertically-oriented co-current contactors upstream of a single separation system. In various embodiments, the method **1200** may be implemented by any suitable type of co-current contacting system that includes multiple vertically-oriented co-current contactors upstream of a single separation system, such as the co-current contacting system **700** described with respect to Fig. 7C or the co-current contacting system **800** described with respect to Fig. 8.

[0196] The method begins at block **1202**, at which a semi-lean solvent stream is flowed into a first vertically oriented co-current contactor of the vertically oriented co-current contacting system. In addition, at block **1204**, a natural gas stream is flowed into the first vertically oriented co-current contactor. More specifically, the semi-lean solvent stream and the natural gas stream are flowed into a vertically oriented mixer of the first vertically oriented co-current contactor.

[0197] At block **1206**, the natural gas stream is contacted with the semi-lean solvent stream within the first vertically oriented co-current contactor to provide a first multi-phase stream. More specifically, the natural gas stream is contacted with the semi-lean solvent stream within the vertically oriented mixer and a vertically oriented mass transfer section of the first vertically oriented co-current contactor. The first multi-phase stream is the natural gas stream with incorporated liquid droplets formed from the semi-lean solvent stream. The incorporated liquid droplets include impurities from the natural gas stream.

[0198] At block **1208**, the first multi-phase stream is flowed into a second vertically oriented co-current contactor of the vertically oriented co-current contacting system. In

addition, at block **1210**, a lean solvent stream is flowed into the second vertically oriented co-current contactor. More specifically, the first multi-phase stream and the lean solvent stream are flowed into a vertically oriented mixer of the second vertically oriented co-current contactor.

[0199] At block **1212**, the first multi-phase stream is contacted with the lean solvent stream within the second vertically oriented co-current contactor to provide a second multi-phase stream. More specifically, the first multi-phase stream is contacted with the lean solvent stream within the vertically oriented mixer and a vertically oriented mass transfer section of the second vertically oriented co-current contactor. The second multi-phase stream is the natural gas stream with additional incorporated liquid droplets formed from the lean solvent stream. The additional incorporated liquid droplets include residual impurities from the natural gas stream.

[0200] At block **1214**, the second multi-phase stream is separated into a purified natural gas stream and a rich solvent stream within a separation system. The separation system may be either vertically oriented or horizontally oriented, depending on the details of the specific implementation. In various embodiments, the use of multiple vertically oriented co-current contactors upstream of a single separation system allows for an increase in the degree of separation of impurities from the natural gas stream with a limited corresponding increase in the size and weight of the entire vertically oriented co-current contacting system.

[0201] The process flow diagram of Fig. 12 is not intended to indicate that the blocks of the method **1200** are to be executed in any particular order, or that all of the blocks of the method **1200** are to be included in every case. Further, any number of additional blocks not shown in Fig. 12 may be included within the method **1200**, depending on the details of the specific implementation.

CLAIMS:

1. A vertically oriented co-current contacting system, including:

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

a vertically oriented mixer, including:

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

a plurality of radial blades extending from the annular support ring, the annular support ring securing the mixer in-line within a pipe, the annular support ring having a plurality of liquid channels configured to allow a liquid stream to flow through the plurality of radial blades and out of injection orifices disposed on the plurality of radial blades; and

a central gas entry cone that is supported by the plurality of radial blades and configured to allow

a first portion of a gas stream to flow through a hollow section of the central gas entry cone and through gas exit slots included in the plurality of radial blades, and

a second portion of the gas stream to flow around the central gas entry cone and between the plurality of radial blades; and

a vertically oriented mass transfer section downstream of the vertically oriented mixer;

wherein the vertically oriented mixer and the vertically oriented mass transfer section provide for efficient incorporation of liquid droplets formed from the liquid stream into the gas stream, and wherein the liquid droplets include impurities from the gas stream; and

a separation system configured to remove the liquid droplets including the impurities from the gas stream.

2. The vertically oriented co-current contacting system of claim 1, wherein the separation system is vertically oriented.

3. The vertically oriented co-current contacting system of claim 1, wherein the separation system is horizontally oriented.

4. The vertically oriented co-current contacting system of any one of claims 1-3, wherein the vertically oriented co-current contacting system includes a first vertically oriented co-current contactor and a second vertically oriented co-current contactor upstream of the separation system.

5. The vertically oriented co-current contacting system of claim 4, wherein the liquid stream that is flowed into the vertically oriented mixer of the first vertically oriented co-current contactor includes a semi-lean solvent stream, and wherein the liquid stream that is flowed into the vertically oriented mixer of the second vertically oriented co-current contactor includes a lean solvent stream.

6. The vertically oriented co-current contacting system of any one of claims 1-4, wherein the gas stream includes a natural gas stream, and wherein the impurities include water.

7. The vertically oriented co-current contacting system of any one of claims 1-4 and 6, wherein the gas stream includes a natural gas stream, and wherein the impurities include an acid gas.

8. The vertically oriented co-current contacting system of any one of claims 1-4, 6, and 7, wherein the separation system includes a cyclonic separator or a distillation column.

9. The vertically oriented co-current contacting system of any one of claims 1-4 and 6-8, wherein a downstream portion of the central gas entry cone includes a blunt ended cone.

10. The vertically oriented co-current contacting system of any one of claims 1-4 and 6-8, wherein a downstream portion of the central gas entry cone includes a tapered ended cone.

11. The vertically oriented co-current contacting system of any one of claims 1-4 and 6-10, wherein the liquid stream includes an absorbent liquid stream.

12. The vertically oriented co-current contacting system of any one of claims 1-4 and 6-11, including a plurality of vertically oriented co-current contacting systems connected in series within the pipe.

13. The vertically oriented co-current contacting system of any one of claims 1-4 and 6-12, wherein the vertically oriented co-current contacting system is implemented within a gas processing system.

14. The vertically oriented co-current contacting system of any one of claims 1-4 and 6-13, wherein the vertically oriented co-current contacting system is used for quench applications or water wash applications.

15. A method for separating impurities from a gas stream, including:

flowing a liquid stream into a vertically oriented mixer of a vertically oriented co-current contactor via an annular support ring and a plurality of radial blades extending from the annular support ring, wherein the liquid stream flows through the plurality of radial blades and out of injection orifices disposed on the plurality of radial blades, and wherein the annular support ring secures the vertically oriented mixer in-line within a pipe;

flowing a gas stream into the vertically oriented mixer via a central gas entry cone that is supported by the plurality of radial blades, wherein a first portion of the gas stream flows through a hollow section of the central gas entry cone and through exit slots included in the plurality of radial blades, and wherein a second portion of the gas stream flows around the central gas entry cone and between the plurality of radial blades;

contacting the gas stream with the liquid stream within the vertically oriented mixer and a vertically oriented mass transfer section of the vertically oriented co-current contactor to provide for incorporation of liquid droplets formed from the liquid stream into the gas stream, wherein the liquid droplets include impurities from the gas stream; and

separating the liquid droplets including the impurities from the gas stream within a separation system.

16. The method of claim 15, including flowing the gas stream through a number of vertically oriented co-current contactors upstream of the separation system.

17. The method of claim 15 or claim 16, including flowing the gas stream through a number of vertically oriented co-current contactors and corresponding separation systems connected in series within the pipe.

18. The method of any one of claims 15-17, wherein the gas stream includes a natural gas stream, and wherein the impurities include water.

19. The method of claim 18, including generating a dehydrated natural gas stream by removing liquid droplets including incorporated water from the natural gas stream.

20. The method of any one of claims 15-17, wherein the gas stream includes a natural gas stream, and wherein the impurities include acid gas.

21. The method of claim 20, including generating a sweetened natural gas stream by removing liquid droplets including incorporated acid gas from the natural gas stream.

22. A method for separating impurities from a natural gas stream, including:

flowing a semi-lean solvent stream into a first vertically oriented co-current contactor of a vertically oriented co-current contacting system;

flowing a natural gas stream into the first vertically oriented co-current contactor;

contacting the natural gas stream with the semi-lean solvent stream within the first vertically oriented co-current contactor to provide a first multi-phase stream, wherein the first multi-phase stream includes the natural gas stream with incorporated liquid droplets formed from the semi-lean solvent stream that include impurities from the natural gas stream;

flowing the first multi-phase stream into a second vertically oriented co-current contactor of the vertically oriented co-current contacting system;

flowing a lean solvent stream into the second vertically oriented co-current contactor;

contacting the first multi-phase stream with the lean solvent stream within the second vertically oriented co-current contactor to provide a second multi-phase stream, wherein the second multi-phase stream includes the natural gas stream with additional incorporated liquid droplets formed from the lean solvent stream that include residual impurities from the natural gas stream; and

separating the second multi-phase stream into a purified natural gas stream and a rich solvent stream within a separation system of the vertically oriented co-current contacting system; wherein each of the first co-current contactor and the second co-current contactor includes

a mixer, including:

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

a plurality of radial blades extending from the annular support ring, the annular support ring securing the mixer in-line within a pipe, the annular support ring having a plurality of liquid channels configured to allow a liquid stream to flow through the plurality of radial blades and out of injection orifices disposed on the plurality of radial blades; and

a central gas entry cone that is supported by the plurality of radial blades and configured to allow

a first portion of a gas stream to flow through a hollow section of the central gas entry cone and through gas exit slots included in the plurality of radial blades, and

a second portion of the gas stream to flow around the central gas entry cone and between the plurality of radial blades.

23. The method of claim 22, wherein the natural gas stream and the semi-lean solvent stream are flowed into a vertically oriented mixer of the first vertically oriented co-current contactor, and wherein the natural gas stream is contacted with the semi-lean solvent stream within the vertically oriented mixer and a vertically oriented mass transfer section of the first vertically oriented co-current contactor.

24. The method of claim 22 or claim 23, wherein the first multi-phase stream and the lean solvent stream are flowed into a vertically oriented mixer of the second vertically oriented co-current contactor, and wherein the first multi-phase stream is contacted with the lean solvent stream within the vertically oriented mixer and a vertically oriented mass transfer section of the second vertically oriented co-current contactor.

25. The method of any one of claims 22-24, wherein the impurities include water, and wherein a dehydrated natural gas stream is generated by removing liquid droplets including incorporated water from the natural gas stream.

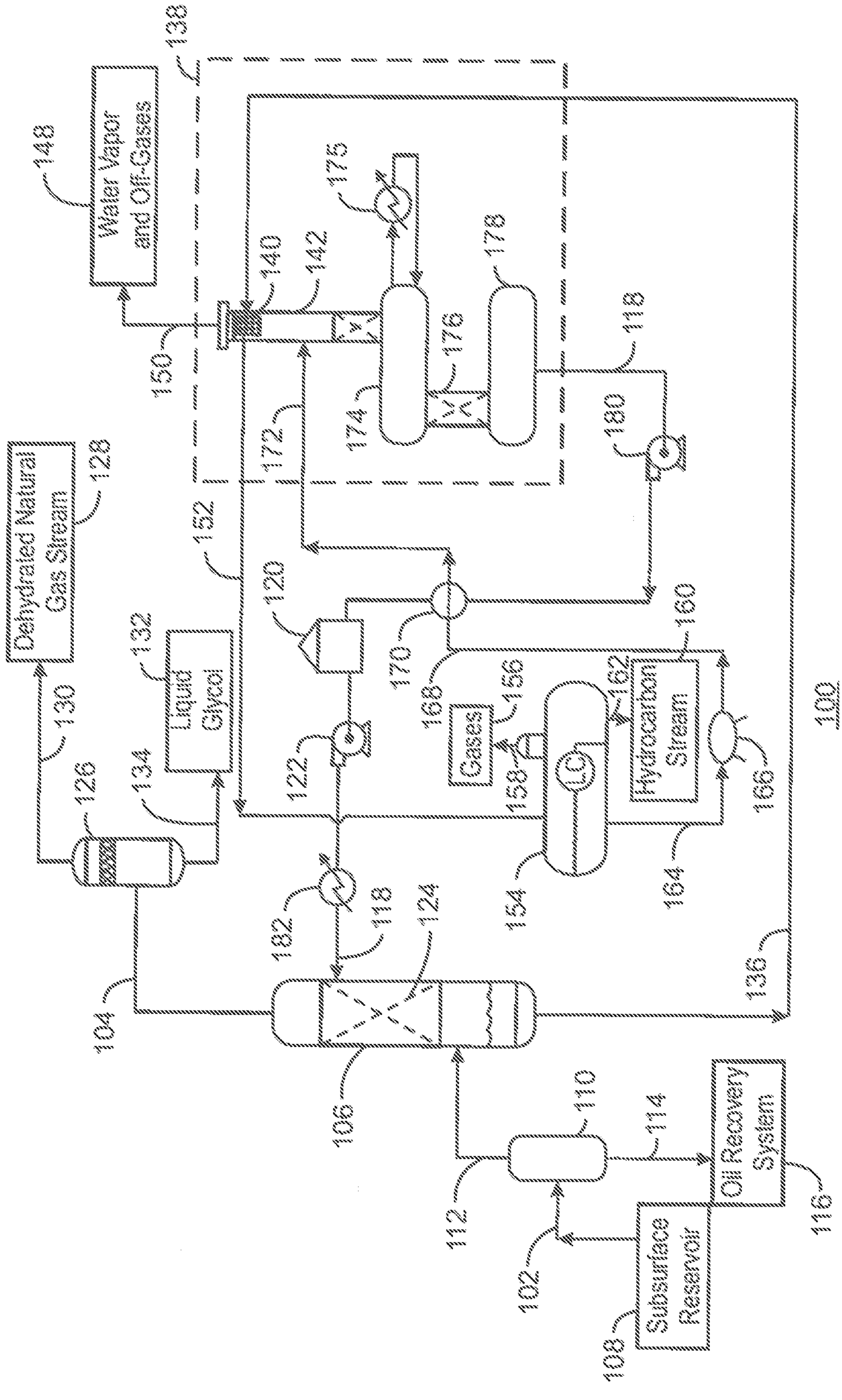
26. The method of any one of claims 22-25, wherein the impurities include acid gas, and wherein a sweetened natural gas stream is generated by removing liquid droplets including incorporated acid gas from the natural gas stream.

27. The method of any one of claims 22-26, including:

regenerating the semi-lean solvent stream and the lean solvent stream from the rich solvent stream within a second vertically oriented co-current contacting system;

recirculating the semi-lean solvent stream to the first vertically oriented co-current contactor; and

recirculating the lean solvent stream to the second vertically oriented co-current contactor.


Dehydrated Natural Gas Stream
128
Water Vapor and Off-Gases
148
138
150
152
154
156
158
160
162
164
166
168
170
172
174
175
176
178
180
182
100
102
104
106
108
110
112
114
116
118
120
122
124
126
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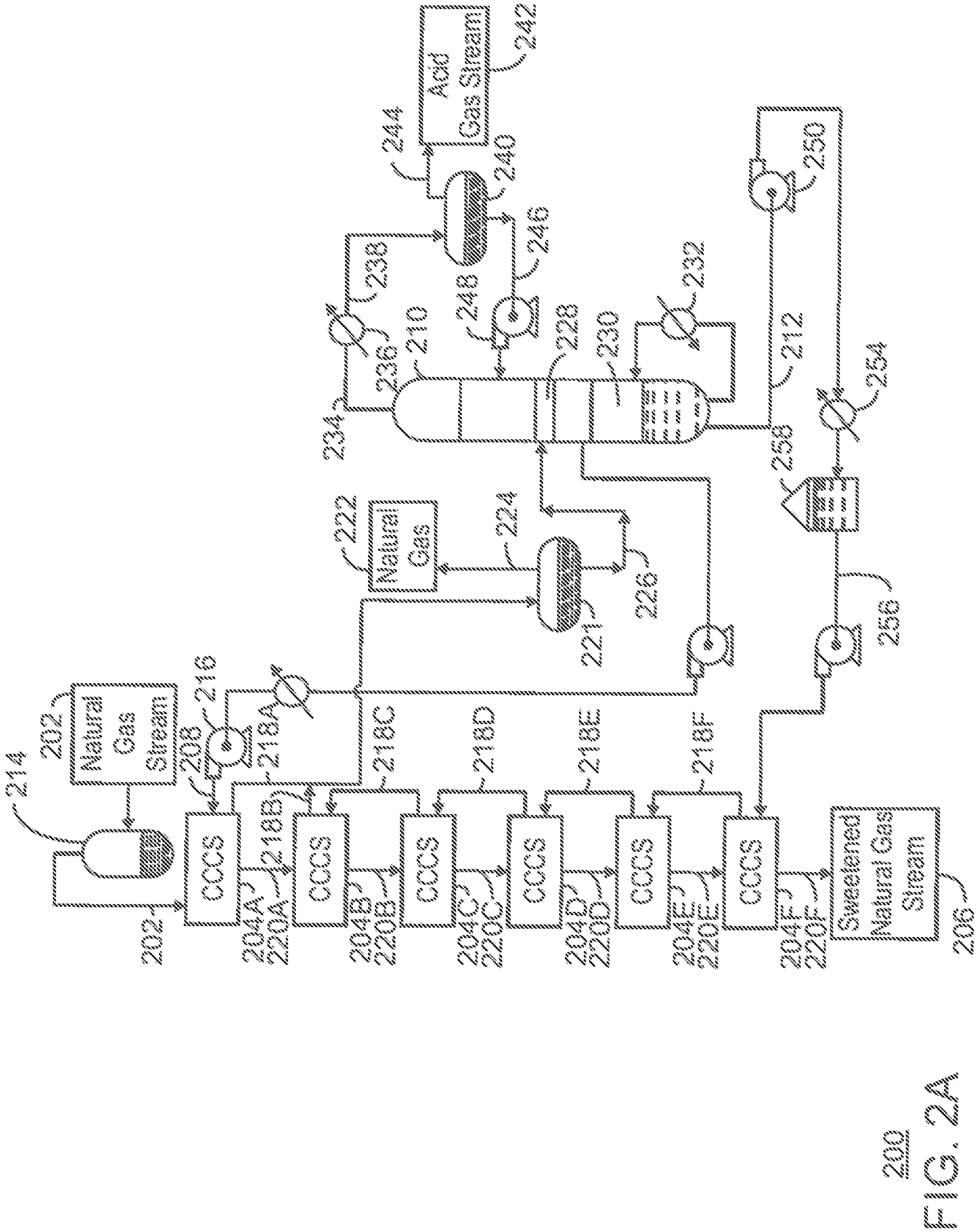
132
134
136
140
142
Liquid Glycol
Gases
Hydrocarbon stream
Subsurface Reservoir
Oil Recovery System

FIG. 1


214
202
Natural Gas Stream
202
208
216
218A
218B
218C
218D
218E
218F
CCS
204A
204B
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204D
204E
204F
220A
220B
220C
220D
220E
220F
Natural Gas
222
224
221
226
Acid Gas Stream
242
244
240
246
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228
230
232
250
212
258
254
256
Sweetened Natural Gas Stream
206

FIG. 2A

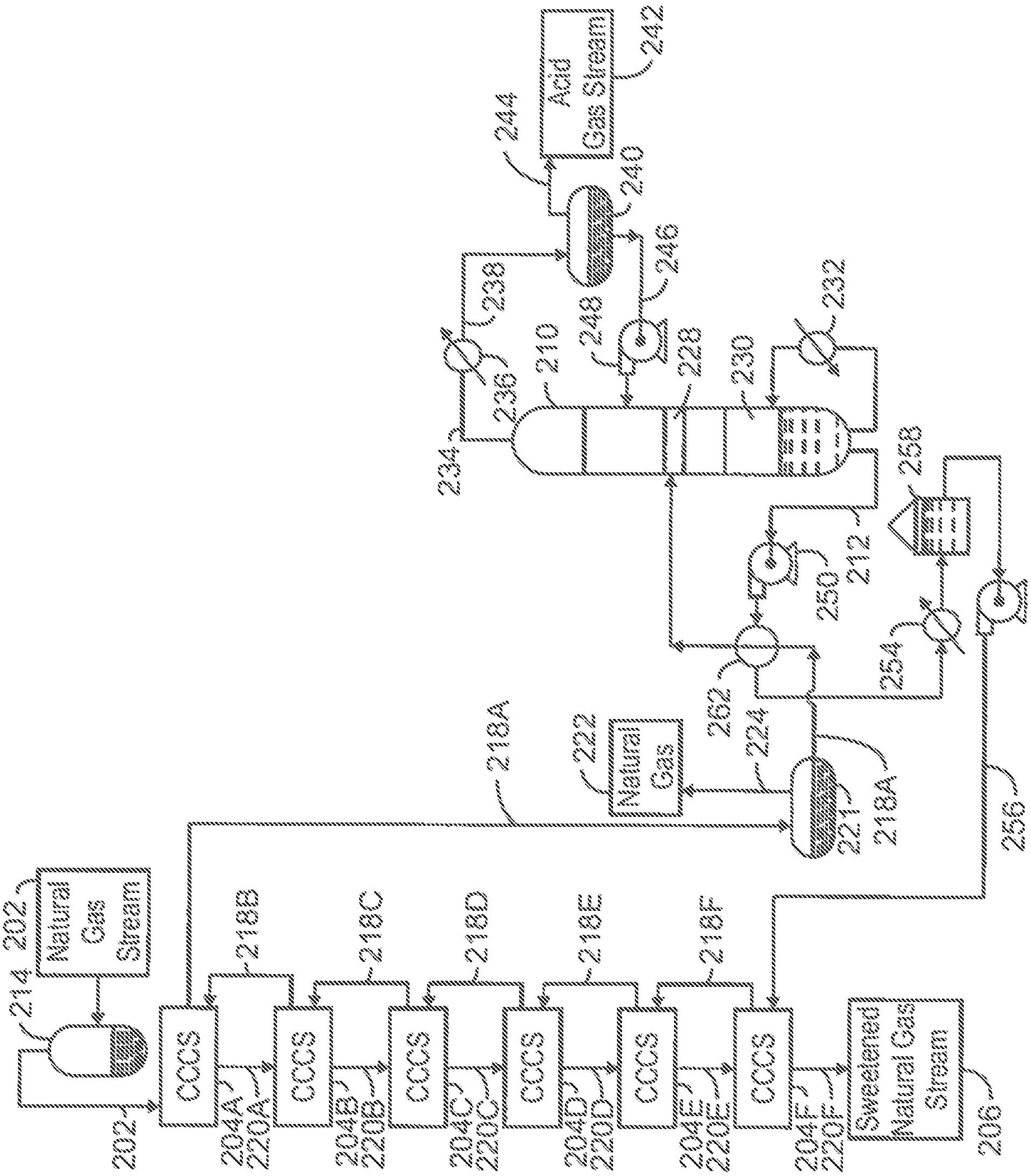
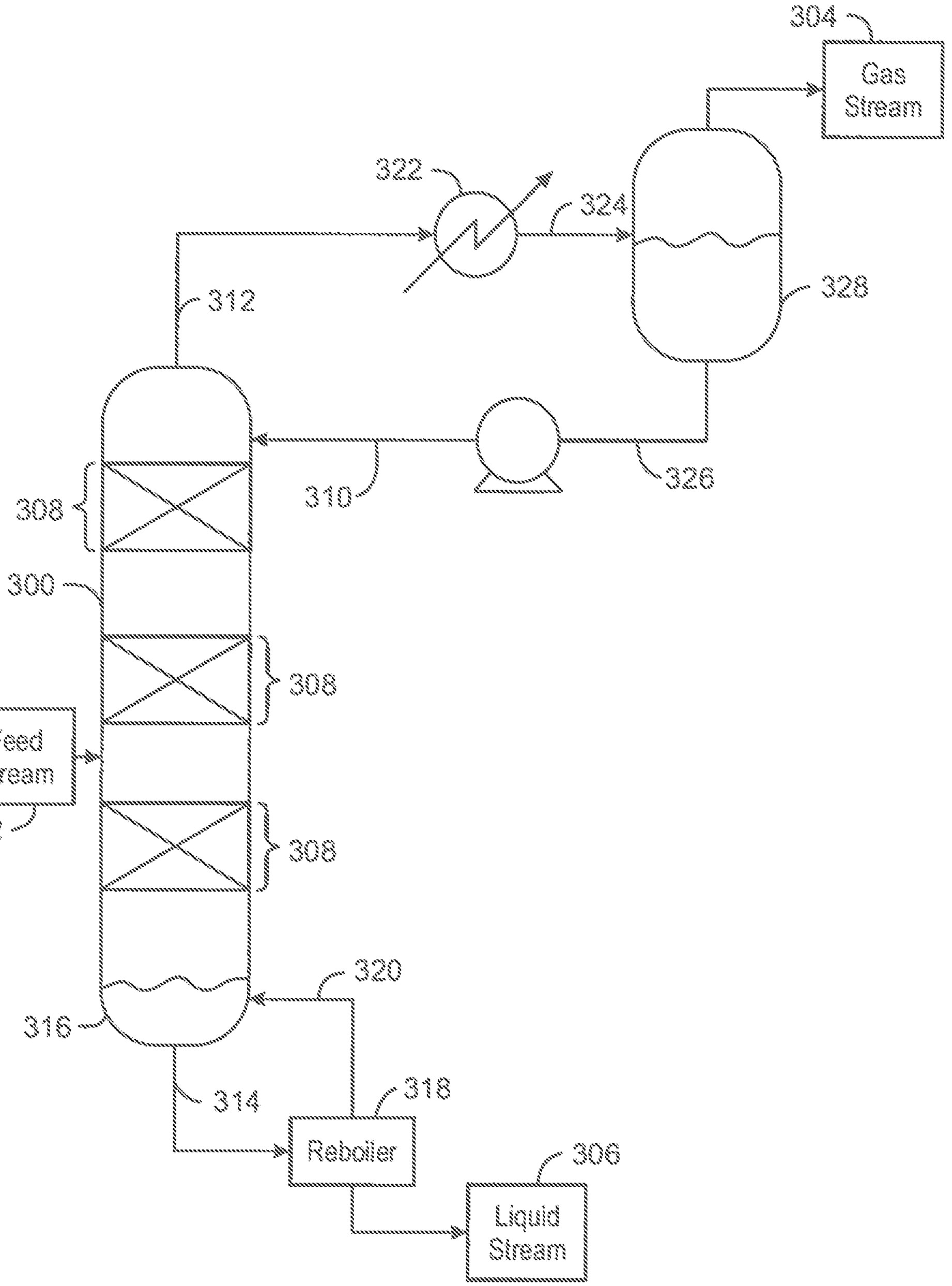
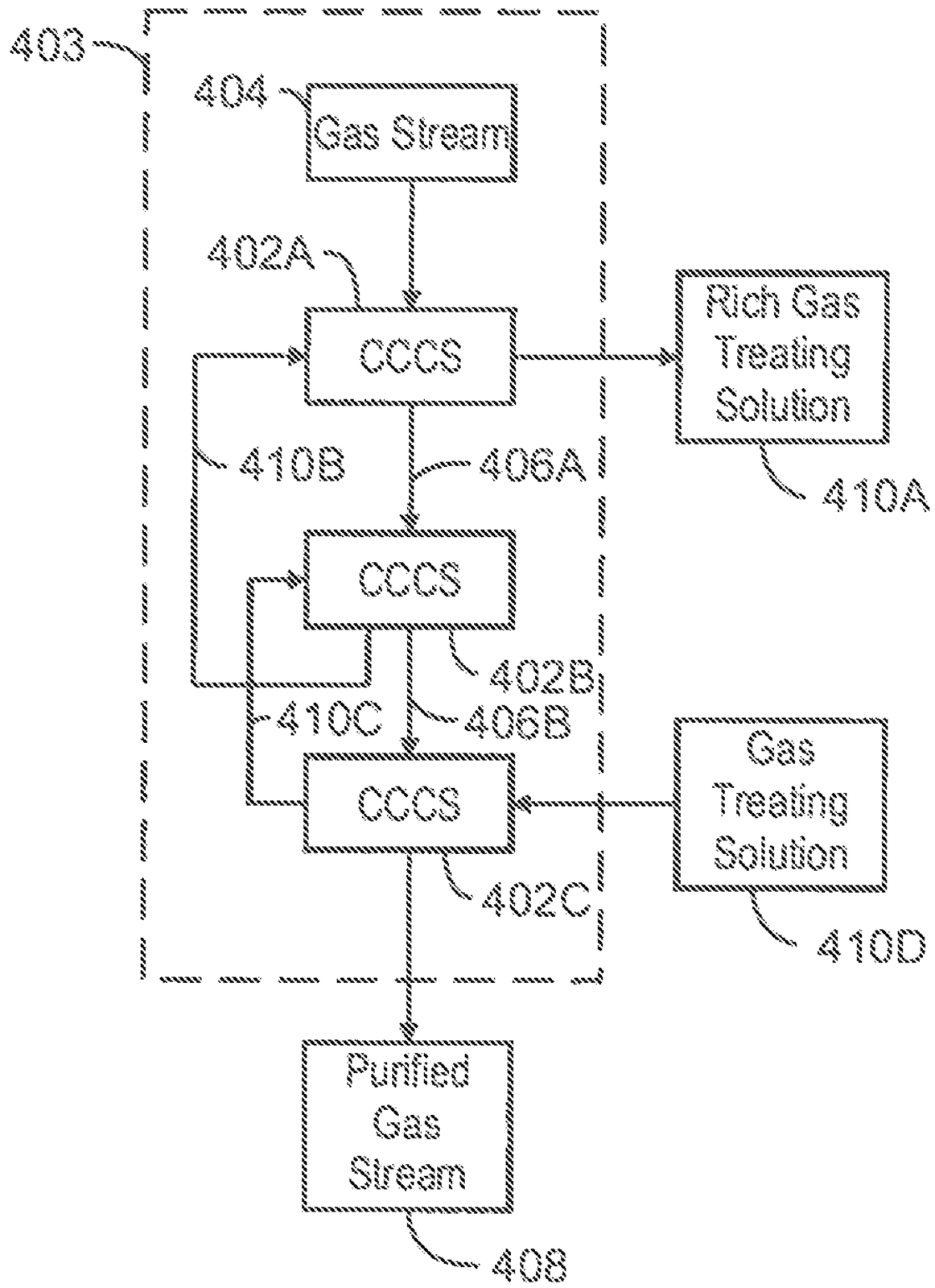

214
202
Natural Gas Stream
202
CCS
204a
220a
CCS
204b
220b
CCS
204c
220c
CCS
204d
220d
CCS
204e
220e
CCS
204f
220f
Sweetened Natural Gas stream
206
260
218A
218B
218C
218D
218E
218F
222
Natural Gas
224
262
254
250
212
256
221
218A
210
228
230
232
234
236
238
248
246
240
244
Acid Gas stream
242

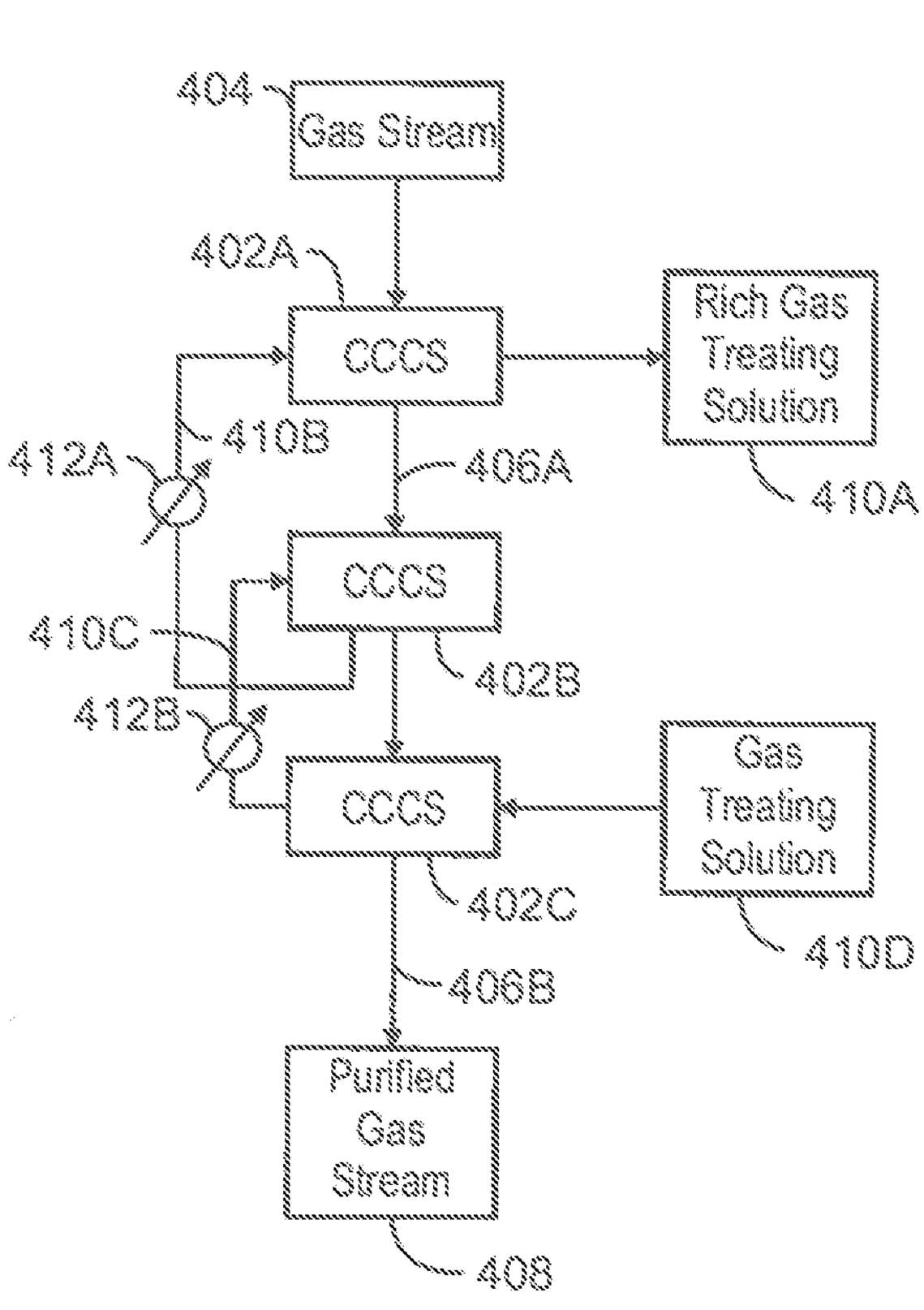
FIG. 2B



[Prior Art]
FIG. 3


403
404
Gas Stream
402A
CCCS
Rich Gas Treating Solution
410B
406A
410A
CCCS
402B
410C
406B
CCCS
Gas Treating Solution
402C
410D
Purified Gas Stream
408

400
FIG. 4A


404
Gas Stream
402A
CCCS
Rich Gas Treating Solution
410B
412A
406A
410A
CCCS
410C
402B
412B
CCCS
Gas Treating Solution
402C
406B
410D
Purified Gas Stream
408

400
FIG. 4B

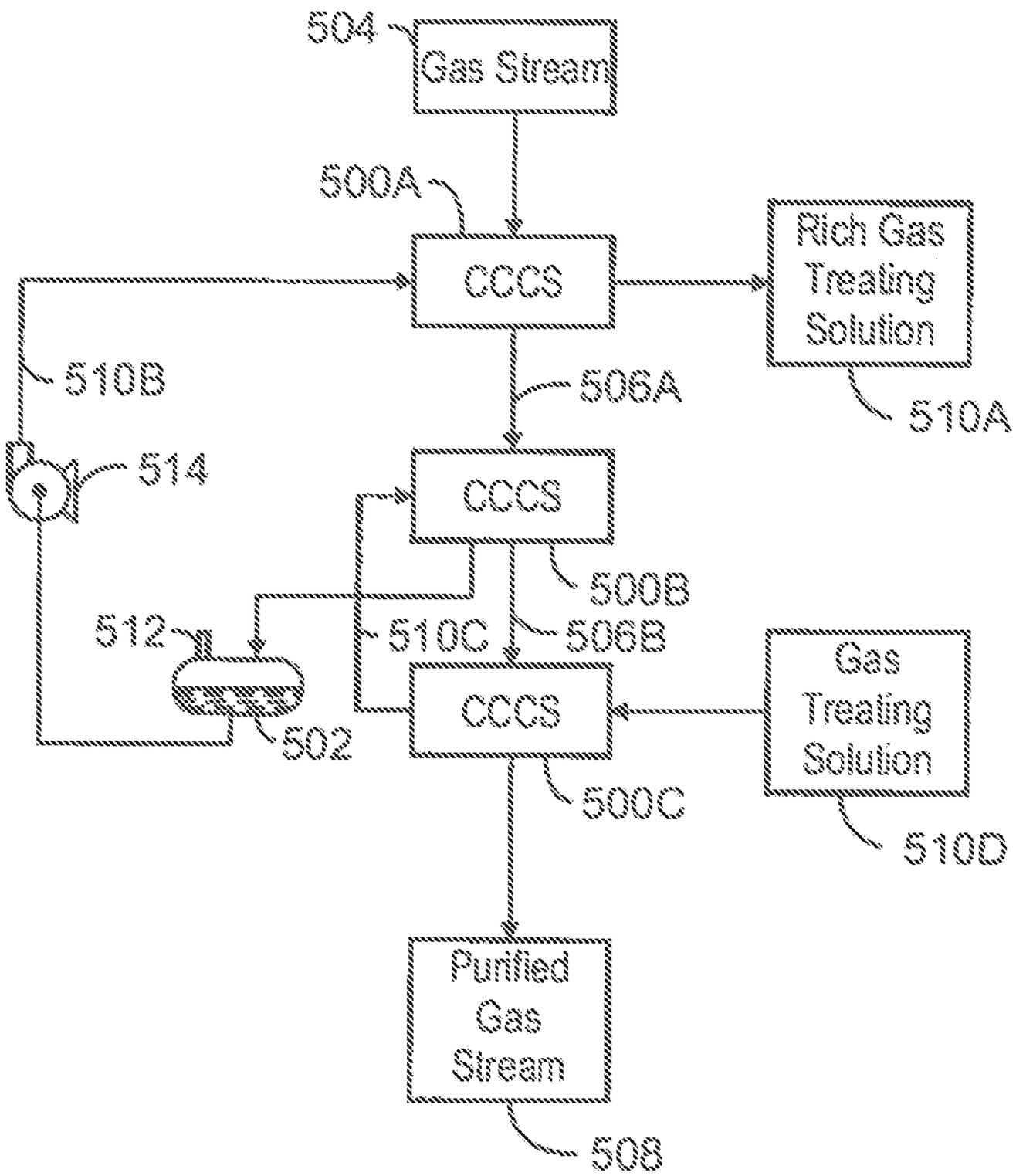
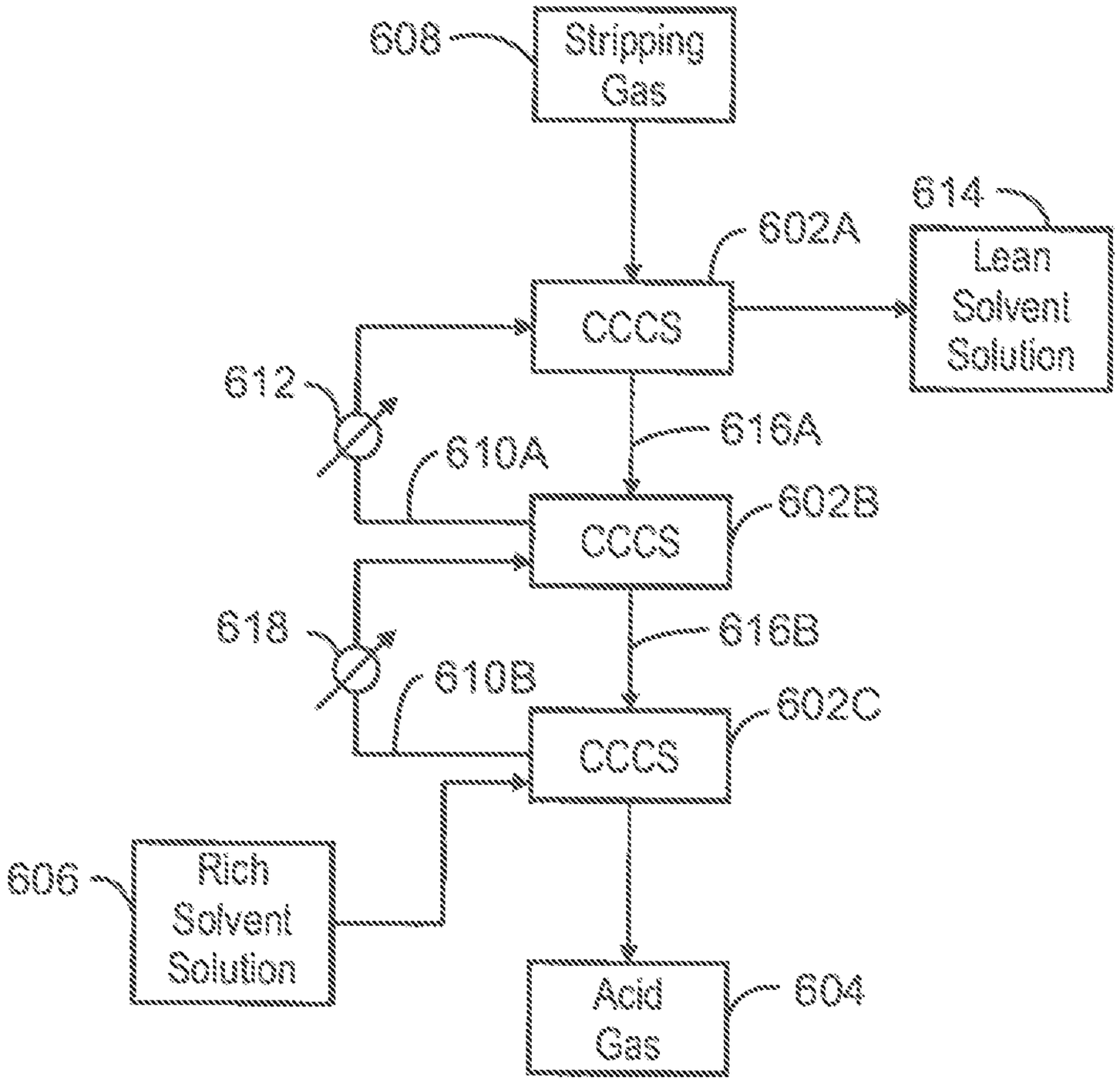
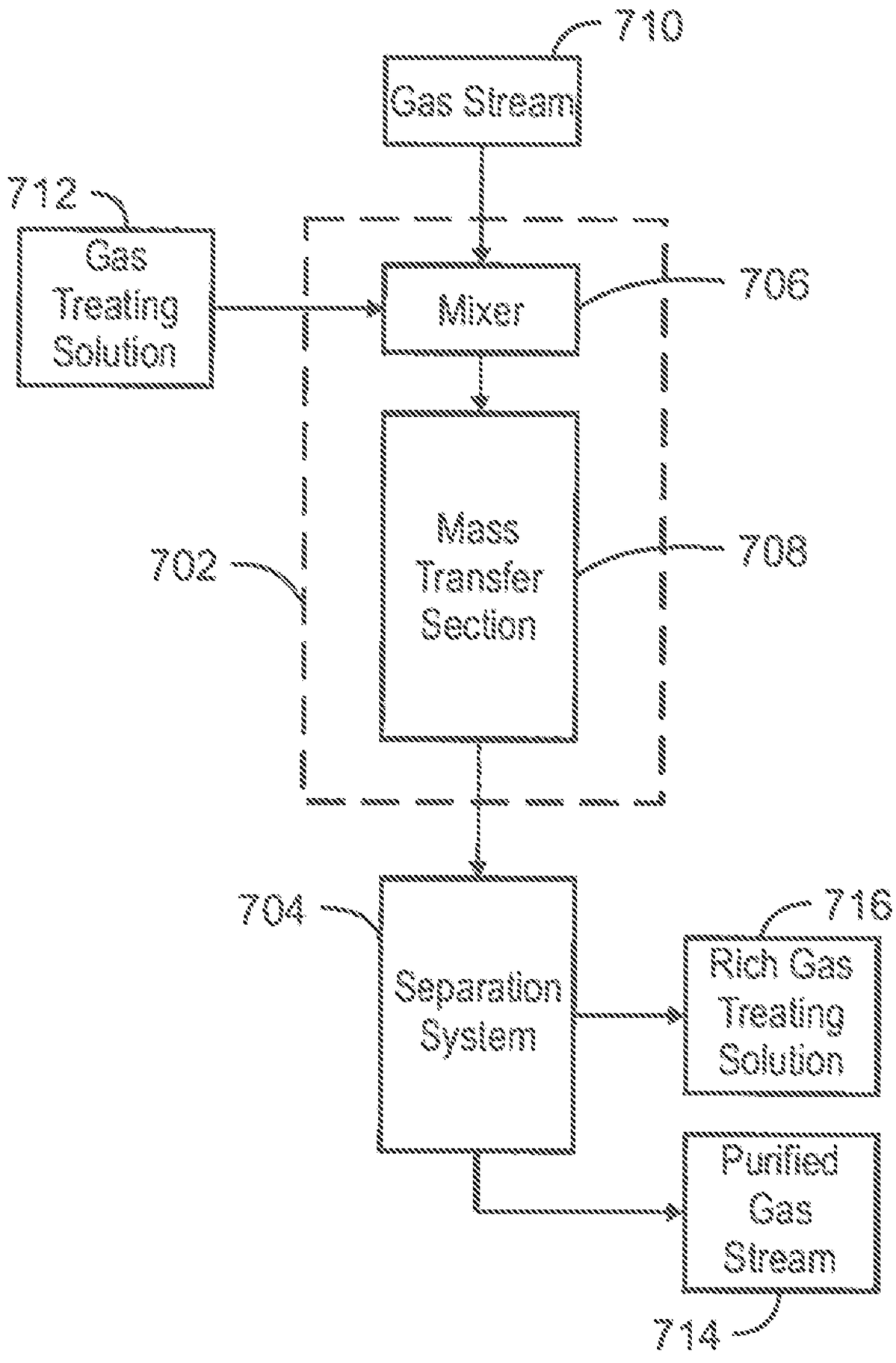

504
Gas Stream
500A
CCCS
Rich Gas Treating Solution
510A
506A
510B
514
CCCS
500B
512
510C
506B
CCCS
Gas Treating Solution
502
500C
510D
Purified Gas Stream
508

FIG. 5


608
Stripping Gas
614
602A
Lean Solvent Solution
CCCS
612
616A
610A
602B
CCCS
618
616B
610B
602C
CCCS
606
Rich Solvent Solution
Acid Gas
604

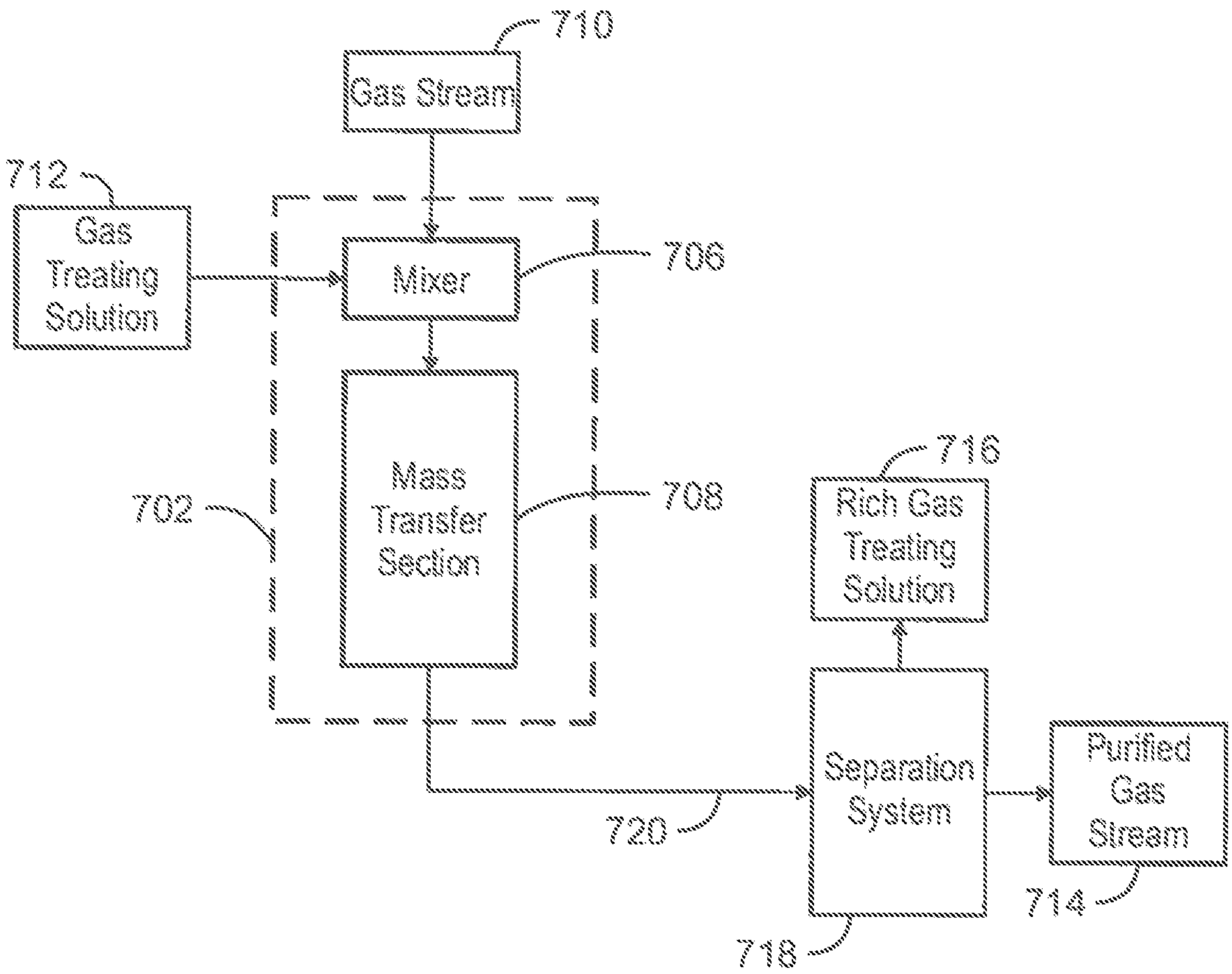
600

FIG. 6

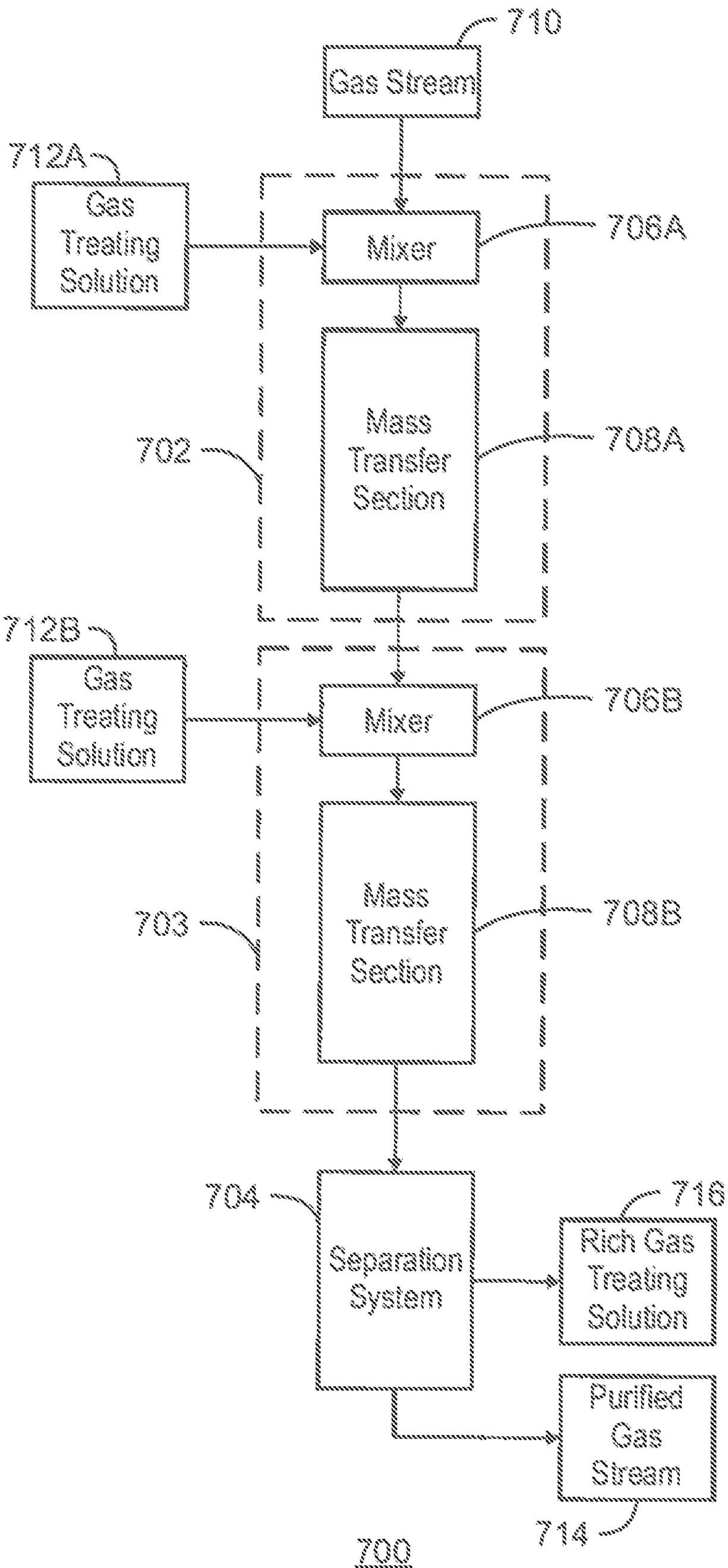

710
Gas Stream
712
Gas Treating Solution
706
Mixer
Mass Transfer Section
702
708
704
Separation System
716
Rich Gas Treating Solution
Purified Gas Stream
714

700

FIG. 7A

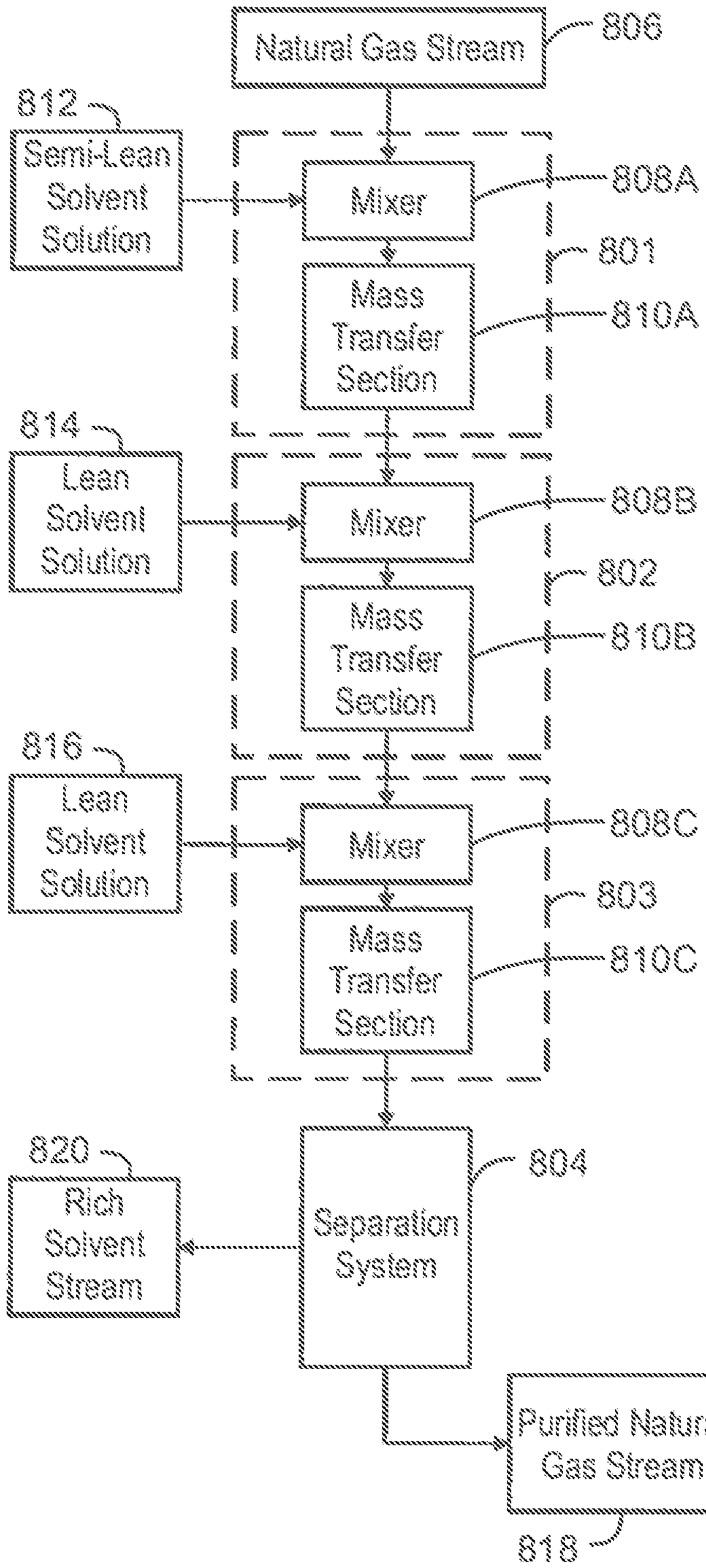

710
Gas Stream
712
Gas Treating Solution
706
Mixer
702
Mass Transfer Section
708
716
Rich Gas Treating Solution
720
Separation System
Purified Gas Stream
714
718

700
FIG. 7B


710
Gas Stream
712A
Gas Treating Solution
Mixer
706A
702
Mass Transfer Section
708A
712B
Gas Treating Solution
Mixer
706B
703
Mass Transfer Section
708B
704
Separation System
716
Rich Gas Treating Solution
Purified Gas Stream
714

700

FIG. 7C


Natural Gas Stream
806
812
Semi-Lean Solvent Solution
Mixer
808A
801
Mass Transfer Section
810A
814
Lean Solvent Solution
Mixer
808B
802
Mass Transfer Section
810B
816
Lean Solvent Solution
Mixer
808C
803
Mass Transfer Section
810C
820
Rich Solvent Stream
Separation System
804
Purified Natural Gas Stream
818

800

FIG. 8

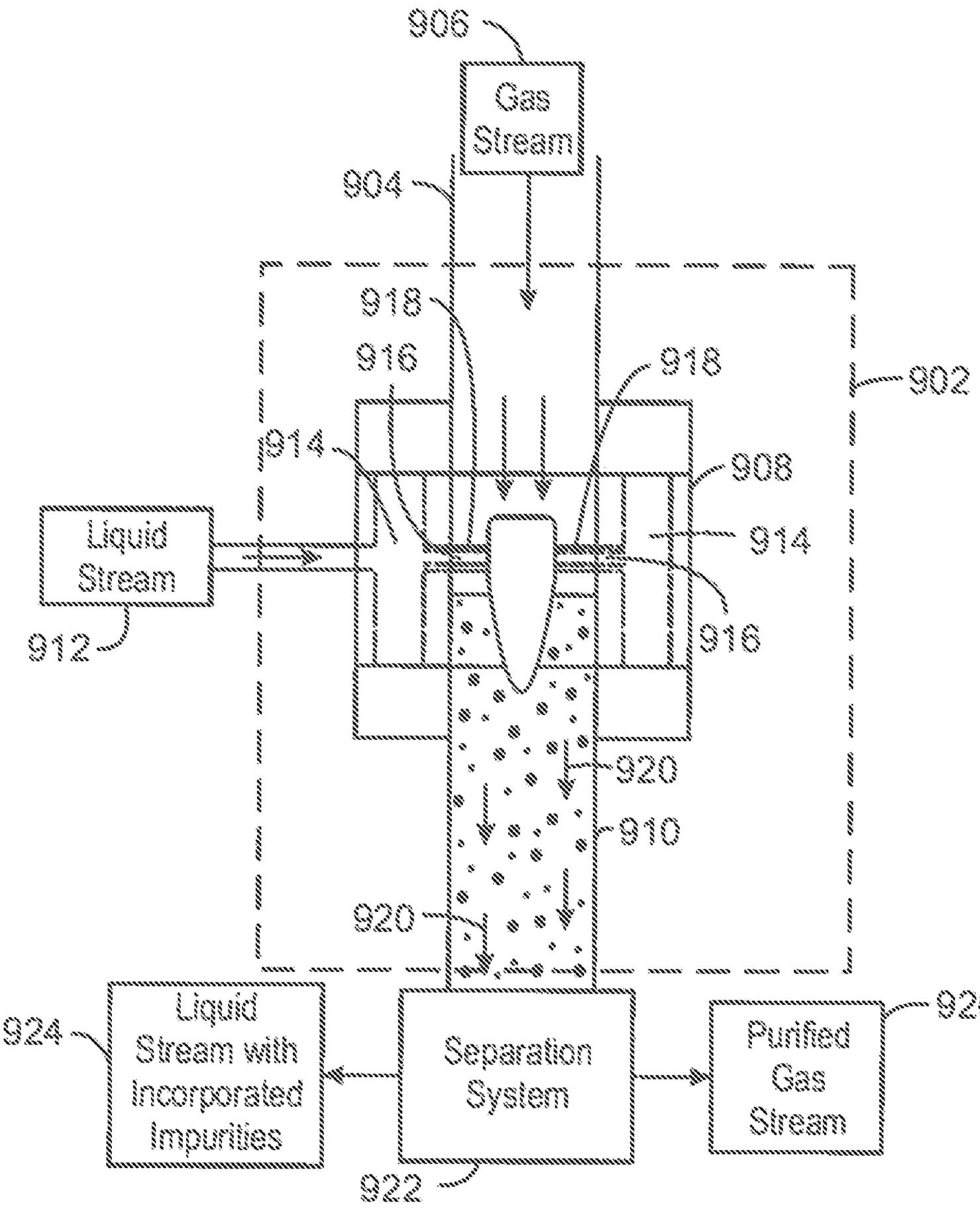

906
Gas Stream
904
918
916
918
902
914
908
Liquid Stream
914
912
916
920
910
920
924
Liquid Stream with Incorporated Impurities
Separation System
926
Purified Gas Stream
922
900

FIG. 9

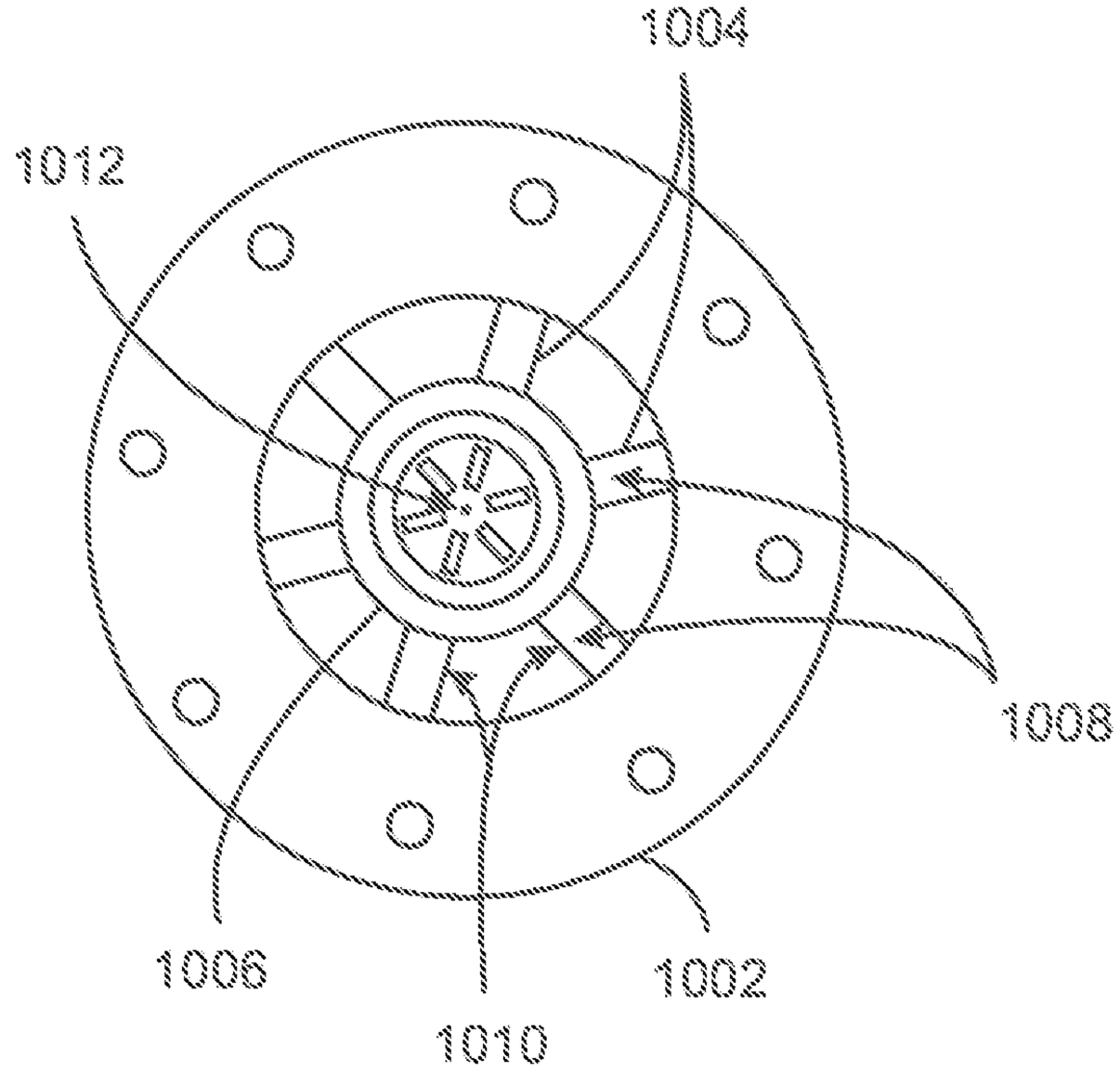
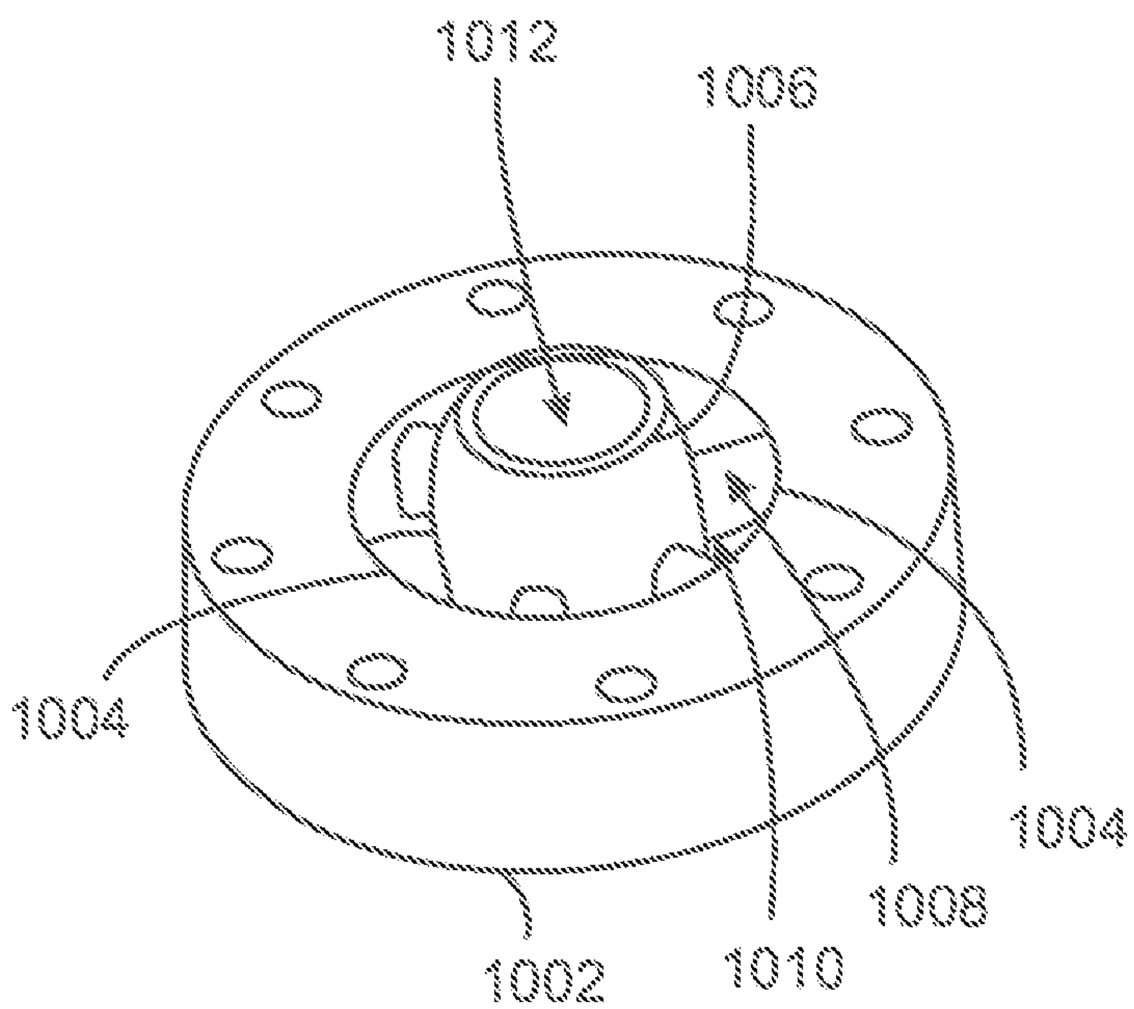
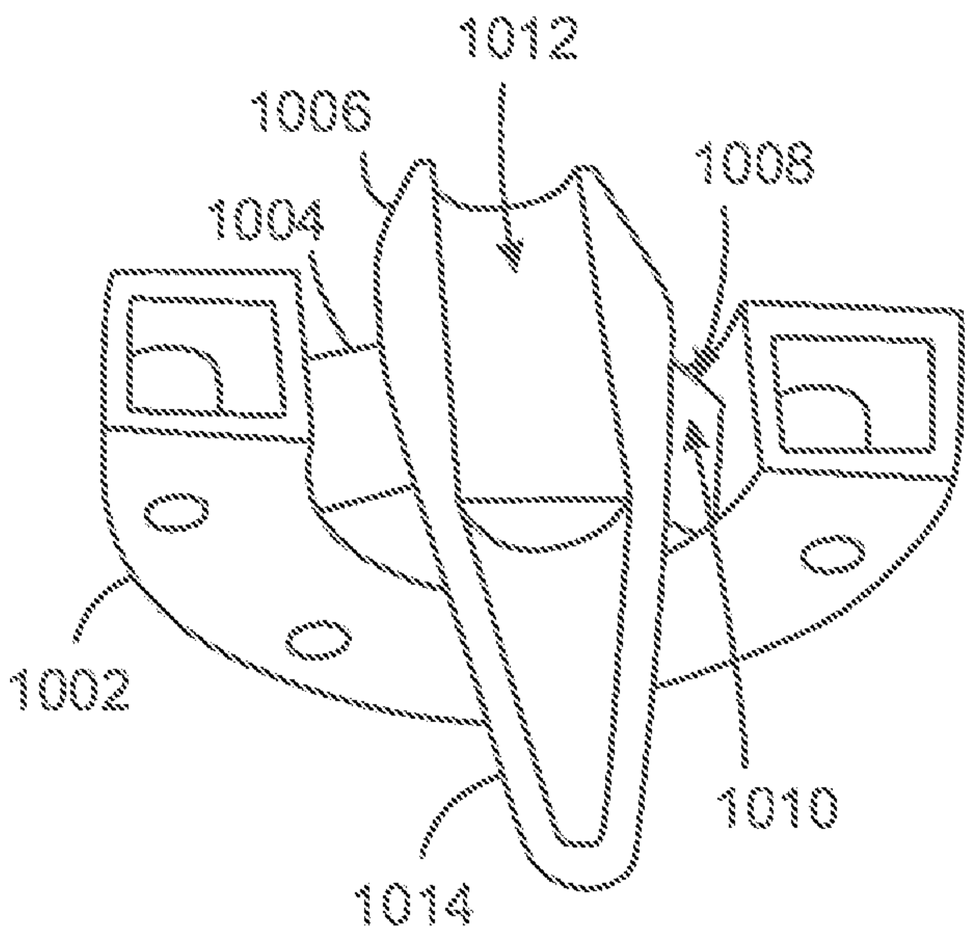


FIG. 10A



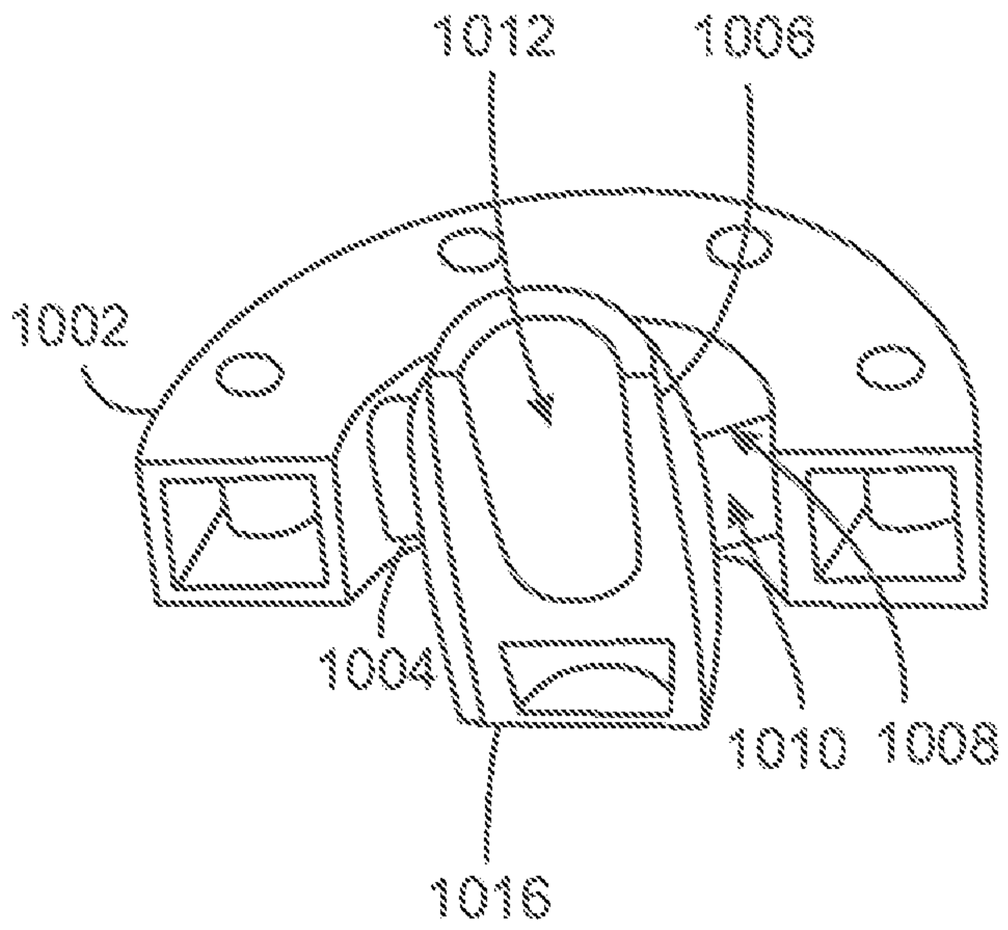
1000

FIG. 10B



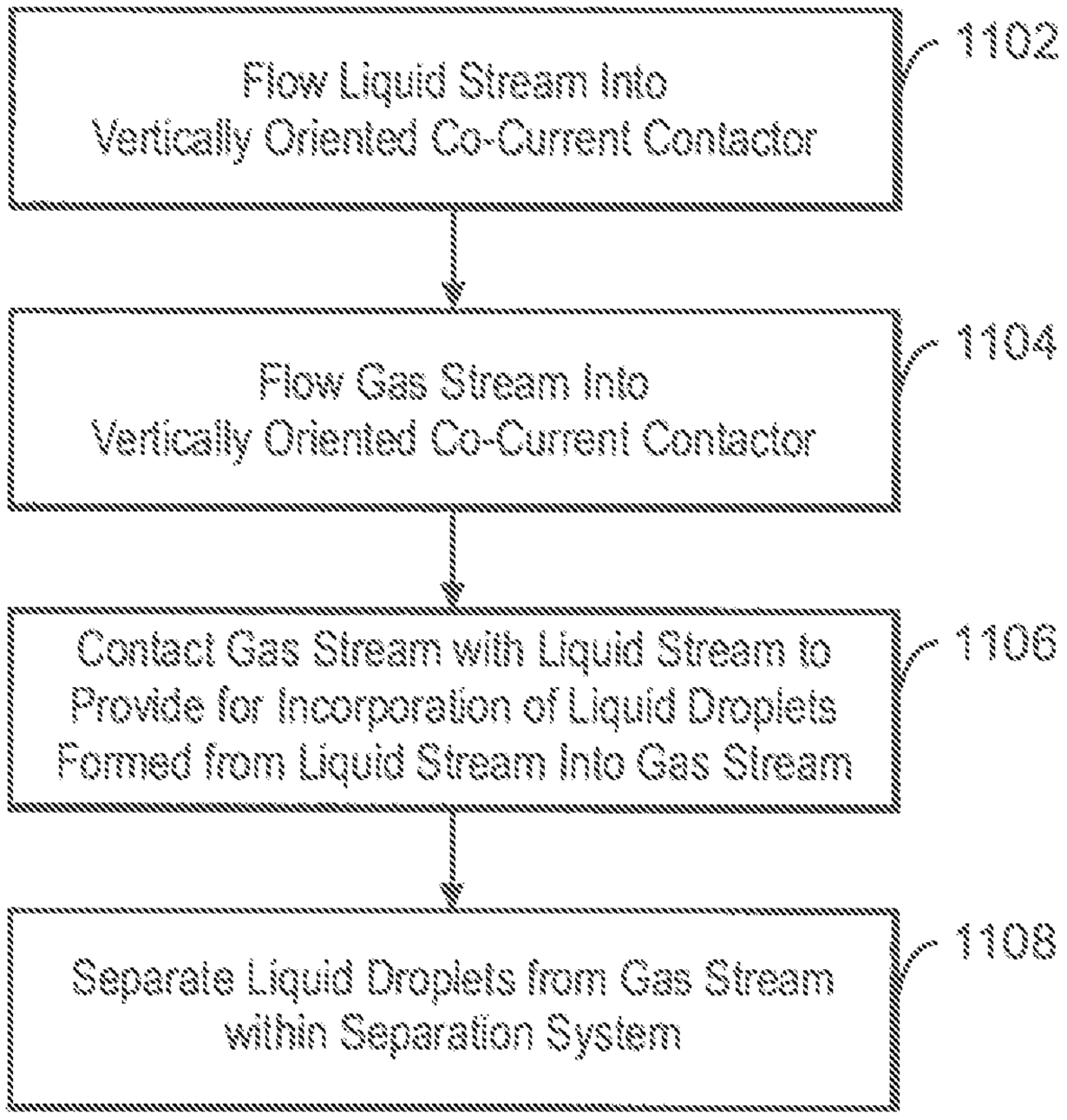
1000

FIG. 10C



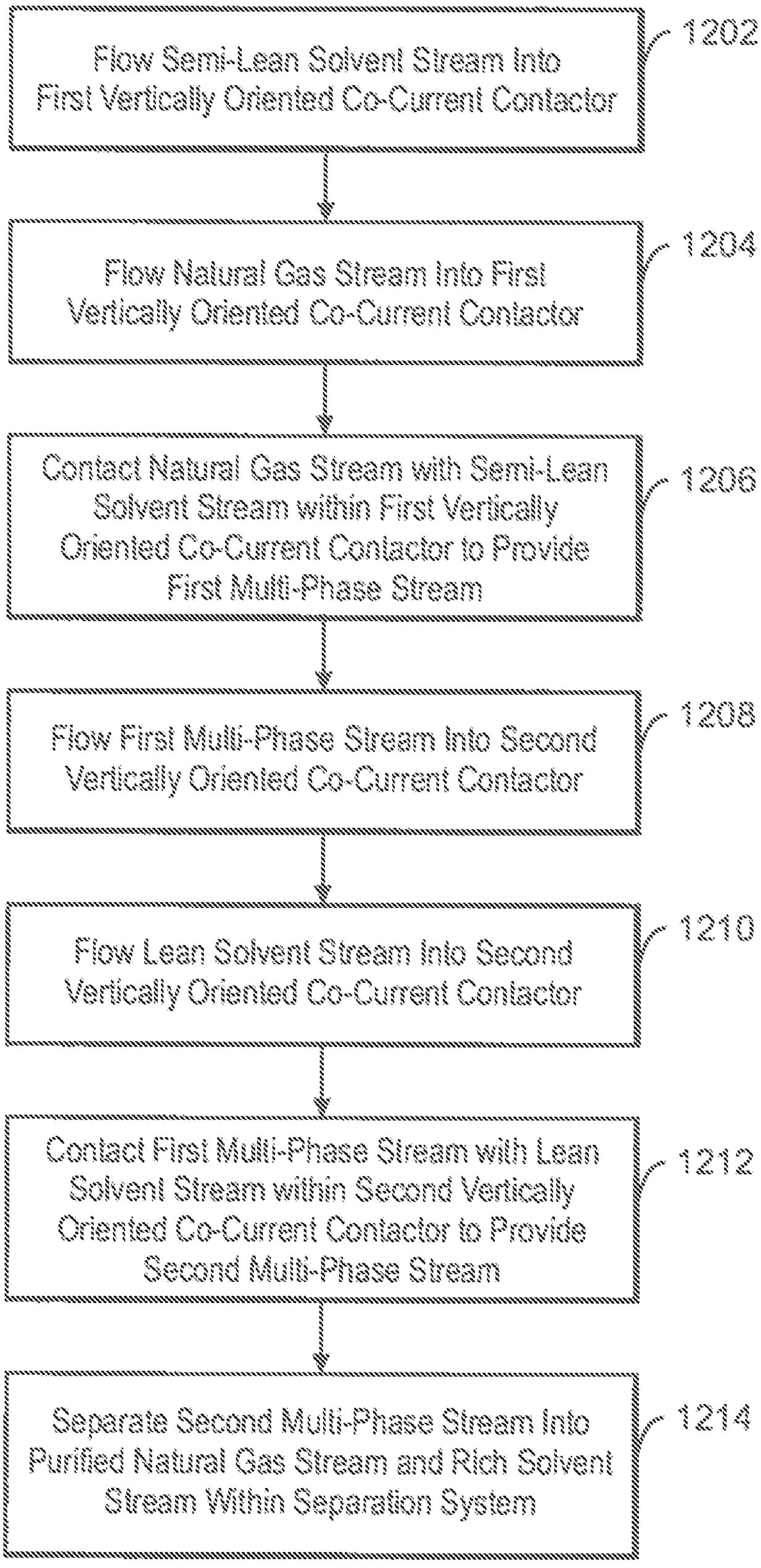
1000

FIG. 10D


Flow Liquid Stream Into Vertically Oriented Co-Current Contactor
1102
Flow Gas Stream Into Vertically Oriented Co-Current Contactor
1104
Contact Gas Stream with Liquid Stream to Provide for Incorporation of Liquid Droplets Formed from Liquid Stream Into Gas Stream
1106
Separate Liquid Droplets from Gas Stream within Separation System
1108

1100

FIG. 11


Flow Semi-Lean Solvent Stream Into First Vertically Oriented Co-Current Contactor
1202
Flow Natural Gas Stream Into First Vertically Oriented Co-Current Contactor
1204
Contact Natural Gas Stream with Semi-Lean Solvent Stream within First Vertically Oriented Co-Current Contactor to Provide First Multi-Phase Stream
1206
Flow First Multi-Phase Stream Into Second Vertically Oriented Co-Current Contactor
1208
Flow Lean Solvent Stream Into Second Vertically Oriented Co-Current Contactor
1210
Contact First Multi-Phase Stream with Lean Solvent Stream within Second Vertically Oriented Co-Current Contactor to Provide Second Multi-Phase Stream
1212
Separate Second Multi-Phase Stream Into Purified Natural Gas Stream and Rich Solvent Stream Within Separation System
1214

1200

FIG. 12