The current invention provides a methodology and apparatus for the liquefaction of normally gaseous material, most notably natural gas, which reduces the number of process vessels required and/or reduces space requirements over conventional apparatus.
LNG SYSTEM WITH OPTIMIZED HEAT EXCHANGER CONFIGURATION

BACKGROUND OF THE INVENTION

[0001] 1. Field of the Invention

[0002] The inventive methodology and associated apparatus disclosed herein relates to the liquefaction of a normally gaseous material, most notably natural gas. In one aspect, the invention concerns a liquefied natural gas (LNG) production system that operates with a reduced number of process vessels and in a smaller space than conventional LNG production systems.

[0003] 2. Description of the Prior Art

[0004] It is common practice to cryogenically treat natural gas to liquefy the same for transport and storage. The primary reason for the liquefaction of natural gas is that liquefaction results in a volume reduction of about 1/600, thereby making it possible to store and transport the liquefied gas in containers of more economical and practical design. For example, when gas is transported by pipeline from a supply source to a distant market, it is desirable to operate the pipeline under a substantially constant and high load factor. Often the deliverability or capacity of the pipeline will exceed demand, while at other times the demand may exceed the deliverability of the pipeline. In order to shave off the peaks where demand exceeds supply, it is desirable to store the excess gas in such a manner that it can be delivered when the supply exceeds demand, thereby enabling future peaks in demand to be met with material from storage. One practical means for doing this is to convert the gas to a liquefied state for storage and to then vaporize the liquid as demand requires.

[0005] Liquefaction of natural gas is of even greater importance in making possible the transport of gas from a supply source to market when the source and market are separated by great distances and a pipeline is not available or is not practical. This is particularly true where transport must be made by ocean-going vessels. Ship transportation in the gaseous state is generally not practical because appreciable pressurization is required to significantly reduce the specific volume of the gas which in turn requires the use of more expensive storage containers.

[0006] In order to store and transport natural gas in the liquid state, the natural gas is preferably cooled to −240° F. to −260° F. where it possesses a near-atmospheric vapor pressure. Numerous systems exist in the prior art for the liquefaction of natural gas in which the gas is liquefied by sequentially passing the gas at an elevated pressure through a plurality of cooling stages whereupon the gas is cooled to successively lower temperatures until the liquefaction temperature is reached. Cooling is generally accomplished by heat exchange with one or more refrigerants such as propane, propylene, ethane, ethylene, methane, or a combination of one or more of the preceding. The refrigerants are sometimes arranged in a cascaded manner. Further cooling of the liquid is possible by expanding the liquefied natural gas to atmospheric pressure in one or more expansion stages. In each stage, the liquefied gas is flashed to a lower pressure thereby producing a two-phase, gas-liquid mixture at a significantly lower temperature. The liquid is recovered and may again be flashed. In this manner, the liquefied gas is further cooled to a temperature suitable for liquefied gas storage at near-atmospheric pressure.

[0007] As previously noted, the present invention concerns the arrangement/selection of apparatus and associated process methodologies whereby the number of process vessels in the overall system is reduced. This reduction in the number of process vessels also reduces space requirements.

OBJECTS AND SUMMARY OF THE INVENTION

[0008] It is an object of this invention to reduce the number of process vessels required for liquefying natural gas.

[0009] It is another object of this invention to reduce the space requirements of a process for liquefying natural gas.

[0010] It is still yet another object of this invention to develop a process methodology and associated apparatus for liquefying natural gas which is less capital intensive than alternative liquefaction methodologies.

[0011] One embodiment of the present invention concerns a process for liquefying natural gas that includes the following steps: (a) cooling a natural gas stream in a first refrigeration cycle via indirect heat exchange with a first refrigerant; and (b) downstream of the first refrigeration cycle, cooling the natural gas stream in a second refrigeration cycle via indirect heat exchange with a second refrigerant. At least one of the first and second refrigerants is a pure component refrigerant, and less than about 10 percent of the natural gas mechanical cooling duty of at least one of the first and second refrigeration cycles is provided by core-in-kettle heat exchangers.

[0012] Another embodiment of the present invention concerns a process for liquefying natural gas that includes the following steps: (a) cooling a natural gas stream in a first refrigeration cycle employing a first refrigerant; (b) downstream of the first refrigeration cycle, cooling the natural gas stream in a second refrigeration cycle employing a second refrigerant; (c) downstream of the second refrigeration cycle, cooling the natural gas stream in a third refrigeration cycle employing a third refrigerant. The third refrigeration cycle is an open refrigeration cycle that uses a portion of the natural gas stream as the third refrigerant, and at least about 90 percent of the combined natural gas mechanical cooling duty of the first, second, and third refrigeration cycles is provided by plate-fin heat exchangers.

[0013] Still another embodiment of the present invention concerns a process for liquefying natural gas comprising the following steps: (a) cooling a natural gas stream in a first methane heat exchanger via indirect heat exchange with at least one predominately-methane first refrigerant stream to thereby produce a first cooled natural gas stream; (b) dividing the first cooled natural gas stream into a first refrigerant portion and a first product portion; (c) expanding the first refrigerant portion to thereby produce a first expanded refrigerant portion; and (d) using the first expanded refrigerant portion as at least a portion of the first refrigerant stream in the first methane heat exchanger.

[0014] Yet another embodiment of the present invention concerns a facility for producing LNG. The facility includes the following components: (a) a first refrigeration cycle for cooling natural gas with a first refrigerant; and (b) a second refrigeration cycle for cooling the natural gas with a second refrigerant. At least one of the first and second refrigerants is a pure component refrigerant, and at least one of the first
and second refrigeration cycles does not include any core-in-kettle heat exchangers that are operable to significantly cool the natural gas.

BRIEF DESCRIPTION OF THE DRAWING FIGURES

[0015] FIG. 1 is a simplified flow diagram of a cryogenic LNG production process which illustrates one embodiment of the methodology and apparatus of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0016] As used herein, the term “natural gas” or “natural gas stream” shall denote any stream principally comprised of methane, which originates in major portion from a natural gas feed stream. A natural gas stream typically contains at least 85 mole percent methane, with the balance being ethane, higher hydrocarbons, nitrogen, carbon dioxide, and minor amounts of other contaminants such as, for example, mercury, hydrogen sulfide, and mercaptans. As used herein, the terms “principally,” “predominately,” “primarily,” and “in major portion,” when used to describe the presence of a particular component of a fluid stream, shall mean that the fluid stream contains at least 50 mole percent of the stated component. For example, a “predominately” methane stream, a “primarily” methane stream, a stream “primarily” comprised of methane, or a stream comprised “in major portion” of methane, each denote a stream containing at least 50 mole percent methane. As used herein, the terms “upstream” and “downstream” shall be used to describe the relative positions of various components of a natural gas liquefaction plant along the main flow path of natural gas through the plant.

[0017] One of the most efficient and effective methodologies for natural gas liquefaction is a cascade-type operation involving expansion cooling. Cascade-type processes utilize one or more refrigerants to transfer heat energy from the natural gas stream to the refrigerant and ultimately to the environment. In essence, the refrigeration system functions as a heat pump by removing thermal energy from the natural gas stream as the stream is progressively cooled to lower and lower temperatures. In so doing, the thermal energy removed from the natural gas stream is ultimately rejected (pumped) to the environment via energy exchange with one or more refrigerants.

[0018] In a preferred embodiment, the present invention employs a cascaded refrigerant system that cools the natural gas stream at an elevated pressure (e.g., about 650 psia), by sequentially passing the natural gas stream through an initial refrigeration cycle, an intermediate refrigeration cycle, and a final refrigeration cycle. In a preferred embodiment of the invention, the initial and intermediate refrigeration cycles are closed refrigeration cycles, while the final refrigeration cycle is an open refrigeration cycle that utilizes a portion of the feed gas as a source of refrigerant and which includes therein a multi-stage expansion cycle to further cool the feed gas and reduce its pressure to near-atmospheric pressure.

[0019] The refrigerants employed in the initial, intermediate, and final refrigeration cycles preferably have their own distinct compositions. In other words, it is preferred for pure component refrigerants, rather than mixed refrigerants, to be employed in the initial, intermediate, and final refrigeration cycles of the present invention. As used herein, the term “mixed refrigerant” denotes a refrigerant that does not contain more than 80 mole percent of any single refrigerant component. As used herein, the term “pure component refrigerant” denotes a refrigerant that is not a mixed refrigerant. Preferably, a pure component refrigerant comprises at least about 80 mole percent of a single refrigerant component, more preferably at least about 90 mole percent of a single hydrocarbon refrigerant component, and most preferably at least 95 mole percent of a single hydrocarbon refrigerant component. In the system of the present invention, it is preferred for the refrigerant having the highest boiling point to be utilized in the initial refrigeration cycle, followed by a refrigerant having an intermediate boiling point employed in the intermediate refrigeration cycle, and finally a refrigerant having the lowest boiling point is employed in the final refrigeration cycle.

[0020] In a preferred embodiment of the present invention, the initial refrigerant employed in the initial refrigeration cycle contains primarily propane, propylene, and/or carbon dioxide. More preferably, the initial refrigerant comprises predominately propane, most preferably, the initial refrigerant consists essentially of propane. The intermediate refrigerant preferably comprises predominately ethane and/or ethylene. More preferably, the intermediate refrigerant comprises predominately ethylene. Most preferably, the intermediate refrigerant consists essentially of ethylene. The final refrigerant preferably comprises predominately methane. Most preferably, the final refrigerant consists essentially of methane.

[0021] Preferably, each of the initial, intermediate, and final refrigeration cycles employs a plurality of distinct cooling steps carried out in one or more heat exchangers. In a preferred embodiment of the present invention, less than about 10 percent of the natural gas mechanical cooling duty of the initial, intermediate, and/or final refrigeration cycles is provided by core-in-kettle and/or spiral-wound heat exchangers, more preferably less than about 5 percent of the natural gas mechanical cooling duty of the initial, intermediate, and/or final refrigeration cycles is provided by core-in-kettle and/or spiral-wound heat exchangers, still more preferably less than 2 percent of the natural gas mechanical cooling duty of the initial, intermediate, and/or final refrigeration cycles is provided by core-in-kettle and/or spiral-wound heat exchangers. Most preferably, none of the natural gas-cooling heat exchangers employed in the initial, intermediate, and final refrigeration cycles are core-in-kettle heat exchangers and/or spiral-wound heat exchangers. Rather, it is preferred that at least about 90 percent of the natural gas mechanical cooling duty of the initial, intermediate, and/or final refrigeration cycles is provided by plate-fin heat exchangers, more preferably at least about 95 percent of the natural gas mechanical cooling duty of the initial, intermediate, and/or final refrigeration cycles is provided by plate-fin heat exchangers. Most preferably, all of the natural gas-cooling heat exchangers employed in the initial, intermediate, and final refrigeration cycles are plate-fin heat exchangers. It is particularly preferred for the plate-fin heat exchangers to be brazed aluminum plate-fin heat exchangers.

[0022] As used herein, the term “natural gas mechanical cooling duty” denotes a responsibility for extracting heat.
from natural gas via indirect heat exchange, expressed in terms of energy per units of time (e.g., BTU/hr). As used herein, the term “core-in-kettle heat exchanger” denotes a heat exchange device comprising an outer vessel shell and an inner core disposed in the vessel shell. A core-in-kettle heat exchanger facilitates indirect heat transfer between a first fluid contained in the vessel shell and a second fluid flowing through the core while the core is at least partly submerged in the first fluid. As used here, the term “spiral wound heat exchanger” denotes a heat exchange device comprising an outer vessel shell and an inner core of wound tubes disposed in the shell. As used herein, the term “plate-fin heat exchanger” denotes a device that defines a plurality of distinct fluid passageways separated by plates. A plate-fin heat exchanger facilitates indirect heat transfer between a first fluid flowing through a first group of fluid passageways and a second fluid flowing through a second group of fluid passageways. Heat is transferred between the first and second fluids via heat flux through the plates. Thus, plate-fin heat exchangers do not require the use of large containment vessels because the first and second fluids are contained in the fluid passageways during heat transfer. As used herein, the term “braided aluminum plate-fin heat exchanger” denotes a plate-fin heat exchanger constructed of multiple aluminum plates brazed to one another.

[0023] In a preferred embodiment of the present invention, the natural gas stream is delivered to the initial refrigeration cycle at an elevated pressure or is compressed to an elevated pressure, that being a pressure greater than about 500 psia, preferably about 5 to about 1000 psia, still more preferably about 550 to about 675 psia, still yet more preferably about 575 to about 650 psia, and most preferably about 600 psia. The steam temperature is typically near ambient to slightly above ambient. A representative temperature range being about 60°F to about 120°F. [0024] Generally, the natural gas feed stream will contain such quantities of C2 to C4 components so as to result in the formation of a C2 to C4 rich liquid in one or more of the cooling stages of the initial and/or intermediate refrigeration cycles. This liquid is removed via gas/liquid separation means, preferably one or more conventional gas/liquid separators. Generally, the sequential cooling of the natural gas in each stage of the initial and/or intermediate refrigeration cycles is controlled so as to remove as much as possible of the C2 and higher molecular weight hydrocarbons from the gas to produce a first gas stream predominating in methane and a second liquid stream containing significant amounts of ethane and heavier components. An effective number of gas/liquid separation means are located at strategic locations downstream of the cooling stages for the removal of liquid streams rich in C2 to C4 components. The exact locations and number of gas/liquid separation means will be dependent on a number of operating parameters, such as the C2 to C4 composition of the natural gas feed stream, the desired BTU content of the final product, the value of the C2 to C4 components for other applications, and other factors routinely considered by those skilled in the art of LNG plant and gas plant operation. The C2 to C4 hydrocarbon stream or streams may be demethanized via a single stage flash or a fractionation column. In the former case, the methane-rich stream can be pressurized and recycled or can be used as fuel gas. In the latter case, the methane-rich stream can be directly returned at pressure to the liquefaction process. The C2 to C4 hydrocarbon stream or streams or the demethanized C2 to C4 hydrocarbon stream may be used as fuel or may be further processed such as by fractionation in one or more fractionation zones to produce individual streams rich in specific chemical constituents (e.g., C2 to C4, C3 to C4, and C4).

[0025] In the last cooling stage of the intermediate refrigeration cycle, the processed natural gas stream, which is predominantly methane (typically greater than 95 mole percent methane and more typically greater than 97 mole percent methane), is condensed (i.e., liquefied) in major portion, preferably in its entirety. The cooled and condensed natural gas stream exiting the intermediate refrigeration cycle is then further cooled in the final refrigeration cycle via indirect heat exchange with the final refrigerant. In a preferred embodiment of the present invention, the final refrigeration cycle is an open methane refrigeration cycle employing a predominantly-methane refrigerant that originates from the natural gas feed stream. [0026] The liquefied gas entering the final refrigeration cycle preferably has a pressure of at least about 250 psia, more preferably at least about 400 psia, and most preferably in the range of from 500 to 800 psia. It is preferred that the expansion section of the final refrigeration cycle is operable to reduce the pressure of the liquefied gas stream by at least about 100 psi, more preferably at least about 250 psi, and most preferably at least 400 psi. The pressure reduction in the expansion section of the final refrigeration cycle is preferably accomplished via a plurality of sequential expansion steps carried out in a plurality of expansion devices. Each expansion device can be a Joule-Thomson expansion valve or a hydraulic expander. As used herein, the term “hydraulic expander” is not limited to an expander which receives and produces liquid streams but is inclusive of expanders which receive a predominantly liquid-phase stream and produce a two-phase (gas/liquid) stream. When a hydraulic expander is employed and properly operated, the greater efficiencies associated with the recovery of power, a greater reduction in stream temperature, and the production of less vapor during the expansion step will frequently be cost-effective even in light of increased capital and operating costs associated with the expander. The pressure of the liquid product entering the final refrigeration cycle is preferably reduced to near atmospheric pressure so that the final LNG product has a near-atmospheric pressure and a temperature of about 240°F to about 260°F.

[0027] One embodiment of the present invention provides a final refrigeration cycle having a reduced number of process vessels compared to similar refrigeration cycles employing multi-step expansion cooling of the liquefied gas stream. In particular, in one embodiment of the present invention, the expansion section of the final refrigeration cycle employs less than three vapor/liquid separation vessels (e.g., flash drums), most preferably less than two vapor/liquid separation vessels. FIG. 1 illustrates one configuration of a final refrigeration cycle that reduces the number of process vessels (e.g., flash drums) relative to similar conventional expansion-type refrigeration cycles.

[0028] The flow schematic and apparatus set forth in FIG. 1 represents a preferred embodiment of the invention employed in an open-cycle cascaded liquefaction process. Those skilled in the art will also recognize that FIG. 1 is a schematic representation and, therefore, many items of equipment that would be needed in a commercial plant for successful operation have been omitted for the sake of clarity. Such items might include, for example, compressor
controls, flow and level measurements and corresponding controllers, temperature and pressure controls, pumps, motors, filters, additional heat exchangers, valves, etc. These items would be provided in accordance with standard engineering practice.

[0029] To facilitate an understanding of FIG. 1, items numbered 1 through 99 generally correspond to process vessels and equipment directly associated with the liquefaction process. Items numbered 100 through 199 correspond to flow lines or conduits which contain methane in major portion. Items numbered 200 through 299 correspond to flow lines or conduits which contain the refrigerant ethylene or optionally, ethane. Items numbered 300 through 399 correspond to flow lines or conduits which contain the refrigerant propane.

[0030] Referring to FIG. 1, gaseous propane is compressed in multistage compressor 18 driven by a gas turbine driver which is not illustrated. The three stages of compression preferably exist in a single unit although each stage of compression may be a separate unit and the units mechanically coupled to be driven by a single driver. Upon compression, the compressed propane is passed through conduit 300 to cooler 16 where it is liquefied. A representative pressure and temperature of this liquefied propane stream exiting cooler 16 is about 100°F. and about 190 psia. Although not illustrated in FIG. 1, it is preferable that a separation vessel be located downstream of cooler 16 and upstream of the high-stage propane brazed aluminum plate-fin heat exchanger 2, for the removal of residual light components from the liquefied propane to provide surge control for the system. The refrigerant stream from this vessel or the stream from cooler 16, as the case may be, is passed through conduit 302 to a high-stage propane brazed aluminum plate-fin heat exchanger 2, wherein the stream flows through core passages 10 and is cooled by indirect heat exchange. The cooled or second stage propane refrigerant stream is produced via conduit 303. This stream is then split via a splitting or separation means (illustrated but not numbered) into two portions, third and fourth propane refrigerant streams, and produced via conduits 304 and 307. The third stage refrigerant stream flows via conduit 304 to a pressure reduction means, illustrated as expansion valve 14, wherein the pressure of the liquefied propane is reduced, thereby evaporating or flashing a portion thereof and producing a high-stage refrigeration stream. This stream then flows through conduit 305 and through core passages 12, wherein the stream flows countercurrent to the stream in passage 10 and the yet to be described streams in passages 4, 6, and 8 and wherein indirect heat exchange occurs. The resulting stream, the high-stage propane recycle stream, is routed via conduit 306 to the high-stage inlet port of propane compressor 18. In the course of such routing, the stream will generally pass through a suction scrubber.

[0031] Also fed to plate-fin heat exchanger 2 are the natural gas stream via conduit 100, a gaseous ethylene stream via conduit 202, and a methane-rich stream via conduit 152. These streams in flow passages 6, 8, and 4 and the propane refrigerant stream in passage 10 flow countercurrent, more preferably countercurrent, to the propane stream in passage 12. Indirect heat exchange occurs between such streams. The streams respectively flowing in passages 4, 6, and 8 are produced via conduits 154, 102, and 204. The stream in conduit 204 will be referred to as a first cooled ethylene stream.

[0032] The cooled natural gas stream in conduit 102, the first cooled ethylene stream in conduit 204, and the fourth propane refrigerant stream in conduit 307 respectively flow through passages 22, 24, and 25 in brazed aluminum plate-fin heat exchanger 20 countercurrent, more preferably countercurrent, to a yet to be identified refrigeration stream thereby producing a further cooled natural gas stream, a second cooled ethylene stream, and a fifth propane refrigerant stream which are produced via conduits 110, 206, and 308. The fifth propane refrigerant stream is then split via a splitting or separation means (illustrated but not numbered) into two portions, the sixth and seventh propane refrigerant streams, and respectively produced via conduits 309 and 312. The sixth propane refrigerant stream flows via conduit 309 to a pressure reduction means, illustrated as expansion valve 27. In expansion valve 27, the pressure of the liquefied propane is reduced, thereby evaporating or flashing a portion thereof and producing a intermediate-stage propane refrigeration stream. This stream then flows through conduit 310 and through core passage 26 wherein said stream flows countercurrent to the streams in passages 22, 24, and 25 and wherein indirect heat exchange occurs. The resulting stream is produced as an intermediate-stage propane recycle stream via conduit 311. This stream is returned to the intermediate-stage inlet port of propane compressor 18, again preferably after passing through a suction scrubber.

[0033] The further cooled natural gas stream and the second cooled ethylene stream are respectively routed via conduits 110 and 206 to respective passages 36 and 38 in brazed aluminum plate-fin heat exchanger 34 wherein the natural gas stream is yet further cooled. The natural gas and ethylene streams are produced from plate-fin heat exchanger 34 via conduits 112 and 208, respectively.

[0034] The seventh propane refrigerant stream in conduit 312 is connected to brazed aluminum plate-fin heat exchanger 28 wherein the stream flows via passage 29 countercurrent, more preferably countercurrent, to and in indirect heat exchange with a low-stage propane refrigerant flowing via passage 30 thereby producing an eighth propane refrigerant stream via conduit 314. The eighth propane refrigerant streams via conduit 314 to a pressure reduction means, illustrated as expansion valve 32, wherein the pressure of the liquefied propane is reduced thereby evaporating or flashing a portion thereof and producing a two-phase refrigerant stream. The expanded refrigerant stream is carried to brazed aluminum plate-fin heat exchanger 34 where it is employed as a cooling agent in passage 37. A low-stage propane refrigeration stream is removed from heat exchanger 34 via conduit 318. This conduit is connected to passage 30 in heat exchanger 28 wherein said stream flows countercurrent and is in indirect heat exchange with the seventh propane refrigerant stream in passage 29 thereby producing a low-stage propane recycle stream. The low-stage propane recycle stream is then returned to the low-stage inlet port of compressor 18, preferably after flow through a suction scrubber, via conduit 320. In compressor 18, the low-stage propane recycle stream is compressed, combined with the intermediate-stage propane recycle stream, and compressed to form a compressed intermediate-stage recycle stream. This stream is then combined with the high-stage propane recycle stream to form a combined high-stage propane recycle stream which is compressed to form the compressed propane refrigerant stream produced via conduit 300.
In one embodiment of the invention, the brazed aluminum plate-fin heat exchangers 2, 20, 28, and 34 of the initial (propane) refrigeration cycle are separate heat exchangers. In another embodiment, the heat exchangers are combined into one or more exchangers. Although resulting in a more complex heat exchanger which possesses intermediate headers, combined approach can offer advantages from a lay-out and cost perspective.

In the intermediate refrigeration cycle depicted in FIG. 1, the natural gas stream is cooled via indirect heat exchange with an ethylene refrigeration stream until it is substantially condensed. As illustrated in FIG. 1, a low-stage ethylene recycle stream delivered via conduit 232 is compressed in compressor 40 and the resulting compressed low-stage ethylene recycle stream is preferably removed from compressor 40 via conduit 234, cooled via inter-stage cooler 71, returned to the compressor via conduit 236 and combined with a high-stage ethylene recycle stream delivered via conduit 216 whereupon the combined stream is compressed to thereby producing a compressed ethylene refrigerant stream via conduit 218. A pressure of approximately 300 psia. Preferably, the two compressor stages of compressor 40 are a single module although they may each be a separate module and the modules mechanically coupled to a common driver. The compressed ethylene refrigerant stream is routed from the compressor 40 to the downstream cooler 72 via conduit 200. The product from cooler 72 flows via conduit 202 and is introduced, as previously discussed, to the initial refrigeration cycle wherein the stream is further cooled and liquefied via heat exchange passages 8, 24, and 38 and then returned to the intermediate refrigeration cycle via conduit 208. This stream in conduit 208 preferably flows to a separation vessel 41 which provides for the removal of residual light components from the liquefied stream and which also provides surge volume for the refrigeration system. A refrigerant stream, referred to herein with regard to the intermediate refrigeration cycle as a first ethylene refrigerant stream, is produced from vessel 41 via conduit 209.

The cooled natural gas stream produced from the initial refrigeration cycle via conduit 112 is combined with a yet to be described methane-rich stream provided via conduit 156. This combined stream in conduit 114 and the first refrigerant ethylene stream in conduit 209 are routed to a brazed aluminum plate-fin heat exchanger 42 wherein these streams flow through core passages 44 and 46 countercurrent, more preferably countercurrent, to and in indirect heat exchange with a yet to be described high-stage ethylene refrigerant stream and optionally, a low-stage ethylene refrigerant stream respectively flowing in passages 48 and 50. A cooled stream referred to herein as a second ethylene refrigerant stream is produced from passage 46 via conduit 210. This stream is then split via a splitting or separation means (illustrated but not numbered) into two portions, third and fourth ethylene refrigerant streams, and produced via conduits 212 and 218. The third ethylene refrigerant stream flows via conduit 212 to a pressure reduction means, illustrated as expansion valve 52, wherein the pressure of the liquefied ethylene is reduced thereby evaporating or flashing a portion thereof and producing a high-stage ethylene refrigeration stream. This stream then flows through conduit 214 and through core passage 48 thereby producing a high-stage ethylene recycle stream which is transported via conduit 216 to the high-stage inlet port of compressor 40.

A further cooled natural gas stream is produced from passage 44 via conduit 116 and is optionally combined with a methane-rich recycle stream delivered via conduit 158. The resulting stream is routed via conduit 120 to a passage 59 of a brazed aluminum plate-fin heat exchanger 58 wherein the stream is cooled and liquefied in major portion and the resulting stream is produced via conduit 122.

The fourth ethylene refrigerant stream is transported via conduit 218 to a passage 54 in a brazed aluminum plate-fin heat exchanger 53. The fourth ethylene refrigerant stream flows countercurrent, more preferably countercurrent, to and is in indirect heat exchange with a low-stage ethylene refrigerant flowing via passage 55 in heat exchanger 53, thereby producing a fifth ethylene refrigerant stream via conduit 220. The fifth ethylene refrigerant stream flows via conduit 220 to a pressure reduction means, illustrated as expansion valve 56, wherein the pressure of the liquefied ethylene is reduced, thereby evaporating or flashing a portion thereof and producing a two-phase ethylene refrigerant stream. The resulting two-phase ethylene refrigerant stream is carried via conduit 222 to heat exchanger 58 wherein the stream is employed as a cooling agent in passage 57. A low-stage ethylene refrigeration stream is removed from heat exchanger 58 via conduit 228. conduit 228 is connected to passage 55 in heat exchanger 53 wherein said stream flows countercurrent and is in indirect heat exchange with the fluid in passage 54 thereby producing a low-stage ethylene recycle stream. This stream is returned to the low-stage inlet port of compressor 40 via conduit 232.

Optionally, and as depicted in FIG. 1, this stream may also flow to plate-fin heat exchanger 42 via conduit 230 and through passage 50 wherein said stream flows countercurrent, more preferably countercurrent, to the fluids in passages 44 and 46 and is further warmed prior to flow to the compressor 40 via conduit 232.

In one embodiment of the invention, brazed aluminum plate-fin heat exchangers 42, 53, and 58 of the intermediate refrigeration cycle are separate heat exchangers. In another embodiment, the heat exchangers are combined into a single exchanger. The liquefied natural gas stream produced from plate-fin heat exchanger 58 via conduit 122 is generally at a temperature of about -125°F and a pressure of about 600 psi. The liquefied stream in conduit 122 is introduced into the final refrigeration cycle where it undergoes cooling by indirect heat exchange with a methane refrigerant and by expansion. The stream in conduit 122 is initially cooled in a main methane economizer 74 via indirect heat exchange with methane refrigerant streams in passages 82, 95, and 96. In a preferred embodiment of the present invention, the methane refrigerant employed in the final refrigeration cycle is derived from the processed natural gas stream, thereby making the final refrigeration cycle an open methane refrigeration cycle. Main methane economizer 74 is preferably a plate-fin heat exchanger, most preferably a brazed aluminum plate-fin heat exchanger. The liquefied natural gas stream introduced into main methane economizer 74 via conduit 122 is cooled in passage 76 and then exits main methane economizer 74 via conduit 124. The cooled stream in conduit 124 is subsequently divided into a first refrigerant portion carried in conduit 125 and a first product portion carried in conduit 126. The first refrigerant portion in
conduit 125 is transported to an expansion means (illustrated as expansion valve 78), wherein the stream is reduced in pressure to thereby produce a first expanded refrigerant portion in conduit 127. The first expanded refrigerant portion in conduit 127 is then introduced into passage 82 of main methane economizer 74 wherein it is employed as a refrigerant to cool the natural gas stream in passage 76. The warmed first refrigerant stream exits passage 82 and methane economizer 74 via conduit 128, and is introduced into the high-stage inlet port of methane compressor 83.

[0042] The first product portion in conduit 126 is carried to a second methane economizer 87 for further cooling. The second methane economizer 87 is preferably a plate-fin heat exchanger, most preferably a brazed aluminum plate-fin heat exchanger. In second methane economizer 87, the first product portion is cooled as it passes through passage 88 and indirectly exchanges heat with the refrigerant streams passing through passages 89 and 90, described in more detail below. A second cooled natural gas stream is produced from second methane economizer 87 via conduit 129. The second cooled natural gas stream in conduit 129 is subsequently divided into a second refrigerant portion carried in conduit 130 and a second product portion carried in conduit 131. The second refrigerant portion carried in conduit 130 is subsequently expanded in expansion valve 91 to thereby produce a second expanded refrigerant portion. The second product portion in conduit 131 is subsequently expanded in expansion valve 92 to thereby produce a two-phase second stream that is subsequently carried to a phase separator 93 via conduit 132. The second expanded refrigerant portion expander 91 is transported via conduit 133 to second methane economizer 87 wherein the second expanded refrigeration portion is employed as a refrigerant in passage 89 to cool the stream flowing in passage 88. After being employed as a cooling agent in passage 89, the warmed second refrigerant portion is removed from second methane economizer 87 via conduit 134 and subsequently introduced into a passage 95 of main methane economizer 74 wherein the warmed second refrigerant portion is used to cool the stream in passage 76. The further warmed second refrigerant portion exits methane economizer 74 via conduit 135 and is subsequently introduced into the intermediate-stage inlet port of methane compressor 83.

[0043] The two-phase in conduit 132 is separated in vapor/liquid separator 93 to thereby produce a gaseous third refrigerant portion via conduit 136 and a liquid third product portion via conduit 142. The gaseous third refrigerant stream in conduit 136 is combined with the compressed stream in conduit 138, described in further detail below. The resulting combined stream flows via conduit 139 to second methane economizer 87 wherein the combined stream is employed as a refrigerant in passage 90 to cool the stream in passage 88. The warmed third portion exits passage 90 of second methane economizer 87 via conduit 140 and is carried to passage 96 of main methane economizer 74 wherein the refrigerant stream is used to cool the stream in passage 76. The further warmed third refrigerant portion exits passage 96 and main methane economizer 74 via conduit 141 and is passed to the low-stage inlet port of methane compressor 83.

[0044] The liquid third product portion that exits separator 93 via conduit 142 is expanded in expansion valve 94 to thereby produce a two-phase expanded third product stream which is carried to LNG storage tank 99 via conduit 143. The vapor portion of the stream introduced in to LNG storage tank 99 and any boil-off vapors generated in tank 99 are removed from tank 99 via conduit 144. This vapor stream in conduit 144 is compressed in compressor 96 to produce the compressed gas stream in conduit 138 that is subsequently combined with the separated vapor stream in conduit 136 before being employed as a refrigerant in the second methane economizer 87 and the main methane economizer 74. The LNG in tank 99 can be stored and subsequently transported to a distant market where it is gasified for use as an energy source.

[0045] As shown in FIG. 1, the three stages of compression provided by methane compressor 83 are preferably contained in a single unit. However, each compression stage may exist as a separate unit where the units are mechanically coupled together to be driven by a single driver. The compressed gas from the low-stage section of compressor 83 preferably passes through an inter-stage cooler 85 and is combined with the intermediate pressure gas in conduit 140 prior to the second-stage of compression. The compressed gas from the intermediate stage of compressor 83 is preferably passed through an inter-stage cooler 84 and is combined with the high pressure gas in conduit 140 prior to the third stage of compression. The compressed gas is discharged from the high-stage methane compressor through conduit 150, is cooled in cooler 86 and is routed to the high-stage propane chiller 2 via conduit 152. The methane-rich stream exiting chiller 2 via conduit 154 is fed to main methane economizer 74 wherein the stream is cooled via indirect heat exchange with one or more of the streams in passages 82, 94, and/or 96. In one embodiment and as illustrated in FIG. 1, the stream delivered via conduit 154 is cooled in the main methane economizer 74 via indirect heat exchange means 97, a portion removed via conduit 156 and the remaining stream further cooled via indirect heat exchange means 98 and produced via conduit 158. This is a preferred embodiment. In this split stream embodiment, a portion of the compressed methane recycle stream delivered via conduit 156 is combined with the natural gas stream via conduit 112 immediately upstream of the intermediate refrigeration cycle and the remaining portion delivered via conduit 158 combined with the stream in conduit 116 immediately upstream of brazed aluminum plate-fin heat exchanger 58 wherein the majority of liquefaction of the natural gas stream occurs. In a simpler embodiment (i.e., less preferred from a process efficiency perspective), the methane recycle stream is cooled in its entirety in the main methane economizer 74 and combined via conduit 158 with the natural gas stream in conduit 112 immediately upstream of the second cycle.

[0046] With regard to the compressor/driver units employed in the process, FIG. 1 depicts both compressor/driver units (i.e., a single compression train) for the propane, ethylene and open-cycle methane compression stages. However in a preferred embodiment for any cascaded process, process reliability can be improved significantly by employing a multiple compression train comprising two or more compressor/driver combinations in parallel in lieu of the depicted single compressor/driver units. In the event that a compressor/driver unit becomes unavailable, the process can still be operated at a reduced capacity.

[0047] In one embodiment of the present invention, the LNG production system of FIG. 1 is simulated on a computer using conventional process simulation software. Examples of suitable simulation software include HYSYS™
from Hyprotech, Aspen Plus® from Aspen Technology Inc.,
and PROII® from Simulation Sciences Inc.

[0048] While specific cryogenic methods, materials, items of
equipment and control instruments are referred to herein,
it is to be understood that such specific recitals are not to be
considered limiting but are included by way of illustration and
to set forth the best mode in accordance with the present
invention.

What is claimed is:
1. A process for liquefying natural gas, said process comprising:
   (a) cooling a natural gas stream in a first refrigeration
cycle via indirect heat exchange with a first refrigerant;
   and
   (b) downstream of step (a), cooling said natural gas
   stream in a second refrigeration cycle via indirect heat
   exchange with a second refrigerant,
   wherein at least one of said first and second refrigerants
   is a pure component refrigerant,
   wherein less than about 10 percent of the natural gas
   mechanical cooling duty of at least one of said first and
   second refrigeration cycles is provided by core-in-
kettle heat exchangers.
2. The process of claim 1 wherein less than about 5
   percent of the natural gas mechanical cooling duty of said
   first and second refrigeration cycles is provided by core-in-
kettle heat exchangers.
3. The process of claim 1 wherein at least about 90 percent of
   the natural gas mechanical cooling duty of said first and
   second refrigeration cycles is provided by one or more
   plate-fin heat exchangers.
4. The process of claim 3 wherein said plate-fin heat
   exchangers are brazed aluminum plate-fin heat exchangers.
5. The process of claim 1 wherein said second refrigerant
   is a pure component refrigerant.
6. The process of claim 1 wherein said first and second
   refrigerants are both pure component refrigerants.
7. The process of claim 1 wherein said first refrigerant
   comprises predominately propane and said second refriger-
   ant comprises predominately ethylene.
8. The process of claim 1 further comprising, downstream
   of step (b), cooling said natural gas stream in a third
   refrigeration cycle via indirect heat exchange with a third
   refrigerant.
9. The process of claim 8 wherein said third refrigerant is
   a pure component refrigerant.
10. The process of claim 8 wherein said third refrigeration
    cycle is an open refrigeration cycle employing a portion of
    said natural gas stream as said third refrigerant.
11. The process of claim 8 wherein said first, second, and
    third refrigerants are all pure component refrigerants.
12. A process for liquefying natural gas comprising:
    (a) cooling a natural gas stream in a first refrigeration
    cycle employing a first refrigerant;
    (b) downstream of step (a), cooling the natural gas stream
    in a second refrigeration cycle employing a second refriger-
    ant;
    (c) downstream of step (b), cooling the natural gas stream
    in a third refrigeration cycle employing a third refriger-
    ant;
    wherein said third refrigeration cycle is an open refriger-
    ation cycle that uses a portion of said natural gas
    stream as said third refrigerant,
    wherein at least about 90 percent of the combined natural
    gas mechanical cooling duty of said first, second, and
    third refrigeration cycles is provided by plate-fin heat
    exchangers.
13. The process of claim 12 wherein said cooling of steps
    (a), (b), and (c) is carried out without the use of any
    core-in-kettle heat or spiral wound exchangers.
14. The process of claim 12 wherein all of said cooling of
    steps (a), (b), and (c) is carried in plate-fin heat exchangers.
15. The process of claim 12 further comprising, cooling
    said natural gas stream via expansion in said third refrig-
    eration cycle.
16. The process of claim 15 wherein the pressure of said
    natural gas stream is reduced by at least about 100 psi in said
    third refrigeration cycle.
17. The process of claim 15 wherein said natural gas
    stream enters said third refrigeration cycle at a pressure of
    at least about 400 psia, wherein the pressure of said natural gas
    stream is reduced by at least 250 psi in said third refriger-
    ation cycle.
18. The process of claim 12 wherein said first refrigerant
    comprises predominately propane and/or propylene, said
    second refrigerant comprises predominately ethane and/or
    ethylene, and said third refrigerant comprises predominately
    methane.
19. A process for liquefying natural gas comprising:
    (a) cooling a natural gas stream in a first methane heat
    exchanger via indirect heat exchange with at least one
    predominately-methane first refrigerant stream to
    thereby produce a first cooled natural gas stream;
    (b) dividing said first cooled natural gas stream into a first
    refrigerant portion and a first product portion;
    (c) expanding said first refrigerant portion to thereby
    produce a first expanded refrigerant portion; and
    (d) using said first expanded refrigerant portion as at least
    a portion of said first refrigerant stream in said first
    methane heat exchanger.
20. The process of claim 19 wherein said first expanded
    refrigerant portion is not subjected to phase separation prior
    to being used as said first refrigerant stream in said first
    methane heat exchanger.
21. The process of claim 19 further comprising, cooling
    said first product portion in a second methane heat
    exchanger via indirect heat exchange with at least one
    predominately-methane second refrigerant stream to thereby
    produce a second cooled natural gas stream.
22. The process of claim 21 further comprising, dividing
    said second cooled natural gas stream into a second refrig-
    erant portion and a second product portion.
23. The process of claim 22 further comprising, expanding
    said second refrigerant portion to thereby produce a
    second expanded refrigerant portion and using said second
    expanded refrigerant portion as at least a portion of said
    second refrigerant stream in said second methane heat
    exchanger.
24. The process of claim 23 wherein said second
    expanded refrigerant portion is not subjected to phase sepa-
    ration prior to being used as said second refrigerant stream
    in said second methane heat exchanger.
25. The process of claim 23 wherein said second
    expanded refrigerant portion is heated in said second meth-
    ane heat exchanger to thereby produce a warmed second
    expanded refrigerant portion, wherein said process further
    comprises employing said warmed second expanded refrig-
erant portion as at least a portion of said first refrigerant stream in said first methane heat exchanger.

26. The process of claim 22 further comprising, expanding said second product portion to thereby produce a two-phase stream comprising a vapor third refrigerant portion and a liquid third product portion and using said third refrigerant portion as at least a portion of said second refrigerant stream in said second methane heat exchanger.

27. The process of claim 26 wherein said third refrigerant portion is heated in said second methane heat exchanger to thereby produce a warmed third refrigerant portion, wherein said process further comprises using said warmed third refrigerant portion as at least a portion of said first refrigerant stream in said first methane heat exchanger.

28. The process of claim 26 further comprising, expanding said third product portion to thereby produce an expanded final product stream comprising liquefied natural gas and introducing at least a portion of said expanded final product stream into an LNG storage tank.

29. The process of claim 28 further comprising, removing vapors from said LNG storage tank and employing said vapors as at least a portion of said first and/or second refrigerant streams.

30. The process of claim 19 further comprising, prior to step (a) cooling said natural gas stream via indirect heat exchange with an initial refrigerant stream, wherein said initial refrigerant stream comprises predominantly propane, propylene, ethane, and/or ethylene.

31. The process of claim 30 wherein said initial refrigerant stream comprises predominantly propane.

32. The process of claim 31 further comprising, prior to step (a) cooling said natural gas stream via indirect heat exchange with intermediate refrigerant stream, wherein said intermediate refrigerant stream comprises predominantly ethane and/or ethylene.

33. A process comprising: gasifying LNG produced by the process of claim 1.

34. A process comprising: gasifying LNG produced by the process of claim 12.

35. A process comprising: gasifying LNG produced by the process of claim 19.

36. A computer simulation process comprising: using a computer to simulate the process of claim 1.

37. A computer simulation process comprising: using a computer to simulate the process of claim 12.

38. A computer simulation process comprising: using a computer to simulate the process of claim 19.

39. A facility for processing natural gas into producing LNG, said facility comprising:
a first refrigeration cycle for cooling natural gas with a first refrigerant; and
a second refrigeration cycle for cooling said natural gas with a second refrigerant,
wherein at least one of said first and second refrigerants is a pure component refrigerant,
wherein at least one of said first and second refrigeration cycles does not comprise any core-in-kettle heat exchangers that are operable to significantly cool said natural gas.

40. The facility of claim 39 wherein said first and second refrigeration cycles do not comprise any core-in-kettle or spiral-wound heat exchangers that are operable to cool said natural gas.

41. The facility of claim 39 wherein said first and second refrigeration cycles include a plurality of plate-fin heat exchangers that are operable to cool said natural gas.

42. The facility of claim 39 wherein said first and second refrigerants are both pure component refrigerants.

43. The facility of claim 39 wherein said first refrigerant comprises predominantly propane and/or propylene and said second refrigerant comprises predominantly ethane and/or ethylene.

44. The facility of claim 39 further comprising, a third refrigeration cycle for cooling said natural gas with a third refrigerant.

45. The facility of claim 44 wherein said third refrigerant comprises predominantly methane.

46. The facility of claim 44 wherein said third refrigeration cycle is an open refrigeration cycle.

47. The facility of claim 39 wherein said third refrigeration cycle includes a plurality of expansion devices for sequentially lowering the pressure of said natural gas, wherein said third refrigeration cycle employs less than three vapor/liquid separation vessels.

48. The facility of claim 47 wherein said third refrigeration cycle employs less than two vapor/liquid separation vessels.

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