MIXED REFRIGERANT LIQUEFACTION PROCESS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application 60/565,589, filed June 23, 2004.

BACKGROUND

Technical Field

[0002] Embodiments of the present inventions generally relate to methods for refrigerating gas streams, such as natural gas, using mixed component refrigerants.

Description of Related Art

[0003] Natural gas is commonly liquefied and transported to supply major energy-consuming nations. To liquefy natural gas, the feed gas is first processed to remove contaminants and hydrocarbons heavier than at least pentane. This purified gas, typically at an elevated pressure, is then chilled through indirect heat exchange by one or more refrigeration cycles. Such refrigeration cycles are costly in terms of both capital expenditure and operation due to the complexity of the required equipment and the efficiency performance of the refrigerant. There is a need, therefore, for a method to improve refrigeration efficiency, reduce equipment size, and reduce operating expenses.

SUMMARY

[0004] Methods for liquefying a natural gas stream are provided. In one embodiment, the method includes placing a mixed component refrigerant in a heat exchange area with a process stream; separating the mixed component refrigerant at one or more pressure levels to produce a refrigerant vapor and a refrigerant liquid; bypassing the refrigerant vapor around the heat exchange area to a compression unit; and passing the refrigerant liquid to the heat exchange area.

[0005] In another embodiment, the method includes placing a mixed component refrigerant in a heat exchange area with a process stream; withdrawing two or more side streams of the mixed component refrigerant from the heat exchange area; separating the side streams of mixed component refrigerant at one or more pressure levels to produce refrigerant vapors and refrigerant liquids; bypassing the refrigerant vapors around the heat exchange area to a compression unit; and passing the refrigerant liquids to the heat exchange area.

[0006] In another embodiment, the method includes placing a mixed component refrigerant in a heat exchange area with a process stream; separating the mixed component refrigerant at one or more pressure levels to produce a refrigerant vapor stream and a refrigerant liquid stream; bypassing the refrigerant vapor stream around the heat exchange area to a compression unit; passing the refrigerant liquid stream to the heat exchange area; and partially evaporating the refrigerant liquid stream within the heat exchange area to retain a liquid fraction of at least 1% by weight.

[0007] In yet another embodiment, the method includes placing a first mixed component refrigerant in a first heat exchange area with a process stream; separating the first mixed component refrigerant at one or more pressure levels to produce a refrigerant vapor stream and a refrigerant liquid stream; bypassing the refrigerant vapor stream around the first heat exchange area to a compression unit; passing the refrigerant liquid stream to the first heat exchange area to cool the process stream; and placing a second mixed component refrigerant in a second heat exchange area with the cooled process stream to liquefy the process stream.

[0008] In yet another embodiment, the method includes placing a first mixed component refrigerant in a first heat exchange area with a process stream; separating the mixed component refrigerant at one or more pressure levels to produce a refrigerant vapor stream and a refrigerant liquid stream; bypassing the refrigerant vapor stream around the first heat exchange area to a compression unit; returning the refrigerant liquid stream to the first heat exchange area to cool the gas stream; placing a second mixed component refrigerant in a second heat exchange area with the cooled

process stream; and evaporating the second mixed component refrigerant at a single pressure level to liquefy the gas stream.

[0009] In still yet another embodiment, the method includes placing a mixed component refrigerant stream in heat exchange with a process stream, the refrigerant stream comprising liquid refrigerant; and discontinuing the heat exchange before the liquid refrigerant stream is completely vaporized.

[0010] In still other embodiments, the method includes liquefying a natural gas stream by placing a mixed component refrigerant in a heat exchange area with a process stream; separating the mixed component refrigerant at one or more pressure levels to produce a refrigerant vapor and a refrigerant liquid; passing at least the refrigerant liquid to the heat exchange area; and partially evaporating the refrigerant liquid within the heat exchange area to retain a liquid phase. In an alternative embodiment, the method includes placing a mixed component refrigerant in a heat exchange area with a process stream; withdrawing two or more side streams of the mixed component refrigerant from the heat exchange area; separating the side streams of mixed component refrigerant at one or more pressure levels to produce refrigerant vapors and refrigerant liquids; passing at least the refrigerant liquids to the heat exchange area; and partially evaporating the refrigerant liquids within the heat exchange area to retain a liquid phase.

DETAILED DESCRIPTION

Introduction and Definitions

[0011] A detailed description will now be provided. Each of the appended claims defines a separate invention, which for infringement purposes is recognized as including equivalents to the various elements or limitations specified in the claims. Depending on the context, all references below to the "invention" may in some cases refer to certain specific embodiments only. In other cases it will be recognized that references to the "invention" will refer to subject matter recited in one or more, but not necessarily all, of the claims. Each of the inventions will now be described in

greater detail below, including specific embodiments, versions and examples, but the inventions are not limited to these embodiments, versions or examples, which are included to enable a person having ordinary skill in the art to make and use the inventions, when the information in this patent is combined with available information and technology. Various terms as used herein are defined below. To the extent a term used in a claim is not defined below, it should be given the broadest definition persons in the pertinent art have given that term as reflected in printed publications and issued patents.

[0012] The terms "mixed component refrigerant" and "MCR" are used interchangeably and mean a mixture that contains two or more refrigerant components. Examples of the MCRs described herein are a "first MCR" and a "second MCR."

[0013] The term "refrigerant component" means a substance used for heat transfer which absorbs heat at a lower temperature and rejects heat at a higher temperature. For example, a "refrigerant component," in a compression refrigeration system, will absorb heat at a lower temperature and pressure through evaporation and will reject heat at a higher temperature and pressure through condensation. Illustrative refrigerant components may include, but are not limited to, alkanes, alkenes, and alkynes having one to 5 carbon atoms, nitrogen, chlorinated hydrocarbons, fluorinated hydrocarbons, other halogenated hydrocarbons, and mixtures or combinations thereof.

[0014] The term "natural gas" means a light hydrocarbon gas or a mixture of two or more light hydrocarbon gases. Illustrative light hydrocarbon gases may include, but are not limited to, methane, ethane, propane, butane, pentane, hexane, isomers thereof, unsaturates thereof, and mixtures thereof. The term "natural gas" may further include some level of impurities, such as nitrogen, hydrogen sulfide, carbon dioxide, carbonyl sulfide, mercaptans and water. The exact percentage composition of the natural gas varies depending upon the reservoir source and any pre-processing steps, such as amine extraction or desiccation via molecular sieves, for example. At least

one example of a "natural gas" composition is a gas containing about 55 mole% of methane or more.

[0015] The terms "gas" and "vapor" are used interchangeably and mean a substance or mixture of substances in the gaseous state as distinguished from the liquid or solid state.

[0016] The term "partially evaporated" describes a substance which may include a mixture of substances that is not 100% vapor. A "partially evaporated" stream may have both a vapor phase and a liquid phase. At least one example of a "partially evaporated" stream includes a stream having a liquid phase of at least 1% by weight, or at least 2% by weight, or at least 3% by weight, or at least 4% by weight, or at least 5% by weight, and the balance being the vapor phase. In one or more specific embodiments, a "partially evaporated" stream has a liquid phase ranging from a low of 1% by weight, or 3% by weight, or 10% by weight to a high of 90% by weight, or 97% by weight, or 99% by weight.

[0017] The term "heat exchange area" means any one type or combination of similar or different types of equipment known in the art for facilitating heat transfer. For example, a "heat exchange area" may be contained or at least partially contained within one or more spiral wound type exchanger, plate-fin type exchanger, shell and tube type exchanger, or any other type of heat exchanger known in the art that is capable of withstanding the process conditions described herein in more detail below.

[0018] The term "compression unit" means any one type or combination of similar or different types of compression equipment, and may include auxiliary equipment, known in the art for compressing a substance or mixture of substances. A "compression unit" may utilize one or more compression stages. Illustrative compressors may include, but are not limited to, positive displacement types, such as reciprocating and rotary compressors for example, and dynamic types, such as centrifugal and axial flow compressors, for example. Illustrative auxiliary equipment may include, but are not limited to, suction knock-out vessels, discharge coolers or chillers, recycle coolers or chillers, and any combination thereof.

Specific Embodiments

[0019] Various specific embodiments are described below, at least some of which are also recited in the claims. For example, at least one embodiment is directed to a method for liquefying a natural gas stream by placing a mixed component refrigerant in a heat exchange area with a process stream and separating the mixed component refrigerant at one or more pressure levels to produce a refrigerant vapor and a refrigerant liquid. The refrigerant vapor bypasses around the heat exchange area to a compression unit, and the refrigerant liquid passes to the heat exchange area.

[0020] At least one other specific embodiment is directed to liquefying a natural gas stream by placing a mixed component refrigerant in a heat exchange area with a process stream and withdrawing two or more side streams of the mixed component refrigerant from the heat exchange area. The side streams of mixed component refrigerant are then separated at one or more pressure levels to produce refrigerant vapors and refrigerant liquids. The refrigerant vapors are bypassed around the heat exchange area to a compression unit, and the refrigerant liquids are passed to the heat exchange area.

[0021] Yet another specific embodiment is directed to liquefying a natural gas stream by placing a mixed component refrigerant in a heat exchange area with a process stream and separating the mixed component refrigerant at one or more pressure levels to produce a refrigerant vapor stream and a refrigerant liquid stream. The refrigerant vapor stream bypasses around the heat exchange area to a compression unit. The refrigerant liquid stream is passed to the heat exchange area, and at least partially evaporated within the heat exchange area to retain a liquid fraction of at least 1% by weight.

[0022] Yet another specific embodiment is directed to a method for liquefying a natural gas stream by placing a first mixed component refrigerant in a first heat exchange area with a process stream and separating the first mixed component refrigerant at one or more pressure levels to produce a refrigerant vapor stream and a refrigerant liquid stream. The refrigerant vapor stream is bypassed around the first

heat exchange area to a compression unit, and the refrigerant liquid stream is passed to the first heat exchange area to cool the process stream. A second mixed component refrigerant is then placed in a second heat exchange area with the cooled process stream to liquefy the process stream.

[0023] Yet another specific embodiment is directed to liquefying a natural gas stream by placing a first mixed component refrigerant in a first heat exchange area with a process stream, and separating the mixed component refrigerant at one or more pressure levels to produce a refrigerant vapor stream and a refrigerant liquid stream. The refrigerant vapor stream is bypassed around the first heat exchange area to a compression unit, and the refrigerant liquid stream is passed to the first heat exchange area to cool the gas stream. A second mixed component refrigerant is placed in a second heat exchange area with the cooled process stream, and evaporated at a single pressure level to liquefy the gas stream.

[0024] Yet another specific embodiment is directed to cooling a process stream of natural gas by placing a mixed component refrigerant stream in heat exchange with a process stream. The refrigerant stream comprises liquid refrigerant, and the heat exchange is discontinued before the liquid refrigerant stream is completely vaporized.

[0025] In still other embodiments, the refrigerant vapor stream or streams need not bypass the heat exchanger or exchangers and/or need not be sent directly to a compression unit. In such embodiments, the vapor stream or streams may, for example, be returned to the heat exchanger or exchangers, or they may bypass the heat exchanger or exchangers and be sent to equipment other than a compression unit. Thus, embodiments of the present method include modifications of any embodiment described herein wherein the refrigerant vapor stream or streams do not bypass the heat exchanger or exchangers and/or are not sent directly to a compression unit. Such embodiments, include, for example, liquefying a natural gas stream by placing a mixed component refrigerant in a heat exchange area with a process stream; separating the mixed component refrigerant at one or more pressure levels to produce a refrigerant vapor and a refrigerant liquid; passing at least the refrigerant liquid to the

heat exchange area; and partially evaporating the refrigerant liquid within the heat exchange area to retain a liquid phase. Such embodiments also include placing a mixed component refrigerant in a heat exchange area with a process stream; withdrawing two or more side streams of the mixed component refrigerant from the heat exchange area; separating the side streams of mixed component refrigerant at one or more pressure levels to produce refrigerant vapors and refrigerant liquids; passing at least the refrigerant liquids to the heat exchange area; and partially evaporating the refrigerant liquids within the heat exchange area to retain a liquid phase.

Specific Embodiments In Drawings

[0026] Specific embodiments shown in the drawings will now be described. It is emphasized that the claims should not be read to be limited to aspects of the drawings. Figure 1 schematically depicts a refrigeration process utilizing an at least partially evaporated mixed component refrigerant to cool or liquefy a process stream or feed gas. Figure 2 schematically depicts a refrigeration process utilizing a heat exchanger having two or more heat exchange areas contained therein to cool or liquefy a process stream or feed gas. Figure 3 schematically depicts a refrigeration process utilizing two mixed component refrigerants to cool or liquefy a process stream or feed gas. Figure 4 schematically depicts another method for refrigerating a process stream or feed gas that utilizes a liquid refrigerant collection system. For simplicity and ease of description, these refrigeration processes will be further described herein as they relate to a process stream or feed gas of natural gas that is sub-cooled to produce liquefied natural gas ("LNG").

FIGURE 1

[0027] Figure 1 schematically depicts a refrigeration process 5 utilizing an at least partially evaporated mixed component refrigerant to at least cool a process stream or feed gas. The feed gas stream 12 is placed in heat exchange with a mixed component refrigerant ("MCR") stream 30 within a heat exchanger 10. As explained in more detail below, the MCR stream 30 is expanded and cooled to remove heat from the feed gas stream 12 within the heat exchanger 10. Although not shown, additional

process streams that require refrigeration can enter the heat exchanger 10. Non-limiting examples of such additional streams include other refrigerant streams, other hydrocarbon streams to be blended with the gas of stream 12 at a later processing stage, and streams that are integrated with one or more fractionation processing steps.

[0028] The heat exchanger 10, as shown in Figure 1, is a single unit containing at least one heat exchange area. Although not shown, but described below, the heat exchanger 10 may include two or more heat exchange areas, such as two, three, four, or five, for example, that may be contained within a single unit, or each area may be contained in a separate unit.

[0029] The feed gas stream 12 is preferably natural gas and may contain at least 55 mole%, or at least 65 mole%, or at least 75 mole% of methane. The MCR stream 30 may include one or more of alkanes, alkenes, and alkynes having one to 5 carbon atoms, nitrogen, chlorinated hydrocarbons, fluorinated hydrocarbons, other halogenated hydrocarbons, and mixtures or combinations thereof. In one or more specific embodiments, the MCR stream 30 is a mixture of ethane and propane. In one or more specific embodiments, the MCR stream 30 is a mixture of ethane, propane and isobutane. In one or more specific embodiments, the MCR stream 30 is a mixture of methane, ethane, and nitrogen.

[0030] The MCR stream 30 is cooled in the heat exchange area 10 and exits the heat exchange area 10 as stream 40. Stream 40 is expanded using an expansion device 45, producing a two-phase stream 50 (i.e. a stream having a vapor phase and a liquid phase). Illustrative expansion devices include, but are not limited to valves, control valves, Joule Thompson valves, Venturi devices, liquid expanders, hydraulic turbines, and the like. Preferably, the expansion device 45 is an automatically actuated expansion valve or Joule Thompson-type valve. The two-phase stream 50 is then separated within a separator 55 to produce a vapor stream 60 and a liquid stream 65. Preferably, the two-phase stream 50 is subjected to a flash separation. The vapor stream 60 bypasses the heat exchange area 10 and is sent directly to the compression unit 75.

[0031] After being reduced in pressure and thus cooled, the liquid stream 65 returns to the heat exchange area 10 where it is completely evaporated or partially evaporated due to the heat exchange with the process gas stream 12 and the MCR stream 30. This completely evaporated or partially evaporated stream exits the heat exchange area 10 as stream 70. In one or more specific embodiments, the stream 70 has a vapor fraction of at least 85% by weight, or at least 90% by weight, or at least 99% by weight, and the balance is the liquid phase fraction. In one or more specific embodiments, the stream 70 is a vapor stream having no liquid phase. Stream 70 then flows to the compression unit 75.

[0032] The compression unit 75 may utilize one or more compression stages depending on the process conditions and requirements. Preferably, the compression unit 75 utilizes two or more compression stages where each stage utilizes an inter-stage cooler to remove the heat of compression. The compressed stream is then sent to the heat exchange area 10 as stream 30. An exemplary compression unit is discussed in more detail below.

[0033] By sending the vapor stream 60 around the heat exchange area 10 directly to the compression unit 75 (i.e. bypassing the refrigerant vapor around the heat exchange area to the compression unit), certain distribution problems associated with two-phase refrigerants may be avoided. The term "two-phase refrigerant" refers to a refrigerant having at least some of the refrigerant in the liquid phase and at least 10% by volume in the vapor phase. Two-phase distribution may result in reduced liquefied gas production and lost revenue because of the inadequate distribution of the two-phase refrigerant within the heat exchange area. The inadequate distribution of the two-phase refrigerant within the heat exchange area results in inefficient heat transfer because the vapor phase of the two-phase refrigerant occupies more volume within the heat exchange area compared to the liquid phase. Since the vapor phase contributes very little to the heat exchange in comparison to the evaporating liquid phase, the cooling capacity of the refrigerant is compromised.

[0034] Furthermore, the hydraulic design of a system that can effectively distribute the two-phase refrigerant to the heat exchanger or exchangers can be expensive in both engineering time and purchased equipment. The behavior of such designs are more difficult to predict in situations that stray too far from the design conditions in terms of temperature, pressure, and/or flow rate. The benefits achieved according to the one or more embodiments described herein are particularly applicable to arrays of heat exchangers in a parallel arrangement that are fed refrigerant from a common source because the vapor phase has been removed eliminating this distribution consideration.

FIGURE 2

[0035] Figure 2 schematically depicts a refrigeration process 100 utilizing a heat exchanger having more than one heat exchange area contained therein to cool or liquefy a process stream or feed gas. The refrigeration process 100 utilizes a heat exchanger 200 having two or more heat exchange areas contained therein, such as three areas as shown in Figure 2, and a MCR compression unit 300. A feed gas stream 102 is cooled against a mixed component refrigerant ("MCR") within the heat exchanger 200. Although not shown, additional process streams that require refrigeration can enter the heat exchanger 200. Non-limiting examples of such additional streams include other refrigerant streams, other hydrocarbon streams to be blended with the gas of stream 102 at a later processing stage, and streams that are integrated with one or more fractionation processing steps.

[0036] The composition of the feed gas stream 102 depends on its source reservoir, but can include up to 99 mole% of methane, up to 15 mole% of ethane, up to 10 mole% of propane, and up to 30 mole% of nitrogen, for example. In one specific embodiment, the feed gas stream 102 may contain at least 55 mole%, or at least 65 mole%, or at least 75 mole% by volume of methane. In another specific embodiment, the feed gas stream 102 may also contain up to 1 mole%, or up to 2 mole%, or up to 5 mole% of non-hydrocarbon compounds, such as water, carbon dioxide, sulfur-containing compounds, mercury, and combinations thereof. In one or

more specific embodiments, the feed gas stream 102 may be subjected to a purification process (not shown) to strip or otherwise remove a majority, if not all, of these non-hydrocarbon compounds from the feed gas stream 102 prior to entering the heat exchanger 200.

[0037] In certain embodiments, the feed gas stream 102 enters the heat exchanger 200 at a temperature within a range of from a low of 15°C, or 25°C, or 35°C to a high of 40°C, or 45°C, or 55°C, and at a pressure within a range of from a low of 4,000 kPa, or 6,000 kPa, or 7,000 kPa to a high of 8,500 kPa, or 10,000 kPa, or 12,000 kPa. The feed gas stream 102 exits the heat exchanger 200 as a chilled stream 104. The chilled stream 104 exits the heat exchanger 200 at a temperature within a range of from a low of -70°C, or -80°C, or -100°C to a high of -60°C, or -50°C, or -35°C. For example, the chilled stream 104 can exit the heat exchanger 200 at a temperature of about -70°C to about -75°C.

MCR

[0038] The mixed component refrigerant ("MCR") is preferably a mixture of ethane, propane and isobutane. The MCR may contain between about 20 mole% and 80 mole% of ethane, between about 10 mole% and 90 mole% of propane, and between about 5 mole% and 30 mole% of isobutane. In one or more specific embodiments, the concentration of ethane within the first MCR ranges from a low of 20 mole%, or 30 mole%, or 40 mole% to a high of 60 mole%, or 70 mole%, or 80 mole%. In one or more specific embodiments, the concentration of propane within the MCR ranges from a low of 10 mole%, or 20 mole%, or 30 mole% to a high of 70 mole%, or 80 mole%, or 90 mole%. In one or more specific embodiments, the concentration of isobutane within the MCR ranges from a low of 3 mole%, or 5 mole%, or 10 mole% to a high of 20 mole%, or 25 mole%, or 30 mole%.

[0039] In one or more specific embodiments, the MCR has a molecular weight of about 32 to about 45. More preferably, the molecular weight of the MCR ranges from a low of 32, or 34, or 35 to a high of 42, or 43, or 45. Further, the molar ratio of the MCR to the feed gas stream 102 ranges from a low of 1.0, or 1.2, or 1.5 to a high of

1.8, or 2.0, or 2.2. In one or more specific embodiments, the molar ratio of the MCR to the feed gas stream 102 is at least 1.0 , or at least 1.2, or at least 1.5.

HEAT EXCHANGER

[0040] Considering the heat exchanger 200 in more detail, the MCR enters the heat exchanger 200 as stream 202. At least a portion of stream 202 is withdrawn from a first heat exchange area of the heat exchanger 200 as a side stream 203. The side stream 203 is expanded to a first pressure using an expansion device 205, producing a two-phase stream 207 (i.e. a stream having a vapor phase and a liquid phase). In one or more specific embodiments, this first pressure ranges from a low of 800 kPa, or 1,200 kPa, or 1,500 kPa to a high of 1,900 kPa, or 2,200 kPa, or 2,600 kPa. Accordingly, the temperature of the expanded stream 207 ranges from a low of 0°C, or 3°C, or 4°C to a high of 6°C, or 10°C, or 15°C. Preferably, the side stream 203 is expanded to a pressure of from 1,600 kPa to 1,800 kPa and a temperature of from 4°C to 6°C.

[0041] The two-phase stream 207 is then separated within a separator 210 to produce a vapor stream 214 and a liquid stream 212. Preferably, the two-phase stream 207 is subjected to a flash separation. The vapor stream 214 bypasses the heat exchanger 200 and is sent directly to the compression unit 300. By sending the vapor stream 214 around the heat exchanger 200 directly to the compression unit 300 (i.e. bypassing the refrigerant vapor around the heat exchange area to the compression unit), the certain distribution problems associated with two-phase refrigerants noted above may be avoided.

[0042] After being reduced in pressure and thus cooled, the liquid stream 212 returns to the heat exchanger 200 where it is completely evaporated or partially evaporated due to the heat exchange within the heat exchanger 200. This completely evaporated or partially evaporated stream exits the heat exchanger 200 as stream 216. In one or more specific embodiments, the stream 216 has a vapor fraction of at least 85% by weight, or at least 90 % by weight, or at least 99% by weight, and the balance is the liquid phase fraction. In one or more specific embodiments, the stream 216 is a

vapor stream having no liquid phase (i.e. completely evaporated). Stream 216 may be combined as shown in Figure 1 with the vapor stream 214 from the separator 210 to form a recycle stream 218 that flows to the compression unit 300.

[0043] At least another portion of stream 202 is withdrawn from a second heat exchange area of the heat exchanger 200 as a side stream 213. The side stream 213 is expanded to a second pressure using an expansion device 215, producing stream 217. The stream 217 has a vapor phase and a liquid phase. In one or more specific embodiments, this second pressure ranges from a low of 250 kPa, or 400 kPa, or 500 kPa to a high of 600 kPa, or 700 kPa, or 850 kPa. Accordingly, the temperature of the expanded stream 217 ranges from a low of -60°C, or -50°C, or -40°C to a high of -30°C, or -20°C, or -10°C. Preferably, the side stream 213 is expanded to a pressure of from 550 kPa to 570 kPa and a temperature of from -35°C to -45°C.

[0044] The two-phase stream 217 is then separated within a separator 220 to produce a vapor stream 224 and a liquid stream 222. Preferably, the two-phase stream 217 is subjected to a flash separation. The vapor stream 224 bypasses the heat exchanger 200 and is sent directly to the compression unit 300. The liquid stream 222, having been reduced in pressure and thus cooled, returns to the heat exchanger 200 where it is completely evaporated or partially evaporated due to the heat exchange within the heat exchanger 200. This completely evaporated or partially evaporated stream exits the heat exchanger 200 as stream 226. In one or more specific embodiments, stream 226 has a vapor fraction of at least 85% by weight, or at least 90% by weight, or at least 99% by weight, and the balance is the liquid phase fraction. Stream 226 may be combined as shown in Figure 1 with the vapor stream 224 from the separator 220 to form a recycle stream 228 that flows to the compression unit 300.

[0045] Yet another portion of stream 202 is withdrawn from a third heat exchange area of the heat exchanger 200 as a side stream 223. The side stream 223 is expanded to a third pressure using an expansion device 225, producing stream 227 that has a vapor phase and a liquid phase. In one or more specific embodiments, this third

pressure ranges from a low of 80 kPa, or 120 kPa, or 150 kPa to a high of 180 kPa, or 200 kPa, or 250 kPa. Accordingly, the temperature of the expanded stream 227 ranges from a low of -110°C, or -90°C, or -80°C to a high of -60°C, or -50°C, or -30°C. Preferably, the side stream 223 is expanded to a pressure of from 160 kPa to 180 kPa and a temperature of from -65°C to -75°C.

[0046] The two-phase stream 227 is then separated within a separator 230 to produce a flash vapor stream 234 and a saturated liquid stream 232. Preferably, the two-phase stream 227 is subjected to a flash separation. The vapor stream 234 bypasses the heat exchanger 200 and is sent directly to the compression unit 300. The saturated liquid stream 232, having been reduced in pressure and thus cooled, returns to the heat exchanger 200 where it is completely evaporated or partially evaporated due to the heat exchange within the heat exchanger 200. This completely evaporated or partially evaporated refrigerant exits the heat exchanger 200 as stream 236. In one or more specific embodiments, stream 236 has a vapor fraction of at least 85% by weight, or at least 90% by weight, or at least 99% by weight, and the balance is the liquid phase fraction. Stream 236 may be combined as shown in Figure 2 with the vapor stream 234 from the separator 230 to form a recycle stream 238 that flows to the compression unit 300.

[0047] In the one or more specific embodiments described above, the expansion device may be any pressure reducing device. Illustrative expansion devices include, but are not limited to valves, control valves, Joule Thompson valves, Venturi devices, liquid expanders, hydraulic turbines, and the like. Preferably, the expansion devices 205, 215, 225 are automatically actuated expansion valves or Joule Thompson-type valves.

[0048] As described above, the vapor streams 214, 224, 234 bypass the heat exchanger 200 and are sent directly to the compression unit 300. This bypass configuration avoids the distribution problems associated with two-phase refrigerants as explained above. Furthermore, the partially evaporated refrigerant exiting the heat exchange area with two phases has been configured to reduce mechanical stress

within the heat exchange area. Mechanical stress may be a product of a rapid temperature transition across the volume occupied by a liquid phase and the volume occupied by a vapor phase. The temperature transition from the volume of the liquid or two-phase fluid portion to the volume of the vapor portion may result in stress fracture during startups, shutdowns, or upsets, or may result in fatigue failure of the exchanger. Therefore, configuring the refrigerant flow conditions allows for incomplete vaporization of the refrigerant liquid streams 212, 222 and 232 without the inherent effects of mechanical stress caused by a rapid temperature gradient. To transition from a system in which the refrigerant is fully evaporated to a system in which the refrigerant is partially evaporated, the flow rate may be increased, the evaporation pressure may be changed, the refrigerant composition may be changed to include more components with higher boiling points, or a combination of any of these design parameters.

MCR COMPRESSION UNIT 300

[0049] The MCR compression unit 300 includes one or more different pressure levels. Preferably, the suction of each compression stage corresponds to the pressure levels of the recycle streams 218, 228, 238. In at least one specific embodiment, the first compression stage includes a suction knock-out vessel 310 and a compressor 320. In at least one specific embodiment, the second compression stage includes a suction knock-out vessel 330, a compressor 340, and a discharge cooler or condenser 350. In at least one specific embodiment, the third compression stage includes a suction knock-out vessel 360, a compressor 370, and a discharge cooler 380. In at least one specific embodiment, the compression unit 300 further includes a final cooler or condenser 390.

[0050] The coolers 350, 380, and 390 may be any type of heat exchanger suitable for the process conditions described herein. Illustrative heat exchangers include, but are not limited to, shell-and-tube heat exchangers, core-in-kettle exchangers and brazed aluminum plate-fin heat exchangers. In one or more specific embodiments, plant cooling water is used as the heat transfer medium to cool the process fluid

within the coolers 350, 380, and 390. In one or more specific embodiments, air is used as the heat transfer medium to cool the process fluid within the coolers 350, 380, and 390. Furthermore, in one or more of the embodiments described above, the bypassed flash vapor streams 214, 224, 234, cool the at least partially evaporated refrigerant streams 216, 226, 236 exiting the heat exchanger 200. As such, the combined streams 218, 228, 238, which recycle to the suction to the compression unit 300, are lower in temperature thereby reducing the duty requirements of the discharge coolers 350, 380, and 390.

[0051] Referring to the first compression stage in more detail, stream 322 exits the first stage 320. In one or more specific embodiments, the pressure of stream 322 ranges from a low of 200 kPa, or 300 kPa, or 400 kPa to a high of 600 kPa, or 700 kPa, or 800 kPa. The temperature of stream 322 ranges from a low of 5°C, or 10°C, or 15°C to a high of 20°C, or 25°C, or 30°C.

[0052] Referring to the second compression stage, stream 342 exits the second stage 340 and is cooled within the discharge cooler 350 to produce stream 352. In one or more specific embodiments, the pressure of stream 342 ranges from a low of 800 kPa, or 1,200 kPa, or 1,400 kPa to a high of 1,800 kPa, or 2,000 kPa, or 2,500 kPa. In one or more specific embodiments temperature of stream 352 ranges from a low of 15°C, or 25°C, or 35°C to a high of 40°C, or 45°C, or 55°C.

[0053] Referring to the third compression stage, stream 372 exits the third stage 370 and is cooled within the discharge cooler 380 to produce stream 382. In one or more specific embodiments, the pressure of stream 372 ranges from a low of 1,600 kPa, or 2,400 kPa, or 2,900 kPa to a high of 3,500 kPa, or 4,000 kPa, or 5,000 kPa. The temperature of stream 372 ranges from a low of 40°C, or 50°C, or 60°C to a high of 100°C, or 120°C, or 150°C. In one or more specific embodiments, the temperature of stream 382 ranges from a low of 0°C, or 10°C, or 20°C to a high of 40°C, or 50°C, or 60°C.

[0054] In one or more certain embodiments, stream 382 flows to the condenser 390 to produce stream 392. The temperature of stream 392 ranges from a low of 0°C,

or 10°C, or 20°C to a high of 40°C, or 45°C, or 55°C. In one or more certain embodiments, stream 392 flows to a surge vessel 295 to provide residence time for operability considerations as the high pressure liquid refrigerant enters heat exchanger 200 as stream 202.

FIGURE 3

[0055] The refrigeration or liquefaction process 100 may further utilize a second heat exchanger 400 and a second MCR compression unit 500 as shown in Figure 3. Figure 3 schematically depicts a refrigeration process that utilizes two mixed component refrigerants in separate heat exchangers to cool or liquefy a process stream or feed gas. However, the first heat exchanger 200 and the second heat exchanger 400 may be contained within a common unit. In either case, the first heat exchanger 200 and the second heat exchanger 400 are preferably arranged in series as shown.

[0056] The chilled stream 104 leaving the first heat exchanger 200 is sub-cooled against a second mixed component refrigerant ("second MCR") within the second heat exchanger 400. The chilled stream 104 exits the second heat exchanger 400 as a liquefied stream 106. In certain embodiments, the liquefied stream 106 exits the heat exchanger 400 at a temperature within a range of from a low of -220°C, or -180°C, or -160°C to a high of -130°C, or -110°C, or -70°C. In one specific embodiment, the liquefied stream 106 exits the heat exchanger 400 at a temperature of about -145°C to about -155°C. In certain embodiments, the liquefied stream 106 exits the heat exchanger 400 at a pressure within a range of from a low of 3,900 kPa, or 5,800 kPa, or 6,900 kPa to a high of 9,000 kPa, or 10,000 kPa, or 12,000 kPa.

SECOND MCR

[0057] In one or more specific embodiments, the second mixed component refrigerant ("second MCR") may be the same as the first mixed component refrigerant ("first MCR"). In one or more specific embodiments, the second MCR may be different. For example, the second MCR may be a mixture of nitrogen, methane, and ethane. In one or more specific embodiments, the second MCR may contain between

about 5 mole% and 20 mole% of nitrogen, between about 20 mole% and 80 mole% of methane, and between about 10 mole% and 60 mole% of ethane. In one or more specific embodiments, the concentration of nitrogen within the second MCR ranges from a low of 5 mole%, or 6 mole%, or 7 mole% to a high of 15 mole%, or 18 mole%, or 20 mole%. In one or more specific embodiments, the concentration of methane within the second MCR ranges from a low of 20 mole%, or 30 mole%, or 40 mole% to a high of 60 mole%, or 70 mole%, or 80 mole%. In one or more specific embodiments, the concentration of ethane within the second MCR ranges from a low of 10 mole%, or 15 mole%, or 20 mole% to a high of 45 mole%, or 55 mole%, or 60 mole%.

[0058] The molecular weight of the second MCR ranges from a low of 18, or 19, or 20 to a high of 25, or 26, or 27. In one or more specific embodiments, the second MCR has a molecular weight of about 18 to about 27. Further, the molar ratio of the second MCR to the chilled stream 104 ranges from a low of 0.5, or 0.6, or 0.7 to a high of 0.8, or 0.9, or 1.0. In one or more specific embodiments, the molar ratio of the second MCR to the chilled stream 104 is at least 0.5, or at least 0.6, or at least 0.7.

[0059] The second MCR may be fed to the first heat exchanger 200 via stream 402 to pre-cool or condense the second MCR prior to entering the second heat exchanger 400. The stream 402 is cooled within the first heat exchanger 200 by indirect heat transfer with the first MCR. The stream 402 has a pressure within the range of from a low of 2900 kPa, or 4300 kPa, or 5500 kPa to a high of 6400 kPa, or 7500 kPa, or 9000 kPa. The stream 402 has a temperature within the range of from a low of 0°C, or 10°C, or 20°C to a high of 40°C, or 50°C, or 70°C.

[0060] The second MCR exits the first heat exchanger 200 as stream 404. In one or more specific embodiments, the stream 402 is completely condensed within the first heat exchanger 200 to a liquid stream 404 having no vapor fraction. In one or more specific embodiments, the stream 402 is partially condensed by indirect heat transfer with the first MCR such that the stream 404 has a liquid fraction of at least 85% by weight, or at least 90% by weight, or at least 95% by weight, or at least 99%

by weight. In one or more specific embodiments, the stream 404 has a pressure within the range of from a low of 2,500 kPa, or 4,000 kPa, or 5,000 kPa to a high of 6,000 kPa, or 7,000 kPa, or 9,000 kPa. In one or more specific embodiments, the stream 404 has a temperature within the range of from a low of -110°C, or -90°C, or -80°C to a high of -60°C, or -50°C, or -30°C.

[0061] In one or more specific embodiments, additional process streams that require refrigeration can enter the heat exchanger 400. Non-limiting examples of such additional streams include other refrigerant streams, other hydrocarbon streams to be blended with the gas of stream 102 at a later processing stage, and streams that are integrated with one or more fractionation processing steps.

SECOND HEAT EXCHANGER

[0062] Considering the second heat exchanger 400 in more detail, the second MCR that has been cooled and at least partially condensed, if not completely condensed, within the first heat exchanger 200, is collected in a surge vessel 406 and fed to the second heat exchanger 400 as stream 410. The second MCR exits the second heat exchanger 400 as stream 415. In one or more specific embodiments, the stream 415 has a pressure within the range of from a low of 2,800 kPa, or 4,200 kPa, or 5,500 kPa to a high of 6,200 kPa, or 7,000 kPa, or 8,500 kPa. In one or more specific embodiments, the stream 415 has a temperature within the range of from a low of -230°C, or -190°C, or -170°C to a high of -140°C, or -120°C, or -70°C.

[0063] In one or more specific embodiments, the stream 415 exiting the second heat exchanger 400 is reduced in pressure (i.e. expanded) using an expansion device 450. The stream 415 is then further reduced in pressure (i.e. expanded) using an expansion device 420 to produce stream 425. As mentioned above, the expansion devices 420, 450 may be any pressure reducing device including, but not limited to valves, control valves, Joule Thompson valves, Venturi devices, liquid expanders, hydraulic turbines, and the like. Preferably, the expansion device 420 is an automatically actuated expansion valve or Joule Thompson-type valve. Preferably, the expansion device 450 is a liquid expander or a hydraulic turbine. In one or more

specific embodiments, stream 425 has a pressure within the range of from a low of 200 kPa, or 300 kPa, or 400 kPa to a high of 500 kPa, or 600 kPa, or 700 kPa; a temperature within the range of from a low of -250°C, or -200°C, or -170°C to a high of -140°C, or -110°C, or -70°C. Preferably, stream 425 is expanded to a pressure of from 435 kPa to 445 kPa and a temperature of from -150°C to -160°C.

[0064] After isenthalpic expansion within the expansion device 420, the stream 425 is completely evaporated or partially evaporated within the second heat exchanger 400 and exits the second heat exchanger 400 as stream 430. In one or more specific embodiments, the stream 425 is completely evaporated or partially evaporated at a single pressure level within the second heat exchanger 400. In one or more specific embodiments, the stream 425 is completely evaporated (i.e. all vapor phase) at a single pressure level within the second heat exchanger 400. In one or more specific embodiments, the single pressure level within the second heat exchanger 400 is maintained within the range of from a low of 150 kPa, or 250 kPa, or 350 kPa to a high of 400 kPa, or 500 kPa, or 600 kPa. Preferably, the single pressure level within the second heat exchanger 400 is between about 350 kPa and about 450 kPa.

SECOND MCR COMPRESSION UNIT

[0065] The stream 430 is then sent to a second compression unit 500. The compression unit 500 may include one or more compression stages depending on the process requirements. In one or more specific embodiments, the compression unit 500 includes two compression stages as shown in Figure 3. For example, the compression unit 500 has a first compression stage 510 and a second compression stage 520.

[0066] In operation, the stream 430 flows through a suction knock-out vessel 510A where a vapor stream continues to the first compression stage 510 and is cooled in after-cooler 515 to produce stream 512. In one or more specific embodiments, stream 512 has a pressure within the range of from a low of 1,900 kPa, or 2,800 kPa, or 3,500 kPa to a high of 4,000 kPa, or 4,800 kPa, or 5,800 kPa; and a temperature

within the range of from a low of 15°C, or 25°C, or 30°C to a high of 40°C, or 50°C, or 60°C.

[0067] Stream 512 flows through a suction knock-out vessel 520A where a vapor stream continues to the second compression stage 520 and is cooled. In one or more specific embodiments, the vapor stream 522 leaving the second compression stage 520 has a pressure within the range of from a low of 2,900 kPa, or 4,300 kPa, or 5,200 kPa to a high of 6,400 kPa, or 7,500 kPa, or 9,000 kPa; and a temperature within the range of from a low of 15°C, or 25°C, or 35°C to a high of 40°C, or 45°C, or 60°C. The vapor stream 522 is then cooled within the after-cool 525 and recycled to the first heat exchanger 200 as stream 402.

FIGURE 4

[0068] Figure 4 schematically depicts another method for refrigerating a process stream or feed gas that utilizes a liquid refrigerant collection system. As shown in Figure 4, liquid refrigerant collected from the separators 510A and 520B may be in fluid communication with a pump 530. The pump 530 returns this liquid refrigerant to the process via stream 532. This allows an effective and efficient way to deal with the mixed component refrigerant that partially evaporates within the heat exchange area. Alternatively, the collected liquid refrigerant from the separators 510A and 520B may be drained and disposed. Similarly, although not shown, the knock-out drums of the compression unit 300 (e.g. drums 310, 330, and 360) may be equipped with a similar liquid refrigerant collection system.

What is claimed is:

1. A method for liquefying a natural gas stream, comprising:

placing a first mixed component refrigerant in a first heat exchange area with a process stream;

separating said first mixed component refrigerant at one or more pressure levels to produce a refrigerant vapor and a refrigerant liquid;

passing said refrigerant liquid to said first heat exchange area; and

partially evaporating said refrigerant liquid within said first heat exchange area to retain a liquid phase, wherein said first heat exchange area is contained within two or more heat exchangers.

2. A method for liquefying a natural gas stream, comprising:

placing a first mixed component refrigerant in a heat exchange area with a process stream;

separating said first mixed component refrigerant at one or more pressure levels to produce a refrigerant vapor and a refrigerant liquid;

passing said refrigerant liquid to the first heat exchange area; and

partially evaporating said refrigerant liquid within the heat exchange area to retain a liquid phase, wherein said first heat exchange area comprises two or more areas contained within a single heat exchanger.

3. The method of claim 2, wherein said first heat exchange area comprises two or more areas wherein each area is contained within a single heat exchanger.

4. The method of claim 1, wherein said first heat exchange area comprises two or more areas contained within two or more heat exchangers.

5. The method of claim 1, wherein said process stream consists essentially of natural gas.

6. The method of claim 1, wherein said first mixed component refrigerant comprises ethane and propane.

7. The method of claim 6 wherein said first mixed component refrigerant further comprises isobutane.

8. The method of claim 1 wherein said first mixed component refrigerant comprises methane, ethane, and nitrogen.

9. The method of claim 1 wherein separating said first mixed component refrigerant comprises expanding said first mixed component refrigerant to a pressure between about 80 kPa and about 2,600 kPa.

10. The method of claim 1 wherein separating said first mixed component refrigerant comprises expanding said first mixed component refrigerant to a pressure between about 250 kPa and about 2,200 kPa.

11. The method of claim 1 wherein separating said first mixed component refrigerant comprises expanding said first mixed component refrigerant to a pressure between about 500 kPa and about 1,900 kPa.

12. The method of claim 1 wherein separating said first mixed component refrigerant comprises expanding a first portion of said first mixed component refrigerant to a first pressure between about 1,500 kPa and about 1,900 kPa, and expanding a second portion of said first mixed component refrigerant to a second pressure between about 500 kPa and about 700 kPa.

13. The method of claim 1 wherein separating said first mixed component refrigerant comprises expanding a first portion of said first mixed component refrigerant to a first pressure between about 800 kPa and about 2,600 kPa; expanding a second portion of said first mixed component refrigerant to a second pressure between about 250 kPa and about 850 kPa; and expanding a third portion of said first mixed component refrigerant to a third pressure between about 80 kPa and about 250 kPa.

14. The method of claim 1 wherein two or more streams of said first mixed component refrigerant are withdrawn from said first heat exchange area before separating said first mixed component refrigerant in said two or more streams.

15. The method of claim 14 wherein a first withdrawn stream of said mixed component refrigerant is expanded to a first pressure between about 1,500 kPa and about 1,900 kPa, and a second withdrawn stream of mixed component refrigerant is expanded to a second pressure between about 500 kPa and about 700 kPa.

16. The method of claim 14 wherein separating said first mixed component refrigerant comprises expanding a first withdrawn stream of said first mixed component refrigerant to a first pressure between about 800 kPa and about 2,600 kPa; expanding a second withdrawn stream of said first mixed component refrigerant to a second pressure between about 250 kPa and about 850 kPa; and expanding a third withdrawn stream of said first mixed component refrigerant to a third pressure between about 80 kPa and about 250 kPa.

17. The method of claim 1 wherein partially evaporating said refrigerant liquid within said first heat exchange area retains a liquid fraction of at least 1% by weight.

18. The method of claim 17 wherein separating said first mixed component refrigerant comprises expanding said first mixed component refrigerant to a pressure between about 80 kPa and about 180 kPa.

19. The method of claim 17 wherein separating said first mixed component refrigerant comprises expanding said first mixed component refrigerant to a pressure between about 250 kPa and about 600 kPa.

20. The method of claim 17 wherein separating said first mixed component refrigerant comprises expanding said first mixed component refrigerant to a pressure between about 800 kPa and about 1900 kPa.

21. The method of claim 17 wherein separating said first mixed component refrigerant comprises expanding a first portion of said first mixed component refrigerant to a first pressure between about 1,200 kPa and about 2,200 kPa, and expanding a second portion of said first mixed component refrigerant to a second pressure between about 400 kPa and about 700 kPa.

22. The method of claim 17 wherein separating said first mixed component refrigerant comprises expanding a first portion of said first mixed component refrigerant to a first pressure between about 1,500 kPa and about 1,900 kPa; expanding a second portion of said first mixed component refrigerant to a second pressure between about 500 kPa and about 600 kPa; and expanding a third portion of said first mixed component refrigerant to a third pressure between about 150 kPa and about 180 kPa.

23. The method of claim 17 wherein at least partially evaporating said refrigerant liquid within said first heat exchange area retains a liquid fraction of at least 3% by weight.

24. The method of claim 1 wherein passing said refrigerant liquid to said first heat exchange area cools said process stream, and further comprising placing a second mixed component refrigerant in a second heat exchange area with said cooled process stream to liquefy said process stream.

25. The method of claim 24 further comprising partially evaporating said refrigerant liquid stream within said first heat exchange area to retain a liquid fraction of at least 1% by weight.

26. The method of claim 24 further comprising partially evaporating said second mixed component refrigerant within said second heat exchange area to retain a liquid fraction of at least 1% by weight.

27. The method of claim 24 wherein separating said first mixed component refrigerant comprises expanding said first mixed component refrigerant to a pressure between about 1,200 kPa and about 2,200 kPa.

28. The method of claim 24 wherein separating said first mixed component refrigerant comprises expanding said first mixed component refrigerant to a pressure between about 400 kPa and about 700 kPa.

29. The method of claim 24 wherein separating said first mixed component refrigerant comprises expanding said first mixed component refrigerant to a pressure between about 120 kPa and about 200 kPa.

30. The method of claim 24 wherein separating said first mixed component refrigerant comprises expanding a first portion of said first mixed component refrigerant to a first pressure between about 1,500 kPa and about 1,900 kPa, and expanding a second portion of said first mixed component refrigerant to a second pressure between about 500 kPa and about 600 kPa.

31. The method of claim 24 wherein separating said first mixed component refrigerant comprises expanding a first portion of said first mixed component refrigerant to a first pressure between about 1,500 kPa and about 1,900 kPa; expanding a second portion of said first mixed component refrigerant to a second pressure between about 500 kPa and about 600 kPa; and expanding a third portion of said first mixed component refrigerant to a third pressure between about 150 kPa and about 180 kPa.

32. The method of claim 24 wherein said second mixed component refrigerant is partially evaporated in said second heat exchange area at a single pressure level.

33. The method of claim 32 wherein partially evaporating said first mixed component refrigerant in said first heat exchange area retains a liquid fraction of at least 1% by weight.

34. The method of claim 32 wherein partially evaporating said second mixed component refrigerant within said second heat exchange area retains a liquid fraction of at least 1% by weight.

35. The method of claim 24 wherein separating said first mixed component refrigerant comprises expanding said first mixed component refrigerant to a pressure between about 1,200 kPa and about 2,200 kPa.

36. The method of claim 24 wherein separating said first mixed component refrigerant comprises expanding said first mixed component refrigerant to a pressure between about 400 kPa and about 700 kPa.

37. The method of claim 24 wherein separating said first mixed component refrigerant comprises expanding said first mixed component refrigerant to a pressure between about 120 kPa and about 200 kPa.

38. The method of claim 24 wherein separating said first mixed component refrigerant comprises expanding a first portion of said first mixed component refrigerant to a first pressure between about 1,500 kPa and about 1,900 kPa, and expanding a second portion of said first mixed component refrigerant to a second pressure between about 500 kPa and about 600 kPa.

39. The method of claim 24 wherein separating said first mixed component refrigerant comprises expanding a first portion of said first mixed component refrigerant to a first pressure between about 1,500 kPa and about 1,900 kPa; expanding a second portion of said first mixed component refrigerant to a second pressure between about 500 kPa and about 600 kPa; and expanding a third portion of said first mixed component refrigerant to a third pressure between about 150 kPa and about 180 kPa.

40. The method of claim 32 wherein partially evaporating said second mixed component refrigerant at a single pressure level comprises flashing said second mixed component refrigerant through a pressure reducing device to a pressure within the range of from 200 kPa to 700 kPa.

41. The method of claim 32 wherein evaporating said second mixed component refrigerant at a single pressure level comprises flashing said second mixed component refrigerant through a valve to a pressure within the range of from 400 kPa to 500 kPa.

42. The method of claim 24 wherein said second mixed component refrigerant is cooled within said first heat exchange area by heat exchange with said first mixed component refrigerant.

43. The method of claim 24 wherein said second mixed component refrigerant is condensed within said first heat exchange area by heat exchange with said first mixed component refrigerant.

44. The method of claim 1 wherein said refrigerant vapor is bypassed around said first heat exchange area to a compression unit.