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Hybrid cycle for the production of liquefied natural gas
Hybrider Kreislauf zur Herstellung von flüssigem Erdgas
Cycle hybride pour la production de gaz naturel liquéfié

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References cited:

HAUSEN, LINDE: "Tieftemperaturtechnik", 1985,
SPRINGER VERLAG, BERLIN

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BACKGROUND OF THE INVENTION

[0001] The production of liquefied natural gas (LNG) is achieved by cooling and condensing a feed gas stream against multiple refrigerant streams provided by recirculating refrigeration systems. Cooling of the natural gas feed is accomplished by various cooling process cycles such as the well-known cascade cycle in which refrigeration is provided by three different refrigerant loops. One such cascade cycle uses methane, ethylene, and propane cycles in sequence to produce refrigeration at three different temperature levels. Another well-known refrigeration cycle uses a propane pre-cooled, mixed refrigerant cycle in which a multicomponent refrigerant mixture generates refrigeration over a selected temperature range (see e.g. US-A-4,334,902 or Haüsen, Linde "Tieftemperaturtechnik", 1985). The mixed refrigerant can contain hydrocarbons such as methane, ethane, propane, and other light hydrocarbons, and also may contain nitrogen. Versions of this efficient refrigeration system are used in many operating LNG plants around the world.

[0002] Another type of refrigeration process for natural gas liquefaction involves the use of a nitrogen expander cycle in which nitrogen gas is first compressed and cooled to ambient conditions with air or water cooling and then is further cooled by counter-current exchange with cold low-pressure nitrogen gas. The cooled nitrogen stream is then worked expanded through a turbo-expander to produce a cold low pressure stream. The cold nitrogen gas is used to cool the natural gas feed and the high pressure nitrogen stream. The work produced by the nitrogen expansion can be used to drive a nitrogen booster compressor connected to the shaft of the expander. In this process, the cold expanded nitrogen is used to liquefy the natural gas and also to cool the compressed nitrogen gas in the same heat exchanger. The cooled pressurized nitrogen is further cooled in the work expansion step to provide the cold nitrogen refrigerant.


[0004] U.S. Patent 3,511,058 describes a LNG production system using a closed loop nitrogen refrigerator with a gas expander or reverse Brayton type cycle. In this process, liquid nitrogen is produced by means of a nitrogen refrigeration loop utilizing two turboexpanders. The liquid nitrogen produced is further cooled by a dense fluid expander. The natural gas undergoes final cooling by boiling the liquid nitrogen produced from the nitrogen liquefier. Initial cooling of the natural gas is provided by a portion of the cold gaseous nitrogen discharged from the warmer of the two expanders in order to better match cooling curves in the warm end of the heat exchanger. This process is applicable to natural gas streams at sub-critical pressures since the gas is liquefied in a free-draining condenser attached to a phase separator drum.

[0005] U.S. Patent 5,768,912 (equivalent to International Patent Publication WO 95/27179) discloses a natural gas liquefaction process which uses nitrogen in a closed loop Brayton type refrigeration cycle. The feed and the high pressure nitrogen can be pre-cooled using a small conventional refrigeration package employing propane, freon, or ammonia absorption cycles. This pre-cooling refrigeration system utilizes about 4% of total power consumed by the nitrogen refrigeration system. The natural gas is then liquefied and sub-cooled to -149°C using a reverse Brayton or turbo-expander cycle employing two or three expanders arranged in series relative to the cooling natural gas.

[0006] German patent DE 24 40 215 to Linde which is considered closest prior art and discloses the preamble of claims 1, 6 and 10 discloses a process for producing LNG by at least partial liquefaction of said natural gas takes place in heat exchange with a liquid multi-component refrigerant and complete liquefaction and sub-cooling of the gas takes place in heat exchange with an expanded gaseous refrigerant.

[0007] A mixed refrigerant system for natural gas liquefaction is described in International Patent Publication WO 96/11370 in which the mixed refrigerant is compressed, partially condensed by an external cooling fluid, and separated into liquid and vapor phases. The resulting vapor is work expanded to provide refrigeration to the cold end of the process and the liquid is sub-cooled and vaporized to provide additional refrigeration.

[0008] International Patent Publication WO 97/13109 discloses a natural gas liquefaction process which uses nitrogen in a closed loop reverse Brayton-type refrigeration cycle. The natural gas at supercritical pressure is cooled against the nitrogen refrigerant, expanded isentropically, and stripped in a fractionating column to remove light components.

[0009] The liquefaction of natural gas is very energy-intensive. Improved efficiency of gas liquefaction processes is highly desirable and is the prime objective of new cycles being developed in the gas liquefaction art. The objective of the present invention, as described below and defined by the claims which follow, is to improve liquefaction efficiency by providing two integrated refrigeration systems.
operation systems wherein one of the systems utilizes one or more vaporizing refrigerant cycles to provide refrigeration down to about -100°C and utilizes a gas expander cycle to provide refrigeration below about -100°C. Various embodiments are described for the application of this improved refrigeration system which enhance the improvements to liquefaction efficiency.

BRIEF SUMMARY OF THE INVENTION

[0010] The invention is a method for the liquefaction of a feed gas as stipulated in the appending claims which method comprises providing at least a portion of the total refrigeration required to cool and condense the feed gas by utilizing a first refrigeration system which comprises at least one recirculating refrigeration circuit, wherein the first refrigeration system utilizes two or more refrigerant components and provides refrigeration in a first temperature range; and a second refrigeration system which provides refrigeration in a second temperature range by work expanding a pressurized gaseous refrigerant stream. The invention also concerns an apparatus for practicing this method according to claim 10.

[0011] The lowest temperature in the second temperature range preferably is less than the lowest temperature in the first temperature range as defined in claim 1. Typically, at least 5% of the total refrigeration power required to liquefy the feed gas is consumed by the first refrigeration system. Under many operating conditions, at least 10% of the total refrigeration power required to liquefy the feed gas can be consumed by the first recirculating refrigeration system. Preferably, the feed gas is natural gas.

[0012] The refrigerant in the first recirculating refrigeration circuit can comprise two or more components selected from the group consisting of nitrogen, hydrocarbons containing one or more carbon atoms, and halocarbons containing one or more carbon atoms. The method refrigerant in the second recirculating refrigeration circuit can comprise nitrogen.

[0013] At least a portion of the first temperature range is between about -40°C and about -100°C, and at least a portion of the first temperature range is preferably between about -60°C and about -100°C. At least a portion of the second temperature range is below about -100°C.

[0014] The first recirculating refrigeration system is operated by

1. compressing a first gaseous refrigerant;
2. cooling and at least partially condensing the resulting compressed refrigerant;
3. reducing the pressure of the resulting at least partially condensed compressed refrigerant;
4. vaporizing the resulting reduced-pressure refrigerant to provide refrigeration in the first temperature range and yield a vaporized refrigerant; and
5. recirculating the vaporized refrigerant to provide the first gaseous refrigerant of (1).

[0015] A portion of the cooling of the resulting compressed refrigerant in (2) can be provided by indirect heat exchange with vaporizing reduced-pressure refrigerant in (4). At least a portion of the cooling in (2) is provided by indirect heat exchange with one or more additional vaporizing refrigerant streams provided by a third recirculating refrigeration circuit. The third recirculating refrigeration circuit typically utilizes a single component refrigerant. The third recirculating refrigeration circuit can utilize a mixed refrigerant comprising two or more components.

[0016] The second recirculating refrigeration system can be operated by

1. compressing a second gaseous refrigerant to provide the pressurized gaseous refrigerant in (b);
2. cooling the pressurized gaseous refrigerant to yield a cooled gaseous refrigerant;
3. work expanding the cooled gaseous refrigerant to provide the cold refrigerant in (b);
4. warming the cold refrigerant to provide refrigeration in the second temperature range; and
5. recirculating the resulting warmed refrigerant to provide the second gaseous refrigerant of (1).

[0017] A portion of the cooling in (2) can be provided by indirect heat exchange by warming the cold refrigerant stream in (4). Also, at least a portion of the cooling in (2) can be provided by indirect heat exchange with the vaporizing refrigerant of (a). At least a portion of the cooling in (2) is, however, provided by indirect heat exchange with one or more additional vaporizing refrigerants provided by a third recirculating refrigeration circuit, which can utilize a single component refrigerant. Alternatively, the third recirculating refrigeration circuit can utilize a mixed refrigerant which comprises two or more components.

[0018] The first recirculating refrigeration circuit and the second recirculating refrigeration circuit can provide, in a single heat exchanger, a portion of the total refrigeration required to liquefy the feed gas.

[0019] In an embodiment of the invention, the first refrigeration system can be operated by

1. compressing a first gaseous refrigerant;
2. cooling and partially condensing the resulting compressed refrigerant to yield a vapor refrigerant fraction and a liquid refrigerant fraction;
3. further cooling and reducing the pressure of the liquid refrigerant fraction, and vaporizing the resulting liquid refrigerant fraction to provide refrigeration in the first temperature range and yield a first vaporized refrigerant;
4. cooling and condensing the vapor refrigerant fraction, reducing the pressure of at least a portion of the resulting liquid, and vaporizing the resulting liquid refrigerant fraction to provide additional refrigeration in the first temperature range and yield a
second vaporized refrigerant; and
(5) combining the first and second vaporized refrigerants to provide the first gaseous refrigerant of (1).

[0020] Vaporization of the resulting liquid in (4) can be effected at a pressure lower than the vaporization of the resulting liquid refrigerant fraction in (3), wherein the second vaporized refrigerant would be compressed before combining with the first vaporized refrigerant. Work from work expanding the cooled gaseous refrigerant in (3) can provide a portion of the work required for compressing the second gaseous refrigerant in (1).

[0021] The feed gas can be natural gas, and if so, the resulting liquefied natural gas stream can be flashed to a lower pressure to yield a light flash vapor and a final liquid product. The light flash vapor can be used to provide the second gaseous refrigerant in the second refrigerant circuit.

BRIEF DESCRIPTION OF SEVERAL VIEWS OF THE DRAWINGS

[0022] Fig. 1 is a schematic flow diagram of a process illustrating the art.

Fig. 2 is a schematic flow diagram of another embodiment of the present invention which utilizes an additional refrigeration system to pre-cool the feed gas, the compressed refrigerant in the vapor recompression refrigeration cycle, and the compressed refrigerant in the gas expander refrigeration cycle.

Fig. 3 is a schematic flow diagram of another embodiment of the present invention which utilizes an additional vapor recompression refrigeration system.

DETAILED DESCRIPTION OF THE INVENTION

[0023] Most LNG production plants today utilize refrigeration produced by compressing a gas to a high pressure, liquefying the gas against a cooling source, expanding the resulting liquid to a low pressure, and vaporizing the resulting liquid to provide the refrigeration. Vaporized refrigerant is recompressed and utilized again in the recirculating refrigeration circuit. This type of refrigeration process can utilize a multi-component mixed refrigerant or a cascaded single component refrigerant cycle for cooling, and is defined generically herein as a vaporizing refrigerant cycle or as a vapor recompression cycle. This type of cycle is very efficient at providing cooling at near ambient temperatures. In this case, refrigerant fluids are available which will condense at a pressure well below the refrigerant critical pressure while rejecting heat to an ambient temperature heat sink, and will also boil at a pressure above atmospheric while absorbing heat from the refrigeration load.

[0024] As the required refrigeration temperature decreases in a single component vapor compression refrigeration system, a particular refrigerant which boils above atmospheric pressure at a temperature low enough to provide the required refrigeration will be too volatile to condense against an ambient temperature heat sink because the refrigerant critical temperature is below ambient temperature. In this situation, cascade cycles can be employed. For example, a two-fluid cascade can be utilized in which a heavier fluid provides the warmer refrigeration while a lighter fluid provides the colder refrigeration. Rather than rejecting heat to an ambient temperature, however, the light fluid rejects heat to the boiling heavier fluid while itself condensing. Very low temperatures can be reached by cascading multiple fluids in this manner.

[0025] A multi-component refrigeration (MCR) cycle can be considered as a type of cascade cycle in which the heaviest components of the refrigerant mixture condense against the ambient temperature heat sink and boil at low pressure while condensing the next lighter component which itself will boil to provide condensing to the still lighter component, and so on, until the desired temperature is reached. The main advantage of a multi-component system over a cascaded system is that the compression and heat exchange equipment is greatly simplified. The multi-component system requires a single compressor and heat exchanger, while the cascade system requires multiple compressors and heat exchangers.

[0026] Both of these cycles become less efficient as the temperature of the refrigeration load decreases because of the necessity to cascade multiple fluids. To provide the temperatures (typically -220 °F to -270 °F) required for LNG production, multiple steps involving multiple components are employed. In each step there are thermodynamic losses associated with the boiling/condensing heat transfer across a finite temperature difference, and with each additional step these losses increase.

[0027] Another type of industrially important refrigeration cycle is the gas expander cycle. In this cycle, the working fluid is compressed, cooled sensibly (without phase change), work expanded as a vapor in a turbine, and warmed while providing cooling to the refrigeration load. This cycle is also defined as a gas expander cycle. Very low temperatures can be obtained relatively efficiently with this type of cycle using a single recirculating cooling loop. In this type of cycle, the working fluid typically does not undergo phase change, so heat is absorbed as the fluid is warmed sensibly. In some cases, however, the working fluid can undergo a small degree of phase change during work expansion.

[0028] The gas expander cycle efficiently provides refrigeration to fluids which are also cooling over a temperature range, and is particularly useful in providing for
very low temperature refrigeration such as that required in producing liquid nitrogen and hydrogen.

A disadvantage of the gas expander refrigeration cycle, however, is that it is relatively inefficient at providing warm refrigeration. The net work required for a gas expander cycle refrigerator is equal to the difference between the compressor work and the expander work, while the work for a cascade or single component refrigeration cycle is simply the compressor work. In the gas expander cycle, expansion work can easily be 50% or more of the compressor work when providing warm refrigeration. The problem with the gas expander cycle in providing warm refrigeration is that any inefficiency in the compressor system is multiplied.

The objective of the present invention is to improve the exploitation of the benefits of the gas expander cycle in providing cold refrigeration while utilizing the benefits of pure or multi-component vapor recompression refrigeration cycles in providing warm refrigeration, and applying this combination of refrigeration cycles to gas liquefaction. This combination refrigeration cycle is particularly useful in the liquefaction of natural gas.

According to the invention, mixed component, pure component, and/or cascaded vapor recompression refrigeration systems are used to provide a portion of the refrigeration needed for gas liquefaction at temperatures below about -40°C and down to about -100°C. The residual refrigeration in the coldest temperature range below about -100°C is provided by work expansion of a refrigerant gas. The recirculation circuit of the refrigerant gas stream used for work expansion is physically independent from but thermally integrated with the recirculation circuit or circuits of the pure or mixed component vapor recompression cycle or cycles. More than 5% and usually more than 10% of the total refrigeration power required for liquefaction of the feed gas can be consumed by the pure or mixed component vapor recompression cycle or cycles. The invention can be implemented in the design of a new liquefaction plant or can be utilized as a retrofit or expansion of an existing plant by adding the gas expander cooling circuit to the existing plant refrigeration system.

The pure or mixed component vapor recompression working fluid or fluids generally comprise one or more components chosen from nitrogen, hydrocarbons having one or more carbon atoms, and halocarbons having one or more carbon atoms. Typical hydrocarbon refrigerants include methane, ethane, propane, i-butane, butane, and i-pentane. Representative halocarbon refrigerants include R22, R23, R32, R134a, and R410a. The gas stream to be work expanded in the gas expander cycle can be a pure component or a mixture of components; examples include a pure nitrogen stream or a mixture of nitrogen with other gases such as methane.

The method of providing refrigeration using a mixed component circuit includes compressing a mixed component stream and cooling the compressed stream using an external cooling fluid such as air, cooling water, or another process stream. A portion of the compressed mixed refrigerant stream is liquefied after external cooling. At least a portion of the compressed and cooled mixed refrigerant stream is further cooled in a heat exchanger and then reduced in pressure and vaporized by heat exchange against the gas stream being liquefied. The evaporated and warmed mixed refrigerant steam is then recirculated and compressed as described above.

The method of providing refrigeration using a pure component circuit consists of compressing a pure component stream and cooling it using an external cooling fluid. A portion of the refrigerant stream is liquefied after external cooling. At least a portion of the compressed and liquefied refrigerant is then reduced in pressure and vaporized by heat exchange against the gas stream being liquefied or against another refrigerant stream being cooled. The resulting vaporized refrigerant steam is then compressed and recirculated as described above.

According to the invention, the pure or mixed component vapor recompression cycle or cycles preferably provide refrigeration to temperature levels below about -40°C, preferably below about -60°C, and down to about -100°C, but do not provide the total refrigeration needed for liquefying the feed gas. These cycles typically may consume more than 5%, and usually more than 10%, of the total refrigeration power requirement for liquefaction of the feed gas. In the liquefaction of natural gas, pure or mixed component vapor recompression cycle or cycles typically can consume greater than 30% of the total power requirement required to liquefy the feed gas. In this application, the natural gas preferred is cooled to temperatures well below -40°C, and preferably below -60°C, by the pure or mixed component vapor recompression cycle or cycles.

The method of providing refrigeration in the gas expander cycle includes compressing a gas stream, cooling the compressed gas stream using an external cooling fluid, further cooling at least a portion of the cooled compressed gas stream, expanding at least a portion of the further cooled stream in an expander to produce work, warming the expanded stream by heat exchange against the stream to be liquefied, and recirculating the warmed gas stream for further compression. This cycle provides refrigeration at temperature levels below the temperature levels of the refrigeration provided by the pure or mixed refrigerant vapor recompression cycle.

In a preferred mode, the pure or mixed component vapor recompression cycle or cycles provide a portion of the cooling to the compressed gas stream prior to its expansion in an expander. In an alternative mode, the gas stream may be expanded in more than one expander. Any known expander arrangement to liquefy a gas stream may be used. The invention may utilize any of a wide variety of heat exchange devices in the refrigeration circuits including plate-fin, wound coil,
nature exiting heat exchanger 128, a significant quantity of light gas is evolved as stream 138 after the flash across valve 134. This gas can be warmed in heat exchangers 128 and 150 and compressed to a pressure sufficient for use as fuel gas in the LNG facility.

Refrigeration to cool the natural gas from ambient temperature to a temperature of about -100°C is provided by a multi-component refrigeration loop as mentioned above. Stream 146 is the high pressure mixed refrigerant which enters heat exchanger 106 at ambient temperature and a typical pressure of about 38 bara. The refrigerant is cooled to a temperature of about -100°C in heat exchangers 106 and 122, exiting as stream 148. Stream 148 is divided into two portions in this embodiment. A smaller portion, typically about 4%, is reduced in pressure adiabatically to about 10 bara and is introduced as stream 149 into heat exchanger 150 to provide supplemental refrigeration as described below. The major portion of the refrigerant as stream 124 is also reduced in pressure adiabatically to a typical pressure of about 10 bara and is introduced to the cold end of heat exchanger 106. The refrigerant flows downward and vaporizes in interior 109 of heat exchanger 128 and leaves at slightly below ambient temperature as stream 152. Stream 152 is then re-combined with minor stream 154 which was vaporized and warmed to near ambient temperature in heat exchanger 150. The combined low pressure stream 156 is then compressed in multi-stage intercooled compressor 158 back to the final pressure of about 38 bara. Liquid can be formed in the intercooler of the compressor, and this liquid is separated and re-combined with the main stream 160 exiting final stage of compression. The combined stream is then cooled back to ambient temperature to yield stream 146.

Final cooling of the natural gas from about -100°C to about -166°C is accomplished using a gas expander cycle employing nitrogen as the working fluid. High pressure nitrogen stream 162 enters heat exchanger 150 typically at ambient temperature and a pressure of about 67 bara, and is then cooled to a temperature of about -100°C in heat exchanger 150. Cooled vapor stream 164 is substantially isentropically work expanded in turbo-expander 132, typically exiting at a pressure of about 11 bara and a temperature of about -168°C. Ideally the exit pressure is at or slightly below the dewpoint pressure of the nitrogen at a temperature cold enough to effect the cooling of the LNG to the desired temperature. Expanded nitrogen stream 130 is then warmed to near ambient temperature in heat exchangers 128 and 150. Supplemental refrigeration is provided to heat exchanger 150 by a small steam 149 of the mixed refrigerant, as described earlier, and this is done to reduce the irreversibility in the process by causing the cooling curves heat exchanger 150 to be more closely aligned. From heat exchanger 150, warmed low pressure nitrogen stream 170 is compressed in multi-stage compressor 168 back to a high pressure of about 67 bara.
As mentioned above, this gas expander cycle can be implemented as a retrofit or expansion of an existing mixed refrigerant LNG plant.

An alternate embodiment is illustrated in Fig. 2 in which another refrigerant (for example propane) is used to pre-cool the feed, nitrogen, and mixed refrigerant streams in heat exchangers 402, 401, and 400 respectively before introduction into heat exchangers 106 and 150. In this embodiment, three levels of pre-cooling are used in heat exchangers 402, 401, and 400, although any number of levels can be used as required. In this case, returning refrigerant fluids 156 and 170 are compressed cold, at an inlet temperature slightly below that provided by the pre-cooling refrigerant. This arrangement could be implemented as a retrofit or expansion of an existing propane pre-cooled mixed refrigerant LNG plant.

Fig. 3 presents an embodiment of the invention in which two separate mixed refrigerant loops are employed before final cooling by the gas expander refrigeration loop. The first refrigeration loop employing compressor 701 and pressure reduction device 703 provides primary cooling to a temperature of about -30°C. A second refrigeration loop employing compressor 702 and expansion devices 704 and 705 is used to provide further cooling to a temperature of about -100°C. This arrangement could be implemented as a retrofit or expansion of an existing dual mixed refrigerant LNG plant.

The invention described above in the embodiments illustrated by Figs. 1-3 can utilize any of a wide variety of heat exchange devices in the refrigeration circuits including wound coil, plate-fin, shell and tube, and kettle type heat exchangers. Combinations of these types of heat exchangers can be used depending upon specific applications. For example, heat exchangers 106, 122, 128 can be wound coil exchangers and heat exchanger 150 can be a plate and fin type exchanger as utilized in Fig. 1.

In the preferred embodiment of the invention, the majority of the refrigeration in the temperature range of about -40°C to about -100°C is provided by indirect heat exchange with at least one vaporizing refrigerant in a recirculating refrigeration circuit. Some of the refrigeration in this temperature range also can be provided by the work expansion of a pressurized gaseous refrigerant.

EXAMPLE (Not Part of the Invention)

Referring to Fig. 1, natural gas is cleaned and dried in pretreatment section 172 for the removal of acid gases such as CO₂ and H₂S along with other contaminants such as mercury. Pretreated feed gas 100 has a flow rate of 24,431 kg-mole/hr, a pressure of 66.5 bara, and a temperature of 32°C. The molar composition of the stream is as follows:

<table>
<thead>
<tr>
<th>Component</th>
<th>Mole Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>0.009</td>
</tr>
<tr>
<td>Methane</td>
<td>0.9378</td>
</tr>
<tr>
<td>Ethane</td>
<td>0.031</td>
</tr>
<tr>
<td>Propane</td>
<td>0.013</td>
</tr>
<tr>
<td>i-Butane</td>
<td>0.003</td>
</tr>
<tr>
<td>Butane</td>
<td>0.004</td>
</tr>
<tr>
<td>i-Pentane</td>
<td>0.0008</td>
</tr>
<tr>
<td>Pentane</td>
<td>0.0005</td>
</tr>
<tr>
<td>Hexane</td>
<td>0.001</td>
</tr>
<tr>
<td>Heptane</td>
<td>0.0006</td>
</tr>
</tbody>
</table>

Pre-treated gas 100 enter first heat exchanger 106 and is cooled to a temperature of -31°C before entering scrub column 108 as stream 102. The cooling is effected by the warming of mixed refrigerant stream 109, which has a flow of 554,425 kg-mole/hr and the following composition:

<table>
<thead>
<tr>
<th>Component</th>
<th>Mole Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>0.014</td>
</tr>
<tr>
<td>Methane</td>
<td>0.343</td>
</tr>
<tr>
<td>Ethane</td>
<td>0.395</td>
</tr>
<tr>
<td>Propane</td>
<td>0.006</td>
</tr>
<tr>
<td>i-Butane</td>
<td>0.090</td>
</tr>
<tr>
<td>Butane</td>
<td>0.151</td>
</tr>
</tbody>
</table>

In scrub column 108, pentane and heavier components of the feed are removed. Bottoms product 110 of the scrub column enters fractionation section 112 where the heavy components are recovered as stream 114 and the propane and lighter components in stream 118 are recycled to heat exchanger 106, cooled to -31°C, and recombined with the overhead product of the scrub column to form stream 120. The flow rate of stream 120 is 24,339 kg-mole/hr.

Stream 120 is further cooled in heat exchanger 122 to a temperature of -102.4°C by warming mixed refrigerant stream 124 which enters heat exchanger 122 at a temperature of -104.0°C. The resulting stream 128 is then further cooled to a temperature of -165.7°C in heat exchanger 128. Refrigeration for cooling in heat exchanger 128 is provided by pure nitrogen stream 130 exiting turbo-expander 166 at -168.0°C with a liquid...
A method for the liquefaction of a feed gas (100) which comprises providing at least a portion of the total refrigeration required to cool and condense the feed gas (100) by utilizing

(a) a first refrigeration system comprising at least one recirculating refrigeration circuit (152, 156, 158, 160, 146, 109, 148, 125), wherein the first refrigeration system utilizes two or more refrigerant components and provides refrigeration in a first temperature range, wherein at least a portion of the first temperature range is between -40°C and -100°C; and

(b) a second refrigeration system (130, 128, 150, 168, 162, 160, 164, 166) which provides refrigeration in a second temperature range by work expanding a pressurized gaseous refrigerant stream, wherein at least a portion of the second temperature range is below -100°C;

wherein a recompression cycle of the first recirculating refrigeration system is operated by

(A) compressing a first gaseous refrigerant (158);

(B) cooling (109) and at least partially condensing the resulting compressed refrigerant (146);

(C) reducing the pressure of the resulting at least partially condensed compressed refrigerant (148);

(D) vaporizing the resulting reduced-pressure refrigerant (125) to provide refrigeration in the first temperature range and yield a vaporized refrigerant (152); and

(E) recirculating (156) the vaporized refrigerant to provide the first gaseous refrigerant of (A);

one or more vaporizing refrigerant cycles to provide refrigeration below about -40°C and down to about -100°C, and utilizes a gas expander cycle to provide refrigeration below about -100°C. The gas expander cycle also may provide some of the refrigeration in the range of about -40°C to about -100°C. Each of these two types of refrigerant systems is utilized in an optimum temperature range which maximizes the efficiency of the particular system. Typically, a significant fraction of the total refrigeration power required to liquefy the feed gas (more than 5% and usually more than 10% of the total) can be consumed by the vaporizing refrigerant cycle or cycles. The invention can be implemented in the design of a new liquefaction plant or can be utilized as a retrofit or expansion of an existing plant by adding gas expander refrigeration circuit to the existing plant refrigeration system.

Claims

1. A method for the liquefaction of a feed gas (100) which comprises providing at least a portion of the total refrigeration required to cool and condense the feed gas (100) by utilizing

(a) a first refrigeration system comprising at least one recirculating refrigeration circuit (152, 156, 158, 160, 146, 109, 148, 125), wherein the first refrigeration system utilizes two or more refrigerant components and provides refrigeration in a first temperature range, wherein at least a portion of the first temperature range is between -40°C and -100°C; and

(b) a second refrigeration system (130, 128, 150, 168, 162, 150, 164, 166) which provides refrigeration in a second temperature range by work expanding a pressurized gaseous refrigerant stream, wherein at least a portion of the second temperature range is below -100°C;

wherein a recompression cycle of the first recirculating refrigeration system is operated by

(A) compressing a first gaseous refrigerant (158);

(B) cooling (109) and at least partially condensing the resulting compressed refrigerant (146);

(C) reducing the pressure of the resulting at least partially condensed compressed refrigerant (148);

(D) vaporizing the resulting reduced-pressure refrigerant (125) to provide refrigeration in the first temperature range and yield a vaporized refrigerant (152); and

(E) recirculating (156) the vaporized refrigerant to provide the first gaseous refrigerant of (A);
characterized in that at least a portion of the cooling in (B) is provided by indirect heat exchange (400) with one or more additional vaporizing refrigerant streams provided by a third recirculating refrigeration circuit.

2. A method of Claim 1 wherein the third recirculating refrigeration circuit utilizes a single component refrigerant.

3. A method of Claim 1 wherein the third recirculating refrigeration circuit utilizes a mixed refrigerant comprising two or more components.

4. A method of any one of the preceding claims wherein in the feed gas is natural gas.

5. A method of any one of the preceding claims wherein the refrigerant in the second recirculating refrigeration circuit comprises nitrogen.

6. A method for the liquefaction of a feed gas (100) which comprises providing at least a portion of the total refrigeration required to cool and condense the feed gas (100) by utilizing

(a) a first refrigeration system comprising at least one recirculating refrigeration circuit (152, 156, 158, 160, 146, 109, 148, 125), wherein the first refrigeration system utilizes two or more refrigerant components and provides refrigeration in a first temperature range, wherein at least a portion of the first temperature range is between -40°C and -100°C; and
(b) a second refrigeration system (130, 128, 150, 170, 168, 162, 150, 164, 166) which provides refrigeration in a second temperature range by work expanding a pressurized gaseous refrigerant stream, wherein at least a portion of the second temperature range is below -100°C;

wherein the second recirculating refrigeration system is operated by

1. compressing (168) a second gaseous refrigerant to provide the pressurized gaseous refrigerant (162);
2. cooling (150) the pressurized gaseous refrigerant (162) to yield a cooled gaseous refrigerant (164);
3. work expanding (166) the cooled gaseous refrigerant to provide the cold refrigerant (130);
4. warming (128) the cold refrigerant (130) to provide refrigeration in the second temperature range; and
5. recirculating the resulting warmed refrigerant (170) to provide the second gaseous refrigerant of (1); characterized in that

at least a portion of the cooling in (2) is provided by indirect heat exchange (401) with one or more additional vaporizing refrigerants provided by a third recirculating refrigeration circuit.

7. A method of Claim 6 wherein the third recirculating refrigeration circuit utilizes a single component refrigerant.

8. A method of Claim 6 wherein the third recirculating refrigeration circuit utilizes a mixed refrigerant which comprises two or more components.

9. A method of Claim 1 wherein at least one of the first and second refrigeration systems comprises a wound coil heat exchanger.

10. An apparatus for the liquefaction of a feed gas (100) by a method of claim 1; said apparatus comprising

(a) a first refrigeration system comprising at least one recirculating refrigeration circuit (152, 156, 158, 160, 146, 109, 148, 125), wherein the first refrigeration system utilizes two or more refrigerant components and provides refrigeration in a first temperature range, wherein at least a portion of the first temperature range is between -40°C and -100°C; and
(b) a second refrigeration system (130, 128, 150, 170, 168, 162, 150, 164, 166) which provides refrigeration in a second temperature range by work expanding a pressurized gaseous refrigerant stream, wherein at least a portion of the second temperature range is below -100°C;

wherein a recompression cycle of the first recirculating refrigeration system comprises

(A) compression means for compressing a first gaseous refrigerant (158);
(B) heat exchange means (106) for cooling and at least partially condensing the resulting compressed refrigerant (146);
(C) means for reducing the pressure of the resulting at least partially condensed compressed refrigerant (148);
(D) heat exchange means for vaporizing the resulting reduced-pressure refrigerant (125) to provide refrigeration in the first temperature range and yield a vaporized refrigerant (152); and
(E) means (156) for recirculating the vaporized refrigerant to provide the first gaseous refrigerant of (A).
characterized in that a heat exchange means (400) provides at least a portion of the cooling of (B) by indirect heat exchange with one or more additional vaporizing refrigerant streams provided by a third recirculating refrigeration circuit.

11. An apparatus of Claim 10, wherein the second recirculating refrigeration system comprises

(1) compression means (168) for compressing a second gaseous refrigerant to provide the pressurized gaseous refrigerant (162);
(2) heat exchange means (150) for cooling the pressurized gaseous refrigerant (162) to yield a cooled gaseous refrigerant (164);
(3) expansion means (166) for work expanding the cooled gaseous refrigerant to provide the cold refrigerant (130);
(4) heat exchange means (128) for warming the cold refrigerant (130) to provide refrigeration in the second temperature range; and
(5) means for recirculating the resulting warmed refrigerant (170) to provide the second gaseous refrigerant of (1).

12. An apparatus of Claim 10 or 11, wherein at least one of the first and second refrigeration systems comprises a wound coil heat exchanger.

dadurch gekennzeichnet, dass zumindest ein Teil der Kühlung in (B) durch indirekten Wärmetausch (400) mit einem oder mehreren zusätzlichen verdampfenden Kälteerzeugungströmen, die durch einen dritten rezirkulierenden Kälteerzeugungskreislauf zur Verfügung gestellt werden, bereitgestellt wird.

Patentansprüche

1. Verfahren zur Verflüssigung eines Beschickungsgases (100), umfassend die Bereitstellung mindestens eines Teils der gesamten zum Kühlen und Kondensieren des Beschickungsgases (100) erforderlichen Kälteerzeugung durch Einsatz

(a) eines ersten Kälteerzeugungssystems, umfassend mindestens einen rezirkulierenden Kälteerzeugungskreislauf (152, 156, 158, 160, 146, 109, 148, 125), wobei das erste Kälteerzeugungssystem zwei oder mehr Kälteerzeugungskomponenten verwendet und die Kälteerzeugung in einem ersten Temperaturbereich bereitstellt, wobei mindestens ein Teil des ersten Temperaturbereichs zwischen -40°C und -100°C liegt; und
(b) eines zweiten Kälteerzeugungssystems (130, 128, 150, 170, 168, 162, 150, 164, 166), das die Kälteerzeugung in einem zweiten Temperaturbereich durch Arbeitsexpansion eines unter Druck gesetzten gasförmigen Kälteerzeugungsstroms bereitstellt, wobei mindestens ein Teil des zweiten Temperaturbereichs unter 100°C liegt, wobei ein Wiederverdichtungszyklus des ersten rezirkulierenden Kälteerzeugungssystems durchgeführt wird durch

(A) Komprimieren eines ersten gasförmigen Kältemittels (158);
(B) Kühlen (109) und zumindest teilweises Kondensieren des resultierenden komprimierten Kältemittels (146);
(C) Verrin gern des Drucks des resultierenden zumindest teilweise kondensierten komprimierten Kältemittels (148);
(D) Verdampfen des resultierenden Kältemittels mit verringer tem Druck (125), um die Kälteerzeugung im ersten Temperaturbereich bereitzustellen und ein verdampftes Kältemittel (152) zu ergeben, und
(E) Zurückführen (156) des verdampften Kältemittels in den Kreislauf, um das erste gasförmige Kältemittel aus (A) bereitzustellen.

2. Verfahren nach Anspruch 1, wobei der dritte rezirkulierende Kälteerzeugungskreislauf ein Einkomponentenkältemittel verwendet.

3. Verfahren nach Anspruch 1, wobei der dritte rezirkulierende Kälteerzeugungskreislauf ein gemischtes, zwei oder mehrere Komponenten enthaltendes Kältemittel verwendet.

4. Verfahren nach einem der vorstehenden Ansprüche, wobei das Beschickungsgas Erdgas ist.

5. Verfahren nach einem der vorstehenden Ansprüche, wobei das Kältemittel im zweiten rezirkulierenden Kälteerzeugungskreislauf Stickstoff umfasst.

6. Verfahren zur Verflüssigung eines Beschickungsgases (100), umfassend die Bereitstellung mindestens eines Teils der gesamten zum Kühlen und Kondensieren des Beschickungsgases (100) erforderlichen Kälteerzeugung durch Einsatz

(a) eines ersten Kälteerzeugungssystems, umfassend mindestens einen rezirkulierenden Kälteerzeugungskreislauf (152, 156, 158, 160,
wobei das erste Kälteerzeugungssystem zwei oder mehrere Kältemittelkomponenten verwendet und die Kälteerzeugung in einem ersten Temperaturbereich bereitstellt, wobei mindestens ein Teil des ersten Temperaturbereichs zwischen -40°C und -100°C liegt; und

(b) eines zweiten Kälteerzeugungssystems (130, 128, 150, 170, 168, 162, 150, 164, 166),
das die Kälteerzeugung in einem zweiten Temperaturbereich durch Arbeitsexpansion eines unter Druck gesetzten gasförmigen Kältemittelstroms bereitstellt, wobei mindestens ein Teil des zweiten Temperaturbereichs unter -100°C liegt,

wobei das zweite rezirkulierende Kälteerzeugungssystem betrieben wird durch

(1) Komprimieren (168) eines zweiten gasförmigen Kältemittels, um das unter Druck gesetzte gasförmige Kältemittel (162) bereitzustellen;

(2) Kühlen (150) des unter Druck gesetzten gasförmigen Kältemittels (162), um ein gekühltes gasförmiges Kältemittel (164) zu ergeben;

(3) Arbeitsexpandieren (166) des gekühlten gasförmigen Kältemittels, um das kalte Kältemittel (130) bereitzustellen;

(4) Erwärmen (128) des kalten Kältemittels (130), um Kälteerzeugung im zweiten Temperaturbereich zur Verfügung zu stellen, und

(5) Zurückleiten des resultierenden erwärmten Kältemittels (170) in den Kreislauf, um das zweite gasförmige Kältemittel von (1) bereitzustellen,

dadurch gekennzeichnet, dass mindestens ein Teil der Kühlung in (2) durch indirekten Wärmetauscher (401) mit einem oder mehreren zusätzlichen verdampfenden Kältemittelzusätzen zur Verfügung gestellt wird, die durch einen dritten rezirkulierenden Kälteerzeugungskreislauf bereitgestellt werden.

7. Verfahren nach Anspruch 6, wobei der dritte rezirkulierende Kälteerzeugungskreislauf ein Einkomponentenkältemittel verwendet.

8. Verfahren nach Anspruch 6, wobei der dritte rezirkulierende Kälteerzeugungskreislauf ein Gemisch, zwei oder mehr Komponenten enthaltendes Kältemittel verwendet.

9. Verfahren nach Anspruch 1, wobei mindestens ei-
Kühlung in (B) durch indirekten Wärmeaustausch mit einem oder mehreren verdampfenden Kältemittelstromen, die durch einen dritten rezipierenden Kälteerzeugungskreislauf zur Verfügung gestellt werden, bereitgestellt.

11. Vorrichtung nach Anspruch 10, wobei das zweite rezipierende Kälteerzeugungssystem umfasst:

1. eine Kompressionsvorrichtung (168) zum Komprimieren eines zweiten gasförmigen Kältemittels, um das unter Druck gesetzte gasförmige Kältemittel (162) bereitzustellen;

2. eine Wärmetauchervorrichtung (150) zum Kühlen des unter Druck gesetzten gasförmigen Kältemittels (162), um ein gekühltes gasförmiges Kältemittel (164) bereitzustellen;

3. eine Expansionsvorrichtung (166) zum Arbeiten an einem gasförmigen Kältemittel (162), um das kalte Kältemittel (130) bereitzustellen;

4. eine Wärmetauchervorrichtung (128) zum Erwärmen des kalten Kältemittels (130), um die Kälteerzeugung im zweiten Temperaturbereich zur Verfügung zu stellen; und

5. eine Anordnung zum Zurückleiten des resultierenden erwärmten Kältemittels (170) in den Kreislauf, um das zweite gasförmige Kältemittel von (1) bereitzustellen.

12. Vorrichtung nach Anspruch 10 oder 11, wobei mindestens eines der ersten und zweiten Kälteerzeugungssysteme einen Wärmetauscher in Form einer gewundenen Spule umfasst.

Revendications

1. Procédé de liquéfaction d'un gaz d'alimentation (100) comprenant la fourniture d'au moins une partie de la réfrigération totale requise pour refroidir et condenser le gaz d'alimentation (100) en utilisant

(a) un premier système de réfrigération comprenant au moins un circuit de réfrigération à recyclage (152, 156, 158, 160, 146, 109, 148, 125), dans lequel le premier système de réfrigération utilise deux composants réfrigérants ou plus et fournit la réfrigération à une première plage de température, dans lequel le moins une partie de la première plage de température est comprise entre -40°C et -100°C; et

(b) un deuxième système de réfrigération (130, 128, 150, 170, 168, 162, 150, 164, 166) qui fournit la réfrigération dans une deuxième plage de température par détente mécanique d'un flux de réfrigérant gazeux pressurisé, dans lequel le moins une partie de la deuxième plage de température est inférieure à -100°C;

dans lequel un cycle de recompression du premier système de réfrigération à recyclage fonctionne par

(A) compression d'un premier réfrigérant gazeux (158);

(B) refroidissement (109) et au moins condensation partielle du réfrigérant comprimé résultant (146);

(C) réduction de la pression du réfrigérant comprimé au moins partiellement condensé (148) résultant;

(D) vaporisation du réfrigérant à pression réduite (125) résultant pour fournir la réfrigération dans la première plage de température et obtenir un réfrigérant vaporisé (152); et

(E) recyclage (156) du réfrigérant vaporisé pour fournir le premier réfrigérant gazeux de (A);

caractérisé en ce qu'au moins une partie du refroidissement dans (B) est assurée par un échange de chaleur indirect (400) avec un ou plusieurs flux additionnels de réfrigérants en vaporisation fournis par un troisième circuit de réfrigération à recyclage.

2. Procédé de la revendication 1, dans lequel le troisième circuit de réfrigération à recyclage utilise un réfrigérant à un seul composant.

3. Procédé de la revendication 1, dans lequel le troisième circuit de réfrigération à recyclage utilise un réfrigérant mixte comprenant deux composants ou plus.

4. Procédé suivant l'une quelconque des revendications précédentes, dans lequel le gaz d'alimentation est du gaz naturel.

5. Procédé suivant l'une quelconque des revendications précédentes, dans lequel le deuxième circuit de réfrigération à recyclage comprend de l'azote.

6. Procédé de liquéfaction d'un gaz d'alimentation (100) comprenant la fourniture d'au moins une partie de la réfrigération totale requise pour refroidir et condenser le gaz d'alimentation (100) en utilisant
(a) un premier système de réfrigération comprenant au moins un circuit de réfrigération à recyclage (152, 156, 158, 160, 109, 148, 125), dans lequel le premier système de réfrigération utilise deux composants réfrigérants ou plus et fournit la réfrigération à une première plage de température, dans lequel au moins une partie de la première plage de température est comprise entre -40°C et -100°C; et

(b) un deuxième système de réfrigération (130, 128, 150, 170, 168, 162, 150, 164, 166) qui fournit la réfrigération dans une deuxième plage de température par détente mécanique d'un flux de réfrigérant gazeux pressurisé, dans lequel au moins une partie de la deuxième plage de température est inférieure à -100°C;

dans lequel le deuxième système de réfrigération à recyclage fonctionne par

(1) compression (168) d'un deuxième réfrigérant gazeux pour fournir le réfrigérant gazeux pressurisé (162);

(2) refroidissement (150) du réfrigérant gazeux pressurisé (162) pour obtenir un réfrigérant gazeux refroidi (164);

(3) détente mécanique (166) du réfrigérant gazeux refroidi pour fournir le réfrigérant froid (130);

(4) chauffage (128) du réfrigérant froid (130) pour fournir la réfrigération dans la deuxième plage de température; et

(5) recyclage du réfrigérant chauffé résultant (170) pour fournir le deuxième réfrigérant gazeux de (1);

caractérisé en ce qu'au moins une partie du refroidissement dans (2) est assurée par un échangeur de chaleur indirect (401) avec un ou plusieurs réfrigérants additionnels en vaporisation fournis par un troisième circuit de réfrigération à recyclage.

7. Procédé de la revendication 6, dans lequel le troisième circuit de réfrigération à recyclage utilise un réfrigérant à un seul composant.

8. Procédé de la revendication 6, dans lequel le troisième circuit de réfrigération à recyclage utilise un réfrigérant mixte qui comprend deux composants ou plus.

9. Procédé suivant la revendication 1, dans lequel au moins un des premier et deuxième systèmes de réfrigération comprend un échangeur de chaleur à serpentin.

10. Appareil pour la liquéfaction d'un gaz entrant (100) par un procédé suivant la revendication 1; ledit appareil comprenant

(a) un premier système de réfrigération comprenant au moins un circuit de réfrigération à recyclage (152, 156, 158, 160, 109, 148, 125), dans lequel le premier système de réfrigération utilise deux composants réfrigérants ou plus et fournit la réfrigération à une première plage de température, dans lequel au moins une partie de la première plage de température est comprise entre -40°C et -104°C; et

(b) un deuxième système de réfrigération (130, 128, 150, 170, 168, 162, 150, 164, 166) qui fournit la réfrigération dans une deuxième plage de température par détente mécanique d'un flux de réfrigérant gazeux pressurisé, dans lequel au moins une partie de la deuxième plage de température est inférieure à -100°C;

dans lequel un cycle de recompression du premier système de réfrigération à recyclage comprend

(A) un moyen de compression pour comprimer un premier réfrigérant gazeux (158);

(B) un moyen d'échange de chaleur (106) pour refroidir et condenser au moins partiellement le réfrigérant comprimé résultant (146);

(C) un moyen de réduction de la pression du réfrigérant comprimé au moins partiellement condensé (148);

(D) un moyen d'échange de chaleur pour vaporiser le réfrigérant à pression réduite résultant (125) afin de fournir la réfrigération dans la première plage de température et d'obtenir un réfrigérant vaporisé (152); et

(E) un moyen (156) pour recycler le réfrigérant vaporisé afin de fournir le premier réfrigérant gazeux de (A),

caractérisé en ce qu'un moyen d'échange de chaleur (400) fournit au moins une partie du refroidissement de (B) par échange de chaleur indirect avec un ou plusieurs flux additionnels de réfrigérants en vaporisation fournis par un troisième circuit de réfrigération à recyclage.

11. Appareil suivant la revendication 10, dans lequel le deuxième système de réfrigération à recyclage
comprend

(1) un moyen de compression (168) pour com-
primer un deuxième réfrigérant gazeux afin de
fournir le réfrigérant gazeux pressurisé (162);

(2) un moyen d'échange de chaleur (150) pour
refroidir le réfrigérant gazeux pressurisé (162)
afin d'obtenir un réfrigérant gazeux refroidi
(164);

(3) un moyen de détente mécanique (166) pour
la détente mécanique du réfrigérant gazeux re-
froidi afin de fournir le réfrigérant froid (130);

(4) un moyen d'échange de chaleur (128) pour
chauffer le réfrigérant froid (130) afin de fournir
la réfrigération dans la deuxième plage de tem-
pérature; et

(5) un moyen de recyclage du réfrigérant chauf-
fé résultant (170) afin de fournir le deuxième
réfrigérant gazeux de (1).

12. Appareil suivant la revendication 10 ou 11, dans le-
quel au moins un des premier et deuxième systè-
mes de réfrigération comprend un échangeur de
chaleur à serpentin.