

INTEGRATION OF COLD SOLVENT AND ACID GAS REMOVAL

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the priority benefit of United States Patent Application No. 62/548,171 filed August 21, 2017 entitled INTEGRATION OF COLD SOLVENT AND ACID GAS REMOVAL, the entirety of which is incorporated by reference herein.

[0002] This application is related to United States Provisional Patent Application No. 62/548,172 filed August 21, 2017 entitled INTEGRATION OF COLD SOLVENT AND ACID GAS REMOVAL, having common inventors and assignee and filed on an even date herewith, the disclosure of which is incorporated by reference herein in its entirety.

BACKGROUND

Field of Disclosure

[0003] The disclosure relates generally to the separation of impurities from a gas stream, such as a natural gas stream. More specifically, the disclosure relates to controlling a temperature of a gas stream, through the use of membrane separation technologies, for example, to reduce a reaction temperature of the gas stream and a solvent.

Description of Related Art

[0004] This section is intended to introduce various aspects of the art, which may be associated with the present disclosure. This discussion is intended to provide a framework to facilitate a better understanding of particular aspects of the present disclosure. Accordingly, it should be understood that this section should be read in this light, and not necessarily as an admission of prior art.

[0005] Membranes work by preferentially permeating the acid gas (e.g., CO₂ and H₂S) through the membrane to a lower pressure, which cools both the process gas and permeate. Membranes are a bulk removal technology, so an amine-based clean-up step to remove H₂S (and sometimes CO₂, though those applications are not the focus here) is almost always required to meet a pipeline gas specification.

[0006] Hindered amines, such as Flexsorb/SE, are engineered to preferentially remove H₂S and let CO₂ slip through with the treated gas. The amines achieve selective H₂S removal by reacting more quickly with H₂S than CO₂. The value in becoming selective to H₂S is that fewer molecules of amine are required to remove the H₂S in the system because fewer side reactions

with CO₂ take place. It is well known in the industry that at colder temperatures (50-80 °F) the reactions with CO₂ slow down significantly and the reaction becomes even further selective towards H₂S. It has been discovered that selectivity to H₂S may be further enhanced, thus reducing solvent circulation by up to an order of magnitude, by chilling the solvent itself before
5 contacting a gas stream. Such solvent chilling further reduces the CO₂ reaction rate. Additionally, providing a very short contact time between the gas stream and the amine solvent permits the amine just enough time to pick up the H₂S but too little contact time to react with an appreciable amount of CO₂. Thus, more CO₂ slips, and less solvent is required. It would therefore be advantageous to provide a method and/or system that reduces the required amount
10 of amine solvent used in a contactor operating with a membrane separation system.

SUMMARY

[0007] The present disclosure provides a method of separating impurities from a natural gas stream. According to the method, a portion of the carbon dioxide (CO₂) and hydrogen sulfide (H₂S) are separated from the natural gas stream in a membrane separation system,
15 thereby creating a partially-treated gas stream and a permeate gas stream. The permeate gas stream is comprised primarily of H₂S and CO₂. The partially-treated gas stream is comprised primarily of natural gas. The partially-treated gas stream and the permeate gas stream are at a lower temperature than the natural gas stream. The partially-treated gas stream is contacted with a first lean solvent stream in a first contactor to separate H₂S from the partially-treated gas
20 stream, thereby producing a first rich solvent stream and a fully-treated gas stream. The permeate gas stream is contacted with a second lean solvent stream in a second contactor to separate H₂S therefrom to produce a second rich solvent stream and a CO₂-rich gas stream. H₂S and CO₂ are removed from the first and second rich solvent streams, thereby producing the first and second lean solvent streams.

[0008] The present disclosure also provides a system for separating impurities from a natural gas stream. A membrane separation system separates a portion of the carbon dioxide (CO₂) and hydrogen sulfide (H₂S) from the natural gas stream, thereby creating a partially-treated gas stream and a permeate gas stream. The permeate gas stream is comprised primarily
25 of H₂S and CO₂ and the partially-treated gas stream is comprised primarily of natural gas. The partially-treated gas stream and the permeate gas stream are at a lower temperature than the natural gas stream. A first contactor contacts the partially-treated gas stream with a first lean solvent stream to separate H₂S from the partially-treated gas stream, thereby producing a first rich solvent stream and a fully-treated gas stream. A second contactor contacts the permeate gas stream with a second lean solvent stream to separate H₂S therefrom to produce a second
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rich solvent stream and a CO₂-rich gas stream. A regenerator removes H₂S and CO₂ from the first and second rich solvent streams, thereby producing the first and second lean solvent streams.

[0009] The foregoing has broadly outlined the features of the present disclosure so that the
5 detailed description that follows may be better understood. Additional features will also be described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] These and other features, aspects and advantages of the disclosure will become
apparent from the following description, appending claims and the accompanying drawings,
10 which are briefly described below.

[0011] **Figure 1** is a schematic diagram of a natural gas separation system according to known principles.

[0012] **Figure 2** is a schematic diagram of a natural gas separation system according to disclosed aspects.

15 [0013] **Figure 3** is a schematic diagram of a natural gas separation system according to still other disclosed aspects.

[0014] **Figure 4** is a schematic diagram of a natural gas separation system according to yet other disclosed aspects.

[0015] **Figure 5** is a side elevational view of a co-current contacting system according to
20 disclosed aspects.

[0016] **Figures 6A – 6D** are side elevational views and perspective views of droplet generators according to disclosed aspects.

[0017] **Figure 7** is a flowchart of a method according to aspects of the disclosure.

[0018] **Figure 8** is a flowchart of a method according to aspects of the disclosure.

25 [0019] It should be noted that the figures are merely examples and no limitations on the scope of the present disclosure are intended thereby. Further, the figures are generally not drawn to scale, but are drafted for purposes of convenience and clarity in illustrating various aspects of the disclosure.

DETAILED DESCRIPTION

30 [0020] To promote an understanding of the principles of the disclosure, reference will now be made to the features illustrated in the drawings and specific language will be used to describe

the same. It will nevertheless be understood that no limitation of the scope of the disclosure is thereby intended. Any alterations and further modifications, and any further applications of the principles of the disclosure as described herein are contemplated as would normally occur to one skilled in the art to which the disclosure relates. For the sake of clarity, some features
5 not relevant to the present disclosure may not be shown in the drawings.

[0021] 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
10 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.

[0022] As one of ordinary skill would appreciate, different persons may refer to the same feature or component by different names. This document does not intend to distinguish
15 between components or features that differ in name only. The figures are not necessarily to scale. Certain features and components herein may be shown exaggerated in scale or in schematic form and some details of conventional elements may not be shown in the interest of clarity and conciseness. When referring to the figures described herein, the same reference numerals may be referenced in multiple figures for the sake of simplicity. In the following
20 description and in the claims, the terms "including" and "comprising" are used in an open-ended fashion, and thus, should be interpreted to mean "including, but not limited to."

[0023] The articles "the," "a" and "an" are not necessarily limited to mean only one, but rather are inclusive and open ended so as to include, optionally, multiple such elements.

[0024] As used herein, the terms "approximately," "about," "substantially," and similar
25 terms are intended to have a broad meaning in harmony with the common and accepted usage by those of ordinary skill in the art to which the subject matter of this disclosure pertains. It should be understood by those of skill in the art who review this disclosure that these terms are intended to allow a description of certain features described and claimed without restricting the scope of these features to the precise numeral ranges provided. Accordingly, these terms
30 should be interpreted as indicating that insubstantial or inconsequential modifications or alterations of the subject matter described and are considered to be within the scope of the disclosure.

[0025] "Exemplary" is used exclusively herein to mean "serving as an example, instance,

or illustration." Any embodiment or aspect described herein as "exemplary" is not to be construed as preferred or advantageous over other embodiments.

[0026] "Acid gas" refers to any gas that produces an acidic solution when dissolved in water. Non-limiting examples of acid gases include hydrogen sulfide (H₂S), carbon dioxide (CO₂), sulfur dioxide (SO₂), carbon disulfide (CS₂), carbonyl sulfide (COS), mercaptans, or mixtures thereof.

[0027] "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.

10 [0028] 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.

[0029] 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.

15 [0030] "Dehydrated natural gas stream" or "dry natural gas stream" refers to a natural gas stream that has undergone a dehydration process. Depending on the application, the dehydrated natural gas stream may have a water content of less than 150 parts per million (ppm), less than 100 ppm, less than 84 ppm, than 50 ppm, less than 7 ppm, or less than 0.1 ppm. Any suitable process for dehydrating the natural gas stream can be used. Typical examples of suitable dehydration processes include, but are not limited to dehydration using glycol or methanol.

[0031] 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.

[0032] As used herein, the term "facility" is used as a general term to encompass oil and gas field gathering systems, processing platform systems, and well platform systems.

25 [0033] 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.

[0034] 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 can be present in small amounts. As used herein, hydrocarbons generally refer to components found in natural gas, oil, or chemical processing facilities.

[0035] The disclosure describes a method and system that takes advantage of the inherent cooling of the outputs of a membrane separation system to reduce the reaction temperature of a gas stream and a solvent in one or more contactor vessels. The contactor vessels may operate according to conventional counter-current contacting principles, or in an aspect, may comprise one or more co-current contacting systems. The solvent, which in a preferred aspect may be a hindered amine, may be cooled to below ambient temperature prior to being fed into the contactor vessels. One or more outputs of the membrane separation system, which may include a treated gas stream and a permeate gas stream, may likewise be cooled or chilled prior to being introduced into a contacting vessel. The effect of such cooling or chilling is that the reaction inside each contacting vessel may be adjusted to be more selective to hydrogen sulfide (H₂S) and less selective to carbon dioxide (CO₂). The H₂S-selectivity may be improved, thereby reducing the solvent flow required for separation.

[0036] **Figure 1** is a schematic diagram of a natural gas separation system according to known principles. System **100** may be used to treat a feed gas stream **110** that has a high sour gas content. The feed gas stream comprises natural gas as well as acid gases such as CO₂ and H₂S. The feed gas stream **110** enters a contactor vessel **112** that enables contact between the feed gas stream **110** and a lean solvent stream **114**, which comprises a solvent that removes acid gases from the feed gas stream. A sweetened gas stream **116**, having most if not all acid gases removed, exits toward the top of the contactor vessel **112**. A rich solvent stream **118**, which is mostly liquid, exits near the bottom of the contactor vessel and enters a regeneration vessel **120**, in which heat from a reboiler **122** generates steam by partially boiling the rich solvent stream. This separates the acid gases from the solvent, which becomes leaner (i.e., containing less acid gases) as it moves down the regeneration vessel. The resulting acid gas stream **124** exits near the top of the regeneration vessel **120** and is cooled in a condenser **126**, which condenses much of the water in the acid gas stream **124**. This water is collected in a reflux accumulator **128** and is pumped using pump **130** back to the top of the regeneration vessel **120** as needed. An acid gas stream **131**, rich in H₂S and CO₂, exits the reflux accumulator **128** and is sent to a sulfur recovery unit (not shown) to remove the sulfur therefrom.

[0037] In the regeneration vessel **120**, the downwardly moving lean solvent exits the bottom of the regeneration vessel. The solvent becomes leaner as the acid gases are stripped therefrom in the regeneration vessel. The lean solvent exits the bottom of the regeneration vessel and enters the reboiler **122**, which heats the lean solvent to vaporize any remaining acid gas therein. A lean, hot amine stream is withdrawn from the reboiler, with a first portion **134**

returned to the regeneration vessel **120** and a second portion **136** pumped using a circulation pump **138** to be fed through a heat exchanger **140**. The heat exchanger **140** exchanges heat between the second portion **136** of the lean, hot amine stream and the rich solvent stream. A slip stream **142** of the second portion **136** may be taken for filtration by using a filter **143** according to known principles, to keep the second portion **136** clean. The second portion is then cooled to ambient temperature in cooler **144** to become the cooled, lean solvent stream **114**, which is recycled to the contactor vessel **112**.

[0038] **Figure 2** is a schematic diagram of a sour gas separation system **200** according to an aspect of the disclosure. Sour gas separation system **200** may be used to treat a feed gas stream **202** that has a high acid gas content. Water is removed from the feed gas stream **202** in a dehydrator **204** to the extent required to prevent water from condensing or hydrates forming in the membrane separation or chilling systems downstream. The dehydrator may be any known type of dehydration system, such as a glycol based solvent dehydration system and process, and more specifically, a triethylene glycol (TEG) unit. The dehydrated gas stream **206** passes through a membrane separation system **208**. The membrane separation system **208** operates according to known principles to separate most of the carbon dioxide and hydrogen sulfide present in the dehydrated gas stream. For example, the membrane separation system **208** may produce a partially-treated gas stream **210** with a composition of 6% carbon dioxide (CO₂), about 500 parts per million (ppm) of hydrogen sulfide (H₂S), with the remainder being natural gas. The membrane separation system **208** may also produce a permeate gas stream **212** with a composition of 50%-95% CO₂ and 0.001%-5.0% H₂S, or 70-95% carbon dioxide and 0.1-2.0% H₂S, with the remainder being natural gas. Due to the nature of the membrane separation system, the temperature of the partially-treated gas stream **210** may be reduced to about 50 °F and its pressure reduced to about 500 psig, while the temperature of the permeate gas stream **212** may be reduced to about 70 °F and its pressure reduced to about 100 psig. A non-limiting example of a suitable membrane separation system can be found in “Typical Amine and Glycol Treating Unit Compared to Gas Membrane Separation System for Wellhead CO₂ Trimming” (Laurance Reid Gas Conditioning Conference, Norman, OK, 2010).

[0039] According to disclosed aspects, the partially-treated gas stream **210** is introduced into a first cold solvent contactor **214**. The first cold solvent contactor **214** contacts the partially-treated gas stream **210** with a first chilled lean solvent stream **216** in a packing layer **215** to separate H₂S out of the partially-treated gas stream **210**. The first chilled lean solvent stream **216** may comprise a hindered amine, such as Flexsorb/SE, which has been engineered to preferentially remove H₂S and permit CO₂ to slip through the process. The hindered amine

achieves selective H₂S removal by reacting more quickly with H₂S than with CO₂. The H₂S-selective hindered amine requires fewer amine molecules to remove the H₂S in the system, when compared with non-H₂S selective amines, because fewer side reactions between the hindered amine and CO₂ take place. Furthermore, at temperatures between 50-80 °F the reaction between the hindered amine and CO₂ slow down significantly, and therefore the interaction between the partially-treated gas stream **210** (which is at a temperature of about 50 °F) and the hindered amine in the first chilled lean solvent stream **216** is even further selective towards H₂S. According to aspects of the disclosure, the selectivity toward H₂S may therefore be enhanced by (a) chilling the first lean solvent stream **216** prior to entering the first cold solvent contactor **214**, and (b) reducing the contact time between the partially-treated gas stream **210** and the first chilled lean solvent stream **216**. Providing a very short contact time (via a shorter packing height or using a co-current contactor, for example) between the sour gas and amine allows the amine just enough time to pick up the H₂S but too little contact time to react with an appreciable amount of CO₂. Thus, more CO₂ slips, and less solvent is required. It has been discovered that by enhancing H₂S selectivity by doing steps (a) and (b) above, a much smaller solvent flow rate is needed to separate the H₂S in the treated gas stream – up to an order of magnitude less than separators operating at higher temperatures. The use of a cold solvent is further described in United States Patent Publication No. 2017/0239612, titled “Cold Solvent Gas Treating System,” the disclosure of which is incorporated by reference herein in its entirety.

[0040] A fully-treated gas stream **218** exits the top of the first cold solvent contactor **214**. The fully-treated gas stream **218** is rich in natural gas and is very low in acid gas. Sometimes to meet product pipeline specifications, the CO₂ concentration in the fully-treated gas stream **218** may be further reduced in a polishing unit **220**, which in an aspect may comprise a co-current contacting system such as is disclosed in United States Patent Publication No. 2015/0352463, “Contacting a Gas Stream with a Liquid Stream”, the disclosure of which is incorporated by reference herein in its entirety. A carbon dioxide gas stream **221**, separated from the fully-treated gas stream **218** in the polishing unit, may be re-compressed in a compressor **219** and combined with a cleaned CO₂ gas stream **228** as further described herein. In this manner, all the CO₂ extracted from the feed gas stream **202** can be recovered, essentially free of H₂S. Such CO₂ extraction and recovery is especially advantageous where there is a ready market for the CO₂. The fully-treated gas stream **218** may be further processed through a dehydration unit **222** to reduce water in the sales gas stream to an acceptable level. A first rich solvent stream **223** exits the bottom of the first cold solvent contactor **214**. The first rich

solvent stream includes the H₂S from the partially-treated gas stream **210** that was separated therefrom in the first cold solvent contactor **214**.

[0041] The permeate gas stream **212**, which as previously described may comprise approximately 50%-95% CO₂ or 70-95% CO₂, is introduced into a second cold solvent contactor **224**. The second cold solvent contactor **224** contacts the permeate gas stream **212** with a second chilled lean solvent stream **226** in a packing layer **225** to separate H₂S out of the permeate gas stream **212**. The second chilled lean solvent stream **226** may comprise a hindered amine, and in a preferred aspect has the same composition as the first chilled lean solvent stream **216**. The second cold solvent contactor **224** may operate in a similar manner as the first cold solvent contactor **214**, and for the sake of brevity its operation will not be further described herein. A cleaned CO₂ gas stream **228**, substantially free of H₂S, exits the top of the second cold solvent contactor **224** to be vented or transported for further use or processing. A second rich solvent stream **230** exits the bottom of the second cold solvent contactor **224**. The second rich solvent stream **230** includes the H₂S from the permeate gas stream **212** that was separated therefrom in the second cold solvent contactor **224**.

[0042] The first and second rich solvent streams **223**, **230** are regenerated to separate the H₂S (and residual CO₂) from the solvent contained therein. In a preferred aspect, the first and second rich solvent streams are combined and sent to a regenerator **232**. Regenerator **232** may include a regeneration vessel, a reboiler, a condenser, and/or an accumulator as shown in **Figure 1** at **120**, **122**, **126**, and **128**, respectively, and in the interests of brevity the specific components will not be further described. An H₂S-rich gas stream **234** is separated out of the regenerator **232** and may be sent to a sulfur recovery unit (not shown) according to known principles. With the H₂S (and CO₂) removed, the solvent now comprises a regenerated or lean solvent stream **236** that can be recirculated to the first and second cold solvent contactors **214**, **224**. Prior to recirculation, however, the lean solvent stream is cooled or chilled in a refrigeration system **238**, which in an aspect may be a propane chiller, an ammonia refrigerator, and/or an absorption chiller. The refrigeration system cools or chills the lean solvent stream **236** to a temperature below the ambient temperature, which may be below 50 °F, or below 45 °F, or below 40 °F, or below 35 °F. This differs from known acid gas separation systems that cool the lean amine prior to recirculation only to near the ambient temperature. As previously explained, chilling the lean solvent stream to below ambient temperature may significantly reduce the required solvent flow rate. The first and second chilled lean solvent streams **216**, **226** exit the refrigeration system and are recirculated to the first and second cold solvent contactors **214**, **224**, respectively.

[0043] Aspects of the disclosure shown in **Figure 2** rely upon the cooling of the dehydrated gas stream **206** by the gas expansion in the membrane separation system **208**. Additional cooling of the partially-treated gas stream **210** and the permeate gas stream **212** may be provided by first and second coolers **242**, **244**, respectively. This may be done to reduce the temperature of the partially-treated gas stream **210** and the permeate gas stream **212** to a temperature that may be more optimal for use in the first and second cold solvent contactors **214**, **224**.

[0044] The schematic of **Figure 2** is not intended to indicate that the sour gas separation system **200** is to include all the components shown in **Figure 2**. Further, any number of additional components may be included within the sour gas separation system **200**, depending on the details of the specific implementation. For example, the sour gas separation system **200** may include any suitable types of heaters, chillers, condensers, liquid pumps, gas compressors, filters, blowers, bypass lines, or other types of separation and/or fractionation equipment, valves, switches, controllers, pressure-measuring devices, temperature-measuring devices, level-measuring devices, or flow-measuring devices, among others.

[0045] **Figure 3** is a schematic diagram of a sour gas separation system **300** according to another aspect of the disclosure, which is similar to system **200**. System **300** differs from system **200** in that the solvent systems are integrated together. The lightly-loaded chilled solvent from the permeate treatment could be pumped and used as a semi-lean solvent for the cold solvent on the process gas, since the latter will have a higher partial pressure of H_2S . As shown in **Figure 3**, water is removed from a feed gas stream **302** in a dehydrator **304**. The dehydrated gas stream **306** passes through a membrane separation system **308**. The membrane separation system operates according to known principles to separate most of the carbon dioxide and hydrogen sulfide present in the dehydrated gas stream. For example, the membrane separation system **308** may produce a partially-treated gas stream **310** with a composition of 6% carbon dioxide (CO_2), about 500 parts per million (ppm) of hydrogen sulfide (H_2S), with the remainder being natural gas. The membrane separation system **308** may also produce a permeate gas stream **312** with a composition of 50%-95% CO_2 and 0.001%-5.0% H_2S , or 70-95% carbon dioxide and 0.1-2.0% H_2S , with the remainder being natural gas. The temperature of the partially-treated gas stream **310** may be reduced to about 50 °F and its pressure reduced to about 500 psig, while the temperature of the permeate gas stream **312** may be reduced to about 70 °F and its pressure reduced to about 100 psig.

[0046] According to disclosed aspects, the partially-treated gas stream **310** is introduced into a first cold solvent contactor **314**. The permeate gas stream **312** is introduced into a second

cold solvent contactor **324**. The second cold solvent contactor **324** contacts the permeate gas stream **312** with a chilled lean solvent stream **326** to separate H₂S out of the permeate gas stream **312**. The chilled lean solvent stream **326** may comprise a hindered amine, such as Flexsorb/SE, as previously described. A cleaned CO₂ gas stream **328**, substantially free of H₂S,
5 exits the top of the second cold solvent contactor **324** to be vented or transported for further use or processing. A semi-lean solvent stream **330** exits the bottom of the second cold solvent contactor **324**. The semi-lean solvent stream **330** includes the H₂S from the permeate gas stream **312** that was separated therefrom in the second cold solvent contactor **324**. The semi-lean solvent stream **330** is pumped using pump **331** to the first cold solvent contactor **314**,
10 which contacts the partially-treated gas stream **310** with the semi-lean solvent stream to separate H₂S out of the partially-treated gas stream **310**.

[0047] A fully-treated gas stream **318** exits the top of the first cold solvent contactor **314**. The fully-treated gas stream **318** is rich in natural gas and is very low in acid gas. To meet pipeline specifications, the acid gas concentration in the fully-treated gas stream **318** may be
15 further reduced in a polishing unit **320** and further processed through a dehydration unit **322** as described in previous aspects. A carbon dioxide gas stream **321**, separated from the fully-treated gas stream **318** in the polishing unit, may be re-compressed in a compressor **319** and combined with a cleaned CO₂ gas stream **328** as further described herein. A rich solvent stream **323** exits the bottom of the first cold solvent contactor **314**. The rich solvent stream includes
20 the H₂S from the partially-treated gas stream **310** that was separated therefrom in the first cold solvent contactor **314**. In an aspect, a slipstream **326a** of chilled lean solvent stream **326** is sent to the top of the first cold solvent contactor **314** above semi-lean solvent stream **330** to further reduce H₂S in the partially-treated gas stream.

[0048] The rich solvent stream **323** is regenerated in a regenerator **332**, which separates the
25 H₂S (and CO₂) from the solvent in the rich solvent stream. Regenerator **332** may include a regeneration vessel, a reboiler, a condenser, and/or an accumulator as shown in **Figure 1** at **120**, **122**, **126**, and **128**, respectively, and in the interests of brevity the specific components will not be further described. An H₂S-rich gas stream **334** is separated out of the regenerator **332** and may be sent to a sulfur recovery unit (not shown) according to known principles. With
30 the H₂S removed, the solvent now comprises a lean solvent stream **336** that can be recirculated to the second cold solvent contactor **324**. Prior to recirculation, however, the lean solvent stream is cooled or chilled in a refrigeration system **338**, which cools or chills the lean solvent stream **336** to a temperature below the ambient temperature, which may be below 50 °F, or below 45 °F, or below 40 °F, or below 35 °F. This differs from known acid gas separation

systems that cool the lean amine prior to recirculation only to near ambient temperature. As previously explained, chilling the lean solvent stream to below ambient temperature may significantly reduce the required solvent flow rate. The chilled lean solvent stream **326** exits the refrigeration system and is recirculated to the second cold solvent contactor.

5 **[0049]** Aspects of the disclosure shown in **Figure 3** rely upon the cooling of the dehydrated gas stream **306** by the membrane separation system **308**. Additional cooling of the partially-treated gas stream **310** and the permeate gas stream **312** may be provided by first and second coolers **342**, **344**, respectively. This may be done to reduce the temperature of the partially-treated gas stream **310** and the permeate gas stream **312** to a temperature that may be more
10 optimal for use in the first and second cold solvent contactors **314**, **324**.

[0050] The schematic of **Figure 3** is not intended to indicate that the sour gas separation system **300** is to include all the components shown in **Figure 3**. Further, any number of additional components may be included within the sour gas separation system **300**, depending on the details of the specific implementation. For example, the sour gas separation system **300**
15 may include any suitable types of heaters, chillers, condensers, liquid pumps, gas compressors, filters, blowers, bypass lines, or other types of separation and/or fractionation equipment, valves, switches, controllers, pressure-measuring devices, temperature-measuring devices, level-measuring devices, or flow-measuring devices, among others.

[0051] **Figure 4** depicts a sour gas separation system **400** according to another aspect of
20 the disclosure, in which a single cold solvent contactor **402** is deployed upstream of the membrane system **404**. In this aspect, the feed gas stream **405** could be chilled in a heat exchanger **406** by cross-exchanging with one or more of the outlets from the membrane system **404**, which may include a fully-treated gas stream **408** and/or a permeate gas stream **410**. After being chilled in the heat exchanger **406** to a temperature of about 50 °F, for example, the feed
25 gas stream **405**, which may be considered a chilled gas stream, may be further chilled in a refrigeration system or chiller **407** and introduced into the cold solvent contactor **402**. The cold solvent contactor **402** contacts the feed gas stream **405** with a lean solvent stream **412** according to known principles to separate H₂S out of the feed gas stream **405**. The lean solvent stream **412** may comprise a hindered amine which, as previously described, achieves selective H₂S
30 removal by reacting more quickly with H₂S than with CO₂. As previously described, providing a very short contact time (via a shorter packing height or using a co-current contactor, for example) between the sour gas and amine allows the amine just enough time to pick up the H₂S but too little contact time to react with an appreciable amount of CO₂. Thus, more CO₂ slips, and less solvent is required.

[0052] A partially-treated gas stream **414** exits the top of the cold solvent contactor **402**. A dehydrator **416** removes water from the partially-treated gas stream **414**, and the treated gas stream is then introduced into the membrane separation system **404**. The membrane system **404** operates according to known principles to separate most of the carbon dioxide and hydrogen sulfide present in the partially-treated gas stream **414**. For example, the membrane system **404** may produce a fully-treated gas stream **408** with a composition of 2%-6% CO₂ at a temperature of about 30 °F and a pressure of about 500 psig. The membrane separation system **404** may also produce a permeate gas stream **410** having a composition of 50%-95% CO₂, or 70-95% CO₂, with the remainder being primarily natural gas with little to no H₂S. To meet pipeline specifications, the H₂S concentration in the sales gas stream **408** may be further reduced in a polishing unit **418** as previously explained. A carbon dioxide gas stream **419**, separated from the treated gas stream **414** in the polishing unit, may be re-compressed in a compressor **421** and combined with the permeate gas stream **410**. A rich solvent stream **420** exits the bottom of the cold solvent contactor **402**. The rich solvent stream **420** includes the H₂S from the feed gas stream **405** that is separated therefrom in the cold solvent contactor **402**. The rich solvent stream **420** is fed to a regenerator **422** that separates the H₂S (and at least some CO₂) from the solvent. An H₂S-rich gas stream **424** exits the regenerator **422** and may be sent to a sulfur recovery unit (not shown) according to known principles. The lean solvent stream **412** may be cooled by a refrigeration system or chiller **423** before being recirculated to the cold solvent contactor **402**.

[0053] The schematic of **Figure 4** is not intended to indicate that the sour gas separation system **400** is to include all the components shown in **Figure 4**. Further, any number of additional components may be included within the sour gas separation system **400**, depending on the details of the specific implementation. For example, the sour gas separation system **400** may include any suitable types of heaters, chillers, condensers, liquid pumps, gas compressors, filters, blowers, bypass lines, or other types of separation and/or fractionation equipment, valves, switches, controllers, pressure-measuring devices, temperature-measuring devices, level-measuring devices, or flow-measuring devices, among others.

[0054] The aspect disclosed in **Figure 4** has several advantages. For example, only a single cold solvent contactor and dehydration system would be required, as opposed to two cold solvent contactors and two to three dehydration systems as shown in other Figures herein. Dehydration takes place at high pressure and low temperature, in which the gas contains less water, particularly for the low pressure permeate system. The entire membrane system operates without the presence of H₂S, thereby improving plant safety. Additionally, the feed gas to the

membrane system may now be cooler, which increases the selectivity to the permeating species, so the CO₂ stream has a lower hydrocarbon content. This last advantage could be applicable regardless of the use of the specific cold solvent(s) disclosed herein for use with the depicted aspects.

- 5 **[0055]** Throughout the disclosure reference is made to gas streams that are ‘partially-treated’ and ‘fully-treated’. These terms are relative to each other, and their use does not imply that a fully-treated gas stream cannot be subject to additional processes or treatments.

- 10 **[0056]** The cold solvent contactors depicted in **Figures 2-4** and described herein are shown as conventional contacting vessels in which an upwardly moving gas stream contacts a downwardly moving solvent in a packing section. According to aspects of the disclosure, the height of the packing sections is reduced to minimize the absorption of CO₂ by the solvent. In another aspect, any of the disclosed cold solvent contactors may operate according to a co-current flow scheme in which the gas stream is moving in the same direction as the solvent it is contacting. The co-current flow scheme may include one or more co-current contacting systems connected in parallel, in series within a pipe, or a combination of parallel and series configurations. A natural gas stream and a solvent stream may move together, i.e., co-currently, within each co-current contacting system. In general, co-current contactors can operate at much higher fluid velocities than counter-current contacting systems. As a result, co-current contacting systems tend to be smaller than counter-current contactors that use standard towers with packing or trays. Further, the co-current contacting systems are smaller than conventional pressure vessels of equivalent processing capacity, and thus are more suited to modular design/construction, offshore deployment, de-bottlenecking applications, and applications where visual pollution may be a factor. In selective H₂S and/or CO₂ separation applications, two to three co-current contacting systems in series may be used to separate said impurities from a gas stream. Additionally, the dehydration and/or polishing steps performed in the disclosed aspects may be performed by one or more co-current contacting systems.

- 25 **[0057]** **Figure 5** illustrates the co-current contacting system **500** in further detail. The co-current contacting system **500** can provide for the separation of components within a gas stream, such as a natural gas stream **501**. The co-current contacting system **500** can include a co-current contactor **502** that is positioned in-line within a pipe **504**. The co-current contactor **502** may include a number of components that provide for the efficient contacting of a liquid droplet stream, such as a lean solvent stream **505**, with a flowing gas stream, such as natural gas stream **501**, for the separation of hydrogen sulfide (H₂S) from the natural gas stream **501**.

[0058] The co-current contactor **502** may include a droplet generator **508** and a mass transfer section **510**. As shown in **Figure 5**, the natural gas stream **501** may be flowed through the pipe **504** and into the droplet generator **508**. The lean solvent stream **505** may also be flowed into the droplet generator **508**, for example, through a hollow space **514** coupled to flow channels **516** in the droplet generator **508**.

[0059] From the flow channels **516**, the lean solvent stream **505** is released into the natural gas stream **501** as fine droplets through injection orifices **518**, and is then flowed into the mass transfer section **510**. This can result in the generation of a treated gas stream **520** within the mass transfer section **510**. The treated gas stream **520** may include small liquid droplets dispersed in a gas phase. For H₂S separation processes, the liquid droplets may include H₂S molecules from the natural gas stream **501** that are absorbed or dissolved into the lean solvent stream **505**.

[0060] The treated gas stream **520** may be flowed from the mass transfer section **510** to a separation system **522**, which includes a cyclonic separator **523** and a collector **524**. Alternatively the separation system may include a mesh screen, or a settling vessel. Preferably, in-line cyclonic separators may be used to realize the benefits of compactness and reduced diameter. The cyclonic separator **523** removes the liquid droplets from the gas phase. The liquid droplets, which as previously stated may include H₂S absorbed or dissolved into the lean solvent stream **505**, are diverted into collector **524**, which directs the collected liquids as a rich solvent stream **517** to a regenerator (not shown). A pressure equalization line **532** may extend from the collector **524** and operates to allow gas in the collector to return to the separation system **522**. In an aspect, this gas flows via a nozzle **533** or eductor situated inside the separation system **522**. A processed gas stream **534**, from which the H₂S and rich solvent has been separated, exits the separation system **522** in an in-line orientation with the pipe **504**. The amount of H₂S in processed gas stream **534**, as measured in weight percentage, is lower than the amount of H₂S in natural gas stream **501**.

[0061] **Figure 6A** is a front view of droplet generator **508** according to disclosed aspects. The droplet generator **508** is a contacting device that may be implemented within a co-current contactor, for example, in the co-current contactor **502** described with respect to the co-current contacting system **500** of **Figure 5**. The front view of the droplet generator **508** represents an upstream view of the droplet generator.

[0062] The droplet generator **508** may include an outer annular support ring **602**, a number of spokes **604** extending from the annular support ring **602**, and a gas entry cone **606**. The

annular support ring **602** may secure the droplet generator **508** in-line within the pipe. In addition, the spokes **604** may provide support for the gas entry cone **606**.

5 **[0063]** The annular support ring **602** may be designed as a flanged connection, or as a removable or fixed sleeve inside the pipe. In addition, the annular support ring **602** may include a liquid feed system and a hollow channel described further with respect to **Figures 6C and 6D**. A liquid stream, such as a lean solvent stream **505**, may be fed to the droplet generator **508** via the hollow channel in the annular support ring **602**. The lean solvent stream **505** may comprise a solvent such as Flexsorb/SE. The hollow channel may allow equal distribution of the liquid stream along the perimeter of the droplet generator **508**.

10 **[0064]** Small liquid channels within the annular support ring **602** may provide a flow path for the lean solvent stream to flow through liquid injection orifices **608** within the spokes **604**. The liquid injection orifices **608** may be located on or near the leading edge of each spoke **604**. Placement of the liquid injection orifices **608** on the spokes **604** may allow the lean solvent stream to be uniformly distributed in a gas stream that is directed between the spokes **604**.
15 Specifically, the lean solvent stream may be contacted by the portion of the natural gas stream **501** flowing through the gaps between the spokes **604**, and can be sheared into small droplets and entrained in the gas phase.

20 **[0065]** A portion of the natural gas stream flows between the spokes to the mass transfer section while the remainder of the gas stream flows into the gas entry cone **606** through a gas inlet **612**. The gas entry cone **606** may block a cross-sectional portion of the pipe. The spokes **604** include gas exit slots **610** that allow the natural gas stream to be flowed out of the gas entry cone **606**. This may increase the velocity of the natural gas stream as it flows through the pipe. The gas entry cone **606** may direct a predetermined amount of the natural gas stream to the gas exit slots **610** on the spokes **604**.

25 **[0066]** Some of the lean solvent stream injected through the spokes **604** may be deposited on the surface of the spokes **604** as a liquid film. As the natural gas stream flows through the gas entry cone **606** and is directed out of the gas exit slots **610** on the spokes **604**, the natural gas stream may sweep, or blow, much of the liquid film off the surface of the spokes **604**. This may enhance the dispersion of the lean solvent stream into the gas phase. Further, the
30 obstruction to the flow of the natural gas stream and the shearing effect created by the exit of the natural gas stream gas through the gas exit slots may provide a zone with an increased turbulent dissipation rate. This may result in the generation of smaller droplets that enhance the mass transfer rate between the lean solvent stream and the natural gas stream.

[0067] The dimensions of various components of the droplet generator **508** may be varied such that the natural gas stream flows at a high velocity. This may be accomplished via either a sudden reduction in the diameter of the annular support ring **602** or a gradual reduction in the diameter of the annular support ring **602**. The outer wall of the droplet generator **508** may be slightly converging in shape, terminating at the point where the natural gas stream and the lean solvent stream are discharged into the downstream pipe. This can allow for the shearing and re-entrainment of any solvent film that is removed from the droplet generator **508**. Further, a radial inward ring, grooved surface, or other suitable equipment may be included on the outer diameter of the droplet generator **508** near the point where the natural gas stream and the lean solvent stream are discharged into the downstream pipe. This may enhance the degree of liquid entrainment within the gas phase.

[0068] The downstream end of the droplet generator **508** may discharge into a section of pipe (not shown). The section of pipe can be a straight section of pipe, or a concentrically expanding section of pipe. The gas entry cone **606** may terminate with a blunt ended cone or a tapered ended cone. In other aspects, the gas entry cone **606** can terminate with a ridged cone, which can include multiple concentric ridges along the cone that provide multiple locations for droplet generation. In addition, any number of gas exit slots **610** may be provided on the cone itself to allow for the removal of solvent film from the droplet generator **508**.

[0069] **Figure 6B** is a side perspective view of the droplet generator **508**. Like numbered items are as described with respect to **Figure 6A**. As shown in **Figure 6B**, the upstream portion of the gas entry cone **606** may extend further into the pipe than the annular support ring **602** and the spokes **604** in the upstream direction. The downstream portion of the gas entry cone **606** can also extend further into the pipe than the annular support ring **602** and the spokes **604** in the downstream direction. The length of the gas entry cone **606** in the downstream direction depends on the type of cone at the end of the gas entry cone **606**, as described further with respect to **Figures 6C** and **6D**.

[0070] **Figure 6C** is a cross-sectional side perspective view of the droplet generator **508** according to a disclosed aspect. Like numbered items are as described with respect to **Figures 6A** and **6B**. According to **Figure 6C**, the gas entry cone **606** of the droplet generator **508** terminates with a tapered ended cone **614**. Terminating the gas entry cone **606** with a tapered ended cone **614** may reduce the overall pressure drop in the pipe caused by the droplet generator **508**.

[0071] **Figure 6D** is a cross-sectional side perspective view of the droplet generator **508a**

according to another disclosed aspect. Like numbered items are as described with respect to **Figures 6A-6C**. According to **Figure 6D**, the gas entry cone **606a** of the droplet generator **508a** terminates with a blunt ended cone **616**. Terminating the gas entry cone **606a** with a blunt ended cone **616** may encourage droplet formation in the center of the pipe.

5 **[0072]** **Figure 7** is a flowchart of a method **700** of separating impurities from a natural gas stream according to disclosed aspects. At block **702** carbon dioxide (CO₂) and hydrogen sulfide (H₂S) are separated from the natural gas stream in a membrane separation system, thereby creating a partially-treated gas stream and a permeate gas stream. The permeate gas stream is comprised primarily of H₂S and CO₂. The partially-treated gas stream is comprised
10 primarily of natural gas. The partially-treated gas stream and the permeate gas stream are at a lower temperature than the natural gas stream. At block **704** the partially-treated gas stream is contacted with a first lean solvent stream in a first contactor to separate H₂S from the partially-treated gas stream, thereby producing a first rich solvent stream and a fully-treated gas stream. At block **706** the permeate gas stream is contacted with a second lean solvent stream in a second
15 contactor to separate H₂S therefrom, to produce a second rich solvent stream and a CO₂ gas stream; At block **708** H₂S is removed from the first and second rich solvent streams, thereby producing the first and second lean solvent streams.

[0073] **Figure 8** is a flowchart of a method **800** of separating impurities from a natural gas stream according to aspects of the disclosure. At block **802** the natural gas stream is cooled
20 through heat exchange with one or more process streams to produce a chilled gas stream. At block **804** the chilled gas stream is contacted with a lean solvent stream in a contactor to separate hydrogen sulfide (H₂S) from the chilled gas stream, thereby producing a rich solvent stream and a partially-treated gas stream. At block **806** H₂S and at least some CO₂ is removed from the rich solvent stream to produce the lean solvent stream. At block **808** the lean solvent
25 stream is recirculated to the contactor. At block **810** CO₂ and H₂S are separated from the partially-treated gas stream in a membrane separation system, thereby creating a fully-treated gas stream and a permeate gas stream. The permeate gas stream is comprised primarily of H₂S and CO₂. The fully-treated gas stream is comprised primarily of natural gas. The fully-treated gas stream and the permeate gas stream are at a lower temperature than the partially-treated
30 gas stream. The fully-treated gas stream and the permeate gas stream comprise the one or more process streams.

[0074] The steps depicted in **Figures 7** and **8** are provided for illustrative purposes only and a particular step may not be required to perform the disclosed methodology. Moreover, **Figures 7** and **8** may not illustrate all the steps that may be performed. The claims, and only

the claims, define the disclosed system and methodology.

[0075] The aspects described herein have several advantages over known technologies. For example, the described technology may greatly reduce the size and cost of systems that treat sour natural gas.

- 5 [0076] Aspects of the disclosure may include any combinations of the methods and systems shown in the following numbered paragraphs. This is not to be considered a complete listing of all possible aspects, as any number of variations can be envisioned from the description above.

1. A method of separating impurities from a natural gas stream, comprising:
10 separating carbon dioxide (CO₂) and hydrogen sulfide (H₂S) from the natural gas stream in a membrane separation system, thereby creating a partially-treated gas stream and a permeate gas stream, the permeate gas stream being comprised primarily of H₂S and CO₂ and the partially-treated gas stream being comprised primarily of natural gas, wherein the partially-treated gas stream and the permeate gas stream are at a lower temperature than the natural gas
15 stream;

contacting the partially-treated gas stream with a first lean solvent stream in a first contactor to separate H₂S from the partially-treated gas stream, thereby producing a first rich solvent stream and a fully-treated gas stream;

- 20 contacting the permeate gas stream with a second lean solvent stream in a second contactor to separate H₂S therefrom to produce a second rich solvent stream and a CO₂ gas stream; and

removing H₂S and CO₂ from the first and second rich solvent streams, thereby producing the first and second lean solvent streams.

2. The method of paragraph 1, further comprising:
25 cooling the partially-treated gas stream prior to the partially-treated gas stream being contacted by the first lean solvent stream; and

cooling the permeate gas stream prior to the permeate gas stream being contacted by the second lean solvent stream.

3. The method of paragraph 2, wherein cooling the partially-treated gas stream and the
30 permeate gas stream is accomplished using one or more coolers.

4. The method of paragraph 1, further comprising cooling at least one of the first and

second lean solvent streams to below ambient temperature after removing H₂S therefrom.

5. The method of paragraph 1, wherein removing H₂S from the first and second rich solvent streams comprises separating H₂S from the first and second rich solvent streams in a regenerator and producing a regenerated solvent stream.

5 6. The method of paragraph 5, further comprising:

dividing the regenerated solvent stream to form the first and second lean solvent streams.

7. The method of paragraph 5, comprising:

forming the second lean solvent stream from the regenerated solvent stream; and

10 forming the first lean solvent stream from the second rich solvent stream.

8. The method of paragraph 1, further comprising:

removing acid gas from the fully-treated gas stream; and

dehydrating the fully-treated stream.

9. The method of paragraph 8, wherein the acid gas comprises CO₂, and further
15 comprising:

compressing the CO₂ removed from the fully-treated gas stream; and

combining the compressed CO₂ with the CO₂ gas stream.

10. The method of any one of paragraphs 1-9, wherein at least one of the first and second contactors is a co-current contacting system, and further comprising:

20 receiving a gas stream, comprising one of the natural gas stream and the permeate gas stream, and a liquid stream, comprising one of the first and second lean solvent streams, in the co-current contacting system located in-line within a pipe, the co-current contacting system including a droplet generator and a mass transfer section;

25 using the droplet generator, generating droplets from the liquid stream and dispersing the droplets into the gas stream;

using the mass transfer section, providing a mixed, two-phase flow having a vapor phase and a liquid phase, wherein the liquid phase includes the liquid stream with H₂S and/or CO₂ absorbed from the gas stream, and wherein the vapor phase includes the gas stream; and

separating the vapor phase from the liquid phase.

11. The method of paragraph 10, wherein the droplet generator comprises:
- an annular support ring securing the droplet generator in-line within the pipe;
 - a plurality of spokes extending from the annular support ring, the annular support ring having a plurality of liquid channels allowing the liquid stream to flow through the plurality of
 - 5 spokes and out of injection orifices disposed on the plurality of spokes; and
 - a gas entry cone supported by the plurality of spokes and allowing:
 - a first portion of the gas stream to flow through a hollow section of the gas entry cone and through gas exit slots included in the plurality of spokes, and
 - a second portion of the gas stream to flow around the gas entry cone and between the
 - 10 plurality of spokes, wherein the second portion of the gas stream is separate from the first portion of the gas stream.
12. The method of any one of paragraphs 10-11, wherein the co-current contacting system is one of a plurality of co-current contacting systems connected in series, said plurality of co-current contacting systems including a last co-current contacting system;
- 15 wherein each of the plurality of co-current contacting system comprises:
- a co-current contactor including a droplet generator and a mass transfer section, the droplet generator generating droplets of the liquid stream and dispersing the droplets into a gas stream received from a previous co-current contacting system, and the mass transfer section providing a mixed, two-phase flow having a vapor phase and a liquid phase; and
 - 20 a separation system that separates the vapor phase from the liquid phase, wherein the vapor phase includes a treated gas stream and the liquid phase includes the liquid from which droplets are generated in a co-current contactor of a previous co-current contacting system.
13. The method of any one of paragraphs 1-12, wherein the lean solvent stream comprises a hindered amine.
- 25 14. A system for separating impurities from a natural gas stream, comprising:
- a membrane separation system configured to separate carbon dioxide (CO₂) and hydrogen sulfide (H₂S) from the natural gas stream, thereby creating a partially-treated gas stream and a permeate gas stream, the permeate gas stream being comprised primarily of H₂S and CO₂ and the partially-treated gas stream being comprised primarily of natural gas, wherein
 - 30 the partially-treated gas stream and the permeate gas stream are at a lower temperature than the natural gas stream;

a first contactor configured to contact the partially-treated gas stream with a first lean solvent stream to separate H₂S from the partially-treated gas stream, thereby producing a first rich solvent stream and a fully-treated gas stream;

5 a second contactor configured to contact the permeate gas stream with a second lean solvent stream to separate H₂S therefrom to produce a second rich solvent stream and a CO₂ gas stream; and

a regenerator configured to remove H₂S and CO₂ from the first and second rich solvent streams, thereby producing the first and second lean solvent streams.

15. The system of paragraph 14, further comprising:

10 a first cooler configured to cool the partially-treated gas stream prior to the partially-treated gas stream being contacted by the first lean solvent stream; and

a second cooler configured to cool the permeate gas stream prior to the permeate gas stream being contacted by the second lean solvent stream.

16. The system of any one of paragraphs 14-15, further comprising a refrigeration system
15 configured to cool at least one of the first and second lean solvent streams to below ambient temperature after removing H₂S therefrom.

17. The system of any one of paragraphs 14-16, further comprising:

a polisher configured to remove acid gas from the fully-treated gas stream; and

a dehydrator configured to remove moisture from the fully-treated stream.

20 18. The system of paragraph 17, wherein the acid gas comprises CO₂, and further comprising:

a compressor configured to compress the CO₂ removed from the fully-treated gas stream.

19. The system of any one of paragraphs 14-18, wherein at least one of the first and second
25 contactors is a co-current contacting system located in-line within a pipe, the co-current contacting system receiving a gas stream, comprising one of the natural gas stream and the permeate gas stream, and a liquid stream, comprising one of the first and second lean solvent streams, the co-current contacting system including;

30 a co-current contactor including a droplet generator and a mass transfer section, the droplet generator configured to generate droplets from the liquid stream and to disperse the droplets into the gas stream, and the mass transfer section configured to provide a mixed, two-

phase flow having a vapor phase and a liquid phase, wherein the liquid phase includes the liquid stream with H₂S and/or CO₂ absorbed from the gas stream, and wherein the vapor phase includes the gas stream; and

a separation system configured to separate the vapor phase from the liquid phase.

5 20. The system of paragraph 19, wherein the droplet generator comprises:

an annular support ring securing the droplet generator in-line within the pipe;

a plurality of spokes extending from the annular support ring, the annular support ring having a plurality of liquid channels allowing the liquid stream to flow through the plurality of spokes and out of injection orifices disposed on the plurality of spokes; and

10 a gas entry cone supported by the plurality of spokes and allowing

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

15 a second portion of the gas stream to flow around the gas entry cone and between the plurality of spokes, wherein the second portion of the gas stream is separate from the first portion of the gas stream.

21. The system of any one of paragraphs 19-20, wherein the co-current contacting system is one of a plurality of co-current contacting systems connected in series, said plurality of co-current contacting systems including a last co-current contacting system;

wherein each of the plurality of co-current contacting system comprises

20 a co-current contactor including a droplet generator and a mass transfer section, the droplet generator generating droplets of the liquid stream and dispersing the droplets into a gas stream received from a previous co-current contacting system, and the mass transfer section providing a mixed, two-phase flow having a vapor phase and a liquid phase; and

25 a separation system that separates the vapor phase from the liquid phase, wherein the vapor phase includes a treated gas stream and the liquid phase includes liquid from which droplets are generated in a co-current contactor of a previous co-current contacting system.

22. The system of any one of paragraphs 14-21, wherein the lean solvent stream comprises a hindered amine.

[0077] It should be understood that the numerous changes, modifications, and alternatives
30 to the preceding disclosure can be made without departing from the scope of the disclosure. The preceding description, therefore, is not meant to limit the scope of the disclosure. Rather,

the scope of the disclosure is to be determined only by the appended claims and their equivalents. It is also contemplated that structures and features in the present examples can be altered, rearranged, substituted, deleted, duplicated, combined, or added to each other.

CLAIMS

1. A method of separating impurities from a natural gas stream, comprising:

separating carbon dioxide (CO₂) and hydrogen sulfide (H₂S) from the natural gas
5 stream in a membrane separation system, thereby creating a partially-treated gas stream and a
permeate gas stream, the permeate gas stream being comprised primarily of H₂S and CO₂ and
the partially-treated gas stream being comprised primarily of natural gas, wherein the partially-
treated gas stream and the permeate gas stream are at a lower temperature than the natural gas
stream;

10 contacting the partially-treated gas stream with a first lean solvent stream comprising a
hindered amine in a first contactor to separate H₂S from the partially-treated gas stream, thereby
producing a first rich solvent stream and a fully-treated gas stream;

contacting the permeate gas stream with a second lean solvent stream comprising a
hindered amine in a second contactor to separate H₂S therefrom to produce a second rich
15 solvent stream and a CO₂ gas stream; and

removing H₂S and CO₂ from the first and second rich solvent streams, thereby
producing the first and second lean solvent streams.

2. The method of claim 1, further comprising:

20 cooling the partially-treated gas stream prior to the partially-treated gas stream being
contacted by the first lean solvent stream; and

cooling the permeate gas stream prior to the permeate gas stream being contacted by
the second lean solvent stream.

25 3. The method of claim 2, wherein cooling the partially-treated gas stream and the
permeate gas stream is accomplished using one or more coolers.

4. The method of any one of claims 1 to 3, further comprising cooling at least one of the
first and second lean solvent streams to below ambient temperature after removing H₂S
30 therefrom.

5. The method of any one of claims 1 to 4, wherein removing H₂S from the first and second rich solvent streams comprises separating H₂S from the first and second rich solvent streams in a regenerator and producing a regenerated solvent stream.

5 6. The method of claim 5, further comprising:

dividing the regenerated solvent stream to form the first and second lean solvent streams.

7. The method of claim 5, comprising:

10 forming the second lean solvent stream from the regenerated solvent stream; and
forming the first lean solvent stream from the second rich solvent stream.

8. The method of any one of claims 1 to 7, further comprising:

removing acid gas from the fully-treated gas stream; and
15 dehydrating the fully-treated stream.

9. The method of claim 8, wherein the acid gas comprises CO₂, and further comprising:

compressing the CO₂ removed from the fully-treated gas stream; and
combining the compressed CO₂ with the CO₂ gas stream.

20

10. The method of any one of claims 1-9, wherein at least one of the first and second contactors is a co-current contacting system, and further comprising:

receiving a gas stream, comprising one of the natural gas stream and the permeate gas stream, and a liquid stream, comprising one of the first and second lean solvent streams, in the
25 co-current contacting system located in-line within a pipe, the co-current contacting system including a droplet generator and a mass transfer section;

using the droplet generator, generating droplets from the liquid stream and dispersing the droplets into the gas stream;

using the mass transfer section, providing a mixed, two-phase flow having a vapor phase and a liquid phase, wherein the liquid phase includes the liquid stream with H₂S and/or CO₂ absorbed from the gas stream, and wherein the vapor phase includes the gas stream; and separating the vapor phase from the liquid phase.

5

11. The method of claim 10, wherein the droplet generator comprises:

an annular support ring securing the droplet generator in-line within the pipe;

a plurality of spokes extending from the annular support ring, the annular support ring having a plurality of liquid channels allowing the liquid stream to flow through the plurality of
10 spokes and out of injection orifices disposed on the plurality of spokes; and

a gas entry cone supported by the plurality of spokes and allowing

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

a second portion of the gas stream to flow around the gas entry cone and
15 between the plurality of spokes, wherein the second portion of the gas stream is separate from the first portion of the gas stream.

12. The method of claim 10 or 11, wherein the co-current contacting system is one of a plurality of co-current contacting systems connected in series, said plurality of co-current
20 contacting systems including a last co-current contacting system;

wherein each of the plurality of co-current contacting system comprises

a co-current contactor including a droplet generator and a mass transfer section, the droplet generator generating droplets of the liquid stream and dispersing the droplets into a gas stream received from a previous co-current contacting system, and the mass
25 transfer section providing a mixed, two-phase flow having a vapor phase and a liquid phase; and

a separation system that separates the vapor phase from the liquid phase, wherein the vapor phase includes a treated gas stream and the liquid phase includes the liquid from which droplets are generated in a co-current contactor of a previous co-current contacting system.

30

13. A system for separating impurities from a natural gas stream, comprising:

a membrane separation system configured to separate carbon dioxide (CO₂) and hydrogen sulfide (H₂S) from the natural gas stream, thereby creating a partially-treated gas stream and a permeate gas stream, the permeate gas stream being comprised primarily of H₂S and CO₂ and the partially-treated gas stream being comprised primarily of natural gas, wherein the partially-treated gas stream and the permeate gas stream are at a lower temperature than the natural gas stream;

a first contactor configured to contact the partially-treated gas stream with a first lean solvent stream comprising a hindered amine to separate H₂S from the partially-treated gas stream, thereby producing a first rich solvent stream and a fully-treated gas stream;

a second contactor configured to contact the permeate gas stream with a second lean solvent stream comprising a hindered amine to separate H₂S therefrom to produce a second rich solvent stream and a CO₂ gas stream; and

a regenerator configured to remove H₂S and CO₂ from the first and second rich solvent streams, thereby producing the first and second lean solvent streams.

14. The system of claim 13, further comprising:

a first cooler configured to cool the partially-treated gas stream prior to the partially-treated gas stream being contacted by the first lean solvent stream; and

a second cooler configured to cool the permeate gas stream prior to the permeate gas stream being contacted by the second lean solvent stream.

15. The system of claim 13 or 14, further comprising a refrigeration system configured to cool at least one of the first and second lean solvent streams to below ambient temperature after removing H₂S therefrom.

16. The system of any one of claims 13 to 15, further comprising:

a polisher configured to remove acid gas from the fully-treated gas stream; and

a dehydrator configured to remove moisture from the fully-treated stream.

17. The system of claim 16, wherein the acid gas comprises CO₂, and further comprising:
a compressor configured to compress the CO₂ removed from the fully-treated gas stream.

5 18. The system of any one of claims 13 to 17, wherein at least one of the first and second contactors is a co-current contacting system located in-line within a pipe, the co-current contacting system receiving a gas stream, comprising one of the natural gas stream and the permeate gas stream, and a liquid stream, comprising one of the first and second lean solvent streams, the co-current contacting system including

10 a co-current contactor including a droplet generator and a mass transfer section, the droplet generator configured to generate droplets from the liquid stream and to disperse the droplets into the gas stream, and the mass transfer section configured to provide a mixed, two-phase flow having a vapor phase and a liquid phase, wherein the liquid phase includes the liquid stream with H₂S and/or CO₂ absorbed from the gas stream, and wherein the vapor phase
15 includes the gas stream; and

a separation system configured to separate the vapor phase from the liquid phase.

19. The system of claim 18, wherein the droplet generator comprises:

an annular support ring securing the droplet generator in-line within the pipe;

20 a plurality of spokes extending from the annular support ring, the annular support ring having a plurality of liquid channels allowing the liquid stream to flow through the plurality of spokes and out of injection orifices disposed on the plurality of spokes; and

a gas entry cone supported by the plurality of spokes and allowing

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

a second portion of the gas stream to flow around the gas entry cone and between the plurality of spokes, wherein the second portion of the gas stream is separate from the first portion of the gas stream.

20. The system of claim 18 or 19, wherein the co-current contacting system is one of a plurality of co-current contacting systems connected in series, said plurality of co-current contacting systems including a last co-current contacting system;

wherein each of the plurality of co-current contacting system comprises

- 5 a co-current contactor including a droplet generator and a mass transfer section, the droplet generator generating droplets of the liquid stream and dispersing the droplets into a gas stream received from a previous co-current contacting system, and the mass transfer section providing a mixed, two-phase flow having a vapor phase and a liquid phase; and
- 10 a separation system that separates the vapor phase from the liquid phase, wherein the vapor phase includes a treated gas stream and the liquid phase includes liquid from which droplets are generated in a co-current contactor of a previous co-current contacting system.