

CRYOGENIC SYSTEM FOR REMOVING ACID GASES FROM A HYDROCARBON GAS STREAM WITH SOLID CO₂ RECOVERY

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. Provisional Patent Application 61/240,850 filed September 9, 2009 entitled Cryogenic System for Removing Acid Gases From a Hydrocarbon Gas Stream, With Solid CO₂ Recovery, the entirety of which is incorporated by reference herein.

BACKGROUND OF THE INVENTION

5 [0002] This section is intended to introduce various aspects of the art, which may be associated with exemplary embodiments of the present disclosure. This discussion is believed to assist in providing 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 admissions of prior art.

10 Field of the Invention

[0003] The present invention relates to the field of component separation. More specifically, the present invention relates to the separation of carbon dioxide and other acid gases from a hydrocarbon fluid stream.

Discussion of Technology

15 [0004] The production of hydrocarbons from a reservoir oftentimes carries with it the incidental production of non-hydrocarbon gases. Such gases include contaminants such as hydrogen sulfide (H₂S) and carbon dioxide (CO₂). When H₂S and CO₂ are produced as part of a hydrocarbon gas stream (such as methane or ethane), the gas stream is sometimes referred to as "sour gas."

20 [0005] Sour gas is usually treated to remove CO₂, H₂S, and other contaminants before it is sent downstream for further processing or sale. The separation process creates an issue as to the disposal of the separated contaminants. In some cases, the concentrated acid gas (consisting primarily of H₂S and CO₂) is sent to a sulfur recovery unit ("SRU"). The SRU converts the H₂S into benign elemental sulfur. However, in some areas (such as the Caspian
25 Sea region), additional elemental sulfur production is undesirable because there is a limited

market. Consequently, millions of tons of sulfur have been stored in large, above-ground blocks in some areas of the world, most notably Canada and Kazakhstan.

[0006] While the sulfur is stored on land, the carbon dioxide gas is oftentimes vented to the atmosphere. However, the practice of venting CO₂ is sometimes undesirable. One proposal to minimizing CO₂ emissions is a process called acid gas injection ("AGI"). AGI means that unwanted sour gases are re-injected into a subterranean formation under pressure and sequestered for potential later use. Alternatively, the carbon dioxide may be used to create artificial reservoir pressure for enhanced oil recovery operations.

[0007] To facilitate AGI, it is desirable to have a gas processing facility that separates the acid gas components from the hydrocarbon gases. However, for "highly sour" streams, that is, production streams containing greater than about 15% CO₂ and/or H₂S, it can be particularly challenging to design, construct, and operate a facility that can economically separate contaminants from the desired hydrocarbons. Many natural gas reservoirs contain relatively low percentages of hydrocarbons (less than 40%, for example) and high percentages of acid gases, principally carbon dioxide, but also hydrogen sulfide, carbonyl sulfide, carbon disulfide and various mercaptans. In these instances, cryogenic gas processing may be beneficially employed.

[0008] Cryogenic gas processing is a distillation process sometimes used for gas separation. Cryogenic gas separation generates a cooled overhead gas stream at moderate pressures (e.g., 300-600 pounds per square inch gauge (psig)). In addition, liquefied acid gas is generated as a "bottoms" product. Since the liquefied acid gas has a relatively high density, hydrostatic head can be beneficially used in an AGI well to assist in the injection process. In this respect, the acid gas may be recovered as a liquid at column pressure (e.g. 300 – 600 psia). This means that the energy required to pump the liquefied acid gas into the formation is lower than the energy required to compress low-pressure acid gases to reservoir pressure.

[0009] Cryogenic gas processing has additional advantages. For example, a solvent is not required for the adsorption of carbon dioxide. In addition, methane recovery may be obtained in a single vessel (as opposed to the multi-vessel systems used in the Ryan-Holmes processes). Finally, depending on the refrigeration capacity, a tight H₂S specification, e.g., down to or less than 4 ppm, may be met for the product gas.

[0010] Challenges also exist with respect to cryogenic distillation of sour gases. When CO₂ is present at concentrations greater than about 5 mol. percent in the gas to be processed,

it will freeze out as a solid in a standard cryogenic distillation unit. The formation of CO₂ as a solid disrupts the cryogenic distillation process. To circumvent this problem, the assignee has previously designed various Controlled Freeze Zone™ (CFZ™) processes. The CFZ™ process takes advantage of the propensity of carbon dioxide to form solid particles by
5 allowing frozen CO₂ particles to form within an open portion of the distillation tower, and then capturing the particles as they fall onto a melt tray. As a result, a clean methane stream (along with any nitrogen or helium present in the raw gas) is generated at the top of the tower, while a cold liquid CO₂/H₂S stream is generated at the bottom of the tower as the bottoms product.

10 [0011] Certain aspects of the CFZ™ process and associated equipment are described in U.S. Pat. No. 4,533,372; U.S. Pat. No. 4,923,493; U.S. Pat. No. 5,062,270; U.S. Pat. No. 5,120,338; and U.S. Pat. No. 6,053,007.

[0012] As generally described in the above U.S. patents, the distillation tower, or column, used for cryogenic gas processing includes a lower distillation zone and an intermediate
15 controlled freezing zone. Preferably, an upper rectification zone is also included. The column operates to create solid CO₂ particles by providing a portion of the column having a temperature range below the freezing point of carbon dioxide, but above the boiling temperature of methane at that pressure. More preferably, the controlled freezing zone is operated at a temperature and pressure that permits methane and other light hydrocarbon
20 gases to vaporize, while causing CO₂ to form frozen (solid) particles.

[0013] As the gas feed stream moves up the column, frozen CO₂ particles break out of the feed stream and gravitationally descend from the controlled freezing zone onto a melt tray. There, the particles liquefy. A carbon dioxide-rich liquid stream then flows from the melt tray down to the lower distillation zone at the bottom of the column. The lower distillation
25 zone is maintained at a temperature and pressure at which substantially no carbon dioxide solids are formed, but dissolved methane boils out. In one aspect, a bottom acid gas stream is created in the distillation zone at 30° to 40° F.

[0014] The controlled freezing zone includes a cold liquid spray. This is a methane-enriched liquid stream known as “reflux.” As the vapor stream of light hydrocarbon gases
30 and entrained sour gases moves upward through the column, the vapor stream encounters the liquid spray. The cold liquid spray aids in breaking out solid CO₂ particles while permitting methane gas to evaporate and flow upward into the rectification zone.

[0015] In the upper rectification zone, the methane (or overhead gas) is captured and piped away for sale or made available for fuel. In one aspect, the overhead methane stream is released at about -130° F. The overhead gas may be partially liquefied by additional cooling, and a part of the liquid returned to the column as the reflux. The liquid reflux is then injected
5 as the cold spray into the rectification zone and the controlled freezing zone. In this respect, the process of generating cold liquid methane for reflux requires equipment ancillary to the CFZ tower. This equipment includes pipes, nozzles, compressors, separators, pumps, and expansion valves.

[0016] The methane produced in the upper rectification zone meets most specifications
10 for pipeline delivery. For example, the methane can meet a pipeline CO₂ specification of less than 2 mol. percent, as well as a 4 ppm H₂S specification, if sufficient reflux is generated. However, more stringent specifications for higher purity natural gas exist for applications such as helium recovery, cryogenic natural gas liquids recovery, conversion to liquid natural gas (LNG), and nitrogen rejection.

[0017] The more stringent specifications may be met by increasing the quantity of liquid methane reflux. This, in turn, requires larger refrigeration equipment. The more vigorously the operator wishes to remove CO₂, the greater the refrigeration requirements become.

[0018] There is a need to reduce the refrigeration requirements of the CFZ process while still reducing the CO₂ content down to very low levels. There is also a need for a cryogenic
20 gas separation system and accompanying processes that are augmented by other CO₂ removal techniques. Further, there is a need for a cryogenic gas separation process that is able to reduce the CO₂ and H₂S content of the gas down to levels acceptable for LNG specifications for downstream liquefaction processes without increasing refrigeration equipment capacity.

SUMMARY OF THE INVENTION

[0019] A system for removing acid gases from a raw gas stream is provided. In one embodiment, the system includes a cryogenic distillation tower. The distillation tower has an intermediate controlled freezing zone. The controlled freezing zone, or spray section, receives a cold liquid spray comprised primarily of methane. The cold spray is preferably a liquid reflux generated from an overhead loop downstream of the distillation tower.

[0020] The cryogenic distillation tower is configured to receive a raw gas stream, and then separate the raw gas stream into (1) an overhead methane gas stream, and (2) a substantially solid material comprised of carbon dioxide.

[0021] The system also has refrigeration equipment downstream of the cryogenic distillation tower. The refrigeration equipment serves to cool the overhead methane stream and then return a portion of the overhead methane stream as reflux to the rectification zone in the cryogenic distillation tower. A portion of the liquid reflux may be sprayed in the controlled freezing zone to cause precipitation of solid carbon dioxide particles.

[0022] The system further comprises a collector tray. The collector tray is positioned below the controlled freezing zone for receiving the solid CO₂ particles as they are precipitated in the controlled freezing zone. Preferably, the collector tray has an inclined base to direct precipitate into a central downcomer. The downcomer, in turn, may optionally include a mechanical translation device such as an auger to move a slurry that includes the solid CO₂ material out of the cryogenic distillation tower and towards a CO₂ recovery facility.

[0023] The CO₂ recovery facility is preferably comprised of a plurality of filters. Thus, the system includes at least a first filter for receiving the slurry. The slurry is separated into a frozen or solid material (referred to as a "filter cake") and a liquid material (referred to as a "filtrate"). The solid material is comprised primarily of carbon dioxide, while the liquid material comprises methane. The liquid material may also comprise smaller amounts of carbon dioxide, hydrogen sulfide, mercury and heavy hydrocarbons. It should be understood that as used herein, the slurry is referred to as include a solid material and a liquid material, but may further include a gaseous material or other non-solid material. The liquid material portion of the slurry may be separated therefrom for further processing. The processing of the non-solid material may convert liquids into gases and/or solids, which may subsequently be used for various purposes, such as reinjection to the recovery facility. However, for ease of reference, the non-solid portion of the slurry, once separated from the slurry, may be referred to herein as the liquid material regardless of the state of the material.

[0024] The system further includes a liquid return line. The liquid return line returns at least a portion of the liquid material from the CO₂ recovery facility to the cryogenic distillation tower. There, further processing of the methane and any acid gas components entrained therein takes place.

[0025] The cryogenic distillation tower preferably includes an upper rectification zone above the controlled freezing zone. The tower may further have a lower distillation zone below the controlled freezing zone. In the latter instance, the cryogenic distillation tower is preferably configured to receive the raw gas stream into the lower distillation zone.

Moreover, the tower receives the liquid material from the liquid return line into the lower distillation zone. Further processing of the methane and trace acid gas components takes place in the lower distillation zone. There, the methane vaporizes in the warm lower distillation zone, travels upward through the controlled freezing zone and upper rectification zone, and merges with the overhead methane stream. The carbon dioxide components will mostly vaporize in the lower distillation zone, move upward into the controlled freezing zone, and precipitate back down on the collector tray. The CO₂ components are then transported to the CO₂ recovery facility with the slurry.

[0026] When the tower includes a lower distillation zone, acid gases will fall out of the relatively warm lower distillation zone as a bottoms liquid stream. The bottoms liquid stream may comprise ethane, propane, butane, hydrogen sulfide, or combinations thereof, in substantially liquid phase. Carbon dioxide may also be present.

[0027] In one arrangement, the cryogenic distillation tower does not include a lower distillation zone. In this instance, the raw gas stream is injected into the distillation tower in the controlled freezing zone. In addition, the liquid return line merges at least a portion of the liquid material with the raw gas stream before the raw gas stream is injected into the cryogenic distillation tower, or simultaneously therewith. The distillation tower will not have a bottoms stream for capturing hydrogen sulfide; instead, hydrogen sulfide and trace elements of methane and carbon dioxide are captured within the CO₂ recovery facility through second and, optionally, third and fourth filters. Hydrogen sulfide and the trace elements of methane and carbon dioxide are released from the filters as cold liquid filtrate. The filtrate is subsequently processed in a distillation tower so that a recovery methane stream is separated from the acid gases. The recovery methane stream is merged with the overhead methane stream for sale as a commercial product.

[0028] In either embodiment, a heat exchanger is optionally provided at the end of the CO₂ recovery facility. The heat exchanger is configured to warm substantially solid material taken at least partially from a final-stage filter cake to produce a substantially pure carbon dioxide stream, in liquid phase. The substantially solid material is warmed by using, for example, the raw gas stream as a heat source.

[0029] A method for removing acid gases from a raw gas stream using an acid gas removal system is also provided herein. The raw gas stream comprises methane, carbon dioxide and, most likely, other components such as ethane and hydrogen sulfide.

[0030] In one embodiment, the method first includes providing a cryogenic distillation tower. The tower has a controlled freezing zone that receives a cold liquid spray comprised primarily of methane. The tower further has a collector tray below the controlled freezing zone.

5 [0031] The method also includes injecting the raw gas stream into the cryogenic distillation tower. In one arrangement, the raw gas stream is injected into the distillation tower in a lower distillation zone below the controlled freezing zone. In another arrangement, the raw gas stream is injected into the distillation tower in the controlled freezing zone itself. Preferably, the raw gas stream has been substantially dehydrated before
10 it is injected into the distillation tower.

[0032] The method further includes chilling the raw gas stream. Chilling the raw gas stream causes carbon dioxide within the raw gas stream to precipitate upon the collector tray as a substantially solid material and become a slurry thereon. At the same time, the pressure in the distillation tower is lower than a feed stream, causing methane within the raw gas
15 stream to flash. The methane travels through a rectification zone above the controlled freezing zone and exits the cryogenic distillation tower as an overhead methane stream.

[0033] The method also includes passing the overhead methane stream through a refrigeration system downstream of the cryogenic distillation tower. The refrigeration system cools at least a portion of the overhead methane stream to a liquid. The method additionally
20 includes returning a portion of the cooled overhead methane stream to the cryogenic distillation tower as liquid reflux. A portion of the liquid reflux, in turn, may serve as the cold liquid spray.

[0034] Also as part of the method, the substantially solid material is removed from the cryogenic distillation tower. In one aspect, removal of the substantially solid material is
25 accomplished through use of a mechanical translation device such as a screw conveyor or auger. The auger may reside within a downcomer of the collector tray as indicated above. The auger cuts through the substantially solid material, or slurry, translating it out of the distillation tower and towards solid CO₂ processing equipment. It is preferred that the collector tray operates at a temperature of, for example, about -70° F to -80° F. This is at or
30 slightly below the freezing point of the CO₂ component.

[0035] The method further includes separating the substantially solid material into a substantially solid filter cake and a substantially liquid filtrate. The filter cake is comprised primarily of carbon dioxide, while the filtrate comprises methane and residual carbon

dioxide. The filtrate may include other components such as heavy hydrocarbons and even light aromatics.

[0036] The separating step may be accomplished by passing the substantially solid material or slurry through a first filter. This produces a first filter cake comprised primarily of solid carbon dioxide, and a first filtrate comprising methane and carbon dioxide, in liquid phase. The first filter may be, for example, a porous media or a centrifuge.

[0037] The separating step may further comprise rinsing the first filter cake using a cold carbon dioxide stream, mixing the first filter cake to produce a first solid-liquid slurry, and delivering the first solid-liquid slurry to a second filter. The second filter produces a second filter cake comprised primarily of solid carbon dioxide, and a second filtrate comprising methane and carbon dioxide, again in liquid phase.

[0038] While a single separation step may be sufficient in some implementations, additional CO₂ removal may be undertaken. For example, the separating step may further comprise rinsing the second filter cake using the cold carbon dioxide stream, mixing the second filter cake to produce a solid-liquid slurry, and delivering the solid-liquid slurry to yet a third filter. This produces a third filter cake comprised primarily of solid carbon dioxide, and a third filtrate comprising yet a smaller amount of methane and carbon dioxide, again in liquid phase.

[0039] The method also includes returning at least a portion of the second liquid material to the cryogenic distillation tower. In one aspect, the second liquid material is directed back to the lower distillation zone. In another aspect, the second liquid material is merged with the raw gas stream and is re-injected into the tower in the controlled freezing zone.

[0040] In one embodiment of the method, the first filtrate and the second filtrate are combined. The combined fluid from the filtrates forms the liquid filtrate that is returned to the cryogenic distillation tower. In this instance, the combined liquid filtrate is preferably injected into the lower distillation zone.

[0041] In another embodiment of the method, only the first filtrate is returned to the distillation tower as the liquid filtrate. In this instance, the first filtrate may be returned back to the controlled freezing zone. The distillation tower preferably will not have a lower distillation zone. The second and, optionally, third (or subsequent) filtrates are delivered to a separate, downstream distillation tower where residual acid gases are finally separated from methane. In this instance, a recovery methane stream is obtained that is merged with the overhead methane stream of the cryogenic distillation tower for sale.

Brief Description of the Drawings

[0042] So that the manner in which the present inventions can be better understood, certain illustrations, charts and/or flow charts are appended hereto. It is to be noted, however, that the drawings illustrate only selected embodiments of the inventions and are therefore not
5 to be considered limiting of scope, for the inventions may admit to other equally effective embodiments and applications.

[0043] Figure 1 is a side view of an illustrative CFZ distillation tower, in one embodiment. A chilled raw gas stream is seen being injected into the intermediate controlled freezing zone of the tower.

10 [0044] Figure 2A is a plan view of a melt tray, in one embodiment. The melt tray resides within the tower below the controlled freezing zone.

[0045] Figure 2B is a cross-sectional view of the melt tray of Figure 2A, taken across line B-B.

15 [0046] Figure 2C is a cross-sectional view of the melt tray of Figure 2A, taken across line C-C.

[0047] Figure 3 is an enlarged side view of stripping trays in the lower distillation zone of the distillation tower, in one embodiment.

[0048] Figure 4A is a perspective view of a jet tray as may be used in either the lower distillation zone or in the upper rectification zone of the distillation tower, in one
20 embodiment.

[0049] Figure 4B is a side view of one of the openings in the jet tray of Figure 4A.

[0050] Figure 5 is a side view of the intermediate controlled freezing zone of the distillation tower of Figure 1. In this view, two illustrative baffles have been added to the intermediate controlled freeze zone.

25 [0051] Figure 6A is a plan view of a collector tray, in one embodiment. In one arrangement of a gas processing facility, the collector tray resides within the tower below the controlled freezing zone.

[0052] Figure 6B is a cross-sectional view of the collector tray of Figure 6A, taken across line B-B.

30 [0053] Figure 6C is a cross-sectional view of the collector tray of Figure 6A, taken across line C-C.

[0054] Figure 6D is a cross-sectional view of the collector tray of Figure 6A, in an alternate embodiment. The view is again taken across line B-B.

[0055] Figure 7 is a schematic diagram showing a gas processing facility for removing acid gases from a raw gas stream in accordance with the present invention, in one embodiment. The collector tray of Figure 6A or Figure 6D is employed.

[0056] Figure 8 is a schematic diagram showing a gas processing facility for removing acid gases from a gas stream in accordance with the present invention, in an alternate embodiment. The collector tray of Figure 6A or Figure 6D is again employed.

[0057] Figure 9 presents a flowchart for a method of removing acid gases from a gas stream in accordance with the present invention, in one embodiment.

Detailed Description of Certain Embodiments

Definitions

[0058] As used herein, the term "hydrocarbon" refers to an organic compound that includes primarily, if not exclusively, the elements hydrogen and carbon. Hydrocarbons generally fall into two classes: aliphatic, or straight chain hydrocarbons, and cyclic, or closed ring hydrocarbons, including cyclic terpenes. Examples of hydrocarbon-containing materials include any form of natural gas, oil, coal, and bitumen that can be used as a fuel or upgraded into a fuel.

[0059] As used herein, the term "hydrocarbon fluids" refers to a hydrocarbon or mixtures of hydrocarbons that are gases or liquids. For example, hydrocarbon fluids may include a hydrocarbon or mixtures of hydrocarbons that are gases or liquids at formation conditions, at processing conditions or at ambient conditions (15° C and 1 atm pressure). Hydrocarbon fluids may include, for example, oil, natural gas, coal bed methane, shale oil, pyrolysis oil, pyrolysis gas, a pyrolysis product of coal, and other hydrocarbons that are in a gaseous or liquid state.

[0060] The term "mass transfer device" refers to any object that receives fluids to be contacted, and passes those fluids to other objects, such as through gravitational flow. One non-limiting example is a tray for stripping out certain fluids. A grid packing is another example.

[0061] As used herein, the term "fluid" refers to gases, liquids, and combinations of gases and liquids, as well as to combinations of gases and solids, and combinations of liquids and solids.

[0062] As used herein, the term "condensable hydrocarbons" means those hydrocarbons that condense at about 15° C and one atmosphere absolute pressure. Condensable

hydrocarbons may include, for example, a mixture of hydrocarbons having carbon numbers greater than 4.

[0063] As used herein, the term “closed loop refrigeration system” means any refrigeration system wherein an external working fluid such as propane or ethylene is used as a coolant to chill an overhead methane stream. This is in contrast to an “open loop refrigeration system” wherein a portion of the overhead methane stream itself is used as the working fluid.

[0064] As used herein, the term “subsurface” refers to geologic strata occurring below the earth's surface.

10 Description of Specific Embodiments

[0065] **Figure 1** presents a schematic view of a cryogenic distillation tower **100** as may be used in connection with the present inventions, in one embodiment. The cryogenic distillation tower **100** may be interchangeably referred to herein as a “cryogenic distillation tower,” a “column,” a “CFZ column,” or a “splitter tower.”

15 [0066] The cryogenic distillation tower **100** of **Figure 1** receives an initial fluid stream **10**. The fluid stream **10** is comprised primarily of production gases. Typically, the fluid stream represents a dried gas stream from a wellhead (not shown), and contains about 65% to about 95% methane. However, the fluid stream **10** may contain a lower percentage of methane, such as about 30% to 65%, or even 20% to 40%.

20 [0067] The methane may be present along with trace elements of other hydrocarbon gases such as ethane. In addition, trace amounts of helium and nitrogen may be present. In the present application, the fluid stream **10** will also include certain contaminants. These include acid gases such as CO₂ and H₂S.

[0068] The initial fluid stream **10** may be at a post-production pressure of approximately 25 600 pounds per square inch (psi) or lower. In some instances, the pressure of the initial fluid stream **10** may be up to about 750 psi or even 1,000 psi.

[0069] The fluid stream **10** is typically chilled before entering the distillation tower **100**. A heat exchanger **150**, such as a shell-and-tube exchanger, is provided for the initial fluid stream **10**. A refrigeration unit (not shown) provides cooling fluid (such as liquid propane) to heat exchanger **150** to bring the temperature of the initial fluid stream **10** down to about -30° to -40° F. The chilled fluid stream may then be moved through an expansion device **152**. The expansion device **152** may be, for example, a Joule-Thompson (“J-T”) valve.

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[0070] The expansion device **152** serves as an expander to obtain additional cooling of the fluid stream **10**. Preferably, partial liquefaction of the fluid stream **10** is also created. A Joule-Thompson (or “J-T”) valve is preferred for gas feed streams that are prone to forming solids. The expansion device **152** is preferably mounted close to the cryogenic distillation tower **100** to minimize heat loss in the feed piping.

[0071] As an alternative to a J-T valve, the expander device **152** may be a turbo expander. A turbo expander provides greater cooling and creates a source of shaft work for processes like the refrigeration unit mentioned above. The refrigeration unit is part of the heat exchanger **150**. In this manner, the operator may minimize the overall energy requirements for the distillation process. However, the turbo-expander may not handle frozen particles as well as the J-T valve.

[0072] In either instance, the heat exchanger **150** and the expander device **152** convert the initial fluid stream **10** into a chilled fluid stream **12**. Preferably, the temperature of the chilled fluid stream **12** is around -40° to -70° F. In one aspect, the cryogenic distillation tower **100** is operated at a pressure of about 550 psi, and the chilled fluid stream **12** is at approximately -62° F. At these conditions, the chilled fluid stream **12** is in a substantially liquid phase, although some vapor phase may inevitably be entrained into the chilled fluid stream **12**. Most likely, no solids formation has arisen from the presence of CO₂.

[0073] The cryogenic distillation tower **100** is divided into three primary sections. These are a lower distillation zone **106**, an intermediate controlled freezing zone, or “spray section” **108**, and an upper distillation or “rectification” zone **110**. In the tower arrangement of **Figure 1**, the chilled fluid stream **12** is introduced into the distillation tower **100** at the controlled freezing zone **108**. However, the chilled fluid stream **12** may alternatively be introduced near the top of the lower distillation zone **106**.

[0074] It is noted in the arrangement of **Figure 1** that the lower distillation zone **106**, the intermediate spray section **108**, the upper rectification zone **110**, and all the components are housed within a single vessel. However, for offshore applications in which height of the tower **100** and motion considerations may need to be considered, or for remote locations in which transportation limitations are an issue, the distillation tower **110** may optionally be split into two separate pressure vessels (not shown). For example, the lower distillation zone **106** and the controlled freezing zone **108** may be located in one vessel, while the upper rectification zone **110** is in another vessel. External piping would then be used to interconnect the two vessels.

[0075] In either embodiment, the temperature of the lower distillation zone **106** is higher than the feed temperature of the chilled fluid stream **12**. The temperature of the lower distillation zone **106** is designed to be well above the boiling point of the methane in the chilled fluid stream **12** at the operating pressure of the column **100**. In this manner, methane is preferentially stripped from the heavier hydrocarbon and liquid acid gas components. Of course, those of ordinary skill in the art will understand that the liquid within the distillation tower **100** is a mixture, meaning that the liquid will “boil” at some intermediate temperature between pure methane and pure CO₂. Further, in the event that there are heavier hydrocarbons present in the mixture (such as ethane or propane), this will increase the boiling temperature of the mixture. These factors become design considerations for the operating temperatures within the distillation tower **100**.

[0076] In the lower distillation zone **106**, the CO₂ and any other liquid-phase fluids gravitationally fall towards the bottom of the cryogenic distillation tower **100**. At the same time, methane and other vapor-phase fluids break out and rise upwards towards the top of the tower **100**. This separation is accomplished primarily through the density differential between the gas and liquid phases. However, the separation process is optionally aided by internal components within the distillation tower **100**. As described below, these include a melt tray **130**, a plurality of advantageously-configured mass transfer devices **126**, and an optional heater line **25**. Side reboilers (not shown) may likewise be added to the lower distillation zone **106** to facilitate removal of CO₂ and heat transfer.

[0077] Referring again to **Figure 1**, the chilled fluid stream **12** may be introduced into the column **100** near the top of the lower distillation zone **106**. Alternatively, it may be desirable to introduce the feed stream **12** into the intermediate spray or controlled freezing zone **108** above the melt tray **130**. The point of injection of the chilled fluid stream **12** is a design issue dictated primarily by the composition of the initial fluid stream **10**.

[0078] It may be preferable to inject the chilled fluid stream **12** directly into the lower distillation zone **106** through a two-phase flashbox type device (or vapor distributor) **124** in the column **100**. The use of a flashbox **124** serves to partially separate the two-phase vapor-liquid mixture in the chilled fluid stream **12**. The flashbox **124** may be slotted such that the two-phase fluid impinges against baffles in the flashbox **124**.

[0079] If significant liquid slugging or frequent process upsets are anticipated, the chilled fluid stream **12** may need to be partially separated in a vessel **173** prior to feeding the column **100**. In this case, the chilled feed stream **12** may be separated in a two phase vessel **173**.

Vapor leaves the two phase vessel **173** through a vessel inlet line **11**, where it enters the column **100** through an inlet distributor **121**. The gas then travels upward through the column **100**. Liquid **13** is discharged from the two phase vessel **173**. The liquid **13** is directed into the column **100** through the distributor **124**. The liquid **13** can be fed to the column **100** by gravity or by a pump **175**.

[0080] In either arrangement, that is, with or without the two phase vessel **173**, the chilled fluid stream **12** (or **11**) enters the column **100**. The liquid component leaves the flashbox **124** and travels down a collection of stripping trays **126** within the lower distillation zone **106**. The stripping trays **126** include a series of downcomers **129** and weirs **128**. These are described more fully below in connection with **Figure 3**. The stripping trays **126**, in combination with the warmer temperature in the lower distillation zone **106**, cause methane to break out of solution. The resulting vapor carries the methane and any entrained carbon dioxide molecules that have boiled off.

[0081] The vapor further proceeds upward through chimneys **131** of the melt tray **130** (seen in **Figure 2B**) and into the freeze zone **108**. The melt tray risers **131** act as a vapor distributor for uniform distribution through the freeze zone **108**. The vapor will then contact cold liquid from spray headers **120** to “freeze out” the CO₂. Stated another way, CO₂ will freeze and then precipitate or “snow” back onto the melt tray **130**. The solid CO₂ then melts and gravitationally flows in liquid form down the melt tray **130** and through the lower distillation zone **106** there below.

[0082] As will be discussed more fully below, the spray section **108** is an intermediate freezing zone of the cryogenic distillation tower **100**. With the alternate configuration in which the chilled fluid stream **12** is separated in vessel **173** prior to entering the tower **100**, a part of the separated liquid/solid slurry **13** is introduced into the tower **100** immediately above the melt tray **130**. Thus, a liquid-solid mixture of sour gas and heavier hydrocarbon components will flow from the distributor **121**, with solids and liquids falling down onto the melt tray **130**.

[0083] The melt tray **130** is configured to gravitationally receive liquid and solid materials, primarily CO₂ and H₂S, from the intermediate spray section **108**. The melt tray **130** serves to warm the liquid and solid materials and direct them downward through the lower distillation zone **106** in liquid form for further purification. The melt tray **130** collects and warms the solid-liquid mixture from the controlled freezing zone **108** in a pool of liquid. The melt tray **130** is designed to release vapor flow back to the controlled freezing zone **108**,

to provide adequate heat transfer to melt the solid CO₂, and to facilitate liquid/slurry drainage to the lower distillation or lower distillation zone **106** of the column **100** below the melt tray **130**.

[0084] **Figure 2A** provides a plan view of the melt tray **130**, in one embodiment. **Figure 2B** provides a cross-sectional view of the melt tray **130**, taken across line **B-B** of **Figure 2A**. **Figure 2C** shows a cross-sectional view of the melt tray **130**, taken across line **C-C**. The melt tray **130** will be described with reference to these three drawings collectively.

[0085] First, the melt tray **130** includes a base **134**. The base **134** may be a substantially planar body. However, in the preferred embodiment shown in **Figures 2A, 2B** and **2C**, the base **134** employs a substantially non-planar profile. The non-planar configuration provides an increased surface area for contacting liquids and solids landing on the melt tray **130** from the intermediate controlled freezing zone **108**. This serves to increase heat transfer from the vapors passing up from the lower distillation zone **106** of the column **100** to the liquids and thawing solids. In one aspect, the base **134** is corrugated. In another aspect, the base **134** is substantially sinusoidal. This aspect of the tray design is shown in **Figure 2B**. It is understood that other non-planar geometries may alternatively be used to increase the heat transfer area of the melt tray **130**.

[0086] The melt tray base **134** is preferably inclined. The incline is demonstrated in the side view of **Figure 2C**. Although most solids should be melted, the incline serves to ensure that any unmelted solids in the liquid mixture drain off of the melt tray **130** and into the lower distillation zone **106** there below.

[0087] In the view of **Figure 2C**, a sump or “downcomer” **138** is seen central to the melt tray **130**. The melt tray base **134** slopes inwardly towards the downcomer **138** to deliver the solid-liquid mixture. The base **134** may be sloped in any manner to facilitate gravitational liquid draw-off.

[0088] As described in U.S. Pat. No. 4,533,372, the melt tray was referred to as a “chimney tray.” This was due to the presence of a single venting chimney. The chimney provided an opening through which vapors may move upward through the chimney tray. However, the presence of a single chimney meant that all gases moving upward through the chimney tray had to egress through the single opening. On the other hand, in the melt tray **130** of **Figures 2A, 2B** and **2C**, a plurality of chimneys **131** (or “risers”) is provided. The use of multiple chimneys **131** provides improved vapor distribution. This contributes to better heat/mass transfer in the intermediate controlled freezing zone **108**.

[0089] The chimneys **131** may be of any profile. For instance, the chimneys **131** may be round, rectangular, or any other shape that allows vapor to pass through the melt tray **130**. The chimneys **131** may also be narrow and extend upwards into the intermediate spray section **108**. This enables a beneficial pressure drop to distribute the vapor evenly as it rises into the CFZ controlled freezing zone **108**. The chimneys **131** are preferably located on peaks of the corrugated base **134** to provide additional heat transfer area.

[0090] The top openings of the chimneys **131** are preferably covered with hats or caps **132**. This minimizes the chance that solids dropping from the controlled freezing zone **108** can avoid falling onto the melt tray **130**. In **Figures 2A, 2B and 2C**, caps **132** are seen above each of the chimneys **131**.

[0091] The melt tray **130** may also be designed with bubble caps. The bubble caps define convex indentations in the base **134** rising from underneath the melt tray **130**. The bubble caps further increase surface area in the melt tray **130** to provide additional heat transfer to the CO₂-rich liquid. With this design, a suitable liquid draw off, such as an increased incline angle, should be provided to insure that liquid is directed to the stripping trays **126** below.

[0092] Referring again to **Figure 1**, the melt tray **130** may also be designed with an external liquid transfer system. The transfer system serves to ensure that all liquid is substantially free of solids and that sufficient heat transfer has been provided. The transfer system first includes a draw-off nozzle **136**. In one embodiment, the draw-off nozzle **136** resides within the draw-off sump, or downcomer **138** (seen in **Figure 2C**). Fluids collected in the downcomer **138** are delivered to a transfer line **135**. Flow through the transfer line **135** may be controlled by a control valve **137** and a level controller “LC” (seen in **Fig. 1**). Fluids are returned to the lower distillation zone **106** via the transfer line **135**. If the liquid level is too high, the control valve **137** opens; if the level is too low, the control valve **137** closes. If the operator chooses not to employ the transfer system in the lower distillation zone **106**, then the control valve **137** is closed and fluids are directed immediately to the mass transfer devices, or “stripping trays” **126** below the melt tray **130** for stripping via an overflow downcomer **139**.

[0093] Whether or not an external transfer system is used, solid CO₂ is warmed on the melt tray **130** and converted to a CO₂-rich liquid. The melt tray **130** is heated from below by vapors from the lower distillation zone **106**. Supplemental heat may optionally be added to the melt tray **130** or just above the melt tray base **134** by various means such as heater line

25. The heater line **25** utilizes thermal energy already available from a bottom reboiler **160** to facilitate thawing of the solids.

[0094] The CO₂-rich liquid is drawn off from the melt tray **130** under liquid level control and gravitationally introduced to the lower distillation zone **106**. As noted, a plurality of stripping trays **126** is provided in the lower distillation zone **106** below the melt tray **130**. The stripping trays **126** are preferably in a substantially parallel relation, one above the other. Each of the stripping trays **126** may optionally be positioned at a very slight incline, with a weir such that a liquid level is maintained on the tray. Fluids gravitationally flow along each tray, over the weir, and then flow down onto the next tray via a downcomer.

[0095] The stripping trays **126** may be in a variety of arrangements. The stripping trays **126** may be arranged in generally horizontal relation to form a sinusoidal, cascading liquid flow. However, it is preferred that the stripping trays **126** be arranged to create a cascading liquid flow that is divided by separate stripping trays substantially along the same horizontal plane. This is shown in the arrangement of **Figure 3**, where the liquid flow is split at least once so that liquid falls into two opposing downcomers **129**.

[0096] **Figure 3** provides a side view of a stripping tray **126** arrangement, in one embodiment. Each of the stripping trays **126** receives and collects fluids from above. Each stripping tray **126** preferably has a weir **128** that serves as a dam to enable the collection of a small pool of fluid on each of the stripping trays **126**. The buildup may be ½ to 1 inch, though any height may be employed. A waterfall effect is created by the weirs **128** as fluid falls from tray **126** to tray **126**. In one aspect, no incline is provided to the stripping trays **126**, but the waterfall effect is created through a higher weir **128** configuration. The fluid is contacted with upcoming vapor rich in lighter hydrocarbons that strip out the methane from the cross flowing liquid in this “contact area” of the trays **126**. The weirs **128** serve to dynamically seal the downcomers **129** to help prevent vapor from bypassing through the downcomers **129** and to further facilitate the breakout of hydrocarbon gases.

[0097] The percentage of methane in the liquid becomes increasingly small as the liquid moves downward through the lower distillation zone **106**. The extent of distillation depends on the number of trays **126** in the lower distillation zone **106**. In the upper part of the lower distillation zone **106**, the methane content of the liquid may be as high as 25 mol percent, while at the bottom stripping tray the methane content may be as low as 0.04 mol percent. The methane content flashes out quickly along the stripping trays **126** (or other mass transfer devices). The number of mass transfer devices used in the lower distillation zone **106** is a

matter of design choice based on the composition of the raw gas stream **10**. However, only a few levels of stripping trays **126** need be typically utilized to remove methane to a desired level of 1% or less in the liquefied acid gas, for example.

[0098] Various individual stripping tray **126** configurations that facilitate methane breakout may be employed. The stripping tray **126** may simply represent a panel with sieve holes or bubble caps. However, to provide further heat transfer to the fluid and to prevent unwanted blockage due to solids, so called “jet trays” may be employed below the melt tray. In lieu of trays, random or structured packing may also be employed.

[0099] **Figure 4A** provides a plan view of an illustrative jet tray **426**, in one embodiment.

Figure 4B provides a cross-sectional view of a jet tab **422** from the jet tray **426**. As shown, each jet tray **426** has a body **424**, with a plurality of jet tabs **422** formed within the body **424**. Each jet tab **422** includes an inclined tab member **428** covering an opening **425**. Thus, a jet tray **426** has a plurality of small openings **425**.

[0100] In operation, one or more jet trays **426** may be located in the stripping **106** and/or rectification **110** sections of the tower **100**. The trays **426** may be arranged with multiple passes such as the pattern of stripping trays **126** in **Figure 3**. However, any tray or packing arrangement may be utilized that facilitates the breakout of methane gas. Fluid cascades down upon each jet tray **426**. The fluids then flow along the body **424**. The tabs **422** are optimally oriented to move the fluid quickly and efficiently across the tray **426**. An adjoined downcomer (not shown) may optionally be provided to move the liquid to the subsequent tray **426**. The openings **425** also permit gas vapors released during the fluid movement process in the lower distillation zone **106** to travel upwards more efficiently to the melt tray **130** and through the chimneys **131**.

[0101] In one aspect, the trays (such as trays **126** or **426**) may be fabricated from fouling-resistant materials, that is, materials that prevent solids-buildup. Fouling-resistant materials are utilized in some processing equipment to prevent the buildup of corrosive metal particles, polymers, salts, hydrates, catalyst fines, or other chemical solids compounds. In the case of the cryogenic distillation tower **100**, fouling resistant materials may be used in the trays **126** or **426** to limit sticking of CO₂ solids. For example, a Teflon™ coating may be applied to the surface of the trays **126** or **426**.

[0102] Alternatively, a physical design may be provided to ensure that the CO₂ does not start to build up in solid form along the inner diameter of the distillation tower **100**. In this respect, the jet tabs **422** may be oriented to push liquid along the wall of the tower **100**,

thereby preventing solids accumulation along the wall of the tower **100** and ensuring good vapor-liquid contact.

[0103] In any of the tray arrangements, as the down-flowing liquid hits the stripping trays **126**, separation of materials occurs. Methane gas breaks out of solution and moves upward in vapor form. The CO₂, however, is cold enough and in high enough concentration that it remains in its liquid form and travels down to the bottom of the lower distillation zone **106**. The liquid is then moved out of the cryogenic distillation tower **100** in an exit line as a bottoms fluid stream **22**.

[0104] Upon exiting the distillation tower **100**, the bottoms fluid stream **22** enters a reboiler **160**. In **Figure 1**, the reboiler **160** is a kettle-type vessel that provides reboiled vapor to the bottom of the stripping trays. A reboiled vapor line is seen at **27**. In addition, reboiled vapor may be delivered through a heater line **25** to provide supplemental heat to the melt tray **130**. The supplemental heat is controlled through a valve **165** and temperature controller **TC**. Alternately, a heat exchanger, such as a thermosyphon heat exchanger (not shown) may be used for the initial fluid stream **10** to economize energy. In this respect, the liquids entering the reboiler **160** remain at a relatively low temperature, for example, about 30° to 40° F. By heat integrating with the initial fluid stream **10**, the operator may warm the cool bottoms fluid stream **22** from the distillation tower **100** while pre-cooling the production fluid stream **10**. For this case, the fluid providing supplemental heat through line **25** is a mixed phase return from the reboiler **160**.

[0105] It is contemplated that under some conditions, the melt tray **130** may operate without heater line **25**. In these instances, the melt tray **130** may be designed with an internal heating feature such as an electric heater. However, it is preferred that a heat system be offered that employs the heat energy available in bottoms fluid stream **22**. The warm fluids in heater line **25** exist in one aspect at 30° to 40° F, so they contain relative heat energy. Thus, in **Figure 1**, vapor stream **25** is shown being directed to the melt tray **130** through a heating coil (not shown) on the melt tray **130**. The vapor stream **25** may alternatively be tied to the transfer line **135**.

[0106] In operation, most of the reboiled vapor stream is introduced at the bottom of the column through line **27**, above the bottom liquid level and at or below the last stripping tray **126**. As the reboiled vapor passes upward through each tray **126**, residual methane is stripped out of the liquid. This vapor cools off as it travels up the tower. By the time the vapor stream from line **27** reaches the corrugated melt tray **130**, the temperature may drop to

about -20° F to 0° F. However, this remains quite warm compared to the melting solid on the melt tray **130**, which may be around -50° F to -70° F. The vapor still has enough enthalpy to melt the solids CO₂ as it comes in contact with the melt tray **130**.

[0107] Referring back to reboiler **160**, fluids in a bottom stream **24** that exit the reboiler **160** in liquid form may optionally pass through an expander valve **162**. The expander valve **162** reduces the pressure of the bottom liquid product, effectively providing a refrigeration effect. Thus, a chilled bottom stream **26** is provided. This also creates hydrostatic head. In this respect, the CO₂-rich liquid exiting the reboiler **160** may be pumped downhole through one or more AGI wells (seen schematically at **250** in **Figure 1**). In some situations, the liquid CO₂ may be pumped into a partially recovered oil reservoir as part of an enhanced oil recovery process. Thus, the CO₂ could be a miscible injectant. As an alternative, the CO₂ may be used as a miscible flood agent for enhanced oil recovery.

[0108] Referring again to the lower distillation zone **106** of the distillation tower **100**, gas moves up through the lower distillation zone **106**, through the chimneys **131** in the melt tray **130**, and into the controlled freezing zone **108**. The controlled freezing zone **108** defines an open chamber having a plurality of spray nozzles **122**. As the vapor moves upward through the controlled freezing zone **108**, the temperature of the vapor becomes much colder. The vapor is contacted by liquid methane coming from the spray nozzles **122**. This liquid methane is much colder than the upwardly-moving vapor, having been chilled by an external refrigeration unit **170**. In one arrangement, the liquid methane exits from spray nozzles **122** at a temperature of approximately -120° F to -130° F. However, as the liquid methane evaporates, it absorbs heat from its surroundings, thereby reducing the temperature of the upwardly-moving vapor. The vaporized methane also flows upward due to its reduced density (relative to liquid methane) and the pressure gradient within the tower **100**.

[0109] As the methane vapors move further up the cryogenic distillation tower **100**, they leave the controlled freezing zone **108** and enter the upper rectification zone **110**. The vapors continue to move upward along with other light gases broken out from the original chilled fluid stream **12**. The combined hydrocarbon vapors move out of the top of the cryogenic distillation tower **100**, becoming an overhead methane stream **14**.

[0110] The hydrocarbon gas in overhead methane stream **14** is moved into the external refrigeration unit **170**. In one aspect, the refrigeration unit **170** uses an ethylene refrigerant or other refrigerant capable of chilling the overhead methane stream **14** down to about -135° to -145° F. This serves to at least partially liquefy the overhead methane stream

14. The refrigerated methane stream **14** is then moved to a reflux condenser or separation chamber **172**.

[0111] The separation chamber **172** is used to separate gas **16** from liquid reflux **18**. The gas **16** represents the lighter hydrocarbon gases, primarily methane, from the original raw gas stream **10**. Nitrogen and helium may also be present. The methane gas **16** is, of course, the “product” ultimately sought to be captured and sold commercially, along with any ethane.

[0112] A portion of the overhead methane stream **14** exiting the refrigeration unit **170** remains condensed. This portion becomes liquid reflux **18** that is separated in the separation chamber **172** and returned to the tower **100**. A pump **19** may be used to move the liquid reflux **18** back into the tower **100**. Alternatively, the separation chamber **172** is mounted above the tower **100** to provide a gravity feed of the liquid reflux **18**. The liquid reflux **18** will include any carbon dioxide that escaped from the upper rectification zone **110**. However, most of the liquid reflux **18** is methane, typically 95% or more, with nitrogen (if present in the initial fluid stream **10**) and traces of hydrogen sulfide (also if present in the initial fluid stream **10**).

[0113] In one cooling arrangement, the overhead methane stream **14** is taken through an open-loop refrigeration system. In this arrangement, the overhead methane stream **14** is taken through a cross-exchanger to chill a return portion of the overhead methane stream used as the liquid reflux **18**. Thereafter, the overhead methane stream **14** is pressurized to about 1,000 psi to 1,400 psi, and then cooled using ambient air and possibly an external propane refrigerant. The pressurized and chilled gas stream is then directed through an expander for further cooling. A turbo expander may be used to recover even more liquid as well as some shaft work. U.S. Pat. No. 6,053,007 entitled “Process For Separating a Multi-Component Gas Stream Containing at Least One Freezable Component,” describes the cooling of an overhead methane stream, and is incorporated herein in its entirety by reference.

[0114] It is understood here that the present inventions are not limited by the cooling method for the overhead methane stream **14**. It is also understood that the degree of cooling between refrigeration unit **170** and the initial refrigeration unit **150** may be varied. In some instances, it may be desirable to operate the refrigeration unit **150** at a higher temperature, but then be more aggressive with cooling the overhead methane stream **14** in the refrigeration unit **170**. Again, the present inventions are not limited to these types of design choices.

[0115] Returning again to **Figure 1**, the liquid reflux **18** is returned into the upper distillation or rectification zone **110**. The liquid reflux **18** is then gravitationally carried through one or more mass transfer devices **116** in the upper rectification zone **110**. In one embodiment, the mass transfer devices **116** are rectification trays that provide a cascading series of weirs **118** and downcomers **119**, similar to trays **126** described above. In lieu of trays, random or structured packing may also be employed.

[0116] As fluids from liquid reflux stream **18** move downward through the rectification trays **116**, additional methane vaporizes out of the upper rectification zone **110**. The methane gases rejoin the overhead methane stream **14** to become part of the gas product stream **16**. However, the remaining liquid phase of liquid reflux **18** falls onto a collector tray **140**. As it does so, the liquid reflux stream **18** unavoidably will pick up a small percentage of hydrocarbon and residual acid gases moving upward from the controlled freezing zone **108**. The liquid mixture of methane and carbon dioxide is collected at a collector tray **140**.

[0117] The collector tray **140** preferably defines a substantially planar body for collecting liquids. However, as with melt tray **130**, collector tray **140** also has one, and preferably a plurality of chimneys for venting gases coming up from the controlled freezing zone **108**. A chimney-and-cap arrangement such as that presented by components **131** and **132** in **Figures 2B** and **2C** may be used. Chimneys **141** and caps **142** for collector tray **140** are shown in the enlarged view of **Figure 5**, discussed further below.

[0118] It is noted here that in the upper rectification zone **110**, any H_2S present has a preference towards being dissolved in the liquid versus being in the gas at the processing temperature. In this respect, the H_2S has a comparatively low relative volatility. By contacting the remaining vapor with more liquid, the cryogenic distillation tower **100** drives the H_2S concentration down to within the desired parts-per-million (ppm) limit, such as a 10 or even a 4 ppm specification. As fluid moves through the mass transfer devices **116** in the upper rectification zone **110**, the H_2S contacts the liquid methane and is pulled out of the vapor phase and becomes a part of the liquid stream **20**. From there, the H_2S moves in liquid form downward through the lower distillation zone **106** and ultimately exits the cryogenic distillation tower **100** as part of the liquefied acid gas bottoms stream **22**.

[0119] In cryogenic distillation tower **100**, the liquid captured at collector tray **140** is drawn out of the upper rectification zone **110** as a liquid stream **20**. The liquid stream **20** is comprised primarily of methane. In one aspect, the liquid stream **20** is comprised of about 93 mol. percent methane, 3% CO_2 , 0.5% H_2S , and 3.5% N_2 . At this point, the liquid stream **20** is

at about -125° F to -130° F. This is only slightly warmer than the reflux fluid **18**. The liquid stream **20** is directed into a spray header collection drum **174**. The purpose of the spray header collection drum **174** is to provide surge capacity for a pump **176**. Upon exiting the spray header collection drum **174**, a spray stream **21** is created. Spray stream **21** is
5 pressurized in a pump **176** for a second reintroduction into the cryogenic distillation tower **100**. In this instance, the spray stream **21** is pumped into the intermediate controlled freezing zone **108** and emitted through nozzles **122**.

[0120] Some portion of the spray stream **21**, particularly the methane, vaporizes and evaporates upon exiting the nozzles **122**. From there, the methane rises through the
10 intermediate controlled freezing zone **108**, through the chimneys in the collector tray **140**, and through the mass transfer devices **116** in the upper rectification zone **110**. The methane leaves the distillation tower **100** as the overhead methane stream **14** and ultimately becomes part of the commercial product in gas stream **16**.

[0121] The spray stream **21** from the nozzles **122** also causes carbon dioxide to
15 desublime from the gas phase. In this respect, some CO₂ momentarily enters the gas phase and moves upward with the methane. However, because of the cold temperature within the controlled freezing zone **108**, the gaseous carbon dioxide quickly turns into a solid phase and begins to "snow." This phenomenon is referred to as desublimation. In this way, some CO₂ never re-enters the liquid phase until it hits the melt tray **130**. This carbon dioxide "snows"
20 upon the melt tray **130**, and melts into the liquid phase. From there, the CO₂-rich liquid cascades down the mass transfer devices or trays **126** in the lower distillation zone **106**, along with liquid CO₂ from the chilled raw gas stream **12** as described above. At that point, any remaining methane from the spray stream **21** of the nozzles **122** should quickly break out into vapor. These vapors move upwards in the cryogenic distillation tower **100** and re-enter the
25 upper rectification zone **110**.

[0122] It is desirable to have chilled liquid contacting as much of the gas that is moving up the tower **100** as possible. If vapor bypasses the spray stream **21** emanating from the nozzles **122**, higher levels of CO₂ could reach the upper rectification zone **110** of the tower **100**. To improve the efficiency of gas/liquid contact in the controlled freezing zone
30 **108**, a plurality of nozzles **122** having a designed configuration may be employed. Thus, rather than employing a single spray source at one or more levels in a reflux fluid stream **21**, several spray headers **120** optionally designed with multiple spray nozzles **122** may be used.

Thus, the configuration of the spray nozzles **122** has an impact on the mass transfer taking place within the controlled freezing zone **108**.

[0123] The assignee herein has previously proposed various nozzle arrangements in co-pending WO Pat. Publ. No. 2008/091316 having an international filing date of November 20, 2007. That application and Figures 6A and 6B therein are incorporated herein by reference for teachings of the nozzle configurations. The nozzles seek to ensure 360° coverage within the controlled freezing zone **108** and provide good vapor-liquid contact and heat/mass transfer. This, in turn, more effectively chills any gaseous carbon dioxide moving upward through the cryogenic distillation tower **100**.

[0124] The use of multiple headers **120** and a corresponding overlapping nozzle **122** arrangement for complete coverage minimizes back-mixing as well. In this respect, complete coverage prevents the fine, low-mass CO₂ particles from moving back up the column and entering the upper rectification zone **110**. Otherwise, these particles would re-mix with methane and enter the overhead methane stream **14**, only to be recycled again.

[0125] It can be seen that the process of cycling vapors through the cryogenic distillation tower **100** ultimately produces a gas comprised of a commercial methane product **16**. The gas product **16** is sent down a pipeline for sale. The gas product **16** preferably meets a pipeline CO₂ specification of 1 to 4 mol. percent, as well as a 4 ppm or less H₂S specification, assuming sufficient reflux is generated. At the same time, acid gases and, if present, heavy hydrocarbons, are removed through bottoms fluid stream **22**.

[0126] It is observed that an inherent inefficiency exists in freezing the acid gas components into a solid in the controlled freezing zone **108**, then melting them into a liquid bottom stream **22** in the lower distillation zone **106**, and then separating the CO₂ from any entrained natural gases using a bottom reboiler **160**. A considerable amount of energy is consumed in connection with freezing the CO₂. This energy is at least partially wasted as the solid components in the controlled freezing zone **108** melt and then re-mix in the lower distillation zone **106** with any H₂S and other heavy hydrocarbons in the liquid phase.

[0127] Because relatively pure CO₂ is more desirable for acid gas injection or disposal, an acid gas enrichment process or other purification method is desired to separate frozen CO₂. This separation should take place at the bottom of the controlled freezing zone **108** or at the top of the lower distillation zone **106**. Thus, instead of melting the CO₂ (and remixing with any liquid H₂S and heavy hydrocarbon components) and gravitationally dropping the liquid-phase components through the lower distillation zone **106**, it is proposed

herein to replace the melt tray **130** with a collector tray. The collector tray will receive precipitates from the controlled freezing zone **108** in the form of a solid-liquid slurry. The solid-liquids slurry will be collected on the collector tray and removed from the cryogenic distillation tower for separate processing.

5 **[0128]** **Figure 6A** provides a plan view of a collector tray **610**, in one embodiment. **Figure 6B** provides a cross-sectional view of the collector tray **610**, taken across line **B-B** of **Figure 6A**. **Figure 6C** shows a cross-sectional view of the collector tray **610**, taken across line **C-C**. The collector tray **610** will be described with reference to these three drawings together.

10 **[0129]** First, the collector tray **610** includes a base **620**. The base **620** may be a substantially planar body, or may have undulations to increase surface area. In either respect, the base **620** is preferably tilted inwardly along opposite sides so that fluids landing on the base **620** will gravitationally drain towards a central downcomer **630**.

15 **[0130]** In the view of **Figure 6C**, a sump or “downcomer” **630** is more clearly seen central to the collector tray **130**. The collector tray base **620** slopes inwardly towards the downcomer **630** to deliver the solid-liquid slurry. The base **620** may be sloped in any manner to facilitate gravitational solid and liquid draw-off.

20 **[0131]** As with the melt tray **130** of **Figure 2A**, the collector tray **610** of **Figures 6A**, **6B** and **6C** has a plurality of chimneys **622**, **624** (or “risers”). The chimneys **622**, **624** provide improved vapor distribution, allowing fluids in the gas phase to travel upward from the lower distillation zone **106** and into the intermediate controlled freezing zone **108**. This also contributes to better heat/mass transfer in the controlled freezing zone **108**.

25 **[0132]** The chimneys **622**, **624** may be of any profile. For instance, the chimneys **622**, **624** may be round, rectangular, or any other shape that allows vapor to pass through the collector tray **610**. The chimneys **622**, **624** may also be narrow and extend upward into the controlled freezing zone **108**. This enables a beneficial pressure drop to distribute the vapor evenly as it rises into the freezing zone **108**.

30 **[0133]** The top openings of the chimneys **622**, **624** are preferably covered with hats or caps **626**. The caps **626** minimize the chance that solids dropping from the controlled freezing zone **108** will bypass the collector tray **610** and travel into the lower distillation zone **706**.

30 **[0134]** Along with the base **620**, the downcomer **630** is preferably inclined. An incline arrangement for a downcomer **630'** is demonstrated in the side view of **Figure 6D**.

Figure 6D is a cross-sectional view of the collector tray **610** of **Figure 6A**, in an alternate embodiment. The view is taken across line **B-B** of **Figure 6A**.

[0135] The collector tray **610** is designed to be incorporated into a cryogenic distillation tower as part of a system for removing acid gases from a raw gas stream. The collector tray **610** is configured to receive solid and liquid particles falling from the controlled freezing zone of a cryogenic distillation tower. The collector tray **610** is further configured to transport slurry made up of the solid and liquid particles out of the tower and to a CO₂ recovery facility.

[0136] **Figure 7** is a schematic diagram showing a gas processing facility **700** for removing acid gases from a hydrocarbon gas stream in accordance with the present invention, in one embodiment. The hydrocarbon gas stream originates from hydrocarbon production activities that take place in a reservoir development area, or “field.” The field may be any location where compressible hydrocarbons are produced. The field may be onshore, near shore or offshore. The field may be operating from original reservoir pressure or may be undergoing enhanced recovery procedures. The systems and methods claimed herein are not limited to the type of field that is under development so long as it is producing compressible hydrocarbons contaminated with acid gas components.

[0137] The gas processing facility **700** utilizes a collector tray such as the collector tray **610** of **Figure 6A**. It can be seen in **Figure 7** that the collector tray **610** is incorporated into a cryogenic distillation tower **705**. The distillation tower **705** has an intermediate controlled freezing zone **708**. The controlled freezing zone **708**, or spray section, receives a cold liquid spray comprised primarily of methane.

[0138] The cold spray is preferably a liquid reflux generated from an overhead loop **714** downstream of the distillation tower **705**. The overhead loop **714** includes refrigeration equipment within a heat exchanger **170** that serves to cool the overhead methane stream **14** and then return a portion of the overhead methane stream **14** to the cryogenic distillation tower **705** as liquid reflux **18**. The liquid reflux **18** is sprayed within the controlled freezing zone **708** through spray headers **120** to cause precipitation of solid carbon dioxide particles. As illustrated in **Figure 7**, the liquid reflux **18** is delivered to an upper rectification section **710**, which will be discussed further below, before being sprayed through the spray headers **120**. Other implementations, may draw some or all of the liquid reflux **18** directly to the spray headers **120** or to the spray header collection drum **174**.

[0139] As with tower **100** of **Figure 1**, the cryogenic distillation tower **705** is configured to receive an initial fluid stream **10** comprised of acid gases. The initial fluid stream **10** contains methane, carbon dioxide and, possibly, trace amounts of ethane, nitrogen, helium and hydrogen sulfide. The initial fluid stream **10** preferably undergoes some degree of dehydration before being injected into the distillation tower **705**. Dehydration may be accomplished by passing the initial fluid stream through a glycol dehydration process. (A dehydration system is not shown in **Figure 7**.)

[0140] In addition, the initial fluid stream **10** is preferably chilled before entering the distillation tower **705**. A heat exchanger **150**, such as a shell-and-tube exchanger, is provided for chilling the initial fluid stream **10**. A refrigeration unit (not shown) provides cooling fluid (such as liquid propane) to heat exchanger **150** to bring the temperature of the initial fluid stream **10** down to about -30° to -40° F. The initial fluid stream **10** may then be moved through an expansion device **152** such as a Joule-Thompson (“J-T”) valve. The result is a chilled raw gas stream **712**. Preferably, the temperature of the chilled raw gas stream **712** is around -40° to -70° F.

[0141] It is noted that in the gas processing facility **700**, the raw gas stream **712** is received into the distillation tower **705** below the controlled freezing zone **708**. More specifically, the raw gas stream **712** is injected into a lower distillation zone **706** below the controlled freezing zone **708**. However, it is understood that the raw gas stream **712** may be directed through a two-phase vessel such as vessel **173** shown in **Figure 1**. This generates a split stream comprised primarily of methane vapor (injected into the controlled freezing zone **708**) and liquid acid gases and, possibly, heavy hydrocarbons (injected into the lower distillation zone **706**.) The two-phase vessel **173** minimizes the possibility of solids plugging the inlet line and internal components of the distillation tower **705**.

[0142] In one aspect, the cryogenic distillation tower **712** is operated at a pressure of about 550 psi in the controlled freezing zone **708**, and the chilled raw gas stream **712** is at approximately -62° F. At these conditions, the raw gas stream **712** is in a substantially liquid phase, although some vapor phase may inevitably be entrained into the chilled gas stream **712**. Most likely, no solids formation has arisen from the presence of CO₂.

[0143] The cryogenic distillation tower **705** also includes an upper rectification zone **710**. The upper rectification zone **710** resides above the controlled freezing zone **708**. As discussed above in connection with the cryogenic distillation tower **100** of **Figure 1**, the distillation zone **710** serves to further separate methane vapor from any entrained carbon

dioxide molecules. The distillation zone **710** releases an overhead methane gas stream **14**. It also distributes a portion of fluid into liquid stream **20** which is passed through spray header collection drum **174**, then to pressure booster **176**, and then injected back into the tower **705** through spray headers **120**.

5 [0144] As noted, the gas processing facility **700** further comprises a collector tray **610**. The collector tray **610** is positioned below the controlled freezing zone **708** for receiving substantially solid material as it is precipitated from the controlled freezing zone **708**. It is preferred that the collector tray **610** operate at a temperature of, for example, about -70° F to -80° F. This is at or slightly below the freezing point of the CO₂. A slurry is thus
10 generated at the collector tray **610**.

[0145] Preferably, the collector tray **610** has an inclined base (shown at **620** in **Figure 6C**) to direct slurry into a central downcomer (shown at **630** in **Figure 6C**). The downcomer **630**, in turn, may optionally include a mechanical translation device such as an auger (shown at **640** in **Figure 6B**) within the downcomer. The auger **640** serves to mechanically move a
15 slurry that includes the solid CO₂ material out of the cryogenic distillation tower **705** and towards a CO₂ recovery facility **740**.

[0146] A slurry exit line **741** is provided in the gas processing facility **700**. The slurry exit line **741** moves slurry from the distillation tower **705** to the CO₂ recovery facility **740**. In this way, carbon dioxide is substantially removed from the distillation tower **705** before it
20 drops into the lower distillation zone **706**. The slurry may be moved gravitationally. Alternatively or in addition, the slurry may be translated with the aid of the auger **640**. Alternatively still, a portion of the cold liquid reflux **18** may be directed from a side wall of the distillation tower **705** into the collector tray **610** to urge the slurry from the collector tray and out of the distillation tower **705**.

25 [0147] There are several potential advantages to extracting CO₂ in a solid state without allowing the solid to melt and exit as part of the bottoms fluid stream **722**. First, when done at the proper temperature and pressure, the process of crystallizing carbon dioxide into a solid state typically produces a substantially pure solid material. While some trace amounts of methane, hydrogen sulfide and heavy hydrocarbons may be entrained in the solids
30 as part of the slurry, separation of solid CO₂ allows for a substantially pure CO₂ product. Stripping of light products such as methane or other acid products such as H₂S is not necessarily required as such products will fall as liquids into the bottoms fluid stream **722**.

[0148] Also, because a substantial portion of the CO₂ within the raw gas stream 712 is recovered as a pure solid, the amount of CO₂ in the bottoms fluid stream will be reduced. This, in turn, lowers the demands on downstream processes such as acid gas enrichment and sulfur recovery units (not shown). In addition, valuable heavy hydrocarbons such as ethane or propane may be more easily recovered from the bottoms fluid stream 722 as the CO₂ content is substantially reduced.

[0149] In addition, removing a substantial portion of the CO₂ within the raw gas stream 712 as a side-draw (at slurry exit line 741) may reduce the vapor and liquid loads in the distillation tower 705. This, in turn, allows for lower capacities in the reboiler 160 and condenser, that is, the separation chamber 172 and reduced refrigeration requirements. More importantly, extraction of solid CO₂ may allow for a smaller diameter tower 705 for an equivalent feed capacity. The size reduction is generally proportional to the amount of solid CO₂ extracted from the tower 705.

[0150] Referring again to **Figure 7**, the carbon dioxide-based slurry is transported through the slurry exit line 741 to the CO₂ recovery facility 740. The CO₂ recovery facility 740 includes a first filter 742. Preferably, the first filter 742 represents a porous media that catches a substantial portion of the solid material from the slurry. The first filter 742 may be, for example, wire mesh. Alternatively, the filter 742 may be a polyester or other synthetic porous material. The filter 742 may alternatively be a centrifugal separator, a hydrocyclone, one or more belt filters, one or more filter presses, or combinations thereof.

[0151] The liquid portion of the slurry is known as a “filtrate.” The filtrate passes through the first filter 742 and is delivered to a liquid line 744. The filtrate comprises primarily CH₄, but may also include CO₂ and H₂S. The liquid line 744 delivers the filtrate to a liquid return line 760. The liquid return line 760 returns the filtrate to the lower distillation zone 706 of the cryogenic distillation tower 705. The CH₄ is vaporized and becomes part of the overhead methane stream 14. The H₂S and any heavy hydrocarbon components are dropped out of the tower 705 as liquids in the bottoms fluid stream 722.

[0152] It is noted that the liquid line 744 may also contain heavy hydrocarbons, particularly measurable components of ethane and propane. These components may be recovered by sending the filtrate 744 through a process similar to a conventional natural gas liquids (“NGL”) train (not shown).

[0153] The first filter 742 captures the solid portion of the slurry, known as a “filter cake.” The filter cake comprises primarily carbon dioxide. The solid filter cake is delivered

along a first solid material line **746**. The filter cake may be carried from the first filter **742** through the first solid material line **746** by means of a screw-conveyor, by Hildebrandt extractors, or by other means known in the art.

[0154] From there, the filter cake may be warmed so that it enters the liquid phase. In one aspect, the solid carbon dioxide from first solid material line **746** is warmed in a heat exchanger **772**. The heat exchanger **772** may, for example, use heat from the initial fluid stream **10** for melting the carbon dioxide. This beneficially cools the initial fluid stream **10** before it enters the heat exchanger **150**. At the same time, the warmed liquid CO₂ is delivered as substantially pure carbon dioxide liquid through CO₂ fluid line **786**.

[0155] In lieu of delivering the frozen carbon dioxide (or filter cake) in solid material line **746** directly to a heat exchanger **772**, the operator may choose to carry the frozen carbon dioxide through additional filtering. In the gas processing facility **700**, the CO₂ recovery facility **740** may include a rinsing vessel **748**. In the rinsing vessel **748**, cold liquid CO₂ is sprayed onto the frozen carbon dioxide. This has the effect of creating a new slurry, with any residual methane and hydrogen sulfide being rinsed away from the solid filter cake as a liquid.

[0156] The cold carbon dioxide used as the rinsing agent is delivered through CO₂ delivery line **784**. The cold CO₂ used as the rinsing agent is preferably drawn from an outlet **778** for the heat exchanger **772**. A cold CO₂ line is shown at **780**.

[0157] Referring again to the rinsing vessel **748**, preferably, the slurry is mixed in the rinsing vessel **748**. A stirring apparatus **747** may be provided in the rinsing vessel **748**. The stirring apparatus **747** may be, for example, a set of blades that rotate through the solid material to create surface area. Creating surface area exposes the solid material to the cold liquid CO₂ from deliver line **784**. This, in turn, helps to rinse the residual methane and hydrogen sulfide from the solid.

[0158] The new slurry is carried from the rinsing vessel **748** through slurry line **750**. The new slurry is delivered to a second filter, noted in **Figure 7** as **752**. The second filter **752** captures the solid portion of the new slurry. The solid portion again comprises primarily carbon dioxide. The solid portion represents a second filter cake, and is delivered along a second solid material line **756**. From there, the second filter cake may be warmed so that it enters the liquid phase.

[0159] It is noted that the rinsing and filtration steps are shown taking place in separate vessels, e.g., a rinsing vessel **748** and a filtration vessel **752**. However, the operator may choose to combine the rinsing and filtration of solid material in a single vessel.

[0160] The liquid portion of the new slurry, known as a second filtrate, passes through the second filter **752** and is delivered to a liquid line **754**. The second filtrate comprises CH₄ and, possibly, H₂S and heavy hydrocarbons. The liquid line **754** delivers the liquid portion of the slurry to the liquid return line **760**. Thus, the liquid representing the second filtrate **754** merges with the liquid representing the first filtrate **754** before being injected into the distillation tower **705** through liquid return line **760**. The CH₄ is vaporized and becomes part of the overhead methane stream **14**. The H₂S and C₂+ compounds are dropped out of the tower **705** as liquids in the bottoms fluid stream **722**. Should either the first filtrate **744** or the second filtrate **754** contain any melted CO₂, the melted CO₂ will evaporate into the controlled freezing zone **708** and ultimately precipitate back onto the collector tray **610** as frozen material.

[0161] Optionally, the first **744** and/or second **754** filtrate may be carried through the liquid return line **760** to a small, peripheral distillation column (not shown) for further purification.

[0162] The operator may choose to carry the substantially pure, solid CO₂ in line **756** directly to the heat exchanger **772**. Alternatively, additional separation of impurities may take place. Box **770** in **Figure 7** depicts one or more additional rinsing and filtration stages for the solid CO₂ in line **756**. The number of rinse and filtration steps is dependent on the desired purity of the CO₂ product. Line **782** is shown delivering cold CO₂ as a rinsing agent. A third (or subsequent) filtrate **774** is released from the additional rinsing and filtration stage **770**. A third (or subsequent) solid CO₂ (or filter cake) is delivered through line **776** to the heat exchanger **772**. A final CO₂ product line is seen at line **786**. The liquid CO₂ product may be used for acid gas injection, or may be delivered for sale as a high-purity product. A customer may, for example, use the liquid CO₂ product for enhanced oil recovery or for other purposes.

[0163] The gas processing facility **700** of **Figure 7** is ideally used in conditions where the chilled raw gas stream **712** has a high CO₂ content, such as greater than approximately 30%. In this condition, significant refrigeration may be required to freeze all CO₂ from the raw gas stream **712**. Therefore, it is believed to be more energy efficient to inject the raw gas stream **712** in the lower distillation zone **706** below the controlled freezing zone **808** and

below the collector tray **610**. Any CO₂ that stays in liquid form and drops out of the distillation tower **705** with the bottoms feed stream **722** will be recovered through the reboiler **160** and re-injected into the lower distillation zone **706**.

[0164] In the illustrative gas processing system **700**, the collector tray **610** and corresponding slurry exit line **741** are positioned well above the raw gas injection point. The operator may choose to raise the point at which the raw gas stream **12** enters the cryogenic distillation tower **705**. It is believed that raising the injection point will increase the amount of fluid from the raw gas stream **712** that is recovered on the collector tray **610** as solid. This is more advantageous where the raw gas stream **712** has a lower CO₂ content, such as about 10 to 30 mol. percent.

[0165] In one simulation conducted by the Applicant, the collector tray **610** and corresponding slurry exit line **741** were positioned at or slightly above the raw gas injection point. The raw gas stream **712** was simulated to have a composition of 70 mol. percent CO₂ and 30 mol. percent CH₄. An initial gas temperature of 40° C was assumed, with an injection flow rate of approximately 10,000 standard m³/hour. The cryogenic distillation tower **705** was simulated to operate at 450 psia.

[0166] In this simulation, approximately 93% of the feed CO₂ exited the cryogenic distillation tower as a solid. Very little fluid was left to travel down the distillation tower in liquid form. This, of course, produced a substantial reduction in volume for the bottoms fluid stream **722** and reduced the load requirements for the reboiler **160** by about 89%. The drawback to this approach is that more refrigeration is required in the heat exchanger **150** upstream of the distillation tower **705** to chill the initial fluid stream **10**. This is partially offset by a slight reduction in refrigeration required in the heat exchanger **170** downstream of the distillation tower **705**.

[0167] **Figure 8** is a schematic diagram showing a gas processing facility **800** for removing acid gases from a gas stream in accordance with the present invention, in an alternate embodiment. The gas processing facility **800** is generally similar to the gas processing facility **700**. In this respect, the gas processing facility **800** also utilizes a collector tray such as the collector tray **610** of **Figure 6A**. The collector tray **610** is incorporated into a cryogenic distillation tower **805**. The distillation tower **805** again has an intermediate controlled freezing zone **808**. The controlled freezing zone **808**, or spray section, receives a cold liquid spray comprised primarily of methane.

[0168] As with tower **705** of **Figure 1**, the cryogenic distillation tower **805** is configured to receive an initial fluid stream **10** comprised of hydrocarbon and acid gases. The initial fluid stream **10** preferably undergoes some degree of dehydration before being injected into the distillation tower **805**. In addition, the initial fluid stream **10** is preferably chilled before entering the distillation tower **805**. A heat exchanger **150**, such as a shell-and-tube exchanger, is provided for chilling the initial fluid stream **10**. A refrigeration unit (not shown) provides cooling fluid (such as liquid propane) within the heat exchanger **150** to bring the temperature of the initial fluid stream **10** down to about -60° to -80° F. The initial fluid stream **10** may then be moved through an expansion device **152** such as a Joule-Thompson (“J-T”) valve. The result is a chilled raw gas stream **812**.

[0169] As noted above, in the gas processing facility **700**, the raw gas stream **712** is received below the controlled freezing zone **708**. More specifically, the raw gas stream **712** is injected into the lower distillation zone **706**. However, in the cryogenic distillation tower **805**, the distillation zone (**706** from **Figure 7**) has been removed, and the collector tray **610** now resides in the controlled freezing zone **808**. In addition, the raw gas stream **812** is injected into the controlled freezing zone **808** above the collector tray **610**. This is consistent with the simulation described above.

[0170] The purpose for moving the injection point for the chilled raw gas stream **812** up into the controlled freezing zone **808** is to obtain a higher solid CO₂ recovery. To effectuate this, the temperature of the chilled raw gas stream **812** is brought down to around -60° to -80° F. This is a lower temperature range than was imposed on the raw gas stream **712** in **Figure 7**. As the raw gas stream **812** enters the tower **805**, it flashes and cools, precipitating the CO₂ in the controlled freezing zone **808**. Any vapor CO₂ will be cooled by the liquid CH₄ reflux descending from the spray headers **120**. This produces a solid that precipitates onto the collector tray **610**, forming a slurry.

[0171] As with gas processing facility **700**, the slurry is moved in gas processing facility **800** from the cryogenic distillation tower **805**, through a slurry exit line **741**, and to a CO₂ recovery system **840**. The CO₂ recovery system **840** may be the same as the CO₂ recovery system **740** of **Figure 7**. In this respect, a slurry comprised primarily of carbon dioxide is moved through a first filter **742**, and then optionally moved through one, two, or three stages of rinsing and filtration until a substantially pure CO₂ solid is obtained. The CO₂ solid is preferably warmed through the heat exchanger **772** and then released through outlet **778** as a liquid. Liquid CO₂ is released as a product through line **786**.

[0172] In the CO₂ recovery system **840** of **Figure 8**, the first filtrate **744** from first filter **742** is returned to the cryogenic distillation tower **805**. This is consistent with the operation of the CO₂ recovery system **740** of **Figure 7**. However, instead of returning the methane-rich first filtrate **744** through the liquid return line **760** and directly into the tower **805**, the first filtrate **744** is merged with the initial fluid stream **10**. In this way, the methane-rich first filtrate **744** may be re-chilled before injection into the controlled freezing zone **808**.

[0173] In the CO₂ recovery system **840**, the second filtrate **754** and subsequent filtrate(s) **874** are not merged with the liquid return line **760**; rather, the second filtrate **754** and the subsequent filtrate(s) **874** are merged together and delivered to a downstream distillation column **892**. The second filtrate **754** and the subsequent filtrate(s) **874** are comprised primarily of hydrogen sulfide, but may contain trace amounts of methane and carbon dioxide. In the reboiler **892**, the methane is released as a recovery methane stream **894**. The recovery methane stream **894** is merged with the methane sales product **16** and delivered to market as sales product **898**.

[0174] The reboiler **892** also releases a liquid **896**. The liquid **896** comprises primarily hydrogen sulfide with trace amounts of carbon dioxide. The H₂S-rich liquid **896** is disposed of or taken through a sulfur recovery unit (not shown). As an alternative, the second filtrate **754** and the subsequent filtrate(s) **874** may be disposed of or taken through a sulfur recovery unit without going through the reboiler **892**. This is particularly applicable if the amount of CH₄ content does not warrant recovery, or require separation.

[0175] As can be seen from **Figures 7** and **8**, different processing schemes may be utilized. The optimum arrangement will depend on a number of variables. These variables include the availability (or capacity) of refrigeration as generated within an overhead heat exchanger such as heat exchanger **170**, the desired purity of the CO₂ product **786** and, most importantly, the composition of the initial fluid stream **10**. Regardless of the selected flow scheme, the basic principle of distillation combined with solid removal and purification will apply.

[0176] In some situations, the initial fluid stream **10** may have a high concentration of hydrogen sulfide, such as greater than about 5 to 10 percent. In some implementations, such as when solid CO₂ recovery is desired, it may be undesirable to run a gas feed stream having a high H₂S concentration through a cryogenic distillation tower as it is believed that high levels of H₂S can solubilize CO₂, thereby preventing solid formation in the controlled freezing zone. In this situation, natural gases with a high ratio of H₂S to CO₂ may be fed to a

pre-treating column (not shown) for selective H₂S removal prior to being introduced to the main distillation tower **705** or **805**. The separation can be achieved using H₂S separation processes such as absorption by selective amines, redox processes, or adsorption. Thereafter, the gas stream may be dehydrated and refrigerated in accordance with the illustrative processing facilities **700** or **800** described above. Additionally or alternatively, other implementations may be insensitive to the state of the CO₂ recovery product and the H₂S may be left in the initial fluid stream.

[0177] An additional advantage to the removal of sulfur species upstream of the distillation tower is that sulfur removal may enable the production of a higher purity CO₂ product **786** from the recovery system **740** or **840**. In addition, a higher purity of C₂+ products may be recovered from the bottoms fluid stream **722**. Of course, small amounts of H₂S can be allowed to slip into the cryogenic distillation tower **705**, **805**, provided the phase behavior within the tower **705**, **805** allows solid CO₂ formation. Such small amounts of H₂S will be recovered in the bottoms fluid stream **22**.

[0178] A method of removing acid gases from a raw gas stream is also provided herein. **Figure 9** is a flow chart that presents a method **900** for removing acid gases from a raw gas stream using an acid gas removal system in accordance with the present inventions, in one embodiment. The raw gas stream comprises methane, carbon dioxide and, most likely, other components such as ethane and hydrogen sulfide.

[0179] The method **900** first includes providing a cryogenic distillation tower. This step is shown at Box **905**. The tower has a controlled freezing zone that receives a cold liquid spray comprised primarily of methane. The tower further has a collector tray below the controlled freezing zone.

[0180] The method **900** also includes injecting the raw gas stream into the cryogenic distillation tower. This is demonstrated at Box **910**. In one arrangement, the raw gas stream is injected into the distillation tower in a lower distillation zone below the controlled freezing zone. In another arrangement, the raw gas stream is injected into the distillation tower in the controlled freezing zone itself. Preferably, the raw gas stream has been substantially dehydrated before it is injected into the distillation tower.

[0181] The method **900** further includes chilling the raw gas stream. This is indicated at Box **915** of **Figure 9**. Chilling the raw gas stream causes carbon dioxide within the raw gas stream to precipitate upon the collector tray as substantially solid material. At the same time, the pressure in the distillation tower is lower than a feed stream, causing methane

within the raw gas stream to substantially vaporize. The methane travels through an upper rectification zone above the controlled freezing zone, and then exits the cryogenic distillation tower as an overhead methane stream.

[0182] The method **900** also includes passing the overhead methane stream through a refrigeration system downstream of the cryogenic distillation tower. This is provided in Box **920**. The refrigeration system cools at least a portion of the overhead methane stream to a liquid.

[0183] The method **900** additionally includes returning a portion of the cooled overhead methane stream to the cryogenic distillation tower as liquid reflux. The liquid reflux, in turn, serves as the cold liquid spray. This is provided at Box **925**.

[0184] Also as part of method **900**, the solid material is substantially removed from the cryogenic distillation tower. This is shown at Box **930**. Preferably, removal of the substantially solid material is accomplished through gravitational flow. Alternatively, a mechanical translation device such as a screw conveyor or auger may be provided. The auger may reside within a downcomer of the collector tray as demonstrated in **Figures 6A, 6B, 6C and 6D**. The auger may alternatively be placed outside of the distillation tower to direct the substantially solid material to the CO₂ recovery system. In either instance, the auger cuts through the substantially solid material, translating it as a slurry out of the distillation tower and towards a CO₂ recovery system.

[0185] The method **900** further includes separating the carbon dioxide slurry into a solid material and a liquid material. This is shown at Box **935**. The first solid material is comprised primarily of carbon dioxide, while the liquid material comprises methane and residual carbon dioxide. The liquid material may include other components such as hydrogen sulfide, heavy hydrocarbons and even light aromatics.

[0186] The separating step of Box **935** may be accomplished by passing the slurry through a first filter. This produces a first filter cake comprised primarily of solid carbon dioxide, and a first filtrate comprising methane and carbon dioxide, in liquid phase. The first filter may be, for example, a porous media or a centrifuge.

[0187] The separating step of Box **935** may further comprise rinsing the first filter cake using a cold carbon dioxide stream, mixing the first filter cake to produce a first solid-liquid slurry, and delivering the first solid-liquid slurry to a second filter. The second filter produces a second filter cake comprised primarily of solid carbon dioxide, and a second

filtrate comprising primarily methane but also carbon dioxide and hydrogen sulfide, again in liquid phase.

[0188] Additional CO₂ removal may be undertaken. For example, the separating step of Box 935 may further comprise rinsing the second filter cake using the cold carbon dioxide stream, mixing the second filter cake to produce a solid-liquids slurry, and delivering the solids-liquid slurry to yet a third filter. This produces a third filter cake comprised primarily of solid carbon dioxide, and a third filtrate comprising methane, hydrogen sulfide, and carbon dioxide, again in liquid phase.

[0189] The method 900 also includes returning at least a portion of the second liquid material to the cryogenic distillation tower. This is shown at Box 940. In one aspect, the second liquid material is directed back to the lower distillation zone. In another aspect, the second liquid material is merged with the raw gas stream and is injected into the tower in the controlled freezing zone.

[0190] In one embodiment of the method 900, the first filtrate and the second filtrate are combined. The combined fluid from the filtrates forms the liquid material that is returned to the cryogenic distillation tower. In this instance, the liquid material is preferably injected into the lower distillation zone.

[0191] In another embodiment of the method 900, only the first filtrate is returned to the distillation tower. In this instance, the first filtrate may be returned back to the controlled freezing zone. The distillation tower preferably will not have a lower distillation zone; instead, the second and, optionally, third filtrates are delivered to a separate, downstream distillation tower where residual acid gases are finally separated from methane. In this instance, a recovery methane stream is obtained that is merged with the overhead methane stream of the cryogenic distillation tower for sale.

[0192] In yet another arrangement of the method 900, the final filter cake is warmed. This is done regardless of whether there are one, two, three or more filtration stages. The final filter cake is a final-stage filter cake taken from the final filter, whatever that may be. This will, of course, include at least a portion of the first solid material. This warming step is shown in Box 945 of Figure 9.

[0193] Warming may be done, for example, by heat exchanging the solid carbon dioxide making up the filter cake with the raw gas stream. The result is a cold, pure carbon dioxide liquid. The pure carbon dioxide may be sold on the market or used for enhanced oil

recovery operations. In addition, a portion of the cold carbon dioxide stream may be used as a rinse for creating the solid-liquid slurry as described above.

[0194] While it will be apparent that the inventions herein described are well calculated to achieve the benefits and advantages set forth above, it will be appreciated that the inventions are susceptible to modification, variation and change without departing from the spirit thereof. Improvements to the operation of an acid gas removal process using a controlled freezing zone are provided. The improvements provide a design for the removal of CO₂ down to very low levels in the product gas. The inventions herein may also reduce the refrigeration requirements of cryogenic distillation towers while meeting LNG specifications for maximum allowable CO₂.

CLAIMS

What is claimed is:

1. A system for removing acid gases from a raw gas stream, comprising:

a cryogenic distillation tower, the tower having a controlled freezing zone that receives a cold liquid spray comprised primarily of methane, the tower receiving and then
5 separating the raw gas stream into an overhead methane gas stream and a substantially solid material comprised of precipitated carbon dioxide;

refrigeration equipment downstream of the cryogenic distillation tower for cooling the overhead methane stream and returning a portion of the overhead methane stream to the cryogenic distillation tower as the cold liquid spray;

10 a collector tray below the controlled freezing zone for receiving the substantially solid material as it is precipitated in the controlled freezing zone and directing the substantially solid material out of the cryogenic distillation tower;

a first filter for receiving the substantially solid material and separating the substantially solid material into a solid component comprised primarily of carbon dioxide,
15 and a non-solid material comprising methane; and

a liquid return line for returning at least a portion of the non-solid material to the cryogenic distillation tower.

2. The system of claim 1, wherein the collector tray comprises a downcomer into which
20 the precipitated substantially solid material falls.

3. The system of claim 1, wherein the collector tray directs the substantially solid material out of the cryogenic distillation tower (i) by gravitational flow, (ii) by operation of a mechanical translation device, (iii) by aid of spraying a portion of the cold liquid spray into
25 the collector tray and against the substantially solid material, or (iv) by combinations thereof.

4. The system of claim 3, wherein:

the collector tray comprises a downcomer into which the precipitated substantially solid material falls;

30 the mechanical translation device is an auger; and
the auger is disposed within the downcomer.

5. The system of claim 1, wherein:

the cryogenic distillation tower further comprises an upper rectification zone above the controlled freezing zone, and a lower distillation zone below the controlled freezing zone; and

5 the cryogenic distillation tower is configured to receive the raw gas stream into the lower distillation zone.

6. The system of claim 5, wherein:

the cryogenic distillation tower is configured to release a bottoms stream from the
10 lower distillation zone, the bottoms stream comprising acid gases in liquid phase; and
the liquid return line returns at least a portion of the first liquid material to the lower distillation zone.

7. The system of claim 6, wherein the bottoms feed stream comprises carbon dioxide,
15 ethane, propane, butane, hydrogen sulfide, aromatic hydrocarbons, or combinations thereof, in substantially liquid phase.

8. The system of claim 6, wherein the first filter comprises (i) a porous medium, (ii) one or more filter presses, (iii) one or more belt presses, (iv) a hydrocyclone, (v) a centrifugal
20 separator, or (vi) combinations thereof.

9. The system of claim 6, wherein the collector tray is operated at a temperature of about -70° F to -80° F.

25 10. The system of claim 8, wherein:

the solid component from the first filter is a first filter cake; and
the liquid material from the first filter is a first filtrate.

11. The system of claim 10, further comprising:

30 a rinsing vessel for rinsing the first filter cake using a cold carbon dioxide stream, and producing a first solid-liquid slurry.

12. The system of claim 11, wherein the rinsing vessel comprises a mixer for mixing the first filter cake so as to produce the first solid-liquid slurry

13. The system of claim 11, further comprising:

5 a second filter comprising a porous medium, the second filter receiving the first solid-liquid slurry and producing a second filter cake comprised primarily of solid carbon dioxide, and a second filtrate comprising methane, in liquid phase.

14. The system of claim 13, wherein the system is configured to combine the first filtrate
10 and the second filtrate, and return the combined first filtrate and second filtrate to the lower distillation zone as the liquid material.

15. The system of claim 14, wherein the first filtrate further comprises methane, carbon dioxide, hydrogen sulfide, or combinations thereof.

16. The system of claim 11, further comprising:

a heat exchanger configured to warm substantially solid material taken primarily from a final-stage filter cake to produce a substantially pure carbon dioxide stream, in liquid phase; and

20 wherein the cold carbon dioxide stream comprises a portion of the substantially pure carbon dioxide stream.

17. The system of claim 16, wherein the final-stage filter cake is produced after the first filter in a second filter or a third filter.

18. The system of claim 5,

wherein the raw gas stream comprises hydrogen sulfide; and

the system further comprises a hydrogen sulfide removal system configured to remove a substantial portion of the hydrogen sulfide from the raw gas stream before the raw
30 gas stream is injected into the cryogenic distillation tower.

19. The system of claim 1, wherein:

the cryogenic distillation tower further comprises an upper rectification zone above the controlled freezing zone; and

the cryogenic distillation tower is configured to receive the raw gas stream into the controlled freezing zone.

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20. The system of claim 19, wherein the first filter comprises a porous medium, one or more filter presses, one or more belt presses, a hydrocyclone, a centrifugal separator, or combinations thereof.

10 21. The system of claim 19, wherein the collector tray is operated at a temperature of about -70° F to -80° F.

22. The system of claim 19, wherein:
the solid material from the first filter is a first filter cake; and
15 the liquid material from the first filter is a first filtrate.

23. The system of claim 22, further comprising:
a rinsing vessel for rinsing the first filter cake using a cold carbon dioxide stream, and
producing a first solid-liquids slurry.

20

24. The system of claim 23, wherein the rinsing vessel comprises a mixer for mixing the first filter cake so as to produce the first solid-liquid slurry

25. The system of claim 24, further comprising:
25 a second filter comprising a porous medium, the second filter receiving the first solids-liquid slurry and producing a second filter cake comprised primarily of solid carbon dioxide, and a second filtrate comprising methane and carbon dioxide, in liquid phase.

26. The system of claim 25, wherein:
30 the liquid return line merges at least a portion of the second liquid material with the raw gas stream before the raw gas stream is injected into the cryogenic distillation tower.

27. The system of claim 26,

further comprising a distillation separator configured to receive the second filtrate and to produce a bottoms liquid stream comprising carbon dioxide, H₂S, or combinations thereof in liquid phase, and a recovery methane stream; and

wherein the recovery methane stream is combined with the overhead methane stream.

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28. The system of claim 27, wherein the first filtrate and the bottoms liquid stream each further comprise hydrogen sulfide.

29. The system of claim 25, further comprising:

10 a heat exchanger configured to warm substantially solid material taken primarily from a final-stage filter cake to produce a substantially pure carbon dioxide stream, in liquid phase; and

wherein the cold carbon dioxide stream comprises a portion of the substantially pure carbon dioxide stream.

15

30. The system of claim 29, wherein the final-stage filter cake is produced in the second filter or a third filter.

31. A method for removing acid gases from a dehydrated raw gas stream, comprising:

20 providing a cryogenic distillation tower, the tower having a controlled freezing zone that receives a cold liquid spray comprised primarily of methane, and a collector tray below the controlled freezing zone;

injecting the raw gas stream into the cryogenic distillation tower;

25 chilling the raw gas stream so as to cause carbon dioxide within the raw gas stream to precipitate upon the collector tray as substantially solid material, while allowing methane to substantially vaporize and exit the cryogenic distillation tower as an overhead methane stream;

30 passing the overhead methane stream through a refrigeration system downstream of the cryogenic distillation tower, the refrigeration system cooling the overhead methane stream;

returning a portion of the cooled overhead methane stream to the cryogenic distillation tower as liquid reflux to serve as the cold liquid spray;

removing the substantially solid material from the cryogenic distillation tower as a slurry;

separating the substantially solid material into a solid material comprised primarily of carbon dioxide, and a liquid material comprising methane; and

5 returning at least a portion of the liquid material to the cryogenic distillation tower.

32. The method of claim 31, wherein:

the collector tray comprises a downcomer into which the precipitated substantially solid material falls, and a mechanical translation device within the downcomer; and

10 removing the substantially solid material from the cryogenic distillation tower comprises operating the mechanical translation device to move the substantially solid material from the downcomer out of the cryogenic distillation tower.

33. The method of claim 31, wherein:

15 the collector tray comprises a downcomer into which the precipitated substantially solid material falls; and

the collector tray directs the substantially solid material out of the cryogenic distillation tower (i) by gravitational flow, (ii) by operation of a mechanical translation device, (iii) by aid of spraying a portion of the cold liquid spray into the collector tray and
20 against the substantially solid material, or (iv) by combinations thereof.

34. The method of claim 31, wherein:

the cryogenic distillation tower further comprises an upper rectification zone above the intermediate controlled freezing zone, and a lower distillation zone below the
25 intermediate controlled freezing zone; and

the raw gas stream is injected into the lower distillation zone.

35. The method of claim 34,

further comprising releasing a bottoms stream from the lower distillation zone, the
30 bottoms stream comprising acid gases in liquid phase; and

wherein returning at least a portion of the liquid material to the cryogenic distillation tower comprises delivering the liquid material to the lower distillation zone.

36. The method of claim 35, wherein the bottoms stream comprises ethane, propane, butane, hydrogen sulfide, carbon dioxide, or combinations thereof, in substantially liquid phase.

37. The method of claim 34, wherein separating the substantially solid material into a solid component comprised primarily of carbon dioxide, and a liquid material comprised primarily of methane, comprises passing the substantially solid material through a first filter, thereby producing a first filter cake comprised primarily of solid carbon dioxide, and a first filtrate comprising methane and carbon dioxide, in liquid phase.

38. The method of claim 37, wherein the separating further comprises:
rinsing the first filter cake using a cold carbon dioxide stream;
mixing the first filter cake to produce a first solid-liquid slurry; and
delivering the first solid-liquid slurry to a second filter, thereby producing a second filter cake comprised primarily of solid carbon dioxide, and a second filtrate comprising methane, in liquid phase.

39. The method of claim 38,
further comprising combining the first filtrate and the second filtrate; and
wherein the second liquid material that is returned to the lower distillation zone comprises the combined first filtrate and second filtrate.

40. The method of claim 39, further comprising:
rinsing the second filter cake using the cold carbon dioxide stream;
mixing the second filter cake to produce a solid-liquid slurry; and
delivering the solid-liquid slurry to a third filter, thereby producing a third filter cake comprised primarily of solid carbon dioxide, and a third filtrate comprising methane, in liquid phase.

41. The method of claim 37, further comprising:
warming substantially solid material taken primarily from a final-stage filter cake to produce a substantially pure carbon dioxide stream, in liquid phase; and

wherein the cold carbon dioxide stream comprises a portion of the substantially pure carbon dioxide stream.

42. The method of claim 41, wherein the warming comprises passing the substantially solid material taken primarily from the final-stage filter cake through a heat exchanger such that heat is exchanged with the raw gas stream.

43. The method of claim 37, wherein the first filter comprises a porous medium or a centrifuge.

44. The method of claim 37,
wherein the dehydrated raw gas stream comprises hydrogen sulfide; and
the method further comprises removing a substantial portion of the hydrogen sulfide from the raw gas stream prior to injecting the raw gas stream into the cryogenic distillation tower.

45. The method of claim 31, wherein:
the cryogenic distillation tower further comprises an upper rectification zone above the intermediate controlled freezing zone; and
the raw gas stream is injected into the controlled freezing zone.

46. The method of claim 45, wherein separating the substantially solid material into a first solid material comprised primarily of carbon dioxide, and a second liquid material comprised primarily of methane, comprises passing the substantially solid material through a first filter, thereby producing a first filter cake comprised primarily of solid carbon dioxide, and a first filtrate comprising methane and carbon dioxide, in liquid phase.

47. The method of claim 46, wherein:
returning at least a portion of the second liquid material to the cryogenic distillation tower comprises (i) injecting the first filtrate directly back into the controlled freezing zone, or (ii) merging the first filtrate with the raw gas stream before the raw gas stream is injected into the cryogenic distillation tower.

48. The method of claim 45, wherein the separating further comprises:
rinsing the first filter cake using a cold carbon dioxide stream;
mixing the first filter cake to produce a first solid-liquids slurry; and
delivering the first solids-liquid slurry to a second filter, thereby producing a second
5 filter cake comprised primarily of solid carbon dioxide, and a second filtrate comprising
methane, carbon dioxide and hydrogen sulfide, in liquid phase.

49. The method of claim 48, further comprising:
rinsing the second filter cake using the cold carbon dioxide stream;
10 mixing the second filter cake to produce a solid-liquids slurry; and
delivering the solids-liquid slurry to a third filter, thereby producing a third filter
cake comprised primarily of solid carbon dioxide, and a third filtrate comprising methane,
carbon dioxide and hydrogen sulfide, in liquid phase.

15 50. The method of claim 49, further comprising:
combining the second filtrate and the third filtrate;
injecting the second filtrate and the third filtrate into a distillation separator, thereby
producing a bottoms liquid stream comprised primarily of carbon dioxide, in liquid phase,
and a recovery methane stream; and
20 combining the overhead methane stream from the cryogenic distillation tower with
the recovery methane stream.

51. The method of claim 46, further comprising:
warming substantially solid material taken primarily from a final-stage filter cake to
25 produce a substantially pure carbon dioxide stream, in liquid phase; and
wherein the cold carbon dioxide stream comprises a portion of the substantially pure
carbon dioxide stream.

52. The method of claim 51, wherein the warming comprises passing the substantially
30 solid material taken primarily from the final-stage filter cake through a heat exchanger such
that heat is exchanged with the raw gas stream.