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(54) LNG SYSTEM WITH ENHANCED TURBOEXPANDER CONFIGURATION

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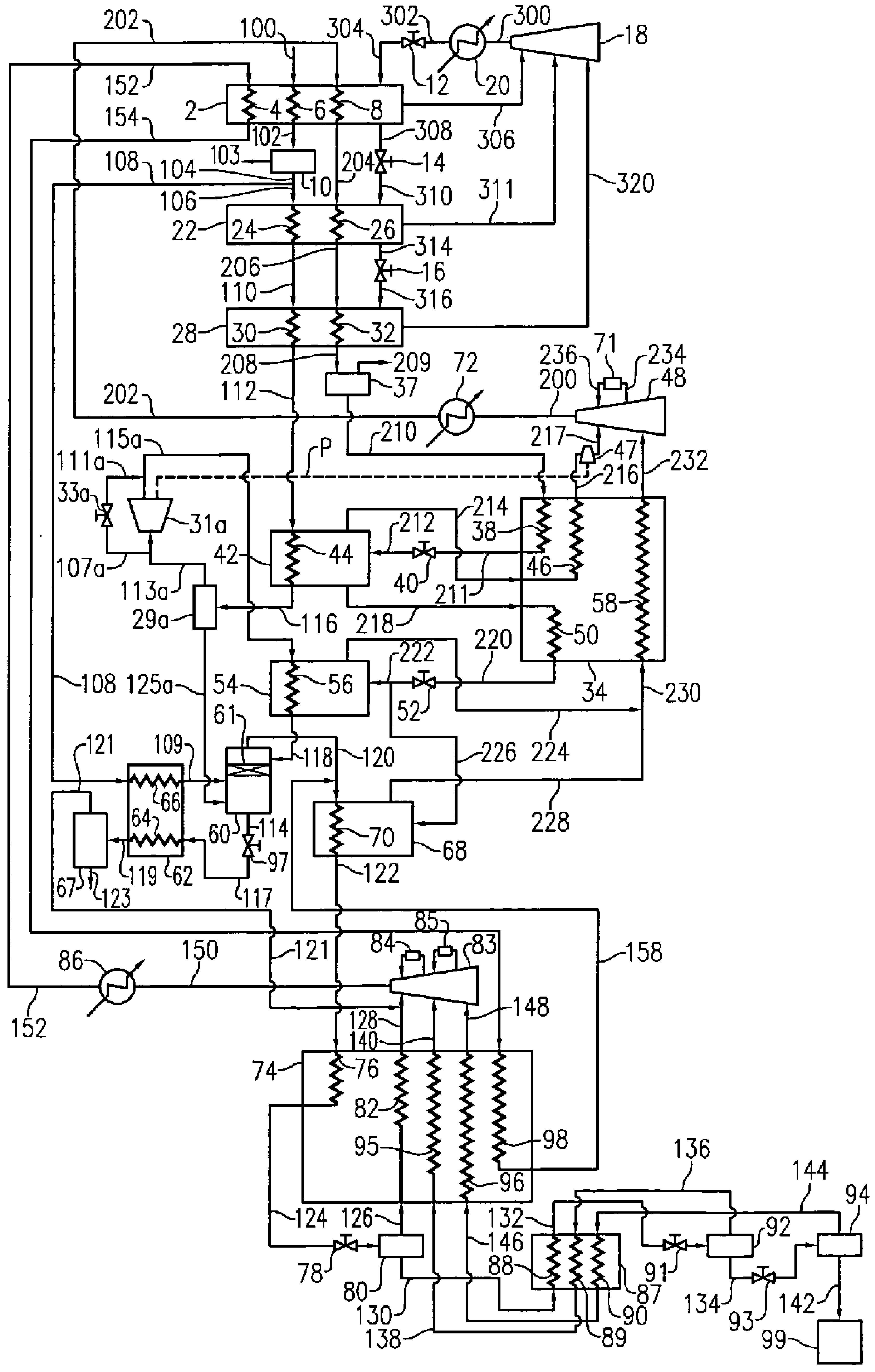
(57) **ABSTRACT**

Natural gas liquefaction system employing a turboexpander to convert excess pressure within a predominantly methane stream into work useable in another location within the liquefaction system. Primarily, the turboexpander is used to compress a refrigerant used in at least one of the refrigeration cycles within the liquefaction system.



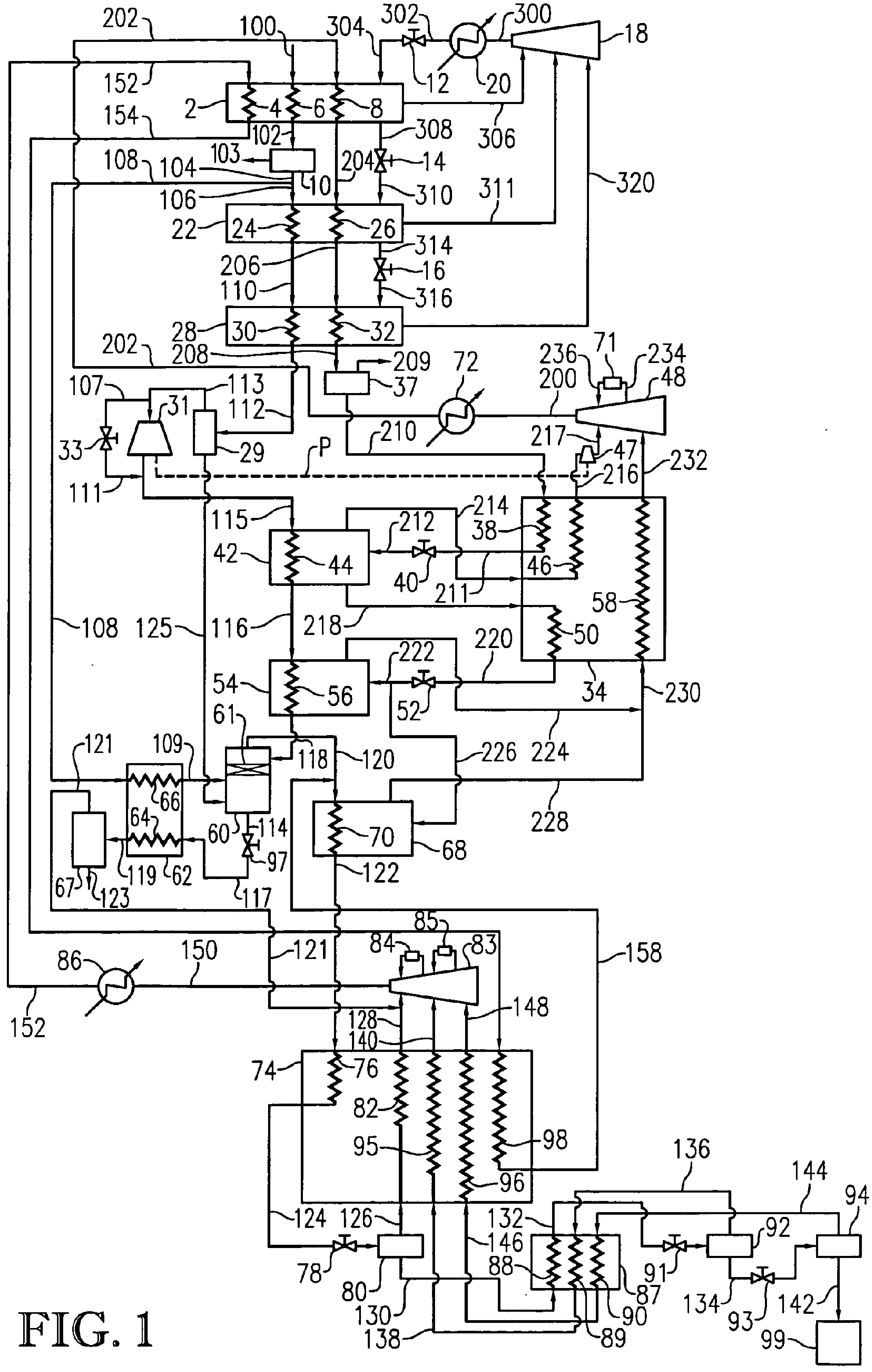

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FIG. 1

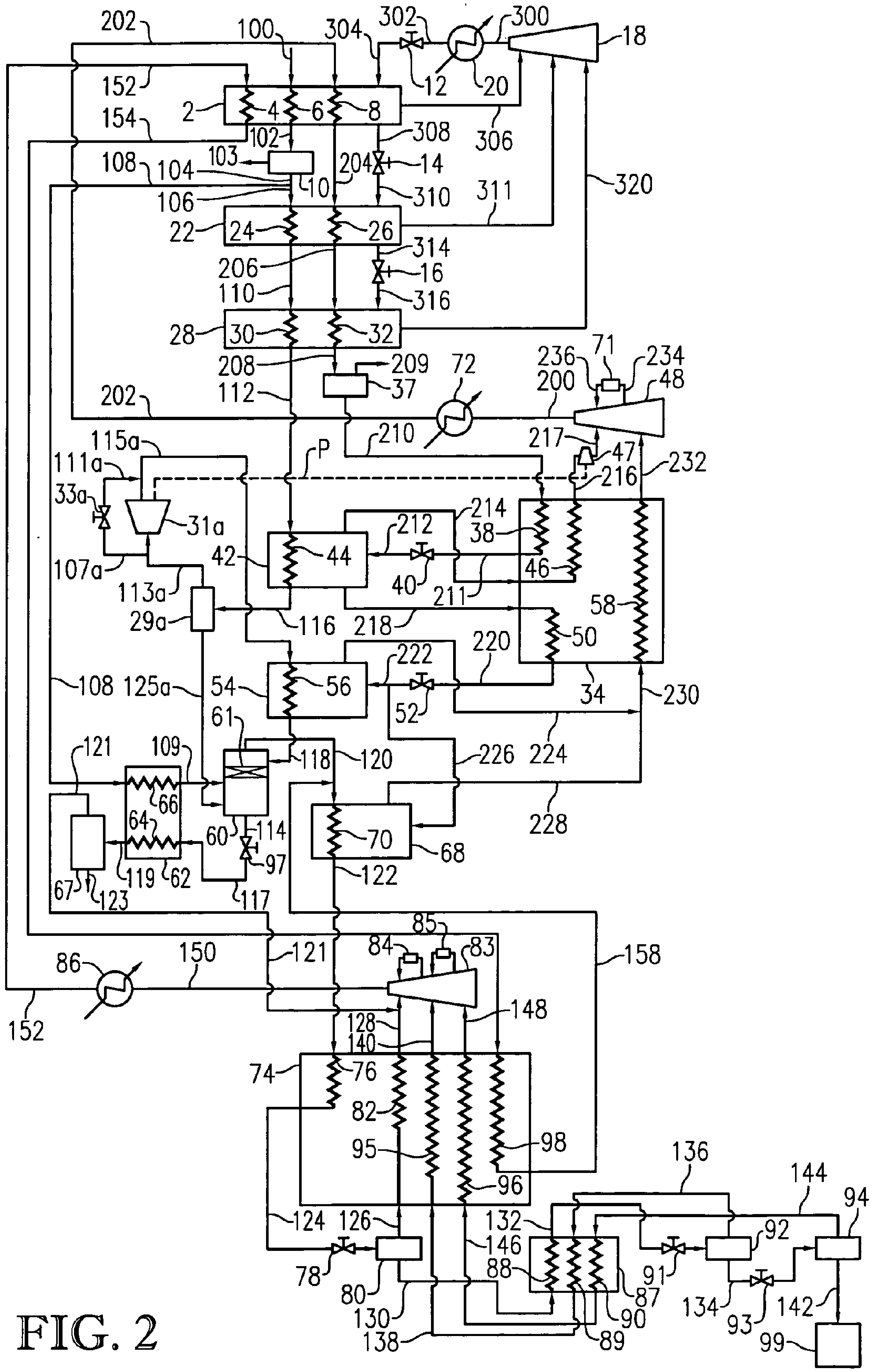
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FIG. 2

LNG SYSTEM WITH ENHANCED TURBOEXPANDER CONFIGURATION

BACKGROUND OF THE INVENTION

[0001] 1. Field of the Invention

[0002] This invention relates to a method and apparatus for liquefying natural gas. In another aspect, the invention concerns an improved liquefied natural gas (LNG) facility employing a turboexpander for converting excess pressure in a predominantly methane stream into work useful in other areas of the process.

[0003] 2. Description of the Prior Art

[0004] The cryogenic liquefaction of natural gas is routinely practiced as a means of converting natural gas into a more convenient form for transportation and storage. Such liquefaction reduces the volume of the natural gas by about 600-fold and results in a product which can be stored and transported at near atmospheric pressure.

[0005] Natural gas is frequently transported by pipeline from the supply source to a distant market. It is desirable to operate the pipeline under a substantially constant and high load factor but 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 or the valleys when supply exceeds demand, it is desirable to store the excess gas in such a manner that it can be delivered when demand exceeds supply. Such practice allows future demand peaks 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.

[0006] The liquefaction of natural gas is of even greater importance when transporting gas from a supply source which is separated by great distances from the candidate market and a pipeline either is not available or is impractical. 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. Such pressurization requires the use of more expensive storage containers.

[0007] 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 the liquefied natural gas (LNG) 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 indirect heat exchange with one or more refrigerants such as propane, propylene, ethane, ethylene, methane, nitrogen, carbon dioxide, or combinations of the preceding refrigerants (e.g., mixed refrigerant systems). A liquefaction methodology which is particularly applicable to the current invention employs an open methane cycle for the final refrigeration cycle wherein a pressurized LNG-bearing stream is flashed and the flash vapors (i.e., the flash gas stream(s)) are subsequently employed as cooling agents, recompressed, cooled, combined with the processed natural gas feed stream and liquefied thereby producing the pressurized LNG-bearing stream.

OBJECTS AND SUMMARY OF THE INVENTION

[0008] It is an object of the present invention to provide a novel natural gas liquefaction system that employs a turboexpander to utilize excess pressure in a predominantly methane stream to generate work to be used elsewhere in the system.

[0009] A further object of the invention is to provide a process of liquefying a natural gas stream that utilizes a turboexpander to power a refrigerant compressor employed in a closed refrigeration cycle of the process.

[0010] It should be understood that the above objects are exemplary and need not all be accomplished by the invention claimed herein. Other objects and advantages of the invention will be apparent from the written description and drawings.

[0011] Accordingly, one aspect of the present invention concerns a method of liquefying a natural gas stream comprising the steps of: (a) cooling a pressurized, predominantly methane stream in a first refrigerant chiller; (b) separating at least a portion of the cooled predominantly methane stream into a primarily liquid stream and a primarily gaseous stream; (c) passing at least a portion of the primarily gaseous stream through a turboexpander to thereby generate work and provide a reduced-pressure predominantly methane stream; and (d) directing at least a portion of the reduced-pressure predominantly methane stream to a heavies removal column for removal of heavy hydrocarbon components.

[0012] Another aspect of the present invention concerns a method of liquefying a natural gas stream comprising the steps of: (a) cooling a pressurized, predominantly methane stream in a first refrigerant chiller; (b) separating at least a portion of the cooled predominantly methane stream into a primarily liquid stream and a primarily gaseous stream; (c) passing at least a portion of the primarily gaseous stream through a turboexpander to thereby generate work and provide a reduced-pressure predominantly methane stream; (d) directing at least a portion of the reduced-pressure predominantly methane stream to a second refrigerant chiller to provide a cooled, reduced-pressure predominantly methane stream; (e) passing at least a portion of the cooled, reduced-pressure predominantly methane stream to a heavies removal column for removal of heavy hydrocarbon components; (e) passing at least a portion of the primarily liquid stream to the heavies removal column; and (f) using a portion of the cooled predominantly methane stream as a stripping gas in the heavies removal column.

[0013] A further aspect of the present invention concerns an apparatus for liquefying a predominantly methane stream comprising: (a) a first refrigerant chiller operable to cool at least a portion of the predominantly methane stream; (b) a separation vessel located downstream of said first refrigerant chiller for separating at least a portion of the cooled predominantly methane stream into a primarily gaseous stream and a primarily liquid stream; (c) a turboexpander located downstream of said separation vessel and capable of generating work as the primarily gaseous stream passes therethrough thereby forming a reduced-pressure predominantly methane stream; and (d) a heavies removal column located downstream of said separation vessel for receiving at least a portion of the primarily liquid stream.

[0014] Still another aspect of the present invention concerns an apparatus for liquefying a predominantly methane stream comprising: (a) a first refrigerant chiller operable to cool at least a portion of the predominantly methane stream; (b) a separation vessel located downstream of said first refrigerant chiller for separating at least a portion of the cooled predominantly methane stream into a primarily gaseous stream and a primarily liquid stream; (c) a turboexpander located downstream of said separation vessel and capable of generating work as the primarily gaseous stream passes therethrough thereby forming a reduced-pressure predominantly methane stream; (d) a heavies removal column located downstream of said separation vessel for receiving at least a portion of the primarily liquid stream; (e) a second refrigerant chiller located downstream of said turboexpander operable to cool at least a portion of the reduced-pressure predominantly methane stream; and (f) a compressor operable to compress the refrigerant used in at least one of said first or second refrigerant chillers, said compressor being powered at least in part by the work produced from said turboexpander.

BRIEF DESCRIPTION OF THE DRAWING FIGURES

[0015] A preferred embodiment of the present invention is described in detail below with reference to the attached drawing figures, wherein:

[0016] **FIG. 1** is a simplified flow diagram of a cascaded refrigeration process for LNG production which employs a turboexpander to reduce the pressure in a methane rich stream exiting a low-stage propane refrigerant chiller/condenser; and

[0017] **FIG. 2** is a simplified flow diagram of a cascaded refrigeration process for LNG production which employs a turboexpander to reduce the pressure in a methane rich stream exiting a high-stage ethylene refrigerant chiller.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0018] A cascaded refrigeration process uses one or more refrigerants for transferring heat energy from the natural gas stream to the refrigerant and ultimately transferring said heat energy to the environment. In essence, the overall refrigeration system functions as a heat pump by removing heat energy from the natural gas stream as the stream is progressively cooled to lower and lower temperatures. The design of a cascaded refrigeration process involves a balancing of thermodynamic efficiencies and capital costs. In heat transfer processes, thermodynamic irreversibilities are reduced as the temperature gradients between heating and cooling fluids become smaller, but obtaining such small temperature gradients generally requires significant increases in the amount of heat transfer area, major modifications to various process equipment, and the proper selection of flow rates through such equipment so as to ensure that both flow rates and approach and outlet temperatures are compatible with the required heating/cooling duty.

[0019] As used herein, the term "open-cycle cascaded refrigeration process" refers to a cascaded refrigeration process comprising at least one closed refrigeration cycle and one open refrigeration cycle where the boiling point of the refrigerant/cooling agent employed in the open cycle is less than the boiling point of the refrigerating agent or agents employed in the closed cycle(s) and a portion of the cooling duty to condense the compressed open-cycle refrigerant/cooling agent is provided by one or more of the closed cycles. In the current invention, a predominately methane stream is employed as the refrigerant/cooling agent in the open cycle. This predominantly methane stream originates from the processed natural gas feed stream and can include the compressed open methane cycle gas streams. As used herein, the terms "predominantly", "primarily", "principally", and "in major portion", when used to describe the presence of a particular component of a fluid stream, shall mean that the fluid stream comprises at least 50 mole percent of the stated component. For example, a "predominantly" methane stream, a "primarily" methane stream, a stream "principally" comprised of methane, or a stream comprised "in major portion" of methane each denote a stream comprising at least 50 mole percent methane.

[0020] As used herein, "refrigerant chiller" refers to a device that cools a feed stream via indirect heat exchange with a refrigerant. "Propane refrigerant chiller" refers to a refrigerant chiller that employs a predominantly propane refrigerant or a refrigerant having a boiling point within 20° C. of propane. "Ethylene refrigerant chiller" refers to a refrigerant chiller that employs a predominantly ethylene refrigerant or a refrigerant having a boiling point within 20° C. of ethylene.

[0021] One of the most efficient and effective means of liquefying natural gas is via an optimized cascade-type operation in combination with expansion-type cooling. Such a liquefaction process involves the cascade-type cooling of a natural gas stream at an elevated pressure, (e.g., about 650 psia) by sequentially cooling the gas stream via passage through a multistage propane cycle, a multistage ethane or ethylene cycle, and an open-end methane cycle which utilizes a portion of the feed gas as a source of methane and which includes therein a multistage expansion cycle to further cool the same and reduce the pressure to near-atmospheric pressure. In the sequence of cooling cycles, the refrigerant having the highest boiling point is utilized first followed by a refrigerant having an intermediate boiling point and finally by a refrigerant having the lowest boiling point. 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.

[0022] Various pretreatment steps provide a means for removing certain undesirable components, such as acid gases, mercaptan, mercury, and moisture from the natural gas feed stream delivered to the LNG facility. The composition of this gas stream may vary significantly. As used herein, a natural gas stream is any stream principally comprised of methane which originates in major portion from a natural gas feed stream, such feed stream for example containing at least 85 mole percent methane, with the balance being ethane, higher hydrocarbons, nitrogen, carbon dioxide, and a minor amount of other contaminants such as mercury, hydrogen sulfide, and mercaptan. The pretreatment steps may be separate steps located either upstream of the cooling cycles or located downstream of one of the early stages of cooling in the initial cycle. The following is a non-inclusive listing of some of the available means which are readily known to one skilled in the art. Acid gases and to a lesser extent mercaptan are routinely removed via a chemical reaction process employing an aqueous amine-bearing solution. This treatment step is generally performed upstream of the cooling stages in the initial cycle. A major portion of the water is routinely removed as a liquid via two-phase gas-liquid separation following gas compression and cooling upstream of the initial cooling cycle and also downstream of the first cooling stage in the initial cooling cycle. Mercury is routinely removed via mercury sorbent beds. Residual amounts of water and acid gases are routinely removed via the use of properly selected sorbent beds such as regenerable molecular sieves.

[0023] The pretreated natural gas feed stream is generally delivered to the liquefaction process at an elevated pressure or is compressed to an elevated pressure generally greater than 500 psia, preferably about 500 psia to about 3000 psia, still more preferably about 500 psia to about 1000 psia, still yet more preferably about 600 psia to about 800 psia. The feed stream temperature is typically near ambient to slightly above ambient. A representative temperature range being 60° F. to 150° F.

[0024] As previously noted, the natural gas feed stream is cooled in a plurality of multistage cycles or steps (preferably three) by indirect heat exchange with a plurality of different refrigerants (preferably three). The overall cooling efficiency for a given cycle improves as the number of stages increases but this increase in efficiency is accompanied by corresponding increases in net capital cost and process complexity. The feed gas is preferably passed through an effective number of refrigeration stages, nominally two, preferably two to four, and more preferably three stages, in a first closed refrigeration cycle in indirect heat exchange with a relatively high boiling refrigerant. Such relatively high boiling point refrigerant is preferably comprised in major portion of propane, propylene, or mixtures thereof, more preferably the refrigerant comprises at least about 75 mole percent propane, even more preferably at least 90 mole percent propane, and most preferably the refrigerant consists essentially of propane. Thereafter, the processed feed gas flows through an effective number of stages, nominally two, preferably two to four, and more preferably two or three, in a second closed refrigeration cycle in indirect heat exchange with a refrigerant having a lower boiling point. Such lower boiling point refrigerant is preferably comprised in major portion of ethane, ethylene, or mixtures thereof, more preferably the refrigerant comprises at least about 75 mole percent ethylene, even more preferably at least 90 mole percent ethylene, and most preferably the refrigerant consists essentially of ethylene. Each cooling stage comprises a separate cooling zone. As previously noted, the processed natural gas feed stream is preferably combined with one or more recycle streams (i.e., compressed open methane cycle gas streams) at various locations in the second cycle thereby producing a liquefaction stream. In the last stage of the second cooling cycle, the liquefaction stream is condensed (i.e., liquefied) in major portion, preferably in its entirety, thereby producing a pressurized LNG-bearing stream. Generally, the process pressure at this location is only slightly lower than the pressure of the pretreated feed gas to the first stage of the first cycle.

[0025] Generally, the natural gas feed stream will contain such quantities of C_2+ components so as to result in the formation of a C_2+ rich liquid in one or more of the cooling stages. 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 is controlled so as to remove as much of the C_2 and higher molecular weight hydrocarbons as possible from the gas to produce a gas stream predominating in methane and a 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 zones for the removal of liquids streams rich in C_2+ components. The exact locations and number of gas/liquid separation means, preferably conventional gas/liquid separators, will be dependant on a number of operating parameters, such as the C_2+ composition of the natural gas feed stream, the desired BTU content of the LNG product, the value of the C_2+ components for other applications, and other factors routinely considered by those skilled in the art of LNG plant and gas plant operation. The C_2+ hydrocarbon stream or streams may be demethanized via a single stage flash or a fractionation column. In the latter case, the resulting methane-rich stream can be directly returned at pressure to the liquefaction process. In the former case, this methane-rich stream can be repressurized and recycle or can be used as fuel gas. The C_2+ hydrocarbon stream or streams or the demethanized C_2+ 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., C_2, C_3, C_4, and C_5+).

[0026] The pressurized LNG-bearing stream is then further cooled in a third cycle or step referred to as the open methane cycle via contact in a main methane economizer with flash gases (i.e., flash gas streams) generated in this third cycle in a manner to be described later and via sequential expansion of the pressurized LNG-bearing stream to near atmospheric pressure. The flash gasses used as a refrigerant in the third refrigeration cycle are preferably comprised in major portion of methane, more preferably the flash gas refrigerant comprises at least 75 mole percent methane, still more preferably at least 90 mole percent methane, and most preferably the refrigerant consists essentially of methane. During expansion of the pressurized LNG-bearing stream to near atmospheric pressure, the pressurized LNG-bearing stream is cooled via at least one, preferably two to four, and more preferably three expansions where each expansion employs an expander as a pressure reduction means. Suitable expanders include, for example, either Joule-Thomson expansion valves or hydraulic expanders. The expansion is followed by a separation of the gas-liquid product with a separator. 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 flash expansion step will frequently more than off-set the higher capital and operating costs associated with the expander. In one embodiment, additional cooling of the pressurized LNG-bearing stream prior to flashing is made possible by first flashing a portion of this stream via one or more hydraulic expanders and then via indirect heat exchange means employing said flash gas stream to cool the remaining portion of the pressurized LNG-bearing stream prior to flashing. The warmed flash gas stream is then recycled via return to an appropriate location, based on temperature and pressure considerations, in the open methane cycle and will be recompressed.

[0027] The liquefaction process described herein may use one of several types of cooling which include but are not limited to (a) indirect heat exchange, (b) vaporization, and (c) expansion or pressure reduction. Indirect heat exchange, as used herein, refers to a process wherein the refrigerant cools the substance to be cooled without actual physical contact between the refrigerating agent and the substance to be cooled. Specific examples of indirect heat exchange means include heat exchange undergone in a shell-and-tube heat exchanger, a core-in-kettle heat exchanger, and a brazed aluminum plate-fin heat exchanger. The physical state of the refrigerant and substance to be cooled can vary depending on the demands of the system and the type of heat exchanger chosen. Thus, a shell-and-tube heat exchanger will typically be utilized where the refrigerating agent is in a liquid state and the substance to be cooled is in a liquid or gaseous state or when one of the substances undergoes a phase change and process conditions do not favor the use of a core-in-kettle heat exchanger. As an example, aluminum and aluminum alloys are preferred materials of construction for the core but such materials may not be suitable for use at the designated process conditions. A plate-fin heat exchanger will typically be utilized where the refrigerant is in a gaseous state and the substance to be cooled is in a liquid or gaseous state. Finally, the core-in-kettle heat exchanger will typically be utilized where the substance to be cooled is liquid or gas and the refrigerant undergoes a phase change from a liquid state to a gaseous state during the heat exchange.

[0028] Vaporization cooling refers to the cooling of a substance by the evaporation or vaporization of a portion of the substance with the system maintained at a constant pressure. Thus, during the vaporization, the portion of the substance which evaporates absorbs heat from the portion of the substance which remains in a liquid state and hence, cools the liquid portion. Finally, expansion or pressure reduction cooling refers to cooling which occurs when the pressure of a gas, liquid or a two-phase system is decreased by passing through a pressure reduction means. In one embodiment, this expansion means is a Joule-Thomson expansion valve. In another embodiment, the expansion means is either a hydraulic or gas expander. Because expanders recover work energy from the expansion process, lower process stream temperatures are possible upon expansion.

[0029] The flow schematic and apparatuses set forth in **FIGS. 1 and 2** represent preferred embodiments of the inventive LNG facility employing systems for extracting work form the feed gas. **FIG. 2** represents an alternate embodiment of the enhanced nitrogen removal system. Those skilled in the art will recognized that **FIGS. 1 and 2** are schematics only 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, and valves, etc. These items would be provided in accordance with standard engineering practice.

[0030] To facilitate an understanding of **FIGS. 1 and 2**, the following numbering nomenclature was employed. Items numbered 1 through 99 are process vessels and equipment which are directly associated with the liquefaction process. Items numbered 100 through 199 correspond to flow lines or conduits which contain predominantly methane streams. Items numbered 200 through 299 correspond to flow lines or conduits which contain predominantly ethylene streams. Items numbered 300 through 399 correspond to flow lines or conduits which contain predominantly propane streams.

[0031] Referring to **FIG. 1**, gaseous propane is compressed in a multistage (preferably three-stage) compressor **18** driven by a gas turbine driver (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 or combination of drivers. Upon compression, the compressed propane is passed through conduit **300** to a cooler **20** where it is cooled and liquefied. A representative pressure and temperature of the liquefied propane refrigerant prior to flashing is about 100° F. and about 190 psia. The stream from cooler **20** is passed through conduit **302** to a pressure reduction means, illustrated as expansion valve **12**, wherein the pressure of the liquefied propane is reduced, thereby evaporating or flashing a portion thereof. The resulting two-phase product then flows through conduit **304** into a high-stage propane refrigerant chiller **2** wherein gaseous methane refrigerant introduced via conduit **152**, natural gas feed introduced via conduit **100**, and gaseous ethylene refrigerant introduced via conduit **202** are respectively cooled via indirect heat exchange means **4**, **6**, and **8**, thereby producing cooled gas streams respectively produced via conduits **154**, **102**, and **204**. The gas in conduit **154** is fed to a main methane economizer **74** which will be discussed in greater detail in a subsequent section and wherein the stream is cooled via indirect heat exchange means **98**. The resulting cooled compressed methane recycle stream produced via conduit **158** is then combined in conduit **120** with the heavies depleted (i.e., light-hydrocarbon rich) vapor stream from a heavies removal column **60** and fed to an ethylene refrigerant chiller **68**.

[0032] The propane gas from chiller **2** is returned to compressor **18** through conduit **306**. This gas is fed to the high-stage inlet port of compressor **18**. The remaining liquid propane is passed through conduit **308**, the pressure further reduced by passage through a pressure reduction means, illustrated as expansion valve **14**, whereupon an additional portion of the liquefied propane is flashed. The resulting two-phase stream is then fed to an intermediate stage propane refrigerant chiller **22** through conduit **310**, thereby providing a coolant for chiller **22**. The cooled feed gas stream from chiller **2** flows via conduit **102** to separation equipment **10** wherein gas and liquid phases are separated. The liquid phase, which can be rich in C_3+ components, is removed via conduit **103**. The gaseous phase is removed via conduit **104** and then split into two separate streams which are conveyed via conduits **106** and **108**. The stream in conduit **106** is fed to propane chiller **22**. The stream in conduit **108** becomes the feed to heat exchanger **62** and ultimately becomes the stripping gas to heavies removal column **60**, which is preferably a stripping column containing internal packing and is discussed in more detail below. Ethylene refrigerant from chiller **2** is introduced to chiller **22** via conduit **204**. In chiller **22**, the feed gas stream, also referred to herein as a methane-rich stream, and the ethylene refrigerant streams are respectively cooled via indirect heat transfer means **24** and **26**, thereby producing cooled methane-rich and ethylene refrigerant streams via conduits **110** and **206**. The thus evaporated portion of the propane refrigerant is separated and passed through conduit **311** to the intermediate-stage inlet of compressor **18**. Liquid propane refrigerant from chiller **22** is removed via conduit **314**, flashed across a pressure reduction means, illustrated as expansion valve **16**, and then fed to a low-stage propane refrigerant chiller/condenser **28** via conduit **316**.

[0033] As illustrated in **FIG. 1**, the methane-rich stream flows from intermediate-stage propane refrigerant chiller **22** to the low-stage propane refrigerant chiller **28** via conduit **110**. In chiller **28**, the stream is cooled via indirect heat exchange means **30**. In a like manner, the ethylene refrigerant stream flows from the intermediate-stage propane refrigerant chiller **22** to low-stage propane refrigerant chiller **28** via conduit **206**. In the latter, the ethylene refrigerant is totally condensed or condensed in nearly its entirety via indirect heat exchange means **32**. The vaporized propane is removed from low-stage propane refrigerant chiller **28** and returned to the low-stage inlet of compressor **18** via conduit **320**.

[0034] As illustrated in **FIG. 1**, the methane-rich stream exiting low-stage propane refrigerant chiller **28** is introduced into a separator vessel **29** via conduit **112** where the stream is separated into a primarily gaseous, methane-rich stream and a primarily liquid stream. The primarily gaseous, methane-rich stream is delivered to turboexpander **31** via conduit **113**. The methane-rich stream passes through turboexpander **31** causing an impeller within the turboexpander to rotate and turn a shaft thereby generating useable work. The extraction of work by the expander improves the efficiency of the process and produces a lower temperature of the methane rich stream than would have been produced if the pressure reduction had been through a valve or similar means. Then, the reduced-pressure predominantly methane stream is carried away toward high-stage ethylene refrigerant chiller **42** via conduit **115**.

[0035] Preferably, the pressure of the fluid in conduit **112** is at least about 638 psia, and more preferably between about 700-1000 psia. After separation in separator vessel **29**, the pressure of the primarily gaseous, methane-rich stream in conduit **113** is measured, and based on that measurement, by-pass valve **33** is selectively opened or closed. For example, if the pressure in conduit **113** exceeds the maximum operating pressure for turboexpander **31**, by-pass valve **33** opens allowing at least a portion of the methane-rich stream contained in conduit **113** to flow around turboexpander **31** via by-pass conduits **107**, **111** and into conduit **115**. Preferably, the pressure of the fluid in conduit **115** is less than 95% of the pressure of the fluid in conduit **113**, more preferably less than 90%, and most preferably less than 85%. The primarily liquid stream from flash drum **29** is fed via conduit **125** to heavies removal column **60**. The primarily liquid stream preferably enters heavies removal column at a location below the column's internal packing **61**.

[0036] Ethylene refrigerant exits low-stage propane refrigerant chiller **28** via conduit **208** and is preferably fed to a separation vessel **37** wherein light components are removed via conduit **209** and condensed ethylene is removed via conduit **210**. The ethylene refrigerant at this location in the process is generally at a temperature of about −24° F. and a pressure of about 285 psia. The ethylene refrigerant then flows to an ethylene economizer **34** wherein it is cooled via indirect heat exchange means **38**, removed via conduit **211**, and passed to a pressure reduction means, illustrated as an expansion valve **40**, whereupon the refrigerant is flashed to a preselected temperature and pressure and fed to high-stage ethylene refrigerant chiller **42** via conduit **212**. Vapor is removed from chiller **42** via conduit **214** and routed to ethylene economizer **34** wherein the vapor functions as a coolant via indirect heat exchange means **46**. The ethylene vapor is then removed from ethylene economizer **34** via conduit **216** and fed to booster compressor **47**. As indicated by dashed line P, booster compressor **47** is powered by turboexpander **31**. Upon exiting booster compressor **47**, the ethylene refrigerant is fed into the high-stage inlet of ethylene compressor **48** via conduit **217**. The ethylene refrigerant which is not vaporized in high-stage ethylene refrigerant chiller **42** is removed via conduit **218** and returned to ethylene economizer **34** for further cooling via indirect heat exchange means **50**, removed from ethylene economizer via conduit **220**, and flashed in a pressure reduction means, illustrated as expansion valve **52**, whereupon the resulting two-phase product is divided into two portions. One portion is introduced into a low-stage ethylene refrigerant chiller **54** via conduit **222**. The other portion is introduced into another low-stage ethylene chiller **68** via conduit **226**.

[0037] After cooling in indirect heat exchange means **44**, the methane-rich stream is removed from high-stage ethylene refrigerant chiller **42** via conduit **116**. As shown in the alternate embodiment of **FIG. 2**, turboexpander **31***a* may be employed to reduce the pressure of the stream in conduit **116**. The overall process is very similar to that shown in **FIG. 1**. The methane-rich stream is introduced into a separator vessel **29***a* via conduit **116** where the stream is separated into a primarily gaseous, methane-rich stream and a primarily liquid stream. The primarily gaseous, methane-rich stream is delivered to turboexpander **31***a* via conduit **113***a*. The methane-rich stream passes through turboexpander **31***a* causing an impeller within the turboexpander to rotate and turn a shaft thereby generating useable mechanical work. Then, the methane-rich stream is carried away toward low-stage ethylene refrigerant chiller **54** via conduit **115***a*.

[0038] Preferably, the pressure of the fluid in conduit **116** is at least about 638 psia, and more preferably between about 700-1000 psia. After separation in flash drum **29***a*, the pressure of the primarily gaseous, methane-rich stream in conduit **113***a* is measured, and based on that measurement, by-pass valve **33***a* is selectively opened or closed. For example, if the pressure in conduit **113***a* exceeds the maximum operating pressure for turboexpander **31***a*, by-pass valve **33***a* opens allowing at least a portion of the methane-rich stream contained in conduit **113***a* to flow around turboexpander **31***a* via by-pass conduits **107***a*, **111***a* and into conduit **115***a*. Preferably, the pressure of the fluid in conduit **115***a* is less than 95% of the pressure of the fluid in conduit **113***a*, more preferably less than 90%, and most preferably less than 85%. The primarily liquid stream from separator vessel **29***a* is fed via conduit **125***a* to heavies removal column **60**.

[**0039**] The methane-rich stream is then condensed in part via cooling provided by indirect heat exchange means **56** in low-stage ethylene refrigerant chiller **54**, thereby producing a two-phase stream which flows via conduit **118** to heavies removal column **60**. The methane-rich stream preferably enters column **60** at a location above the internal packing **61**. As previously noted, the methane-rich stream in line **104** was split so as to flow via conduits **106** and **108**. The contents of conduit **108**, which is referred to herein as the stripping gas, is first fed to heat exchanger **62** wherein this stream is cooled via indirect heat exchange means **66** thereby becoming a cooled stripping gas stream which then flows via conduit **109** to heavies removal column **60**. The stripping gas enters heavies removal column at a location below the internal packing **61**. A heavies-rich liquid stream containing a significant concentration of C_4+ hydrocarbons, such as benzene, cyclohexane, other aromatics, and/or heavier hydrocarbon components, is removed from heavies removal column **60** via conduit **114**, preferably flashed via a flow control means **97**, preferably a control valve which can also function as a pressure reduction, and transported to heat exchanger **62** via conduit **117**. Preferably, the stream flashed via flow control means **97** is flashed to a pressure about or greater than the pressure at the high stage inlet port to methane compressor **83**. Flashing also imparts greater cooling capacity to the stream. In heat exchanger **62**, the stream delivered by conduit **117** provides cooling capabilities via indirect heat exchange means **64** and exits heat exchanger **62** via conduit **119**. In heavies removal column **60**, the two-phase stream introduced via conduit **118** is contacted with the cooled stripping gas stream introduced via conduit **109** in a countercurrent manner thereby producing a heavies-depleted vapor stream via conduit **120** and a heavies-rich liquid stream via conduit **114**.

[**0040**] The heavies-rich stream in conduit **119** is subsequently separated into liquid and vapor portions or preferably is flashed or fractionated in vessel **67**. In either case, a heavies-rich liquid stream is produced via conduit **123** and a second methane-rich vapor stream is produced via conduit **121**. In the preferred embodiment, which is illustrated in **FIG. 1**, the stream in conduit **121** is subsequently combined with a second stream delivered via conduit **128**, and the combined stream fed to the high-stage inlet port of the methane compressor **83**.

[**0041**] As previously noted, the gas in conduit **154** is fed to main methane economizer **74** wherein the stream is cooled via indirect heat exchange means **98**. The resulting cooled compressed methane recycle or refrigerant stream in conduit **158** is combined in the preferred embodiment with the heavies-depleted vapor stream from heavies removal column **60**, delivered via conduit **120**, and fed to a low-stage ethylene refrigerant chiller **68**. In low-stage ethylene refrigerant chiller **68**, this stream is cooled and condensed via indirect heat exchange means **70** with the liquid effluent from valve **52** which is routed to low-stage ethylene refrigerant chiller **68** via conduit **226**. The condensed methane-rich product from low-stage condenser **68** is produced via conduit **122**. The vapor from low-stage ethylene refrigerant chiller **54**, withdrawn via conduit **224**, and the vapor from low-stage ethylene refrigerant chiller **68**, withdrawn via conduit **228**, are combined and routed, via conduit **230**, to ethylene economizer **34** wherein the vapors function as a coolant via indirect heat exchange means **58**. The stream is then routed via conduit **232** from ethylene economizer **34** to the low-stage inlet of ethylene compressor **48**. It is also within the scope of the invention to locate booster compressor **47** in conduit **232** instead of between conduits **216** and **217** as shown in **FIGS. 1 and 2**. In this manner, booster compressor compresses the ethylene in conduit **232** prior to introduction into the low-stage inlet of ethylene compressor **48**. Similarly, booster compressor **47** may be placed in conduits **306**, **311**, or **320** so as to "pre-compress" a particular propane stream prior to introduction of the propane stream into the respective high, intermediate, or low-stage inlets of compressor **18**.

[**0042**] As shown in **FIG. 1**, the compressor effluent from vapor introduced via the low-stage side of ethylene compressor **48** is removed via conduit **234**, cooled via inter-stage cooler **71**, and returned to compressor **48** via conduit **236** for injection with the high-stage stream present in conduit **216**. Preferably, the two-stages are a single module although they may each be a separate module and the modules mechanically coupled to a single driver or combination of drivers. The compressed ethylene product from compressor **48** is routed to a downstream cooler **72** via conduit **200**. The product from cooler **72** flows via conduit **202** and is introduced, as previously discussed, to high-stage propane refrigerant chiller **2**.

[**0043**] The pressurized LNG-bearing stream, preferably a liquid stream in its entirety, in conduit **122** is preferably at a temperature in the range of from about −200 to about −50° F., more preferably in the range of from about −175 to about −100° F., most preferably in the range of from −150 to −125° F. The pressure of the stream in conduit **122** is preferably in the range of from about 500 to about 700 psia, most preferably in the range of from 550 to 625 psia.

[**0044**] The stream in conduit **122** is directed to a main methane economizer **74** wherein the stream is further cooled by indirect heat exchange means/heat exchanger pass **76** as hereinafter explained. It is preferred for main methane economizer **74** to include a plurality of heat exchanger passes which provide for the indirect exchange of heat between various predominantly methane streams in the economizer **74**. Preferably, methane economizer **74** comprises one or more plate-fin heat exchangers. The cooled stream from heat exchanger pass **76** exits methane economizer **74** via conduit **124**. It is preferred for the temperature of the stream in conduit **124** to be at least about 10° F. less than the temperature of the stream in conduit **122**, more preferably at least about 25° F. less than the temperature of the stream in conduit **122**. Most preferably, the temperature of the stream in conduit **124** is in the range of from about −200 to about −160° F. The pressure of the stream in conduit **124** is then reduced by a pressure reduction means, illustrated as expansion valve **78**, which evaporates or flashes a portion of the liquid stream thereby generating a two-phase stream. The two-phase stream from expansion valve **78** is then passed to high-stage methane flash drum **80** where it is separated into a flash gas stream discharged through conduit **126** and a liquid phase stream (i.e., pressurized LNG-bearing stream) discharged through conduit **130**. The flash gas stream is then transferred to main methane economizer **74** via conduit **126** wherein the stream functions as a coolant in heat exchanger pass **82** and aids in the cooling of the stream in heat exchanger pass **76**. Thus, the predominantly methane stream in heat exchanger pass **82** is warmed, at least in part, by indirect heat exchange with the predominantly methane stream in heat exchanger pass **76**. The warmed stream exits heat exchanger pass **82** and methane economizer **74** via conduit **128**. It is preferred for the temperature of the warmed predominantly methane stream exiting heat exchanger pass **82** via conduit **128** to be at least about 10° F. greater than the temperature of the stream in conduit **124**, more preferably at least about 25° F. greater than the temperature of the stream in conduit **124**. The temperature of the stream exiting heat exchanger pass **82** via conduit **128** is preferably warmer than about −50° F., more preferably warmer than about 0° F., still more preferably warmer than about 25° F., and most preferably in the range of from 40 to 100° F.

[**0045**] The liquid-phase stream exiting high-stage flash drum **80** via conduit **130** is passed through a second methane economizer **87** wherein the liquid is further cooled by downstream flash vapors via indirect heat exchange means **88**. The cooled liquid exits second methane economizer **87** via conduit **132** and is expanded or flashed via pressure reduction means, illustrated as expansion valve **91**, to further reduce the pressure and, at the same time, vaporize a second portion thereof. This two-phase stream is then passed to an intermediate-stage methane flash drum **92** where the stream is separated into a gas phase passing through conduit **136** and a liquid phase passing through conduit **134**. The gas phase flows through conduit **136** to second methane economizer **87** wherein the vapor cools the liquid introduced to economizer **87** via conduit **130** via indirect heat exchanger means **89**. Conduit **138** serves as a flow conduit between indirect heat exchange means **89** in second methane economizer **87** and heat exchanger pass **95** in main methane economizer **74**. The warmed vapor stream from heat exchanger pass **95** exits main methane economizer **74** via conduit **140** and is conducted to the intermediate-stage inlet of methane compressor **83**.

[**0046**] The liquid phase exiting intermediate-stage flash drum **92** via conduit **134** is further reduced in pressure by passage through a pressure reduction means, illustrated as a expansion valve **93**. Again, a third portion of the liquid is evaporated or flashed. The two-phase stream from expansion valve **93** is passed to a final or low-stage flash drum **94**. In flash drum **94**, a vapor phase is separated and passed through conduit **144** to second methane economizer **87** wherein the vapor functions as a coolant via indirect heat exchange means **90**, exits second methane economizer **87** via conduit **146**, which is connected to the first methane economizer **74** wherein the vapor functions as a coolant via heat exchanger pass **96**. The warmed vapor stream from heat exchanger pass **96** exits main methane economizer **74** via conduit **148** and is conducted to the low-stage inlet of compressor **83**.

[**0047**] The liquefied natural gas product from low-stage flash drum **94**, which is at approximately atmospheric pressure, is passed through conduit **142** to a LNG storage tank **99**. In accordance with conventional practice, the liquefied natural gas in storage tank **99** can be transported to a desired location (typically via an ocean-going LNG tanker). The LNG can then be vaporized at an onshore LNG terminal for transport in the gaseous state via conventional natural gas pipelines.

[**0048**] As shown in **FIG. 1**, the high, intermediate, and low stages of compressor **83** are preferably combined as single unit. However, each stage may exist as a separate unit. The compressed gas from the low-stage section 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 passed through an inter-stage cooler **84** and is combined with the high pressure gas provided via conduits **121** and **128** prior to the third-stage of compression. The compressed gas (i.e., compressed open methane cycle gas stream) is discharged from high stage methane compressor through conduit **150**, is cooled in cooler **86**, and is routed to the high pressure propane refrigerant chiller **2** via conduit **152** as previously discussed. The stream is cooled in chiller **2** via indirect heat exchange means **4** and flows to main methane economizer **74** via conduit **154**. The compressed open methane cycle gas stream from chiller **2** which enters the main methane economizer **74** undergoes cooling in its entirety via flow through indirect heat exchange means **98**. This cooled stream is then removed via conduit **158** and combined with the processed natural gas feed stream upstream of the low-stage ethylene chiller **68**.

[**0049**] In one embodiment of the present invention, the LNG production systems illustrated in **FIGS. 1 and 2** are 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 PRO/II® from Simulation Sciences Inc.

[**0050**] The preferred forms of the invention described above are to be used as illustration only, and should not be used in a limiting sense to interpret the scope of the present invention. Obvious modifications to the exemplary embodiments, set forth above, could be readily made by those skilled in the art without departing from the spirit of the present invention.

[**0051**] The inventors hereby state their intent to rely on the Doctrine of Equivalents to determine and assess the reasonably fair scope of the present invention as pertains to any apparatus not materially departing from but outside the literal scope of the invention as set forth in the following claims.

What is claimed is:

1. A method of liquefying a natural gas stream, said method comprising the steps of:

(a) cooling a pressurized, predominantly methane stream in a first refrigerant chiller;

(b) separating at least a portion of the cooled predominantly methane stream into a primarily liquid stream and a primarily gaseous stream;

(c) passing at least a portion of the primarily gaseous stream through a turboexpander to thereby generate work and provide a reduced-pressure predominantly methane stream; and

(d) directing at least a portion of the reduced-pressure predominantly methane stream to a heavies removal column for removal of heavy hydrocarbon components.

2. The method according to claim 1; and

(e) passing at least a portion of the primarily liquid stream to the heavies removal column.

3. The method according to claim 1,

said heavies removal column being a stripping column having internal packing.

4. The method according to claim 3; and

(f) using a portion of the cooled predominantly methane stream as a stripping gas in the heavies removal column.

5. The method according to claim 4, said at least a portion of the reduced-pressure predominantly methane stream entering the heavies removal column at a location above the internal packing,

said stripping gas entering the heavies removal column at a location below the internal packing.

6. The method according to claim 5; and

(g) introducing at least a portion of the primarily liquid stream into the heavies removal column at a location below the internal packing.

7. The method according to claim 6; and

(h) separating in the heavies removal column the at least a portion of the primarily liquid stream, the stripping gas, and the at least a portion of the reduced-pressure predominantly methane stream into a heavies depleted stream and a heavies rich stream.

8. The method according to claim 7; and

(i) cooling said heavies depleted stream in an ethylene refrigerant chiller.

9. The method according to claim 7; and

(j) directing said heavies depleted stream to an open-methane refrigeration cycle.

10. The method according to claim 9,

said open-methane refrigeration cycle comprising a plurality of expansion-cooling steps.

11. The method according to claim 1; and

(k) measuring the pressure of the primarily gaseous stream prior to step (c), and based on the pressure measurement, selectively opening or closing a by-pass valve capable of diverting at least part of the primarily gaseous stream around the turboexpander.

12. The method according to claim 1,

said first refrigerant chiller comprising a propane refrigerant chiller.

13. The method according to claim 1,

said first refrigerant chiller comprising an ethylene refrigerant chiller.

14. The method according to claim 1; and

(l) using at least a portion of the work generated by the turboexpander to power a compressor.

15. The method according to claim 14; and

(m) directing the reduced-pressure predominantly methane stream to a second refrigerant chiller prior to step (d).

16. The method according to claim 15,

said compressor being used to compress a refrigerant employed in the operation of at least one of said first or second refrigerant chillers.

17. The method according to claim 15,

said second refrigerant chiller comprising an ethylene refrigerant chiller.

18. The method according to claim 1,

said predominantly methane stream having a pressure of at least about 638 psia immediately prior to step (b).

19. The method according to claim 18,

said reduced-pressure predominantly methane stream having a pressure that is less than about 95% of the pressure of the predominantly methane stream immediately prior to step (b).

20. The method according to claim 1,

steps (a), (b), (c), and (d) being carried out in a cascade-type LNG facility having at least three sequential cooling cycles, each employing a different refrigerant.

21. The method according to claim 20,

said cascade-type LNG facility employing an open-methane refrigeration cycle.

22. The method according to claim 1; and

(n) vaporizing liquefied natural gas produced via steps (a)-(d).

23. A computer simulation process comprising the step of using a computer to simulate the method of claim 1.

24. A liquefied natural gas product produced by the method of claim 1.

25. A method of liquefying a natural gas stream, said method comprising the steps of:

(a) cooling a pressurized, predominantly methane stream in a first refrigerant chiller;

(b) separating at least a portion of the cooled predominantly methane stream into a primarily liquid stream and a primarily gaseous stream;

(c) passing at least a portion of the primarily gaseous stream through a turboexpander to thereby generate work and provide a reduced-pressure predominantly methane stream;

(d) directing at least a portion of the reduced-pressure predominantly methane stream to a second refrigerant chiller to provide a cooled, reduced-pressure predominantly methane stream;

(e) passing at least a portion of the cooled, reduced-pressure predominantly methane stream to a heavies removal column for removal of heavy hydrocarbon components;

(e) passing at least a portion of the primarily liquid stream to the heavies removal column; and

(f) using a portion of the cooled predominantly methane stream as a stripping gas in the heavies removal column.

26. The method according to claim 25,

said heavies removal column being a stripping column having internal packing.

27. The method according to claim 26; and

(g) introducing at least a portion of the primarily liquid stream into the heavies removal column at a location below the internal packing.

28. The method according to claim 25; and

(h) measuring the pressure of the primarily gaseous stream prior to step (c), and based on the pressure measurement, selectively opening or closing a by-pass valve capable of diverting at least part of the primarily gaseous stream around the turboexpander.

29. The method according to claim 25,

said first refrigerant chiller comprising a propane refrigerant chiller.

30. The method of according to claim 25,

said first refrigerant chiller comprising an ethylene refrigerant chiller.

31. The method according to claim 25,

said second refrigerant chiller comprising an ethylene refrigerant chiller.

32. The method according to claim 25,

(i) using at least a portion of the work generated by the turboexpander to power a compressor.

33. The method according to claim 32,

said compressor being used to compress a refrigerant employed in the operation of at least one of the first or second refrigerant chillers.

34. The method according to claim 25,

said predominantly methane stream having a pressure of at least about 638 psia immediately prior to step (b).

35. The method according to claim 34,

said reduced-pressure predominantly methane stream having a pressure that is less than about 95% of the pressure of the predominantly methane stream immediately prior to step (b).

36. The method according to claim 25; and

(j) separating in the heavies removal column the at least a portion of the primarily liquid stream, the stripping gas, and the at least a portion of the reduced-pressure predominantly methane stream into a heavies depleted stream and a heavies rich stream.

37. The method according to claim 36; and

(k) cooling said heavies depleted stream in an ethylene refrigerant chiller.

38. The method according to claim 36; and

(l) directing said heavies depleted stream to an open-methane refrigeration cycle.

39. The method according to claim 38,

said open-methane refrigeration cycle comprising a plurality of expansion-cooling steps.

40. The method according to claim 25,

steps (a)-(f) being carried out in a cascade-type LNG facility having at least three sequential cooling cycles, each employing a different refrigerant.

41. The method according to claim 40,

said cascade-type LNG facility employing an open-methane refrigeration cycle.

42. The method according to claim 25; and

(m) vaporizing liquefied natural gas produced via steps (a)-(f).

43. A computer simulation process comprising the step of using a computer to simulate the method of claim 25.

44. A liquefied natural gas product produced by the method of claim 25.

45. An apparatus for liquefying a predominantly methane stream, said apparatus comprising:

(a) a first refrigerant chiller operable to cool at least a portion of the predominantly methane stream;

(b) a separation vessel located downstream of said first refrigerant chiller for separating at least a portion of the cooled predominantly methane stream into a primarily gaseous stream and a primarily liquid stream;

(c) a turboexpander located downstream of said separation vessel and capable of generating work as the primarily gaseous stream passes therethrough thereby forming a reduced-pressure predominantly methane stream; and

(d) a heavies removal column located downstream of said separation vessel for receiving at least a portion of the primarily liquid stream.

46. The apparatus according to claim 45; and

(e) a second refrigerant chiller located downstream of said turboexpander operable to cool at least a portion of the reduced-pressure predominantly methane stream.

47. The apparatus according to claim 46,

said second refrigerant chiller comprising an ethylene refrigerant chiller

48. The apparatus according to claim 46; and

(f) a compressor operable to compress the refrigerant used in at least one of said first or second refrigerant chillers, said compressor being powered at least in part by the work produced from said turboexpander.

49. The apparatus according to claim 45,

said heavies removal column comprising a stripping column having internal packing.

50. The apparatus according to claim 45; and

(g) a bypass line including a bypass valve capable of diverting at least a portion of the primarily gaseous stream around said turboexpander.

51. The apparatus according to claim 45,

said first refrigerant chiller comprising a propane refrigerant chiller.

52. The apparatus according to claim 45,

said first refrigerant chiller comprising an ethylene refrigerant chiller.

53. The apparatus according to claim 45; and

(h) an open-methane refrigeration cycle located downstream from said heavies removal column.

54. An apparatus for liquefying a predominantly methane stream, said apparatus comprising:

(a) a first refrigerant chiller operable to cool at least a portion of the predominantly methane stream;

(b) a separation vessel located downstream of said first refrigerant chiller for separating at least a portion of the cooled predominantly methane stream into a primarily gaseous stream and a primarily liquid stream;

(c) a turboexpander located downstream of said separation vessel and capable of generating work as the primarily gaseous stream passes therethrough thereby forming a reduced-pressure predominantly methane stream;

(d) a heavies removal column located downstream of said separation vessel for receiving at least a portion of the primarily liquid stream;

(e) a second refrigerant chiller located downstream of said turboexpander operable to cool at least a portion of the reduced-pressure predominantly methane stream; and

(f) a compressor operable to compress the refrigerant used in at least one of said first or second refrigerant chillers, said compressor being powered at least in part by the work produced from said turboexpander.

55. The apparatus according to claim 54,

said heavies removal column comprising a stripping column having internal packing.

56. The apparatus according to claim 54; and

(g) a by-pass line including a by-pass valve capable of diverting at least a portion of the primarily gaseous stream around said turboexpander.

57. The apparatus according to claim 54,

said first refrigerant chiller comprising a propane refrigerant chiller.

58. The apparatus according to claim 54,

said first refrigerant chiller comprising an ethylene refrigerant chiller.

59. The apparatus according to claim 54; and

(h) an ethylene refrigerant chiller located downstream from said heavies removal column.

60. The apparatus according to claim 54; and

(i) an open-methane refrigeration cycle located downstream from said heavies removal column.

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