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(71) Applicant: **AIR PRODUCTS AND CHEMICALS, INC.**
Allentown, PA 18195-1501 (US)

(72) Inventors:
- **Btostow, Adam Adrian**
  Emmaus, PA Pennsylvania 18049 (US)
- **Kinard, Glenn Eugene**
  Allentown, PA Pennsylvania 18103-3759 (US)

(74) Representative: **Muir, Benjamin M. J.**
Beck Greener
Fulwood House
12 Fulwood Place
London WC1V 6HR (GB)

(54) **Natural gas liquefaction with feed water removal**

(57) A method and apparatus for drying and liquefying a natural gas stream is described, in which: (a) the water containing natural gas feed stream (10) is cooled (11); (b) the cooled natural gas feed stream (12) is dried (13) and further cooled (15); (c) the dried cooled natural gas stream (16) is heated (11); (d) the dried rewarmed natural gas stream (17) is cooled and liquefied (1) and at least one compressed refrigerant feed stream (3) is cooled by counter-current indirect heat exchange with an expanded cold refrigerant; and (e) the compressed cold refrigerant stream or streams are expanded (38,39), and thereby further cooled, to provide said expanded cold refrigerant; wherein the cooling of the natural gas feed stream in step (a) and heating of the dried cooled natural gas stream in step (c) is by indirect heat exchange (11) between said two streams.

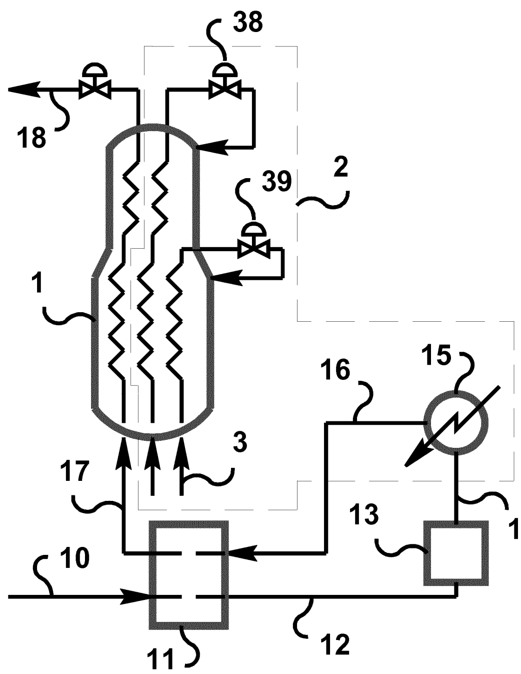

Fig. 1

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Description

BACKGROUND OF THE INVENTION

[0001] The present invention relates to a method and apparatus for drying and liquefying a natural gas stream.

[0002] Where a natural gas stream contains water it is necessary first to dry the stream, to remove all, or substantially all, of the water therefrom, before liquefaction of the natural gas can take place. In order to remove water (and other impurities, such as mercury) from the natural gas prior to liquefaction, it is moreover common practice to first cool the feed to below ambient temperature, especially when the ambient temperature is high.

[0003] An example of a liquefaction cycle that includes such a pre-cooling step is the propane pre-cooled mixed refrigerant ("C3MR") cycle. In such methods, propane (or a different liquid refrigerant in a vapor compression cycle) may be used to cool the natural gas feed to a desired temperature prior to the drying step taking place. Then the same liquid refrigerant can be used at a lower pressure to further cool the now dried feed prior to said feed being introduced into the main cryogenic heat exchanger ("MCHE"). The refrigerant used for liquefaction, for example mixed refrigerant ("MR"), is also pre-cooled to about the same temperature. Therefore, all streams entering the warm end of the MCHE are at about the same temperature, thereby minimizing thermal stresses in MCHE.

[0004] The pre-cooling of a water-containing natural gas may pose an additional problem. That is, if the temperature of the natural gas during this cooling step is not tightly controlled, there can be a risk of hydrate formation. Using a single-component liquid refrigerant, such as propane, that is vaporized to pre-cool the natural gas feed allows for good temperature control, because at any given pressure the temperature at which such a refrigerant vaporizes will not vary (whereas, for example, with a mixed refrigerant stream the vaporization temperature will vary with any changes in the ratio of the different refrigerants present in the stream as well as with any changes in the pressure of the stream).

[0005] An example of prior art that addresses hydrate formation in a C3MR cycle is that described in US 4,755,200, the disclosure of which is incorporated herein by reference, where a natural gas feed is chilled using a single component vapor compression cycle prior to water removal. The resulting dry natural gas is further cooled by indirect heat exchange with mixed refrigerant vapor from the MCHE prior to being fed to the MCHE.

[0006] However, one drawback with the C3MR process discussed in US 4, 755, 200, and other such processes where a single- component liquid refrigerant in a vapor compression cycle is used to pre- cool the natural gas feed prior to liquefaction of the natural gas in a MCHE that uses a mixed refrigerant, is that they require the use of an additional refrigeration loop (namely the propane or other single- component loop) . This increases both the footprint and the capital investment cost of the liquefaction plant.

[0007] There are also known natural gas liquefaction cycles that do not involve the use of propane for pre-cooling the natural gas feed stream. These include the single mixed refrigerant ("SMR") cycle, such as for example that described in US 6,347,531, the dual mixed refrigerant ("DMR") cycle, such as for example that described in US 6,119,479, and the nitrogen recycle ("N2 recycle") cycle, such as for example that described in US 2010/0122551, the disclosures of each of which are incorporated herein by reference.

[0008] In such methods a portion of refrigerant (MR or gaseous nitrogen) may be withdrawn from one of the main refrigeration loops and used to cool the feed prior to water removal. Since MR, or a pure gaseous refrigerant such as nitrogen, provide refrigeration over a range of temperatures, it is difficult to control temperature to prevent hydrate formation. In addition, the MR composition is optimized to provide refrigeration at colder temperatures, and the nitrogen recycle cycle (reverse-Brayton cycle) is inherently inefficient at warmer temperatures. From the standpoint of efficiency there is a need to minimize the pre-cooling duty.

[0009] US 6, 793, 712, the disclosure of which is incorporated herein by reference, discloses a cascade process where a water- containing natural gas feed is first dried and then expanded in an isentropic expander. The resulting cold natural gas is heated in a first heat exchanger and then in a second heat exchanger, prior to acid gas removal. It is then cooled back down by indirect heat exchange with the cold natural gas in the second heat exchanger prior to further water removal, and is then further cooled in the first heat exchanger, again by indirect heat exchange with the cold natural gas. The natural gas is then further cooled and liquefied. The disadvantage of such a process is that it requires at least one piece of rotating machinery (i.e. the isentropic expander) and two heat exchangers (or one heat exchanger with side- headers), and the reduced feed pressure resulting from expansion in the isentropic expander lowers liquefaction efficiency.

[0010] Thus, there is a need in the art for alternative and/or improved natural gas liquefaction cycles (such as, but not limited to, the SMR, DMR, and N2 recycle cycles) in situations where the natural gas feed is required to be pre- cooled for water removal.

[0011] It is an object of embodiments of the present invention to provide a liquefaction cycle in which the temperature mismatch at the bottom of the MCHE is minimized, and the overall efficiency of the liquefaction cycle is enhanced.

[0012] It is further an object of preferred embodiments of the present invention to provide for good temperature control during pre-cooling of the natural gas feed so as to prevent or minimize hydrate formation.

BRIEF SUMMARY OF THE INVENTION

[0013] According to a first aspect of the present invention a method for drying and liquefying a natural gas stream is provided, the method comprising:

(a) cooling a natural gas feed stream, that contains water, to produce a cooled natural gas stream;
(b) removing water from and further cooling the cooled natural gas feed stream to produce a dried cooled natural gas stream;
(c) heating the dried cooled natural gas stream to produce a dried rewarmed natural gas stream;
(d) cooling and liquefying the dried rewarmed natural gas stream and cooling at least one compressed refrigerant feed stream by counter-current indirect heat exchange with an expanded cold refrigerant, to produce a liquefied natural gas product stream, at least one compressed cold refrigerant stream, and an expanded warmed refrigerant stream; and
(e) expanding and thereby further cooling the compressed cold refrigerant stream or streams to provide said expanded cold refrigerant;

wherein the cooling of the natural gas feed stream in step (a) and heating of the dried cooled natural gas stream in step (c) is by indirect heat exchange between said two streams.

[0014] According to a second aspect of the present invention an apparatus for drying and liquefying a natural gas stream is provided, the apparatus comprising:

an economizer heat exchanger for receiving a water-containing natural gas feed stream and a dried cooled natural gas stream and for cooling the water-containing natural gas feed stream and warming the dried cooled natural gas stream by indirect heat exchange with each other, so as to produce a cooled water-containing natural gas feed stream and a dried rewarmed natural gas stream;
natural gas feed water removal and natural gas feed cooling systems, in fluid flow communication with the economizer heat exchanger and each other, for receiving the cooled water-containing natural gas feed stream from the economizer heat exchanger, drying and further cooling said stream, and returning the resulting dried cooled natural gas stream to the economizer heat exchanger;
a main cryogenic heat exchanger for cooling and liquefying the dried rewarmed natural gas stream and for cooling at least one compressed refrigerant feed stream by counter-current indirect heat exchange with an expanded cold refrigerant, so as to produce a liquefied natural gas product stream, at least one compressed cold refrigerant stream, and an expanded warmed refrigerant stream;
a conduit arrangement for transferring the dried rewarmed natural gas stream from the economizer heat exchanger to the warm end of the main cryogenic heat exchanger, and for withdrawing the liquefied natural gas product stream from the cold end of the main cryogenic heat exchanger; and
a refrigerant expansion system, in fluid flow communication with the main cryogenic heat exchanger, for receiving at least one compressed cold refrigerant stream from the cold end of the cryogenic heat exchanger, expanding and thereby further cooling said cold refrigerant, and returning expanded cold refrigerant to the cold end of the cryogenic heat exchanger.

BRIEF DESCRIPTION OF SEVERAL VIEWS OF THE DRAWINGS

[0015] FIG. 1 is a schematic flow diagram of an apparatus and method for drying and liquefying a natural gas stream in accordance with one embodiment of the present invention.

[0016] FIG. 2 is a schematic flow diagram of an exemplary closed loop mixed refrigerant system and process for use in the apparatus and method for drying and liquefying a natural gas stream depicted in FIG. 1.

[0017] FIG. 3 is a schematic flow diagram of an apparatus and method for drying and liquefying a natural gas stream in accordance with another embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0018] As described above, in the first aspect of the present invention a method for drying and liquefying a natural gas stream is provided comprising the above mentioned steps of (a) cooling a natural gas feed stream, (b) removing water from and further cooling the cooled natural gas feed stream, (c) heating the dried cooled natural gas stream, (d) cooling and liquefying the dried rewarmed natural gas stream and cooling at least one compressed refrigerant feed stream by counter-current indirect heat exchange with an expanded cold refrigerant, and (e) expanding and thereby further cooling the compressed cold refrigerant stream or streams to provide said expanded cold refrigerant, wherein the cooling of the natural gas feed stream in step (a) and heating of the dried cooled natural gas stream in step (c) is by indirect heat exchange between said two streams.

[0019] As used herein, the term "expanding" refers to the reduction in pressure of the fluid in question by any suitable means, and in the case of a liquid may, unless otherwise indicated, involve at least partial vaporization or simply a reduction in pressure.

[0020] As used herein, the term "dried" refers to a fluid from which all or substantially all the water has been removed. More specifically, it means that either all water has been removed, or that the residual amount of water that remains is sufficiently low as to have a negligible effect on the subsequent processing of the fluid. In particular, in the case of a "dried natural gas stream" either all water has been removed, or any residual water remaining in said stream is present in a sufficiently low amount as to not cause any operational problems in the downstream cooling and liquefaction process due to water freezeout.

[0021] As used herein, the phrase "indirect heat exchange" refers to heat exchange between two fluids where the two fluids are kept separate from each other by some form of physical barrier (for example, in a shell and tube heat exchanger indirect heat exchange occurs, as the tube-side fluid is kept separate from the shell-side fluid by the walls of the tubes). This is in contrast to "direct heat exchange", where the fluids come into contact and can mix (as, for example, in a scrubbing column, where mass transfer in addition to heat transfer can take place between the counter-current streams flowing through the column).

[0022] In a preferred embodiment, in step (c) the dried cooled natural gas stream is heated to about the same temperature as the temperature of the at least one compressed refrigerant feed stream, such that the temperatures of the dried rewarmed natural gas stream and the at least one compressed refrigerant feed stream at the start of step (d) are about the same. Preferably, the natural gas feed stream at the start of step (a) is also at about the same temperature as the temperatures of the dried rewarmed natural gas stream and the at least one compressed refrigerant feed stream at the start of step (d).

[0023] Preferably, in step (c) the the dried cooled natural gas stream is heated to a temperature that is the same as or within 20°C of, more preferably within 10°C of, the temperature of the at least one compressed refrigerant feed stream, such that there is no or less than 20°C, more preferably less than 10°C, temperature difference between the dried rewarmed natural gas stream and the at least one compressed refrigerant feed stream at the start of step (d) . Preferably, temperature of the natural gas feed stream at the start of step (a) is also the same as or within 20°C, more preferably within 10°C, of the temperatures of the dried rewarmed natural gas stream and the at least one compressed refrigerant feed stream at the start of step (d) .

[0024] In a preferred embodiment, step (d) is carried out in a cryogenic heat exchanger of the shell and tube type, most preferably a wound coil heat exchanger.

[0025] In a preferred embodiment, in step (b) of the method the cooled natural gas feed stream is first dried, to remove water therefrom, and is then further cooled to produce the dried cooled natural gas stream. Alternatively, said steps can be carried out in the reverse order, wherein the feed stream is first further cooled and then dried to produce the dried cooled natural gas stream. However, the latter option is generally less preferred.

[0026] In one embodiment, the refrigerant in steps (d) and (e) is either a mixed refrigerant (comprising for example a mixture of hydrocarbons and/or perfluorohydrocarbons), in which case the compressed cold refrigerant stream or streams in step (d) are liquid or mixed phase streams and the expanded warmed refrigerant stream in step (d) is a mixed phase or vapor stream, or is a gaseous refrigerant (such as for example a pure, e.g. 99 mol.% or higher, nitrogen or argon) that remains in substantially gaseous form throughout steps (d) and (e) (i.e. wherein at most 12 mol.%, more preferably at most 5 mol.%, and most preferably none of the refrigerant is in liquid form at any point throughout steps (d) and (e)).

[0027] In preferred embodiments, the method further comprises the step: (f) compressing, and preferably cooling (for example by way of one or more interstage and/or after- coolers), the expanded warmed refrigerant stream to provide said at least one compressed refrigerant feed stream that is cooled in step (d) .

[0028] In one embodiment, step (f) comprises compressing and cooling the expanded warmed refrigerant stream to provide both said at least one compressed refrigerant feed stream that is cooled in step (d) and an additional compressed refrigerant stream, the method further comprising expanding said additional compressed refrigerant stream to further cool said stream and using said further cooled additional refrigerant stream in step (b) to further cool the cooled natural gas feed stream by indirect heat exchange. Preferably, step (f) comprises compressing, cooling and phase separating the expanded warmed refrigerant stream to provide a vapor stream of compressed refrigerant and a liquid stream of compressed refrigerant, said vapor stream forming at least one compressed refrigerant feed stream that is cooled and at least partially liquefied in step (d), and at least a portion of said liquid stream forming the additional refrigerant stream that is expanded and then used in step (b) to further cool the cooled natural gas feed stream by indirect heat exchange.

[0029] In another embodiment, in step (d) the dried rewarmed natural gas stream is cooled and liquefied to produce the liquefied natural gas product stream and an additional liquefied natural gas stream, said additional liquefied natural gas stream being used in step (b) to further cool the cooled natural gas feed stream. Preferably, in step (b) the cooled natural gas feed stream is further cooled by countercurrent direct heat exchange with said additional liquefied natural gas stream.

[0030] As also described above, in the second aspect of the present invention an apparatus for drying and liquefying a natural gas stream is provided which comprises the above mentioned economizer heat exchanger, natural gas feed water removal and natural gas feed cooling systems, main cryogenic heat exchanger, conduit arrangement, and refrigerant expansion system. Said apparatus is suitable for carrying out the method according to the first aspect. Accordingly, in a further preferred embodiment of the first aspect, the method according to the first aspect of the invention is carried out in the apparatus according to the second aspect.

[0031] In a preferred embodiment of the apparatus according to the second aspect, the main cryogenic heat exchanger is of the shell and tube type, and most preferably is a wound coil heat exchanger.

[0032] The natural gas feed water removal system is, preferably, upstream of the natural gas feed cooling system, such that cooled water-containing natural gas from the economizer heat exchanger is first dried in said water removal system, and dried natural gas from said water removal system is then further cooled in said cooling system to produce dried cooled natural gas that is then returned to the economizer heat exchanger. Alternatively, the order of said systems can be reversed, such that cooled water-containing natural gas from the economizer heat exchanger is first further cooled in said cooling system and then dried in said water removal system. Again, however, said latter option is generally less preferred.

[0033] Optionally, where the natural gas feed water removal system is upstream of the natural gas feed cooling system, the dried natural gas from the water removal system may be returned to the economizer heat exchanger and further cooled therein prior to being sent to and further cooled in the cooling system to produce dried cooled natural gas that is then returned to the economizer heat exchanger.

[0034] In a preferred embodiment, the apparatus further comprises a refrigerant compression system (which is preferably a refrigerant compression and cooling system, said cooling being for example provided by one or more interstage and/or after- coolers), in fluid flow communication with the main cryogenic heat exchanger, for receiving the expanded warmed refrigerant stream from the warm end of the cryogenic heat exchanger, compressing (and preferably cooling) said refrigerant, and returning at least one compressed refrigerant feed stream to the warm end of the cryogenic heat exchanger. The main cryogenic heat exchanger, refrigerant expansion system, and refrigerant compression system may form, or form part of a closed loop refrigerant system, the refrigerant contained and circulating within said closed loop system comprising said compressed and expanded refrigerant streams. As in the method according to the first aspect, said refrigerant may, for example, be a mixed refrigerant (comprising for example a mixture of hydrocarbons and/or perfluorohydrocarbons), or or a pure gaseous refrigerant such as, for example, pure (e.g. 99 mol. % or higher) nitrogen or argon.

[0035] In one embodiment, the natural gas feed cooling system is an indirect heat exchanger, and the apparatus further comprises an additional expansion system, in fluid flow communication with the refrigerant compression and cooling system and the natural gas feed cooling system, for receiving a stream of compressed and cooled refrigerant from the refrigerant compression and cooling system and expanding said stream to further cool said stream, the natural gas feed cooling system using said further cooled stream to further cool the cooled natural gas feed stream by indirect heat exchange. The refrigerant compression and cooling system may further comprise at least one phase separator, for separating the compressed and cooled refrigerant into liquid and vapor phases, said phase separator or separators being in fluid flow communication with the main cryogenic heat exchanger and the additional expansion system such that a vapor stream of compressed refrigerant is fed to the warm end of the cryogenic heat exchanger and a liquid stream of compressed refrigerant is fed to the additional expansion system.

[0036] In an alternative embodiment, the apparatus further comprises a conduit arrangement for transferring an additional liquefied natural gas stream from the main cryogenic heat exchanger to the natural gas feed cooling system, said feed cooling system using said additional liquefied natural gas stream to further cool the cooled natural gas feed stream. For example, the natural gas feed cooling system may in this case be a system (such as for example a scrub column) in which the cooled natural gas feed stream is further cooled by countercurrent direct heat exchange with said additional liquefied natural gas stream.

[0037] Accordingly, the present invention includes the following aspects, numbered #1 to #20:

#1. A method for drying and liquefying a natural gas stream, the method comprising:

(a) cooling a natural gas feed stream, that contains water, to produce a cooled natural gas stream;
(b) removing water from and further cooling the cooled natural gas feed stream to produce a dried cooled natural gas stream;
(c) heating the dried cooled natural gas stream to produce a dried rewarmed natural gas stream;
(d) cooling and liquefying the dried rewarmed natural gas stream and cooling at least one compressed refrigerant feed stream by counter-current indirect heat exchange with an expanded cold refrigerant, to produce a liquefied natural gas product stream, at least one compressed cold refrigerant stream, and an expanded warmed refrigerant stream; and
(e) expanding and thereby further cooling the compressed cold refrigerant stream or streams to provide said expanded cold refrigerant;

wherein the cooling of the natural gas feed stream in step (a) and heating of the dried cooled natural gas stream in step (c) is by indirect heat exchange between said two streams.

#2. A method according to #1, wherein in step (c) the dried cooled natural gas stream is heated to a temperature that is the same as or within 20°C of the temperature of the at least one compressed refrigerant feed stream, such that there is no or less than 20°C temperature difference between the dried rewarmed natural gas stream and the at least one compressed refrigerant feed stream at the start of step (d).

#3. A method according to #2, wherein the temperature of the natural gas feed stream at the start of step (a) is also the same as or within 20°C of the temperatures of the dried rewarmed natural gas stream and the at least one compressed refrigerant feed stream at the start of step (d).

#4. A method according to any one of #1 to #3, wherein step (d) is carried out in a wound coil cryogenic heat exchanger.

#5. A method according to any one of #1 to #4, wherein in step (b) the cooled natural gas feed stream is first dried, to remove water therefrom, and is then further cooled to produce the dried cooled natural gas stream.

#6. A method according to any one of #1 to #5, wherein the refrigerant in steps (d) and (e) is either a mixed refrigerant, the compressed cold refrigerant stream or streams in step (d) being liquid or mixed phase streams and the expanded warmed refrigerant stream in step (d) being a mixed phase or vapor stream, or is a gaseous refrigerant that remains in substantially gaseous form throughout steps (d) and (e).

#7. A method according to any one of #1 to #6, wherein the method further comprises:

(f) compressing the expanded warmed refrigerant stream to provide said at least one compressed refrigerant feed stream that is cooled in step (d).

#8. A method according to #7, wherein step (f) comprises compressing and cooling the expanded warmed refrigerant stream to provide both said at least one compressed refrigerant feed stream that is cooled in step (d) and an additional compressed refrigerant stream, the method further comprising expanding said additional compressed refrigerant stream to further cool said stream and using said further cooled additional refrigerant stream in step (b) to further cool the cooled natural gas feed stream by indirect heat exchange.

#9. A method according to #8, wherein step (f) comprises compressing, cooling and phase separating the expanded warmed refrigerant stream to provide a vapor stream of compressed refrigerant and a liquid stream of compressed refrigerant, said vapor stream forming at least one compressed refrigerant feed stream that is cooled and at least partially liquefied in step (d), and at least a portion of said liquid stream forming the additional refrigerant stream that is expanded and then used in step (b) to further cool the cooled natural gas feed stream by indirect heat exchange.

#10. A method according to any one of #1 to #7, wherein in step (d) the dried rewarmed natural gas stream is cooled and liquefied to produce the liquefied natural gas product stream and an additional liquefied natural gas stream, said additional liquefied natural gas stream being used in step (b) to further cool the cooled natural gas feed stream.

#11. A method according to #10, wherein in step (b) the cooled natural gas feed stream is further cooled by countercurrent direct heat exchange with said additional liquefied natural gas stream.

#12. An apparatus for drying and liquefying a natural gas stream, the apparatus comprising:

an economizer heat exchanger for receiving a water-containing natural gas feed stream and a dried cooled natural gas stream and for cooling the water-containing natural gas feed stream and warming the dried cooled natural gas stream by indirect heat exchange with each other, so as to produce a cooled water-containing natural gas feed stream and a dried rewarmed natural gas stream;
natural gas feed water removal and natural gas feed cooling systems, in fluid flow communication with the economizer heat exchanger and each other, for receiving the cooled water-containing natural gas feed stream from the economizer heat exchanger, drying and further cooling said stream, and returning the resulting dried cooled natural gas stream to the economizer heat exchanger;
a main cryogenic heat exchanger for cooling and liquefying the dried rewarmed natural gas stream and for cooling at least one compressed refrigerant feed stream by counter-current indirect heat exchange with an expanded cold refrigerant, so as to produce a liquefied natural gas product stream, at least one compressed cold refrigerant stream, and an expanded warmed refrigerant stream;
a conduit arrangement for transferring the dried rewarmed natural gas stream from the economizer heat exchanger to the warm end of the main cryogenic heat exchanger, and for withdrawing the liquefied natural gas product stream from the cold end of the main cryogenic heat exchanger; and
a refrigerant expansion system, in fluid flow communication with the main cryogenic heat ex-

changer, for receiving at least one compressed cold refrigerant stream from the cold end of the cryogenic heat exchanger, expanding and thereby further cooling said cold refrigerant, and returning expanded cold refrigerant to the cold end of the cryogenic heat exchanger.

#13. An apparatus according to #12, wherein the main cryogenic heat exchanger is a wound coil heat exchanger.

#14. An apparatus according to #12 or #13, wherein the natural gas feed water removal system is upstream of the natural gas feed cooling system, such that cooled water-containing natural gas from the economizer heat exchanger is first dried in said water removal system, and dried natural gas from said water removal system is then further cooled in said cooling system to produce dried cooled natural gas that is then returned to the economizer heat exchanger.

#15. An apparatus according to any one of #12 to #14, wherein the apparatus further comprises:

a refrigerant compression system, in fluid flow communication with the main cryogenic heat exchanger, for receiving the expanded warmed refrigerant stream from the warm end of the cryogenic heat exchanger, compressing said refrigerant, and returning at least one compressed refrigerant feed stream to the warm end of the cryogenic heat exchanger.

#16. An apparatus according to #15, wherein the main cryogenic heat exchanger, refrigerant expansion system, and refrigerant compression system form or form part of a closed loop refrigerant system, the refrigerant contained and circulating within said closed loop system comprising said compressed and expanded refrigerant streams, said refrigerant being a mixed refrigerant or pure nitrogen or argon.

#17. An apparatus according to #15 or #16, wherein the refrigerant compression system compresses and cools the expanded warmed refrigerant, and the natural gas feed cooling system is an indirect heat exchanger, and wherein the apparatus further comprises an additional expansion system, in fluid flow communication with the refrigerant compression system and the natural gas feed cooling system, for receiving a stream of compressed and cooled refrigerant from the refrigerant compression system and expanding said stream to further cool said stream, the natural gas feed cooling system using said further cooled stream to further cool the cooled natural gas feed stream by indirect heat exchange.

#18. An apparatus according to #17, wherein the refrigerant compression system further comprises at least one phase separator, for separating the compressed and cooled refrigerant into liquid and vapor phases, said phase separator or separators being in fluid flow communication with the main cryogenic heat exchanger and the additional expansion system such that a vapor stream of compressed refrigerant is fed to the warm end of the cryogenic heat exchanger and a liquid stream of compressed refrigerant is fed to the additional expansion system.

#19. An apparatus according to any one of #12 to #16, wherein the apparatus further comprises a conduit arrangement for transferring an additional liquefied natural gas stream from the main cryogenic heat exchanger to the natural gas feed cooling system, the feed cooling system using said additional liquefied natural gas stream to further cool the cooled natural gas feed stream.

#20. An apparatus according to #19, wherein the natural gas feed cooling system is a scrub column, in which the cooled natural gas feed stream is further cooled by countercurrent direct heat exchange with said additional liquefied natural gas stream.

[0038] Solely by way of example, certain specific embodiments of the invention will now be described, with reference to the accompanying drawings.

[0039] Referring to Figure 1, an exemplary apparatus and method for drying and liquefying a natural gas stream in accordance with one embodiment of the present invention is depicted. Water-containing natural gas feed stream 10 is first cooled in an economizer heat exchanger 11. The resulting cooled water-containing natural gas feed stream 12 is fed to natural gas feed water removal system 13 to cold dry the stream, thereby producing dried natural gas stream 14. There may a phase separator on stream 12 (not shown for simplicity) to remove any condensed water from said stream prior to its introduction into water removal system 13. Dried natural gas stream 14 is further cooled in natural gas feed cooling system (feed cooler) 15 to produce dried cooled natural gas stream 16. Dried cooled natural gas stream 16 is then warmed back up in economizer heat exchanger 11, by countercurrent indirect heat exchange with water-containing natural gas feed stream 10, to produce rewarmed dried natural gas stream 17. Thus, in the economizer heat exchanger 11 the water-containing natural gas feed stream 10 is cooled, and dried cooled natural gas stream 16 is warmed, by indirect heat exchange between the two streams. Rewarmed dried natural gas stream 17 is then sent to the main cryogenic heat exchanger (MCHE) 1 for further cooling and liquefaction.

[0040] Economizer heat exchanger 11 can be any type of heat exchange suitable for for effecting countercurrent indirect heat exchange between the water- containing natural gas feed stream 10 and dried cooled natural gas stream 16, such as, for example, a shell- and- tube, plate- and- fin, or printed circuit heat exchanger.

[0041] Water removal system 13 may be any type of system suitable for drying/dehydrating a water-containing natural gas stream. Various types of water removal system are known in the art, including both absorption systems, such as, for example, a glycol dehydrator or adsorption systems, such as, for example, molecular sieves and activated alumina.

[0042] Feed cooler 15 uses a colder- than- ambient stream to further cool the natural gas stream. Feed cooler 15 may, for example, be an indirect heat exchanger that uses as said colder- than- ambient stream a stream of refrigerant from the same closed loop of refrigerant that is also used to provide the cooling duty for the MCHE 1, an example of such an arrangement being depicted in Figure 2, which will be described in further detail below. Alternatively (and albeit less preferably), said colder- than- ambient stream may, for example, form part of a separate refrigerant loop, such as where feed cooler 15 is a packaged chiller that uses its own, separate refrigerant loop. In either case, feed cooler 15 can be of any flow arrangement, such as countercurrent or kettle, and type, such as shell- and- tube, plate- and- fin, or diffusion-bonded, for effecting indirect heat exchange between the natural gas and colder- than- ambient streams.

[0043] In Figure 1, water removal system 13 is located upstream of feed cooler 15, such that the cooled water-containing natural gas feed stream from economizer heat exchanger 11 is dried by the water removal system before being further cooled in the feed cooler. If feed cooler 15 is downstream of the water removal system 13 (as shown in Figure 1) then the colder-than-ambient stream used by feed cooler 15 cools an already dried natural gas stream, with the resulting dried and cooled natural gas stream 16 then being used in economizer heat exchanger 11 to cool the water-containing natural gas feed stream 10 as required prior to water removal. This is particularly advantageous where the colder-than-ambient stream used by feed cooler 15 is a mixed refrigerant or a pure gaseous refrigerant (such as nitrogen), such as may be the case where the colder-than-ambient stream is a stream of refrigerant from the same closed loop of refrigerant that is also used to provide the cooling duty for the MCHE 1, as cooling the water-containing natural gas feed stream 10 in the economizer heat exchanger 11 in this manner provides better control over the temperature of water-containing natural gas feed stream 10 during cooling than if a mixed refrigerant or a pure gaseous refrigerant (such as nitrogen) were to be used to cool said water-containing natural gas feed stream 10 directly. Hence, cooling the water-containing natural gas feed stream 10 in this manner can reduce the risk of hydrate formation in the water-containing natural gas feed stream during cooling prior to water removal.

[0044] In an alternative arrangement (not depicted), feed cooler 15 may instead be placed upstream of the water removal system 13. However, where the feed cooler 15 is using a mixed refrigerant or a pure gaseous refrigerant there will then also be a greater risk of hydrate formation in the water-containing natural gas feed stream during cooling (in said feed cooler 15) prior to water removal. If feed cooler 15 is instead a packaged chiller that uses a separate refrigeration loop comprising, for example, a pure liquid refrigerant (or an azeotrope) in a vapor compression cycle then there may not be any increased risk of hydrate formation, but the requirement for an additional refrigeration loop (i.e. that of the packaged chiller) will increase the capital investment cost and footprint of the plant.

[0045] Thus, positioning the water removal system 13 upstream of the feed cooler 15 is, in general, preferred.

[0046] The rewarmed dried natural gas stream 17 exiting economizer heat exchanger 11 is, as noted above, introduced into the warm end of main cryogenic heat exchanger (MCHE) 1 and is cooled and liquefied to produce liquefied natural gas product stream 18, which is withdrawn from the cold end of heat exchanger 1. MCHE 1 forms part of a refrigeration system 2, such as a closed-loop refrigerant system (using, for example, a mixed refrigerant or pure gaseous refrigerant), for cooling and liquefying the rewarmed dried natural gas stream 17. In said system, one or more feed streams of compressed refrigerant 3 are also cooled in the MCHE 1 to produced one or more compressed cold refrigerant streams, which are then withdrawn from the MCHE 1 and expanded to further cool the refrigerant, the expanded cold refrigerant then being returned to the MCHE 1 to provide the cooling duty for cooling and liquefying the rewarmed dried natural gas stream 17 and cooling the compressed cold refrigerant streams 3. The expanded warmed refrigerant, resulting from countercurrent heat exchange with said rewarmed dried natural gas stream 17 and compressed refrigerant streams 3, is then withdrawn from the MCHE 1, compressed, and returned to the MCHE 1 as the one or more feed streams 3 of compressed refrigerant.

[0047] In the example illustrated in Figure 1, two feed streams of compressed refrigerant 3 are introduced into the warm end of MCHE 1, with one stream being cooled and withdrawn as a compressed cold refrigerant stream from the cold end of the MCHE 1, and the other being cooled and withdrawn as a compressed cold refrigerant stream from an intermediate location of the MCHE 1. The compressed cold refrigerant stream withdrawn from the cold end is then expanded across throttle valve 38, which adiabatic (isenthalpic) expansion further cools the refrigerant, thereby providing an expanded cold refrigerant that is returned to the cold end of the MCHE 1 to provide cooling duty. Similarly, the compressed cold refrigerant stream withdrawn from the intermediate location is expanded across throttle valve 39, which adiabatic (isenthalpic) expansion further cools the refrigerant, thereby providing an expanded cold refrigerant that is returned to the intermediate location of the MCHE 1 to provides cooling duty. The expanded cold refrigerant flows through the MCHE in the opposite direction to the rewarmed dried natural gas stream 17 and compressed refrigerant feed streams 3, cooling said streams by countercurrent indirect heat exchange. Further aspects of an exemplary refrigeration system 2, of which the MCHE 1 forms a part, will be described in further detail below with reference to Figure 2.

[0048] Although in Figure 1, throttle valves 38 and 39 are used to expand the cooled compressed refrigerant streams, in the present invention any type of device or system for expanding (i.e. reducing the pressure of) said streams in order to reduce the temperature of said streams may be used. Thus, any device or system for adiabatically expanding said streams may be used, including centrifugal or reciprocating expanders that expand the refrigerant stream while producing external work (i.e. wherein isentropic, rather than isenthalpic, expansion of the refrigerant is occurring). For example, where the cooled compressed refrigerant streams are liquid streams, hydraulic turbines (dense fluid expanders) that isentropically expand the refrigerant could be used.

[0049] As depicted in Figure 1, the MCHE 1 is a wound-coil heat exchanger (or other heat exchanger of the shell-and- tube type) containing two bundles (the intermediate location, from which one of the two compressed cold refrigerant streams is withdrawn, being between the two bundles), rewarmed dried natural gas stream 17 being for example cooled and optionally partially or fully liquefied in the first bundle, and fully liquefied (if not already so) and/or sub- cooled in the second bundle. Equally, however, other types and arrangements of heat exchanger may be used. For example, where the MCHE is a would- coil (or other type of shell- and- tube) heat exchanger, it may contain more or less bundles, and the bundles may be located in the same or different shells (interconnected by suitable conduits, in the case of the latter) . The MCHE may also be any other type of cryogenic heat exchange suitable for effecting counter- current indirect heat exchange. For example, the MCHE could be of the plate- and- fin type. Nevertheless, the use of a MCHE of the wound- coil type is generally preferred.

[0050] The rewarmed dried natural gas stream 17 and compressed refrigerant feed stream or steams 3 preferably enter the MCHE 1 at the same or a similar temperature, so as to minimize any temperature mismatch between the streams entering the warm end of the MCHE. Preferably, rewarmed dried natural gas stream 17 and stream or streams 3 are within 10 °C of each other. Typically, the water-containing natural gas feed stream 10 is also at a similar temperature to streams 17 and 3, and thus is typically likewise within 10 °C of the temperatures of streams 17 and 3.

[0051] The use of the economizer heat exchanger 11, arranged and operating as described above, provides a number of benefits. The cooling of water-containing natural gas stream 10 in economizer heat exchanger 11 results in a colder natural gas stream (stream 12) being fed to water removal system 13 than would otherwise be the case if water-containing natural gas stream 10 were fed directly to water removal system 13, which in turn allows for more optimal water removal from said natural gas stream. More specifically, cooling the water-containing natural gas stream prior to its introduction into water removal system 13 can reduce the load on said system (as where the cooling results in some of the water in the stream being condensed out and removed prior to introduction of the stream into the water removal system) and/or increase the efficiency with which said system removes water (as, for example, where the water removal system is an adsorptive system, where the adsorbent can adsorb more water at lower temperatures). Cooling the water-containing natural gas stream prior to its introduction into water removal system 13 also allows the temperature of the natural gas being fed into the water removal system 13 to be controlled, and so avoids operational difficulties as could otherwise result from the temperature of the natural gas straying above the temperature at which the water removal system 13 is designed to operate (which could result in inadequate removal of water from the natural gas in system 13, and accordingly unacceptable levels of water in the natural gas downstream of said system).

[0052] Moreover (and as is demonstrated in the Examples that follow), the inventors have found that by cooling the water-containing natural gas stream 10 in economizer heat exchanger 11 against the dried cooled natural gas stream 16 the overall efficiency of the drying and liquefaction process can be improved. The use of economizer heat exchanger 11 significantly reduces the cooling duty required of natural gas feed cooling system 15, as a significant proportion of the cooling duty for cooling the water-containing natural gas stream 10 prior to water removal in water removal system 13 is in this case supplied by recovering the cold from the dried cooled natural gas (i.e. from stream 16) after water removal. Although this also means that the natural gas stream (i.e. rewarmed natural gas stream 17) that is fed into the MCHE 1 is warmer than would otherwise be the case if the dried cooled natural gas stream 16 were instead to be fed directly into the MCHE 1, the inventors have nevertheless found that the overall power consumption of the process is still reduced (in particular where the refrigerant used by the feed cooling system 15 is a stream of refrigerant from the same closed loop of refrigerant that is used to provide cooling duty in the MCHE 1). Where the feed cooling system 15 is a packaged chiller that uses its own, separate, refrigeration loop, the reduction in the cooling duty required of feed cooling system 15 may also allow a smaller packaged chiller to be used, thereby allow for capital cost savings.

[0053] Furthermore, the heating of dried cooled natural gas stream 16 in economizer heat exchanger 11 to provide a dried rewarmed natural gas (i.e. stream 17) at a similar temperature to that of the compressed refrigerant (i.e. streams 3) also entering the warm end of the MCHE 1 allows any temperature mismatch between the streams entereing the warm end of the MCHE 1 to be minimized. This in turn minimizes mechanical stresses that would otherwise occur (in particular in a wound coil heat exchanger) due to differential thermal expansion of components at the warm end of the MCHE 1, and thus minimizes the potential for damage to the MCHE 1 as a result thereof. In certain types of MCHE, such as a MCHE of the brazed aluminum coil type, a possible alternative arrangement (not in accordance with the present invention) for avoiding any such temperature mismatch would be to introduce the dried natural gas stream into the MCHE at a colder temperature than that of the compressed refrigerant streams and at a different location, more towards the cold end of the exchanger, through a so- called side- header instead of using an economizer heat exchanger to rewarm the natural gas stream after it has been dried. However, the use of side- headers makes the manufacturing of such an MCHE more complicated, and thus this is also undesirable.

[0054] Referring now to Figure 2, an exemplary closed loop refrigerant system and process (indicated as system 2 in Figure 1) is depicted that may be employed in the system depicted in Figure 1. The closed loop system and process in this case contains and uses a mixed-refrigerant, and comprises, in addition to the MCHE 1, throttle valves 38 and 39 and feed cooler 15 (all as previously described), a refrigerant compression and cooling system (comprising refrigerant compressor 21, refrigerant cooler 22, and phase separator 23) and further throttle valves 28 and 29.

[0055] In this case, the two feed streams of compressed refrigerant 3 that are introduced into the warm end of MCHE 1 are a liquid stream of mixed-refrigerant 27 and a vapor stream of mixed refrigerant 24. The vapor stream 24 is cooled and partially or fully liquefied and withdrawn as a compressed cold (liquid or mixed-phase) refrigerant stream from the cold end of the MCHE 1, and the liquid stream is cooled and withdrawn as a compressed cold (liquid) refrigerant stream from the intermediate location of the MCHE 1. These streams are then adiabatically expanded across throttle valves 38 and 39, respectively, to provide expanded cold refrigerant streams (that may be at least partially vaporized as a result of said expansion) that are returned to the cold end and intermediate location, respectively, of the MCHE 1.

[0056] The expanded cold mixed refrigerant flows through MCHE (i.e. through the shell side in the case of a wound-core or other type of shell and tube heat exchanger) and is warmed (and, if still liquid or mixed phase, vaporized) by indirect heat exchange with the natural gas in stream 17 and compressed mixed refrigerant in streams 3. The expanded warmed refrigerant (i.e. the mixed refrigerant obtained after it has undergone heat exchange with the natural gas in stream 17 and compressed mixed refrigerant in streams 3) is collected and withdrawn from the warm end of the heat exchanger as stream 20.

[0057] Stream 20 is compressed in refrigerant compressor 21, cooled in refrigerant cooler 22, and separated into a liquid stream 25 (MRL) and vapor stream 24 (MRV) in phase separator 23. Although in the illustrated embodiment refrigerant cooler 22 is depicted as a after-cooler separate from refrigerant compressor 21, refrigerant compressor 21 could be a multi-stage compressor and in this case refrigerant cooler 22 could comprise one or a series of intercoolers, in addition to or instead of an after-cooler. Refrigerant cooler 22 may, for example, also comprise a pre-cooler for cooling stream 20 prior to compression in refrigerant compressor 21. The vapor stream 24 from the phase separator 23 is then introduced into the cold end of the MCHE 1 as the aforementioned vapor stream of compressed mixed refrigerant (that is cooled and partially or fully liquefied in the MCHE 1 and withdrawn from the cold end thereof). The liquid stream 25 from the phase separator 23 is split into liquid stream 27 (a major portion) and liquid stream 26. Liquid stream 27 is introduced into the cold end of the MCHE 1 as the aforementioned liquid stream of compressed mixed refrigerant (that is cooled in the MCHE 1 and withdrawn from the intermediate location thereof).

[0058] Liquid steam 26 of mixed refrigerant is expanded across throttle valve 28 to further cool (and in this case at least partially vaporize) the stream, and this further cooled stream is used in feed cooler 15 to provide refrigeration (via indirect heat exchange) for further cooling dried natural gas stream 14 to produce dried cooled natural gas stream 16. The resulting warmed (and now fully vaporized) mixed refrigerant stream exiting feed cooler 15 may optionally be back-pressured by valve 29, and is then recombined at the suction of refrigerant compressor 21 with the expanded warmed refrigerant stream 20 withdrawn from the warm end of MCHE 1.

[0059] Referring now to Figure 3, an alternative exemplary apparatus and method of drying and liquefying a natural gas stream is depicted, which is modified from that depicted in Figure 1 in two main respects (either of which modifications to the method of Figure 1 could be made independently, as well as in combination as is shown in Figure 3).

[0060] The first modification is that, in the apparatus and method depicted in Figure 3, the dried natural gas stream exiting natural gas feed water removal system 13 is first returned to economizer heat exchanger 11 for further cooling therein prior to being sent to the natural gas feed cooling system. Thus, as shown in Figure 3, the water-containing natural gas feed stream 10 is first cooled in economizer heat exchanger 11 to produce cooled water-containing natural gas feed stream 12 that is, in this case, withdrawn from an intermediate location of the economizer heat exchanger 11. The cooled water-containing natural gas feed stream 12 is fed to water removal system 13 to cold dry said stream, thereby producing dried natural gas stream 14 which is then returned to the intermediate location of the economizer heat exchanger 11 and further cooled therein prior to being withdrawn from the cold end of the economizer heat exchanger 11 as stream 30 and sent to the natural gas feed cooling system.

[0061] The second modification is that in, in the apparatus and method depicted in Figure 3, the natural gas feed cooling system uses a stream of liquefied natural gas 34 obtained from the MCHE 1 as the colder-than-ambient stream for cooling the dried natural gas stream 14/30. Natural gas feed cooling system could again be an indirect heat exchange system but, in this arrangement, it is preferred that said natural gas feed cooling system comprises a scrub column 31 (or other system in which the natural gas stream is further cooled by direct countercurrent heat exchange with the liquefied natural gas, thereby also allowing mass transfer to take place between the countercurrent streams). This allows the method to be applied to a situation where there is a need to remove heavy components from natural gas feed prior to liquefaction, as the scrub column 31 can remove these components in addition to cooling the natural gas.

[0062] More specifically, dried natural gas stream 30, which has already been cooled in the economizer heat exchanger 11, enters the scrub column 31 (which, in this example, is a simple rectifier) and brought into direct countercurrent contact with a reflux stream of liquefied natural gas, which both further cools and strips heavy components from stream 30. Heavy bottoms product is removed as stream 32. Lighter overhead product, constituting the dried cooled natural gas stream 33, is then (as before) rewarmed in economizer heat exchanger 11 and enters the warm end of MCHE 1 as rewarmed dried natural gas stream 17. The rewarmed dried natural gas stream 17 is partially liquefied (for example in the first wound-coil bundle of the MCHE) to produce a mixed-phase natural gas stream 34 that is withdrawn from an intermediate location of the MCHE. This mixed-phase stream 34 is then separated in a reflux drum 35 or other phase separator into a liquid stream of natural gas 36 and a vapor stream of natural gas 37. The liquid stream 36 is then returned to scrub column 31, to provide reflux as described above. The vapor stream 37 is returned to the intermediate location of the MCHE and is cooled and liquefied (for example in a second wound-coil bundle of the MCHE) to produce the liquefied natural gas (LNG) product stream 18.

[0063] In a possible modification of the system/apparatus and method depicted in Figure 3, the MCHE 1 could for example be a wound-coil heat exchanger that has three bundles (instead of the two depicted), one for pre-cooling the feed to generate reflux for the scrub column, one to liquefy it, and one to sub-cool it.

[0064] It will be apparent to those skilled in the art that the methods and apparatus illustrated in Figures 1 to 3 represent also only some of the possible arrangements. Different MR arrangements in accordance with the present invention could involve multiple phase separators, multiple stages of compression, liquid pumps, and so forth. Any MR liquid stream could be utilized by feed cooler 15 and returned fully or partially vaporized to different locations within the closed loop MR system. In a closed loop nitrogen recycle cycle, a portion of gaseous refrigerant could likewise be used for the same purpose.

EXAMPLE

[0065] Referring to Fig. 1, water-containing natural gas feed stream 10, comprising 0.8% nitrogen, 88.2% methane, 6.9% ethane, 2.5% propane, and balance heavier hydrocarbons, saturated with water, and at a pressure of 1024 psia (7060 kPa) and temperature of 118.6 °F (48.1 °C) is to be liquefied. Natural gas stream 12 leaves the economizer heat exchanger 11 at 71.6 °F (22 °C). Natural gas stream 14 leaves the water removal system 13 dry at 78.8 °F (26 °C) (a little warmer due to heat of absorption). It is then cooled in the feed cooler 15 to 66.1 °F (18.9 °C). The cooling utility fluid used in feed cooler 15 is a portion of MR withdrawn from the main MR loop. The MR enters feed cooler 15 as a two-phase stream, comprising 52.5% vapor, at -76.2 °F (-60.1 °C). It leaves as a fully vaporized stream at 57.0 °F (13.9 °C). It contains 1.7% nitrogen, 24.5% methane, 43.7% ethane, 13.7% propane, and 17.1% isopentane. Dried cooled natural gas stream 16 is warmed back up in the economizer heat exchanger 11 to 115.0 °F (46.1 °C). Dried rewarmed natural gas stream 17 enters the MCHE 1 and leaves as liquefied stream 18 at -247.9 °F (-155.5 °C).

[0066] The MR streams (in this case a vapor MR stream and a liquid MR stream) 3, comprising nitrogen, methane, ethane, propane, and isopentane, enter the warm end of the MCHE at 116.6 °F (47 °C), a temperature close to the temperature of the rewarmed dried natural gas stream 17.

Table 1

Case		1	2
Power	%	**100.0%**	**97.6%**
Cooler Duty	%	**100.0%**	**26.6%**

[0067] Table 1 compares the current invention to a conventional prior art arrangement. Case 1 is a conventional SMR cycle producing about 2 million tons per annum of LNG, with no feed heat exchanger, and the feed cooler exchanger (necessarily) upstream of the water removal system. Case 2 is the configuration (according to Figure 1 of the present application) described in the above example. As can be seen, in the present invention the feed cooler duty (i.e. the cooling duty required of feed cooler 15) is reduced by about 73%, and the liquefaction power requirement (i.e. the total power required by the operation of both MCHE 1 and feed cooler 15) is reduced by 2.4%.

[0068] The quantitative result shown in Table 1 is almost exactly the same if in the method according to the present invention the feed cooler 15 is placed upstream instead of downstream of the water removal system 13. In this case, natural gas stream 12 leaves the economizer heat exchanger 11 at 83.9 °F (28.8 °C) and is cooled in feed cooler 15 to 71.6 °F (22 °C) prior to being fed to water removal system 13, and dried cooled natural gas stream 16 re-enters economizer heat exchanger 11 at 78.8 °F (26 °C). The same feed cooler duty and liquefaction power savings (as compared to the conventional prior art arrangement) are achieved. However, the configuration shown in Figure 1 is better suited to avoiding hydrate formation in the feed as feed cooler 15 (and, thus, mixed refrigerant from the refrigerant loop providing also cooling duty to the MCHE) is in the Figure 1 configuration not being used to cool the natural gas stream before the drying step has taken place.

[0069] It will be appreciated that the invention is not restricted to the details described above with reference to the preferred embodiments, and that numerous modifications and variations can be made without departing form the scope of the invention as defined in the following claims.

Claims

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

    (a) cooling a natural gas feed stream, that contains water, to produce a cooled natural gas stream;
    (b) removing water from and further cooling the cooled natural gas feed stream to produce a dried cooled natural gas stream;
    (c) heating the dried cooled natural gas stream to produce a dried rewarmed natural gas stream;
    (d) cooling and liquefying the dried rewarmed natural gas stream and cooling at least one compressed refrigerant feed stream by counter-current indirect heat exchange with an expanded cold refrigerant, to produce a liquefied natural gas product stream, at least one compressed cold refrigerant stream, and an expanded warmed refrigerant stream; and
    (e) expanding and thereby further cooling the compressed cold refrigerant stream or streams to provide said expanded cold refrigerant;

    wherein the cooling of the natural gas feed stream in step (a) and heating of the dried cooled natural gas stream in step (c) is by indirect heat exchange between said two streams.

2. The method of Claim 1, wherein in step (c) the dried cooled natural gas stream is heated to a temperature that is the same as or within 20°C of the temperature of the at least one compressed refrigerant feed stream, such that there is no or less than 20°C temperature difference between the dried rewarmed natural gas stream and the at least one compressed refrigerant feed stream at the start of step (d).

3. The method of Claim 2, wherein the temperature of the natural gas feed stream at the start of step (a) is also the same as or within 20°C of the temperatures of the dried rewarmed natural gas stream and the at least one compressed refrigerant feed stream at the start of step (d).

4. The method of any preceding claim, wherein step (d) is carried out in a wound coil cryogenic heat exchanger.

5. The method of any preceding claim, wherein in step (b) the cooled natural gas feed stream is first dried, to remove water therefrom, and is then further cooled to produce the dried cooled natural gas stream.

6. The method of any preceding claim, wherein the refrigerant in steps (d) and (e) is either a mixed refrigerant, the compressed cold refrigerant stream or streams in step (d) being liquid or mixed phase streams and the expanded warmed refrigerant stream in step (d) being a mixed phase or vapor stream, or is a gaseous refrigerant that remains in substantially gaseous form throughout steps (d) and (e).

7. The method of any preceding claim, wherein the method further comprises:

    (f) compressing the expanded warmed refrigerant stream to provide said at least one compressed refrigerant feed stream that is cooled in step (d).

8. The method of Claim 7, wherein step (f) comprises compressing and cooling the expanded warmed refrigerant stream to provide both said at least one compressed refrigerant feed stream that is cooled in step (d) and an additional compressed refrigerant stream, the method further comprising expanding said additional compressed refrigerant stream to further cool said stream and using said further cooled additional refrigerant stream in step (b) to further cool the cooled natural gas feed stream by indirect heat exchange.

9. The method of Claim 8, wherein step (f) comprises compressing, cooling and phase separating the expanded warmed refrigerant stream to provide a vapor stream of compressed refrigerant and a liquid stream of compressed refrigerant, said vapor stream forming at least one compressed refrigerant feed stream that is cooled and at least partially liquefied in step (d), and at least a portion of said liquid stream forming the additional refrigerant stream that is expanded and then used in step (b) to further cool the

cooled natural gas feed stream by indirect heat exchange.

10. The method of any one of Claims 1 to 7, wherein in step (d) the dried rewarmed natural gas stream is cooled and liquefied to produce the liquefied natural gas product stream and an additional liquefied natural gas stream, said additional liquefied natural gas stream being used in step (b) to further cool the cooled natural gas feed stream.

11. The method of Claim 10, wherein in step (b) the cooled natural gas feed stream is further cooled by countercurrent direct heat exchange with said additional liquefied natural gas stream.

12. An apparatus for drying and liquefying a natural gas stream, the apparatus comprising:

an economizer heat exchanger for receiving a water-containing natural gas feed stream and a dried cooled natural gas stream and for cooling the water-containing natural gas feed stream and warming the dried cooled natural gas stream by indirect heat exchange with each other, so as to produce a cooled water-containing natural gas feed stream and a dried rewarmed natural gas stream;
natural gas feed water removal and natural gas feed cooling systems, in fluid flow communication with the economizer heat exchanger and each other, for receiving the cooled water-containing natural gas feed stream from the economizer heat exchanger, drying and further cooling said stream, and returning the resulting dried cooled natural gas stream to the economizer heat exchanger;
a main cryogenic heat exchanger for cooling and liquefying the dried rewarmed natural gas stream and for cooling at least one compressed refrigerant feed stream by counter-current indirect heat exchange with an expanded cold refrigerant, so as to produce a liquefied natural gas product stream, at least one compressed cold refrigerant stream, and an expanded warmed refrigerant stream;
a conduit arrangement for transferring the dried rewarmed natural gas stream from the economizer heat exchanger to the warm end of the main cryogenic heat exchanger, and for withdrawing the liquefied natural gas product stream from the cold end of the main cryogenic heat exchanger; and
a refrigerant expansion system, in fluid flow communication with the main cryogenic heat exchanger, for receiving at least one compressed cold refrigerant stream from the cold end of the cryogenic heat exchanger, expanding and thereby further cooling said cold refrigerant, and returning expanded cold refrigerant to the cold end of the cryogenic heat exchanger.

13. An apparatus according to Claim 12, wherein the main cryogenic heat exchanger is a wound coil heat exchanger.

14. An apparatus according to Claim 12 or 13, wherein the natural gas feed water removal system is upstream of the natural gas feed cooling system, such that cooled water-containing natural gas from the economizer heat exchanger is first dried in said water removal system, and dried natural gas from said water removal system is then further cooled in said cooling system to produce dried cooled natural gas that is then returned to the economizer heat exchanger.

15. An apparatus according to any one of Claims 12 to 14, wherein the apparatus further comprises:

a refrigerant compression system, in fluid flow communication with the main cryogenic heat exchanger, for receiving the expanded warmed refrigerant stream from the warm end of the cryogenic heat exchanger, compressing said refrigerant, and returning at least one compressed refrigerant feed stream to the warm end of the cryogenic heat exchanger.

16. An apparatus according to Claim 15, wherein the main cryogenic heat exchanger, refrigerant expansion system, and refrigerant compression system form or form part of a closed loop refrigerant system, the refrigerant contained and circulating within said closed loop system comprising said compressed and expanded refrigerant streams, said refrigerant being a mixed refrigerant or pure nitrogen or argon.

17. An apparatus according to Claim 15 or 16, wherein the refrigerant compression system compresses and cools the expanded warmed refrigerant, and the natural gas feed cooling system is an indirect heat exchanger, and wherein the apparatus further comprises an additional expansion system, in fluid flow communication with the refrigerant compression system and the natural gas feed cooling system, for receiving a stream of compressed and cooled refrigerant from the refrigerant compression system and expanding said stream to further cool said stream, the natural gas feed cooling system using said further cooled stream to further cool the cooled natural gas feed stream by indirect heat exchange.

18. An apparatus according to Claim 17, wherein the refrigerant compression system further comprises at least one phase separator, for separating the compressed and cooled refrigerant into liquid and vapor

phases, said phase separator or separators being in fluid flow communication with the main cryogenic heat exchanger and the additional expansion system such that a vapor stream of compressed refrigerant is fed to the warm end of the cryogenic heat exchanger and a liquid stream of compressed refrigerant is fed to the additional expansion system.

19. An apparatus according to any one of Claims 12 to 16, wherein the apparatus further comprises a conduit arrangement for transferring an additional liquefied natural gas stream from the main cryogenic heat exchanger to the natural gas feed cooling system, the feed cooling system using said additional liquefied natural gas stream to further cool the cooled natural gas feed stream.

20. An apparatus according to Claim 19, wherein the natural gas feed cooling system is a scrub column, in which the cooled natural gas feed stream is further cooled by countercurrent direct heat exchange with said additional liquefied natural gas stream.

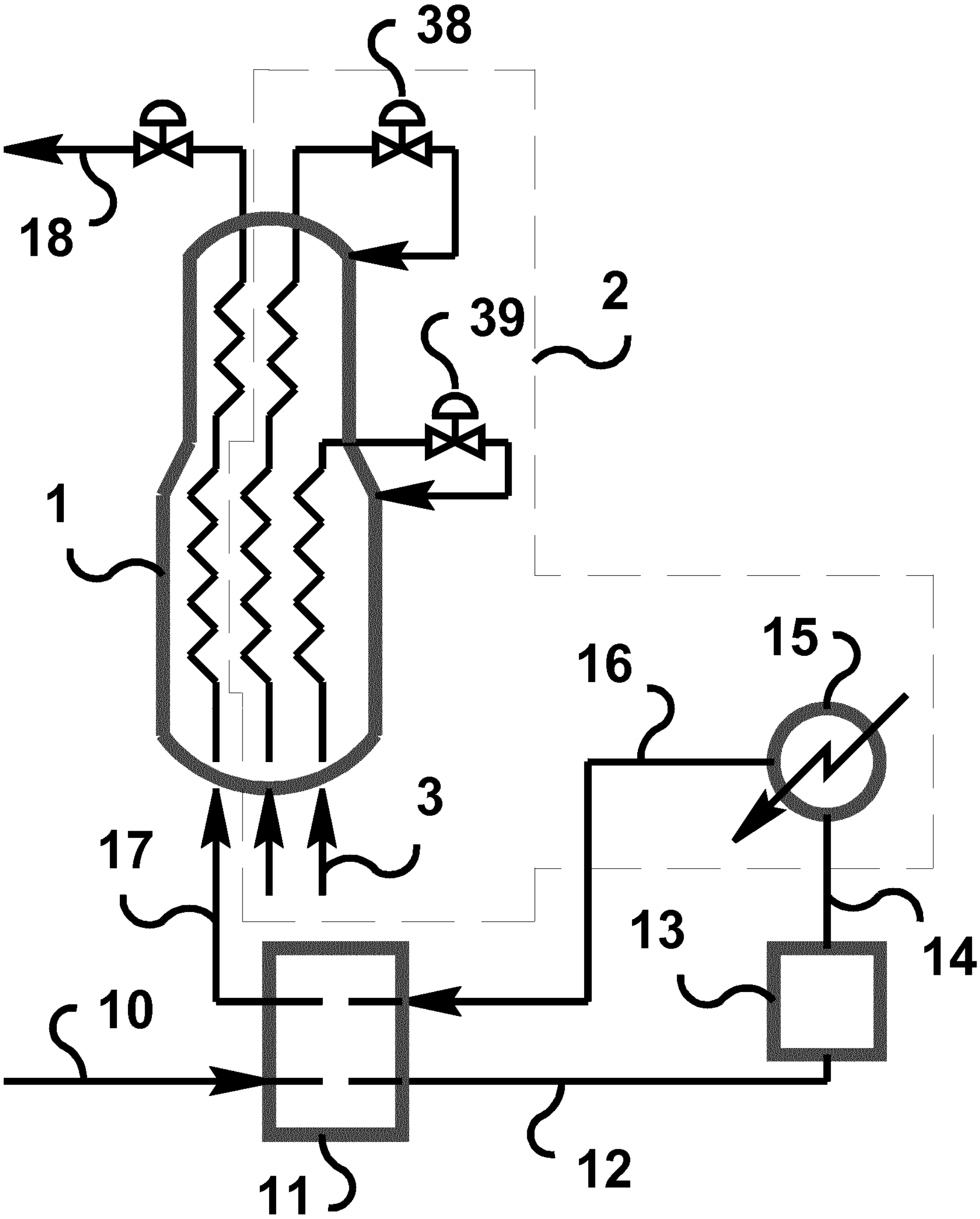

Fig. 1

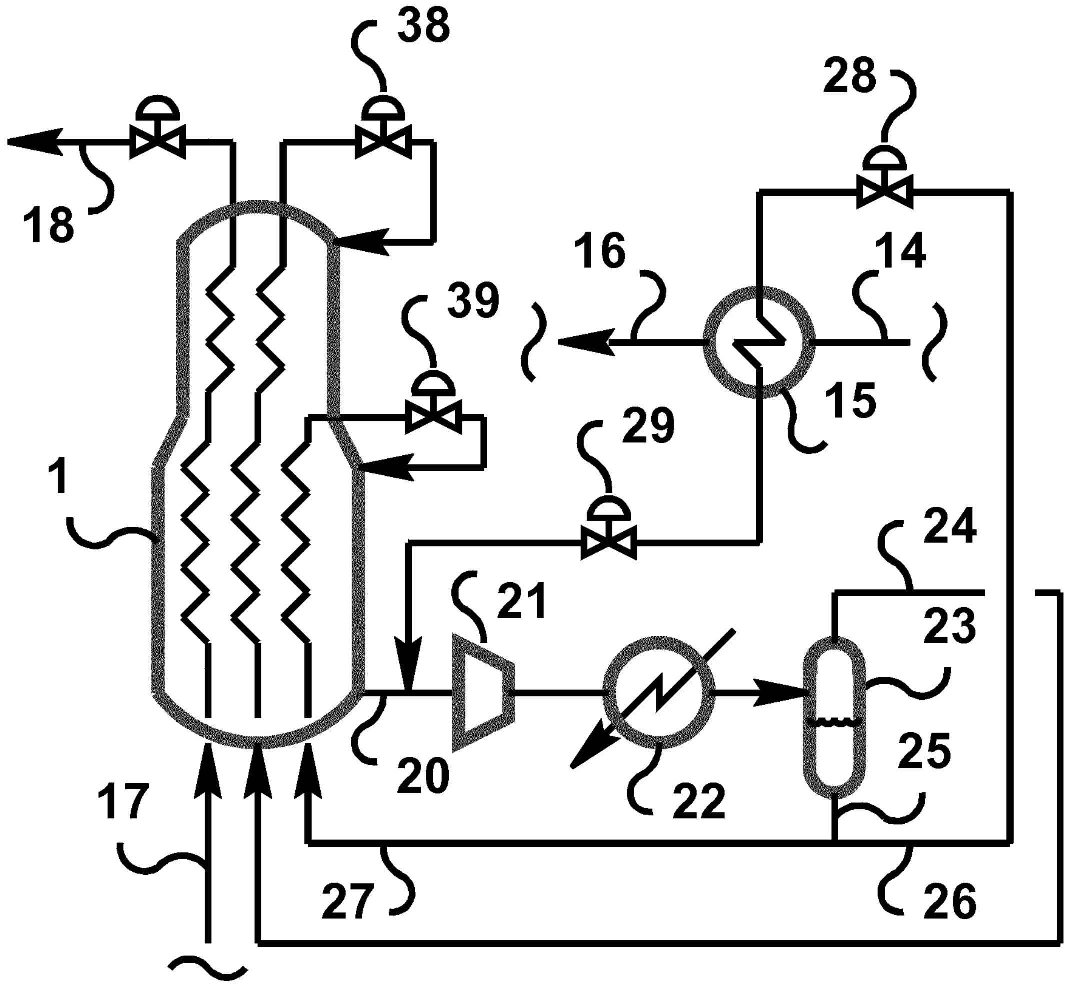

Fig. 2

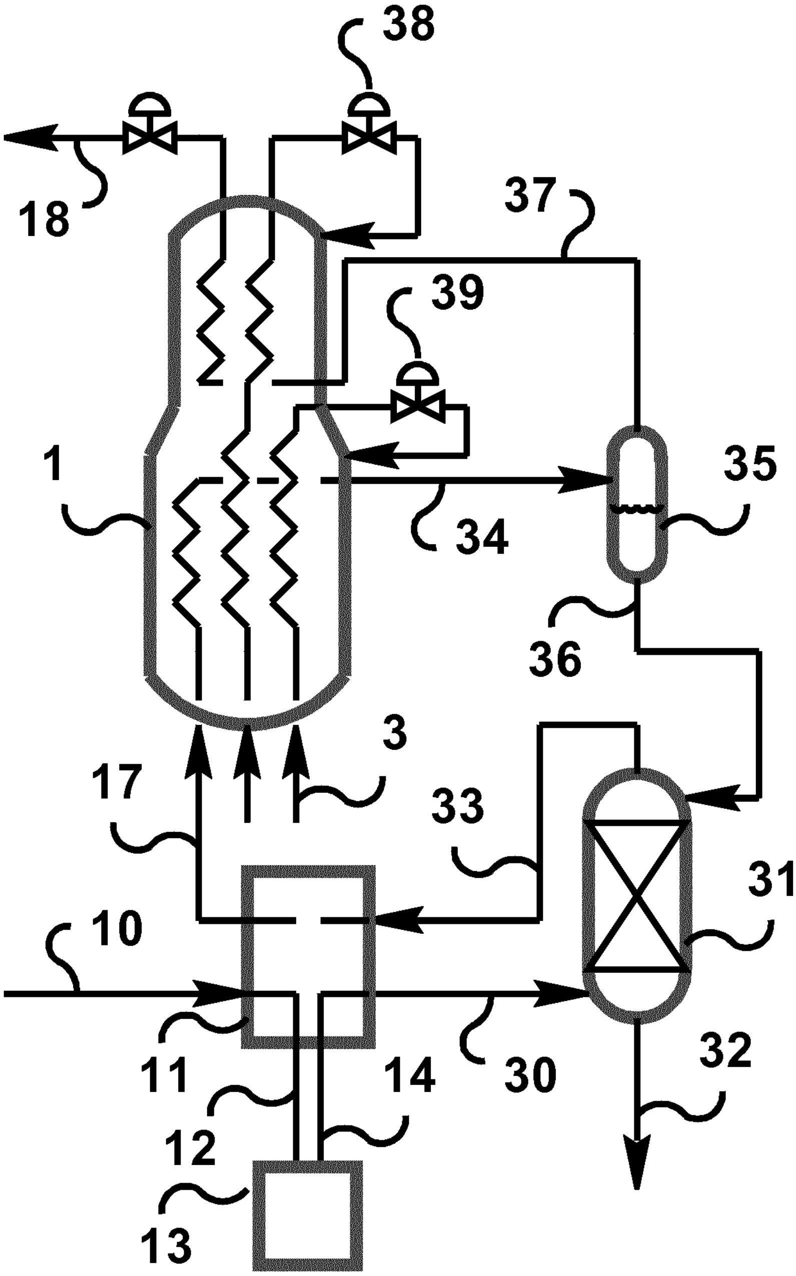

Fig. 3

REFERENCES CITED IN THE DESCRIPTION

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