PRE-COOLING OF NATURAL GAS BY HIGH PRESSURE COMPRESSION AND EXPANSION

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Patent Application 62/266,985, filed December 14, 2015 entitled PRE-COOLING OF NATURAL GAS BY HIGH PRESSURE COMPRESSION AND EXPANSION, the entirety of which is incorporated by reference herein.

[0002] This application is related to U.S. Provisional Patent Application number 62/266,976 titled "Method and System for Separating Nitrogen from Liquefied Natural Gas Using Liquefied Nitrogen;" U.S. Provisional Patent Application No. 62/266,979 titled "Expander-Based LNG Production Processes Enhanced With Liquid Nitrogen;" and U.S. Provisional Patent Application No. 62/266,983 titled "Method of Natural Gas Liquefaction on LNG Carriers Storing Liquid Nitrogen;" all having common inventors and assignee and filed on an even date herewith, the disclosure of which is incorporated by reference herein in their entirety.

FIELD OF THE INVENTION

[0003] The invention relates to the liquefaction of natural gas to form liquefied natural gas (LNG), and more specifically, to the production of LNG in remote or sensitive areas where the construction and/or maintenance of capital facilities, and/or the environmental impact of a conventional LNG plant may be detrimental.

BACKGROUND

[0004] LNG production is a rapidly growing means to supply natural gas from locations with an abundant supply of natural gas to distant locations with a strong demand for natural gas. The conventional LNG production cycle includes: a) initial treatments of the natural gas resource to remove contaminants such as water, sulfur compounds and carbon dioxide; b) the separation of some heavier hydrocarbon gases, such as propane, butane, pentane, etc. by a variety of possible methods including self-refrigeration, external refrigeration, lean oil, etc.; c) refrigeration of the natural gas substantially by external refrigeration to form liquefied natural gas at near atmospheric pressure and about -160 °C; d) transport of the LNG product in ships or tankers designed for this purpose to a market location; e) re-pressurization and regasification

of the LNG at a regasification plant to a pressurized natural gas that may distributed to natural gas consumers. Step (c) of the conventional LNG cycle usually requires the use of large refrigeration compressors often powered by large gas turbine drivers that emit substantial carbon and other emissions. Large capital investment in the billions of US dollars and extensive infrastructure are required as part of the liquefaction plant. Step (e) of the conventional LNG cycle generally includes re-pressurizing the LNG to the required pressure using cryogenic pumps and then re-gasifying the LNG to pressurized natural gas by exchanging heat through an intermediate fluid but ultimately with seawater or by combusting a portion of the natural gas to heat and vaporize the LNG.

[0005] Although LNG production in general is well known, technology improvements may still provide LNG producers with significant opportunities as it seeks to maintain its leading position in the LNG industry. For example, floating LNG (FLNG) is a relatively new technology option for producing LNG. The technology involves the construction of the gas treating and liquefaction facility on a floating structure such as barge or a ship. FLNG is a technology solution for monetizing offshore stranded gas where it is not economically viable to construct a gas pipeline to shore. FLNG is also increasingly being considered for onshore and near-shore gas fields located in remote, environmentally sensitive and/or politically challenging regions. The technology has certain advantages over conventional onshore LNG in that it has a reduced environmental footprint at the production site. The technology may also deliver projects faster and at a lower cost since the bulk of the LNG facility is constructed in shipyards with lower labor rates and reduced execution risk.

[0006] Although FLNG has several advantageous over conventional onshore LNG, significant technical challenges remain in the application of the technology. For example, the FLNG structure must provide the same level of gas treating and liquefaction in an area or space that is often less than one quarter of what would be available for an onshore LNG plant. For this reason, there is a need to develop technology that reduces the footprint of the liquefaction facility while maintaining its capacity to thereby reduce overall project cost. Several liquefaction technologies have been proposed for use on an FLNG project. The leading technologies include a single mixed refrigerant (SMR) process, a dual mixed refrigerant (DMR) process, and expander-based (or expansion) process.

[0007] In contrast to the DMR process, the SMR process has the advantage of allowing all the equipment and bulks associated with the complete liquefaction process to fit within a single FLNG module. The SMR liquefaction module is placed on the topside of the FLNG structure

as a complete SMR train. This "LNG-in-a-Box" concept is favorable for FLNG project execution because it allows for the testing and commissioning of the SMR train at a different location from where the FLNG structure is constructed. It may also allow for the reduction in labor cost since it reduces labor hours at ship yards where labor rates tend to be higher than labor rates at conventional fabrication yards. The SMR process has the added advantage of being a relatively efficient, simple, and compact refrigerant process when compared to other mixed refrigerant processes. Furthermore, the SMR liquefaction process is typically 15% to 20% more efficient than expander-based liquefaction processes.

[0008] The choice of the SMR process for LNG liquefaction in an FLNG project has its advantages; however, there are several disadvantages to the SMR process. For example, the required use and storage of combustible refrigerants such as propane significantly increases loss prevention issues on the FLNG. The SMR process is also limited in capacity, which increases the number of trains needed to reach the desired LNG production. For these reasons and others, a significant amount of topside space and weight is required for the SMR trains. Since topside space and weight are significant drivers for FLNG project cost, there remains a need to improve the SMR liquefaction process to further reduce topside space, weight and complexity to thereby improve project economics.

[0009] The expander-based process has several advantages that make it well suited for FLNG projects. The most significant advantage is that the technology offers liquefaction without the need for external hydrocarbon refrigerants. Removing liquid hydrocarbon refrigerant inventory, such as propane storage, significantly reduces safety concerns on FLNG projects. An additional advantage of the expander-based process compared to a mixed refrigerant process is that the expander-based process is less sensitive to offshore motions since the main refrigerant mostly remains in the gas phase. However, application of the expander-based process to an FLNG project with LNG production of greater than 2 million tons per year (MTA) has proven to be less appealing than the use of the mixed refrigerant process. The capacity of an expander-based process train is typically less than 1.5 MTA. In contrast, a mixed refrigerant process train, such as that of known dual mixed refrigerant processes, can have a train capacity of greater than 5 MTA. The size of the expander-based process train is limited since its refrigerant mostly remains in the vapor state throughout the entire process and the refrigerant absorbs energy through its sensible heat. For these reasons, the refrigerant volumetric flow rate is large throughout the process, and the size of the heat exchangers and piping are proportionately greater than those of a mixed refrigerant process. Furthermore, the

limitations in compander horsepower size results in parallel rotating machinery as the capacity of the expander-based process train increases. The production rate of an FLNG project using an expander-based process can be made to be greater than 2 MTA if multiple expander-based trains are allowed. For example, for a 6 MTA FLNG project, six or more parallel expander-based process trains may be sufficient to achieve the required production. However, the equipment count, complexity and cost all increase with multiple expander trains. Additionally, the assumed process simplicity of the expander-based process compared to a mixed refrigerant process begins to be questioned if multiple trains are required for the expander-based process while the mixed refrigerant process can obtain the required production rate with one or two trains. For these reasons, there is a need to develop a high LNG production capacity FLNG liquefaction process with the advantages of an expander-based process. There is a further need to develop an FLNG technology solution that is better able to handle the challenges that vessel motion has on gas processing.

[0010] United States Patent No. 6,412,302 describes a feed gas expander-based process where two independent closed refrigeration loops are used to cool the feed gas to form LNG. In an embodiment, the first closed refrigeration loop uses the feed gas or components of the feed gas as the refrigerant. Nitrogen gas is used as the refrigerant for the second closed refrigeration loop. This technology requires smaller equipment and topside space than a dual loop nitrogen expander-based process. For example, the volumetric flow rate of the refrigerant into the low pressure compressor can be 20 to 50% smaller for this technology compared to a dual loop nitrogen expander-based process. The technology, however, is still limited to a capacity of less than 1.5 MTA.

[0011] United States Patent No. 8,616,012 describes a feed gas expander-based process where feed gas is used as the refrigerant in a closed refrigeration loop. Within this closed refrigeration loop, the refrigerant is compressed to a pressure greater than or equal to 1,500 psia (10,340 kPa), or more preferably greater than 2,500 psia (17,240 kPA). The refrigerant is then cooled and expanded to achieve cryogenic temperatures. This cooled refrigerant is used in a heat exchanger to cool the feed gas from warm temperatures to cryogenic temperatures. A subcooling refrigeration loop is then employed to further cool the feed gas to form LNG. In one embodiment, the subcooling refrigeration loop is a closed loop with flash gas used as the refrigerant. This feed gas expander-based process has the advantage of not being limited to a train capacity range of less than 1 MTA. A train size of approximately 6 MTA has been considered. However, the technology has the disadvantage of a high equipment count and

increased complexity due to its requirement for two independent refrigeration loops and the compression of the feed gas. Furthermore, the high pressure operation also means that the equipment and piping will be much heavier than that of other expander-based processes.

[0012] GB 2,486,036 describes a feed gas expander-based process that is an open loop refrigeration cycle including a precooling expander loop and a liquefying expander loop, where the gas phase after expansion is used to liquefy the natural gas. According to this document, including a liquefying expander in the process significantly reduces the recycle gas rate and the overall required refrigeration power. This technology has the advantage of being simpler than other technologies since only one type of refrigerant is used with a single compression string. However, the technology is still limited to capacity of less than 1.5 MTA and it requires the use of liquefying expander, which is not standard equipment for LNG production. The technology has also been shown to be less efficient than other technologies for the liquefaction of lean natural gas.

[0013] United States Patent No. 7,386,996 describes an expander-based process with a pre-cooling refrigeration process preceding the main expander-based cooling circuit. The pre-cooling refrigeration process includes a carbon dioxide refrigeration circuit in a cascade arrangement. The carbon dioxide refrigeration circuit may cool the feed gas and the refrigerant gases of the main expander-based cooling circuit at three pressure levels: a high pressure level to provide the warm-end cooling; a medium pressure level to provide the intermediate temperature cooling; and a low pressure level to provide cold-end cooling for the carbon dioxide refrigeration circuit. This technology is more efficient and has a higher production capacity than expander-based processes lacking a pre-cooling step. The technology has the additional advantage for FLNG applications since the pre-cooling refrigeration cycle uses carbon dioxide as the refrigerant instead of hydrocarbon refrigerants. The carbon dioxide refrigeration circuit, however, comes at the cost of added complexity to the liquefaction process since an additional refrigerant and a substantial amount of extra equipment is introduced. In an FLNG application, the carbon dioxide refrigeration circuit may be in its own module and sized to provide the pre-cooling for multiple expander-based processes. This arrangement has the disadvantage of requiring a significant amount of pipe connections between the pre-cooling module and the main expander-based process modules. The "LNG-in-a-Box" advantages discussed above are no longer realized.

[0014] Thus, there remains a need to develop a pre-cooling process that does not require additional refrigerant and does not introduce a significant amount of extra equipment to the

LNG liquefaction process. There is an additional need to develop a pre-cooling process that can be placed in the same module as the liquefaction module. Such a pre-cooling process combined with an SMR process or an expander-based process would be particularly suitable for FLNG applications where topside space and weight significantly impacts the project economics. There remains a specific need to develop an LNG production process with the advantages of an expander-based process and which, in addition, has a high LNG production capacity without significantly increasing facility footprint. There is a further need to develop an LNG technology solution that is better able to handle the challenges that vessel motion has on gas processing. Such a high capacity expander-based liquefaction process would be particularly suitable for FLNG applications where the inherent safety and simplicity of expander-based liquefaction process are greatly valued.

SUMMARY OF THE INVENTION

[0015] The invention provides a method of producing liquefied natural gas (LNG). A natural gas stream is provided from a supply of natural gas. The natural gas stream may be compressed in at least two serially arranged compressors to a pressure of at least 2,000 psia to form a compressed natural gas stream. The compressed natural gas stream may be cooled to form a cooled compressed natural gas stream. The cooled compressed natural gas stream may be expanded in at least one work producing natural gas expander to a pressure that is less than 3,000 psia and no greater than the pressure to which the at least two serially arranged compressors compress the natural gas stream, to thereby form a chilled natural gas stream. The chilled natural gas stream may then be liquefied.

[0016] The invention also provides an apparatus for the liquefaction of natural gas. At least two serially arranged compressors compress a natural gas stream to a pressure greater than 2,000 psia, thereby forming a compressed natural gas stream. A cooling element cools the compressed natural gas stream to form a cooled compressed natural gas stream. At least one work-producing expander expands the cooled compressed natural gas stream to a pressure less than 3,000 psia and no greater than the pressure to which the at least two serially arranged compressors compress the natural gas stream, to thereby form a chilled natural gas stream. A liquefaction train liquefies the chilled natural gas stream.

[0017] The invention further provides a floating LNG structure, comprising. At least two serially arranged compressors compress a natural gas stream to a pressure greater than 2,000 psia, thereby forming a compressed natural gas stream. A cooling element cools the compressed natural gas stream to form a cooled compressed natural gas stream. At least one

work-producing expander expands the cooled compressed natural gas stream to a pressure less than 3,000 psia and no greater than the pressure to which the at least two serially arranged compressors compress the natural gas stream, to thereby form a chilled natural gas stream. A liquefaction train liquefies the chilled natural gas stream.

BRIEF DESCRIPTION OF THE FIGURES

[0018] **Figure 1** is a schematic diagram of a high pressure compression and expansion (HPCE) module according to disclosed aspects.

[0019] **Figure 2** is a graph shown a heating and cooling curve for an expander-based refrigeration process.

[0020] **Figure 3** is a schematic diagram showing an arrangement of single-mixed refrigerant (SMR) liquefaction modules according to known principles.

[0021] **Figure 4** is a schematic diagram showing an arrangement of SMR liquefaction modules according to disclosed aspects.

[0022] **Figure 5** is a schematic diagram of an HPCE module according to disclosed aspects.

[0023] **Figure 6** is a schematic diagram of an HPCE module and a feed gas expander-based liquefaction module according to disclosed aspects.

[0024] **Figure 7** is a flowchart of a method of liquefying natural gas to form LNG according to disclosed aspects.

DETAILED DESCRIPTION

[0025] Various specific aspects, embodiments, and versions will now be described, including definitions adopted herein. Those skilled in the art will appreciate that such aspects, embodiments, and versions are exemplary only, and that the invention can be practiced in other ways. Any reference to the "invention" may refer to one or more, but not necessarily all, of the embodiments defined by the claims. The use of headings is for purposes of convenience only and does not limit the scope of the present invention. For purposes of clarity and brevity, similar reference numbers in the several Figures represent similar items, steps, or structures and may not be described in detail in every Figure.

[0026] All numerical values within the detailed description and the claims herein are modified by "about" or "approximately" the indicated value, and take into account experimental error and variations that would be expected by a person having ordinary skill in the art.

[0027] As used herein, the term "compressor" means a machine that increases the pressure of a gas by the application of work. A "compressor" or "refrigerant compressor" includes any unit, device, or apparatus able to increase the pressure of a gas stream. This includes compressors having a single compression process or step, or compressors having multi-stage compressions or steps, or more particularly multi-stage compressors within a single casing or shell. Evaporated streams to be compressed can be provided to a compressor at different pressures. Some stages or steps of a cooling process may involve two or more compressors in parallel, series, or both. The present invention is not limited by the type or arrangement or layout of the compressor or compressors, particularly in any refrigerant circuit.

[0028] As used herein, "cooling" broadly refers to lowering and/or dropping a temperature and/or internal energy of a substance by any suitable, desired, or required amount. Cooling may include a temperature drop of at least about 1 °C, at least about 5 °C, at least about 10 °C, at least about 15 °C, at least about 25 °C, at least about 35 °C, or least about 50 °C, or at least about 75 °C, or at least about 85 °C, or at least about 95 °C, or at least about 100 °C. The cooling may use any suitable heat sink, such as steam generation, hot water heating, cooling water, air, refrigerant, other process streams (integration), and combinations thereof. One or more sources of cooling may be combined and/or cascaded to reach a desired outlet temperature. The cooling step may use a cooling unit with any suitable device and/or equipment. According to some embodiments, cooling may include indirect heat exchange, such as with one or more heat exchangers. In the alternative, the cooling may use evaporative (heat of vaporization) cooling and/or direct heat exchange, such as a liquid sprayed directly into a process stream.

[0029] As used herein, the term "expansion device" refers to one or more devices suitable for reducing the pressure of a fluid in a line (for example, a liquid stream, a vapor stream, or a multiphase stream containing both liquid and vapor). Unless a particular type of expansion device is specifically stated, the expansion device may be (1) at least partially by isenthalpic means, or (2) may be at least partially by isentropic means, or (3) may be a combination of both isentropic means and isenthalpic means. Suitable devices for isenthalpic expansion of natural gas are known in the art and generally include, but are not limited to, manually or automatically, actuated throttling devices such as, for example, valves, control valves, Joule-Thomson (J-T) valves, or venturi devices. Suitable devices for isentropic expansion of natural gas are known in the art and generally include equipment such as expanders or turbo expanders that extract or derive work from such expansion. Suitable devices for isentropic expansion of liquid streams

are known in the art and generally include equipment such as expanders, hydraulic expanders, liquid turbines, or turbo expanders that extract or derive work from such expansion. An example of a combination of both isentropic means and isenthalpic means may be a Joule-Thomson valve and a turbo expander in parallel, which provides the capability of using either alone or using both the J-T valve and the turbo expander simultaneously. Isenthalpic or isentropic expansion can be conducted in the all-liquid phase, all-vapor phase, or mixed phases, and can be conducted to facilitate a phase change from a vapor stream or liquid stream to a multiphase stream (a stream having both vapor and liquid phases) or to a single-phase stream different from its initial phase. In the description of the drawings herein, the reference to more than one expansion device in any drawing does not necessarily mean that each expansion device is the same type or size.

[0030] The term "gas" is used interchangeably with "vapor," and is defined as a substance or mixture of substances in the gaseous state as distinguished from the liquid or solid state. Likewise, the term "liquid" means a substance or mixture of substances in the liquid state as distinguished from the gas or solid state.

[0031] A "heat exchanger" broadly means any device capable of transferring heat energy or cold energy from one medium to another medium, such as between at least two distinct fluids. Heat exchangers include "direct heat exchangers" and "indirect heat exchangers." Thus, a heat exchanger may be of any suitable design, such as a co-current or counter-current heat exchanger, an indirect heat exchanger (e.g. a spiral wound heat exchanger or a plate-fin heat exchanger such as a brazed aluminum plate fin type), direct contact heat exchanger, shell-and-tube heat exchanger, spiral, hairpin, core, core-and-kettle, printed-circuit, double-pipe or any other type of known heat exchanger. "Heat exchanger" may also refer to any column, tower, unit or other arrangement adapted to allow the passage of one or more streams therethrough, and to affect direct or indirect heat exchange between one or more lines of refrigerant, and one or more feed streams.

[0032] As used herein, the term "indirect heat exchange" means the bringing of two fluids into heat exchange relation without any physical contact or intermixing of the fluids with each other. Core-in-kettle heat exchangers and brazed aluminum plate-fin heat exchangers are examples of equipment that facilitate indirect heat exchange.

[0033] As used herein, the term "natural gas" refers to a multi-component gas obtained from a crude oil well (associated gas) or from a subterranean gas-bearing formation (non-associated gas). The composition and pressure of natural gas can vary significantly. A typical

natural gas stream contains methane (C_1) as a significant component. The natural gas stream may also contain ethane (C_2), higher molecular weight hydrocarbons, and one or more acid gases. The natural gas may also contain minor amounts of contaminants such as water, nitrogen, iron sulfide, wax, and crude oil.

[0034] Certain embodiments and features have been described using a set of numerical upper limits and a set of numerical lower limits. It should be appreciated that ranges from any lower limit to any upper limit are contemplated unless otherwise indicated. All numerical values are "about" or "approximately" the indicated value, and take into account experimental error and variations that would be expected by a person having ordinary skill in the art.

[0035] All patents, test procedures, and other documents cited in this application are fully incorporated by reference to the extent such disclosure is not inconsistent with this application and for all jurisdictions in which such incorporation is permitted.

[0036] Aspects disclosed herein describe a process for pre-cooling natural gas to a liquefaction process for the production of LNG by the addition of a high pressure compression and high pressure expansion process to the feed gas. More specifically, the invention describes a process where a pretreated natural gas is compressed to pressure greater than 2,000 psia (13,790 kPA), or more preferably greater than 3,000 psia (20,680 kPA). The hot compressed gas is cooled by exchanging heat with the environment to form a compressed pretreated gas. The compressed pretreated gas is near-isentropically expanded to a pressure less than 3,000 psia (20,680 kPA), or more preferably to a pressure less than 2,000 psia (13,790 kPA) to form a chilled pretreated gas, where the pressure of the chilled pretreated gas is less than the pressure of the compressed pretreated gas. The chilled pretreated gas may be directed to one or more SMR liquefaction trains, or the chilled pretreated gas may be directed to one or more expander-based liquefaction trains where the gas is further cooled to form LNG.

[0037] Figure 1 is an illustration of an aspect of the pre-cooling process. The pre-cooling process is referred to herein as a high pressure compression and expansion (HPCE) process **100**. The HPCE process **100** may comprise a first compressor **102** which compresses a pretreated natural gas stream **104** to form an intermediate pressure gas stream **106**. The intermediate pressure gas stream **106** may flow through a first heat exchanger **108** where the intermediate pressure gas stream **106** is cooled by indirectly exchanging heat with the environment to form a cooled intermediate pressure gas stream **110**. The first heat exchanger **108** may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled intermediate pressure gas stream **110** may then be compressed within a second compressor **112**

to form a high pressure gas stream **114**. The pressure of the high pressure gas stream **114** may be greater than 2,000 psia (13,790 kPA), or more preferably greater than 3,000 psia (20,680 kPA). The high pressure gas stream **114** may flow through a second heat exchanger **116** where the high pressure gas stream **114** is cooled by indirectly exchanging heat with the environment to form a cooled high pressure gas stream **118**. The second heat exchanger **116** may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled high pressure gas stream **118** may then be expanded within an expander **120** to form a chilled pretreated gas stream **122**. The pressure of the chilled pretreated gas stream **122** may be less than 3,000 psia (20,680 kPA), or more preferably less than 2,000 psia (13,790 kPA), and the pressure of the chilled pretreated gas stream **122** is less than the pressure of the cooled high pressure gas stream **118**. In a preferred aspect, the second compressor **112** may be driven solely by the shaft power produced by the expander **120**, as indicated by the dashed line **124**.

[0038] In an aspect, the SMR liquefaction process may be enhanced by the addition of the HPCE process upstream of the SMR liquefaction process. More specifically, in this aspect, pretreated natural gas may be compressed to a pressure greater than 2,000 psia (13,790 kPA), or more preferably greater than 3,000 psia (20,680 kPA). The hot compressed gas is then cooled by exchanging heat with the environment to form a compressed pretreated gas. The compressed pretreated gas is then near-isentropically expanded to pressure less than 3,000 psia (20,680 kPA), or more preferably to a pressure less than 2,000 psia (13,790 kPA) to form a chilled pretreated gas, where the pressure of the chilled pretreated gas is less than the pressure of the compressed pretreated gas. The chilled pretreated gas is then directed to multiple SMR liquefaction trains where the chilled pretreated gas is further cooled to form LNG.

[0039] The combination of the HPCE process with SMR trains has several advantages over the conventional SMR process where pretreated natural gas is sent directly to the SMR liquefaction trains. For example, the precooling of the natural gas using the HPCE process allows for an increase in LNG production rate within the SMR trains for a given horsepower within the SMR trains. As described with respect to Figures 3 and 4, SMR trains that are each powered by a gas turbine having an output of about 50 megawatts (MW) can be reduced from five trains producing LNG at 1.5 MTA each to four trains with an increased capacity of 1.9 MTA each. For this given example, the HPCE module has effectively replaced one of the SMR modules. The replacement of one SMR module for an HPCE module is advantageous since the HPCE module is expected to be smaller, of less weight, and having significantly lower cost than the SMR module. Like the SMR module, the HPCE module may have an equivalent size

gas turbine to provide compression power, and it will also have an equivalent amount of air or water coolers. Unlike the SMR module, however, the HPCE module does not have an expensive main cryogenic heat exchanger. The vessels and pipes associated with the refrigerant flow within an SMR module are eliminated in the HPCE module. Furthermore, there are no expensive cryogenic pipes in the HPCE module and all the fluid streams remain in a single phase in the HPCE module.

[0040] Another advantage is that the required storage of refrigerant is reduced since the number of SMR trains has been reduced by one. Also, since a large fraction of the warm temperature cooling of the gas occurs in the HPCE module, the heavier hydrocarbon components of the mixed refrigerant can be reduced. For example, the propane component of the mixed refrigerant may be eliminated without any significant reduction in efficiency of the SMR process.

[0041] Another advantage is that for the SMR process which receives chilled pretreated gas from the HPCE process, the volumetric flow rate of the vaporized refrigerant of the SMR process can be more than 25% less than that of an conventional SMR process receiving warm pretreated gas. The lower volumetric flow of refrigerant may reduce the size of the main cryogenic heat exchanger and the size of the low pressure mixed refrigerant compressor. The lower volumetric flow rate of the refrigerant is due to its higher vaporizing pressure compared to that of a conventional SMR process.

[0042] Known propane-precooled mixed refrigeration processes and dual mixed refrigeration (DMR) processes may be viewed as versions of an SMR process combined with a pre-cooling refrigeration circuit, but there are significant differences between such processes and aspects of the present disclosure. For example, the known processes use a cascading propane refrigeration circuit or a warm-end mixed refrigerant to pre-cool the gas. Both these known processes have the advantage of providing 5% to 15% higher efficiency than the SMR process. Furthermore, the capacity of a single liquefaction train using these known processes can be significantly greater than that of a single SMR train. The pre-cooling refrigeration circuit of these technologies, however, comes at the cost of added complexity to the liquefaction process since additional refrigerants and a substantial amount of extra equipment is introduced. For example, the DMR's disadvantage of higher complexity and weight may outweigh its advantages of higher efficiency and capacity when deciding between and DMR process and SMR process for an FLNG application. The known processes have considered the addition of a pre-cooling process upstream of the SMR process as being driven principally by

the need for higher thermal efficiencies and higher LNG production capacity for a single train. The HPCE process combined with the SMR process has not been realized previously because it does not provide the higher thermal efficiencies that the refrigerant-based precooling process provides. As described above, the thermal efficiency of the HPCE process with SMR is about the same as a standalone SMR process. The disclosed aspects are believed to be novel based at least in part on its description of a pre-cooling process that aims to reduce the weight and complexity of the liquefaction process rather than increase thermal efficiency, which in the past has been the biggest driver for the addition of a pre-cooling process for onshore LNG applications. For the newer applications of FLNG, footprint, weight, and complexity of the liquefaction process may be a bigger driver of project cost. Therefore the disclosed aspects are of particular value.

[0043] In an aspect, an expander-based liquefaction process may be enhanced by the addition of an HPCE process upstream of the expander-based process. More specifically, in this aspect, a pretreated natural gas stream may be compressed to pressure greater than 2,000 psia (13,790 kPA), or more preferably greater than 3,000 psia (20,680 kPA). The hot compressed gas may then be cooled by exchanging heat with the environment to form a compressed pretreated gas. The compressed pretreated gas may be near-isentropically expanded to a pressure less than 3,000 psia (20,680 kPA), or more preferably to a pressure less than 2,000 psia (13,790 kPA) to form a chilled pretreated gas, where the pressure of the chilled pretreated gas is less than the pressure of the compressed pretreated gas. The chilled pretreated gas is directed to an expander-based process where the gas is further cooled to form LNG. In a preferred aspect, the chilled pretreated gas may be directed to a feed gas expander-based process.

[0044] Figure 2 shows a typical temperature cooling curve **200** for an expander-based liquefaction process. The higher temperature curve **202** is the temperature curve for the natural gas stream. The lower temperature curve **204** is the composite temperature curve of a cold cooling stream and a warm cooling stream. As illustrated, the cooling curve is marked by three temperature pinch-points **206**, **208**, and **210**. Each pinch point is a location within the heat exchanger where the combined heat capacity of the cooling streams is less than that of the natural gas stream. This imbalance in heat capacity between the streams results in reduction in the temperature difference between the cooling stream to the minimally acceptable temperature difference which provides effective heat transfer rate. The lowest temperature pinch-point **206** occurs where the colder of the two cooling streams, typically the cold cooling

stream, enters the heat exchanger. The intermediate temperature pinch-point **208** occurs where the second cooling stream, typically the warm cooling stream, enters the heat exchanger. The warm temperature pinch-point **210** occurs where the cold and warm cooling streams exit the heat exchanger. The warm temperature pinch-point **210** causes a need for a high mass flow rate for the warmer cooling stream, which subsequently increases the power demand of the expander-based process.

[0045] One proposed method to eliminate the warm temperature pinch-point **210** is to precool the feed gas with an external refrigeration system such as a propane cooling system or a carbon dioxide cooling system. For example, United States Patent No. 7,386,996 eliminates the warm temperature pinch-point by using a pre-cooling refrigeration process comprising a carbon dioxide refrigeration circuit in a cascade arrangement. This external pre-cooling refrigeration system has the disadvantage of significantly increasing the complexity of the liquefaction process since an additional refrigerant system with all its associated equipment is introduced. Aspects disclosed herein reduce the impact of the warm temperature pinch-point **210** by precooling the feed gas stream by compressing the feed gas to a pressure greater than 2,000 psia (12,790 kPA), cooling the compressed feed gas stream, and expanding the compressed gas stream to a pressure less than 3,000 psia (20,690 kPA), where the expanded pressure of the feed gas stream is less than the compressed pressure of the feed gas stream. This process of cooling the feed gas stream results in a significant reduction in the in the required mass flow rate of the expander-based process cooling streams. It also improves the thermodynamic efficiency of the expander-based process without significantly increasing the equipment count and without the addition of an external refrigerant.

[0046] In a preferred aspect, the expander-based process may be a feed gas expander-based process. The feed gas expander-based process may be an open loop feed gas process where the recycling loop comprises a warm-end expander loop and a cold-end expander loop. The warm-end expander may discharge a first cooling stream and the cold-end expander may discharge the second cooling stream. The temperature of the first cooling stream is higher than the temperature of the second cooling stream. In an aspect, the pressure of the first cooling stream is higher than the pressure of the second cooling stream. In another aspect, the cold-end expander discharges a two-phase stream that is separated into a second cooling stream and a second pressurize LNG stream. Specifically, a produced natural gas stream may be treated to remove impurities, if present, such as water, heavy hydrocarbons, and sour gases, to make the natural gas suitable for liquefaction. The treated natural gas may be directed to the HPCE

process where it is compressed to a pressure greater than 2,000 psia (12,790 kPA), or more preferably greater than 3,000 psia (20,680 kPA). The hot compressed gas may then be cooled by exchanging heat with the environment to form a compressed treated natural gas. The compressed treated natural gas may be near-isentropically expanded to a pressure less than 3,000 psia (20,680 kPA), or more preferably to a pressure less than 2,000 psia (12,790 kPA) to form a chilled treated natural gas, where the pressure of the chilled treated natural gas is less than the pressure of the compressed treated natural gas. The chilled treated natural gas may be completely liquefied by indirect exchange of heat with the first cooling stream and the second cooling stream to produce a first pressurized LNG stream. The first pressurized LNG stream may be mixed with the second pressurized LNG stream to form a pressurized LNG stream. The pressurized LNG stream may be directed to at least one two-phase separation stage where the pressure of the pressurized LNG stream is reduced and the resulting two-phase stream is separated into a flash gas stream and an LNG product stream. The flash gas stream may exchange heat with the pressurized LNG stream and the chilled treated natural gas stream prior to being compressed for fuel gas and/or compressed to mix with the recycling second cooling stream.

[0047] The combination of the HPCE process with the feed gas expander-based process has several advantages over a conventional feed gas expander-based process. Including the HPCE process therewith may increase the efficiency of the of the feed gas expander-based process by 20 to 25%. Thus, the feed-gas expander process of this invention has an efficiency approaching that of an SMR process while still providing the advantages of no external refrigerant use, ease of operation, and reduced equipment count. Furthermore, the refrigerant flow rates and the size of the recycle compressors are expected to be significantly lower for the exapander-base process combined with the HPCE process. For these reasons, the production capacity of a single liquefaction train according to disclosed aspects may be greater than 50% above the production capacity of a similarly sized conventional expander-based liquefaction process.

[0048] Figure 3 is an illustration of an arrangement of SMR liquefaction modules on a FLNG **300**. Natural gas **302** that is pretreated or otherwise suitable for liquefaction may be distributed evenly between five identical or near identical SMR liquefaction modules or trains **304**, **306**, **308**, **310**, **312**. As an example, each SMR liquefaction module may receive approximately 50 MW of compression power from either a gas turbine or an electric motor (not shown) to drive the compressors of the SMR liquefaction modules. Each SMR

liquefaction module may produce approximately 1.5 MTA of LNG for a total stream day production of approximately 7.5 MTA of LNG for the FLNG application.

[0049] Figure 4 is an illustration of an arrangement of an HPCE module **404** with the SMR liquefaction modules or trains **406**, **408**, **410**, **412** on a FLNG **400** according to disclosed aspects. Natural gas **402** that is pretreated or otherwise suitable for liquefaction may be directed to the HPCE module **404** to produce a chilled pretreated gas stream **405**. The HPCE module **404** may receive approximately 50 MW of compression power, for example, from either a gas turbine or an electric motor (not shown) to drive one or more compressors within the HPCE module **404**. The chilled pretreated gas may be distributed evenly between the four identical or near identical SMR liquefaction modules **406**, **408**, **410**, **412**. Each SMR liquefaction module may receive approximately 50 MW of compression power from either a gas turbine or an electric motor (not shown) to drive the compressors of the respective SMR liquefaction modules. Each SMR liquefaction module may produce approximately 1.9 MTA of LNG for a total stream day production of approximately 7.6 MTA of LNG for the FLNG application.

[0050] Figure 5 is an illustration of an aspect of the HPCE module **500** referenced in Figure 4. A natural gas stream **502** that has been pretreated to remove impurities, or is otherwise suitable for liquefaction, is fed into a first compressor **504** to form a first intermediate pressure gas stream **506**. The first intermediate pressure gas stream **506** may flow through a first heat exchanger **508** where the first intermediate pressure gas stream **506** is cooled by indirectly exchanging heat with the environment to form a cooled first intermediate pressure gas stream **510**. The first heat exchanger **508** may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled first intermediate pressure gas stream **510** may then be compressed within a second compressor **512** to form a second intermediate pressure gas stream **514**. The second intermediate pressure gas stream **514** may flow through a second heat exchanger **516** where the second intermediate pressure gas stream **514** is cooled by indirectly exchanging heat with the environment to form a cooled second intermediate pressure gas stream **518**. The second heat exchanger **516** may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled second intermediate pressure gas stream **518** may then be compressed within a third compressor **520** to form a high pressure gas stream **522**. The pressure of the high pressure gas stream **522** may be greater than 2,000 psia (13,790 kPA), or more preferably greater than 3,000 psia (20,680 kPA). The high pressure gas stream **522** may flow through a third heat exchanger **524** where the high pressure gas stream **522** is cooled by indirectly exchanging heat with the environment to form a cooled high pressure gas stream **526**. The

third heat exchanger **524** may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled high pressure gas stream **526** may then be expanded within an expander **528** to form a chilled pretreated gas stream **530**. The pressure of the chilled pretreated gas stream **530** may be less than 3,000 psia (20,680 kPA), or more preferably less than 2,000 psia (13,790 kPA), and the pressure of the chilled pretreated gas stream **530** may be less than the pressure of the cooled high pressure gas stream **526**. In an aspect, the third compressor **520** may be driven solely by the shaft power produced by the expander **528**, as illustrated by line **532**.

[0051] Figure 6 is an illustration of an HPCE process **601** combined with a feed gas expander-based LNG liquefaction process **600**. Natural gas may be treated to remove impurities, if present, such as water, heavy hydrocarbons, and sour gases, to produce a treated natural gas stream **602** that is suitable for liquefaction. The treated natural gas stream **602** may be mixed with a recycled refrigerant gas stream **604** to form a combined stream **606**. The combined stream **606** may be directed to the HPCE process **601** where the combined streams **606** are compressed within a first compressor **608** to form an intermediate pressure gas stream **610**. The intermediate pressure gas stream **610** may flow through a first heat exchanger **612** where the intermediate pressure gas stream **610** is cooled by indirectly exchanging heat with the environment to form a cooled intermediate pressure gas stream **614**. The first heat exchanger **612** may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled intermediate pressure gas stream **614** may then be compressed within a second compressor **616** to form a high pressure gas stream **618**. The pressure of the high pressure gas stream **618** may be greater than 2,000 psia (13,790 kPA), or more preferably greater than 3,000 psia (20,680 kPA). The high pressure gas stream **618** may flow through a second heat exchanger **620** where the high pressure gas stream **618** is cooled by indirectly exchanging heat with the environment to form a cooled high pressure gas stream **622**. The second heat exchanger **620** may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled high pressure gas stream **622** may then be expanded within an HPCE expander **624** to form a chilled pretreated gas stream **626**. The pressure of the chilled pretreated gas stream **626** is less than 3,000 psia (20,680 kPA), or more preferably less than 2,000 psia (13,790 kPA), and where the pressure of the chilled pretreated gas stream **626** is less than the pressure of the cooled high pressure gas stream **622**. In an aspect, the second compressor **616** may be driven solely by the shaft power produced by the expander **624**, as represented by the dashed line **628**.

[0052] As illustrated in Figure 6, the chilled pretreated gas stream **626** leaves the HPCE process **601** and is directed to a feed gas expander-based process **600**. The chilled pretreated

gas stream **626** may be separated into a second chilled pretreated gas stream **630**, a first refrigerant stream **632**, and a second refrigerant stream **634**. The first refrigerant stream **632** may be expanded in a first expander **636** to produce a first cooling stream **638**. The first cooling stream **638** enters at least one cryogenic heat exchanger **640** where it exchanges heat with the second chilled pretreated gas stream **630** and the second refrigerant stream **634** to cool said streams. The first cooling stream **638** exits the at least one cryogenic heat exchanger **640** as a first warm stream **642**. The second refrigerant stream **634**, after being cooled in the at least one cryogenic heat exchanger **640**, may be expanded in a second expander **644** to produce a two-phase stream **646**. The pressure of the two-phase stream **646** may be the same or may be lower than the pressure of the first cooling stream **638**. The two-phase stream **646** may be separated into its vapor component and its liquid component in a first two-phase separator **648** to form a second cooling stream **650** and a second pressurized LNG stream **652**. The temperature of the first cooling stream **638** is higher than the temperature of the second cooling stream **650**. The second cooling stream **650** enters the at least one cryogenic heat exchanger **640** where it exchanges heat with the second chilled pretreated gas stream **630** and the second refrigerant stream **634** to cool said streams. The second cooling stream **650** exits the at least one heat exchanger **640** as a second warm stream **654**. The second chilled pretreated natural gas stream **630** exchanges heat with the first cooling stream **638** and the second cooling stream **650** to produce a first pressurized LNG stream **656**. The first pressurized LNG stream **656** may be reduced in pressure in a hydraulic turbine **658** after exiting the at least one heat exchanger **640**. The first pressurized LNG stream **656** may be mixed with the second pressurized LNG stream **652** to form a combined pressurized LNG stream **660**. The combined pressurized LNG stream **660** may be directed to a second two-phase separator **662** where the pressure of the combined pressurized LNG stream **660** is reduced, and the resulting two-phase stream is separated into an end flash gas stream **664** and a product LNG stream **667**. The end flash gas stream **664** may exchange heat with the first pressurized LNG stream **656** within an end flash gas heat exchanger **668** prior to directing the first pressurized LNG stream **656** to the hydraulic turbine **658**. Additionally, the end flash gas stream **664** may enter the at least one cryogenic heat exchanger **640** to exchange heat with the second chilled pretreated gas stream **630** and the second refrigerant stream **634** to cool said streams. The end flash gas stream **664** exits the at least one heat exchanger **640** as a third warm stream **670**. The third warm stream **670** may be compressed in a first recycle gas compressor **672** and may exchange heat with the environment in a first recycle heat exchanger **674** to form a first recycle gas stream **676**. The first recycle gas stream **676** may be combined with the second warm stream **654** and, together, may be

compressed in a second recycle gas compressor **678**, and may exchange heat with the environment in a second recycle heat exchanger **680** to form a second recycle gas stream **682**. The second recycle gas stream **682** may be combined with the first warm stream **642** and, together, may be compressed in third and fourth recycle gas compressors **684**, **686** and may exchange heat with the environment in a third recycle heat exchanger **688** to form the recycle refrigerant gas stream **604**. The third recycle gas compressor **684** may be driven solely by the shaft power produced by the first expander **636**, as shown by the dashed line **690**. The fourth recycle gas compressor **686** may be driven solely by the shaft power produced by the second expander **644**, as shown by the dashed line **692**.

[0053] Figure 7 illustrates a method **700** of producing LNG according to disclosed aspects. At block **702** a natural gas stream may be provided from a supply of natural gas. At block **704** the natural gas stream may be compressed in at least two serially arranged compressors to a pressure of at least 2,000 psia to form a compressed natural gas stream. At block **706** the compressed natural gas stream may be cooled to form a cooled compressed natural gas stream. At block **708** the cooled compressed natural gas stream may be expanded in at least one work producing natural gas expander to a pressure that is less than 3,000 psia and no greater than the pressure to which the at least two serially arranged compressors compress the natural gas stream, to thereby form a chilled natural gas stream. At block **710** the chilled natural gas stream may be liquefied.

[0054] Disclosed aspects may include any combinations of the methods and systems shown in the following numbered paragraphs. This is not to be considered a complete listing of all possible aspects, as any number of variations can be envisioned from the description above.

[0055] 1. A method of producing liquefied natural gas (LNG), the method comprising:

providing a natural gas stream from a supply of natural gas;

compressing the natural gas stream in at least two serially arranged compressors to a pressure of at least 2,000 psia to form a compressed natural gas stream;

cooling the compressed natural gas stream to form a cooled compressed natural gas stream;

expanding, in at least one work producing natural gas expander, the cooled compressed natural gas stream to a pressure that is less than 3,000 psia and no greater than the pressure to which the at least two serially arranged compressors compress the natural gas stream, to thereby form a chilled natural gas stream; and

liquefying the chilled natural gas stream.

[0056] 2. The method of paragraph 1, wherein liquefying the chilled natural gas stream is performed in one or more single mixed refrigerant (SMR) liquefaction trains.

[0057] 3. The method of paragraph 1, wherein liquefying the chilled natural gas stream is performed in one or more expander-based liquefaction modules.

[0058] 4. The method of paragraph 3, wherein the expander-based liquefaction module is a nitrogen gas expander-based liquefaction module.

[0059] 5. The method of paragraph 3, wherein the expander-based liquefaction module is a feed gas expander-based liquefaction module.

[0060] 6. The method of paragraph 5, wherein the feed gas expander-based liquefaction module is an open loop feed gas expander-based liquefaction module.

[0061] 7. The method of paragraph 6, wherein a recycle refrigerant stream of the open loop feed gas expander-based process is combined with the natural gas stream prior to the compressing step.

[0062] 8. The method of paragraph 7, wherein the chilled natural gas stream is a first chilled natural gas stream, and further comprising separating the first chilled natural gas stream into a second chilled natural gas stream, a first refrigerant stream, and a second refrigerant stream.

[0063] 9. The method of paragraph 7, further comprising:

discharging a first cooling stream from a warm-end expander forming part of the feed gas expander-based liquefaction module, the first cooling stream having a first temperature; and

discharging a second cooling stream from a cold-end expander forming part of the feed gas expander-based liquefaction module, the second cooling stream having a second temperature;

wherein the first temperature is higher than the second temperature.

[0064] 10. The method of paragraph 9, further comprising:

expanding the first refrigerant stream in the warm-end expander to produce the first cooling stream; and

expanding the second refrigerant stream in the cold-end expander to produce the second

cooling stream.

[0065] 11. The method of paragraph 7, further comprising:

discharging a first cooling stream from a warm-end expander forming part of the feed gas expander-based liquefaction module, the first cooling stream having a first temperature; and

discharging a two-phase stream from a cold-end expander forming part of the feed gas expander-based liquefaction module, the two-phase stream having a second temperature;

wherein the first temperature is higher than the second temperature.

[0066] 12. The method of paragraph 11, further comprising:

expanding the first refrigerant stream in the warm-end expander to produce the first cooling stream; and

expanding the second refrigerant stream in the cold-end expander to produce the two-phase stream.

[0067] 13. The method of paragraph 11, further comprising separating the two-phase stream into a second cooling stream and a first pressurized LNG stream.

[0068] 14. The method of any of paragraphs 9-13, wherein a pressure of the first cooling stream is the same or similar to a pressure of the second cooling stream.

[0069] 15. The method of any of paragraphs 9-13, wherein a pressure of the first cooling stream is higher than a pressure of the second cooling stream.

[0070] 16. The method of any of paragraphs 9-13, wherein the liquefying step comprises cooling the second chilled natural gas stream to form a second pressurized LNG stream by exchanging heat with the first cooling stream and the second cooling stream.

[0071] 17. The method of paragraph 16, wherein the second pressurized LNG stream is mixed with the first pressurized LNG stream prior to expanding the second pressurized LNG stream.

[0072] 18. The method of paragraph 16, further comprising:

reducing a pressure of the second pressurized LNG stream such that the second pressurized LNG stream undergoes at least one stage of pressure reduction; and

separating the reduced-pressure second pressurized LNG stream into an end-flash gas stream and an LNG stream.

[0073] 19. The method of paragraph 18, further comprising cooling the second pressurized LNG stream and the second chilled natural gas stream using the end-flash gas stream.

[0074] 20. The method of paragraph 19, further comprising:

after cooling the second pressurized LNG stream and the second chilled natural gas stream using the end-flash gas stream, compressing the end-flash gas stream and mixing the compressed end-flash gas stream with one or more recycling refrigerant streams.

[0075] 21. The method of paragraph 19, further comprising:

after cooling the second pressurized LNG stream and the second chilled natural gas stream using the end-flash gas stream, compressing the end-flash gas stream and using the compressed end-flash gas stream as fuel.

[0076] 22. The method of any of paragraphs 1-21, wherein the at least two compressors compress the natural gas stream to a pressure greater than 3,000 psia.

[0077] 23. The method of any of paragraphs 1-22, wherein the natural gas expander is a work producing expander that expands the cooled compressed natural gas stream to a pressure less than 2,000 psia.

[0078] 24. The method of any of paragraphs 1-23, wherein the natural gas expander is mechanically coupled to at least one compressor.

[0079] 25. The method of any of paragraphs 1-24, wherein cooling the compressed natural gas stream comprises cooling the compressed natural gas stream in at least one heat exchanger that exchanges heat with the environment.

[0080] 26. The method of any of paragraphs 1-25, wherein one of the at least two serially arranged compressors is driven by the natural gas expander.

[0081] 27. The method of any of paragraphs 1-26, wherein the at least two serially arranged compressors comprise three serially arranged compressors, and wherein one of the three serially arranged compressors is driven by the natural gas expander.

[0082] 28. The method of any of paragraphs 1-27, further comprising:

performing the compressing, cooling, expanding, and liquefying steps on a topside of a floating LNG structure.

[0083] 29. The method of paragraph 28, wherein the compressing, cooling, and expanding steps are performed within a single module on the topside of the floating LNG structure.

[0084] 30. An apparatus for the liquefaction of natural gas, comprising:

at least two serially arranged compressors configured to compress a natural gas stream to a pressure greater than 2,000 psia, thereby forming a compressed natural gas stream;

a cooling element configured to cool the compressed natural gas stream, thereby forming a cooled compressed natural gas stream;

at least one work-producing expander configured to expand the cooled compressed natural gas stream to a pressure less than 3,000 psia and no greater than the pressure to which the at least two serially arranged compressors compress the natural gas stream, to thereby form a chilled natural gas stream; and

a liquefaction train configured to liquefy the chilled natural gas stream.

[0085] 31. The apparatus of paragraph 30, wherein the liquefaction train comprises one of a single mixed refrigerant (SMR) liquefaction module and an expander-based liquefaction module.

[0086] 32. The apparatus of paragraph 31, wherein the expander-based liquefaction module is one of a nitrogen gas expander-based liquefaction module and a feed gas expander-based liquefaction module.

[0087] 33. The apparatus of paragraph 32, wherein the feed gas expander-based liquefaction module is an open loop feed gas expander-based liquefaction module.

[0088] 34. The apparatus of paragraph 33, further comprising a recycle refrigerant stream of the open loop feed gas expander-based process that is combined with the natural gas stream prior to the natural gas stream being compressed by the two or more serially-arranged compressors;

wherein the chilled natural gas stream is a first chilled natural gas stream that is separated into a second chilled natural gas stream, a first refrigerant stream, and a second refrigerant stream.

[0089] 35. The apparatus of paragraph 34, wherein the feed gas expander-based liquefaction module comprises:

a warm-end expander configured to expand the first refrigerant stream to form a first cooling stream discharged therefrom, the first cooling stream having a first temperature; and

a cold-end expander configured to expand the second refrigerant stream to form one of

a second cooling stream and a two-phase stream discharged therefrom, the second cooling stream having a second temperature;

wherein the first temperature is higher than the second temperature.

[0090] 36. The apparatus of paragraph 35, further comprising separating the two-phase stream into a second cooling stream and a first pressurized LNG stream.

[0091] 37. The apparatus of paragraphs 35-36, wherein a pressure of the first cooling stream is:

the same or similar to a pressure of the second cooling stream, or

higher than the pressure of the second cooling stream.

[0092] 38. The apparatus of any of paragraphs 35-37, further comprising a heat exchanger configured to cool the second chilled natural gas stream to form a second pressurized LNG stream by exchanging heat with the first cooling stream and the second cooling stream.

[0093] 39. The apparatus of any of paragraphs 30-38, wherein the at least two compressors compress the natural gas stream to a pressure greater than 3,000 psia.

[0094] 40. The apparatus of any of paragraphs 30-39, wherein the natural gas expander is a work producing expander configured to expand the cooled compressed natural gas stream to a pressure less than 2,000 psia.

[0095] 41. The apparatus of any of paragraphs 30-40, wherein the natural gas expander is mechanically coupled to at least one compressor.

[0096] 42. The apparatus of any of paragraphs 30-41, wherein the cooling element comprises a heat exchanger configured to cool the compressed natural gas stream by exchanging heat with the environment.

[0097] 43. The apparatus of any of paragraphs 30-42, wherein one of the at least two serially arranged compressors is driven by the natural gas expander.

[0098] 44. The apparatus of any of paragraphs 30-43, wherein the at least two serially arranged compressors comprise three serially arranged compressors, and wherein one of the three serially arranged compressors is driven by the natural gas expander.

[0099] 45. The apparatus of any of paragraphs 30-44, wherein the at least two serially arranged compressors, the cooling element, the at least one work-producing expander, and the liquefaction train are disposed on a floating LNG structure.

[0100] 46. The apparatus of paragraph 45, wherein the at least two serially arranged compressors, the cooling element, and the at least one work-producing expander are disposed within a single module on a topside of the floating LNG structure.

[0101] 47. A floating LNG structure, comprising:

at least two serially arranged compressors configured to compress a natural gas stream to a pressure greater than 2,000 psia, thereby forming a compressed natural gas stream;

a cooling element configured to cool the compressed natural gas stream, thereby forming a cooled compressed natural gas stream;

at least one work-producing expander configured to expand the cooled compressed natural gas stream to a pressure less than 3,000 psia and no greater than the pressure to which the at least two serially arranged compressors compress the natural gas stream, to thereby form a chilled natural gas stream; and

a liquefaction train configured to liquefy the chilled natural gas stream.

[0102] While the foregoing is directed to aspects of the present disclosure, other and further aspects of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

CLAIMS

1. A method of producing liquefied natural gas (LNG), the method comprising:

providing a natural gas stream from a supply of natural gas;

compressing the natural gas stream in at least two serially arranged compressors to a pressure of at least 2,000 psia to form a compressed natural gas stream;

cooling the compressed natural gas stream to form a cooled compressed natural gas stream;

expanding, in at least one work producing natural gas expander, the cooled compressed natural gas stream to a pressure that is less than 3000 psia and no greater than the pressure to which the at least two serially arranged compressors compress the natural gas stream, to thereby form a chilled natural gas stream; and

liquefying the chilled natural gas stream.

2. The method of claim 1, wherein liquefying the chilled natural gas stream is performed in one or more single mixed refrigerant (SMR) liquefaction trains.

3. The method of claim 1, wherein liquefying the chilled natural gas stream is performed in one or more expander-based liquefaction modules, and wherein the expander-based liquefaction module is one of a nitrogen gas expander-based liquefaction module and a feed gas expander-based liquefaction module.

4. The method of claim 3, wherein the feed gas expander-based liquefaction module is an open loop feed gas expander-based liquefaction module, and wherein a recycle refrigerant stream of the open loop feed gas expander-based process is combined with the natural gas stream prior to the compressing step.

5. The method of claim 4, wherein the chilled natural gas stream is a first chilled natural gas stream, and further comprising:

separating the first chilled natural gas stream into a second chilled natural gas stream, a first refrigerant stream, and a second refrigerant stream;

discharging a first cooling stream from a warm-end expander forming part of the feed gas expander-based liquefaction module, the first cooling stream having a first temperature; and

discharging a second cooling stream from a cold-end expander forming part of the feed gas expander-based liquefaction module, the second cooling stream having a second temperature;

wherein the first temperature is higher than the second temperature.

6. The method of claim 5, further comprising:

expanding the first refrigerant stream in the warm-end expander to produce the first cooling stream; and

expanding the second refrigerant stream in the cold-end expander to produce the second cooling stream.

7. The method of claim 4, further comprising:

discharging a first cooling stream from a warm-end expander forming part of the feed gas expander-based liquefaction module, the first cooling stream having a first temperature;
discharging a two-phase stream from a cold-end expander forming part of the feed gas expander-based liquefaction module, the two-phase stream having a second temperature, wherein the first temperature is higher than the second temperature;

expanding the first refrigerant stream in the warm-end expander to produce the first cooling stream;

expanding the second refrigerant stream in the cold-end expander to produce the two-phase stream; and

separating the two-phase stream into a second cooling stream and a first pressurized LNG stream.

8. The method of any of claims 5-7, wherein the liquefying step comprises cooling the second chilled natural gas stream to form a second pressurized LNG stream by exchanging heat with the first cooling stream and the second cooling stream.

9 The method of claim 8, wherein the second pressurized LNG stream is mixed with the first pressurized LNG stream prior to expanding the second pressurized LNG stream.

10. The method of claim 8, further comprising:

reducing a pressure of the second pressurized LNG stream such that the second pressurized LNG stream undergoes at least one stage of pressure reduction;

separating the reduced-pressure second pressurized LNG stream into an end-flash gas stream and an LNG stream; and

cooling the second pressurized LNG stream and the second chilled natural gas stream using the end-flash gas stream.

11. The method of claim 10, further comprising:

after cooling the second pressurized LNG stream and the second chilled natural gas stream using the end-flash gas stream, compressing the end-flash gas stream and mixing the compressed end-flash gas stream with one or more recycling refrigerant streams.

12. The method of claim 10, further comprising:

after cooling the second pressurized LNG stream and the second chilled natural gas stream using the end-flash gas stream, compressing the end-flash gas stream and using the compressed end-flash gas stream as fuel.

13. The method of any of claims 1-12, wherein the at least two compressors compress the natural gas stream to a pressure greater than 3,000 psia.

14. The method of any of claims 1-13, wherein the natural gas expander is a work producing expander that expands the cooled compressed natural gas stream to a pressure less than 2,000 psia.

15. The method of any of claims 1-14, wherein the natural gas expander is mechanically coupled to at least one compressor.

16. The method of any of claims 1-15, wherein cooling the compressed natural gas stream comprises cooling the compressed natural gas stream in at least one heat exchanger that exchanges heat with the environment.

17. The method of any of claims 1-16, wherein one of the at least two serially arranged compressors is driven by the natural gas expander.

18. The method of any of claims 1-17, further comprising:

performing the compressing, cooling, expanding, and liquefying steps on a topside of a floating LNG structure.

19. The method of claim 18, wherein the compressing, cooling, and expanding steps are performed within a single module on the topside of the floating LNG structure.

20. An apparatus for the liquefaction of natural gas, comprising:

at least two serially arranged compressors configured to compress a natural gas stream to a pressure greater than 2,000 psia, thereby forming a compressed natural gas stream;

a cooling element configured to cool the compressed natural gas stream, thereby forming a cooled compressed natural gas stream;

at least one work-producing expander configured to expand the cooled compressed natural gas stream to a pressure less than 3,000 psia and no greater than the pressure to which the at least two serially arranged compressors compress the natural gas stream, to thereby form a chilled natural gas stream; and

a liquefaction train configured to liquefy the chilled natural gas stream.

21. The apparatus of claim 20, wherein the liquefaction train comprises one of a nitrogen gas expander-based liquefaction module and an open loop feed gas expander-based liquefaction module, and further comprising a recycle refrigerant stream of the open loop feed gas expander-based process that is combined with the natural gas stream prior to the natural gas stream being compressed by the two or more serially-arranged compressors, wherein the chilled natural gas stream is a first chilled natural gas stream that is separated into a second chilled natural gas stream, a first refrigerant stream, and a second refrigerant stream.

22. The apparatus of claim 21, wherein the feed gas expander-based liquefaction module comprises:

a warm-end expander configured to expand the first refrigerant stream to form a first cooling stream discharged therefrom, the first cooling stream having a first temperature; and

a cold-end expander configured to expand the second refrigerant stream to form one of a second cooling stream and a two-phase stream discharged therefrom, the second cooling stream having a second temperature;

wherein the first temperature is higher than the second temperature.

23. The apparatus of any of claims 20-22, wherein the natural gas expander is a work producing expander configured to expand the cooled compressed natural gas stream to a pressure less than 2,000 psia.

24. The apparatus of any of claims 20-23, wherein the cooling element comprises a heat exchanger configured to cool the compressed natural gas stream by exchanging heat with the environment.

25. The apparatus of any of claims 20-24, wherein the at least two serially arranged compressors, the cooling element, the at least one work-producing expander, and the liquefaction train are disposed on a floating LNG structure.

26. The apparatus of claim 25, wherein the at least two serially arranged compressors, the cooling element, and the at least one work-producing expander are disposed within a single module on a topside of the floating LNG structure.

27. A floating LNG structure, comprising:

at least two serially arranged compressors configured to compress a natural gas stream to a pressure greater than 2,000 psia, thereby forming a compressed natural gas stream;

a cooling element configured to cool the compressed natural gas stream, thereby forming a cooled compressed natural gas stream;

at least one work-producing expander configured to expand the cooled compressed natural gas stream to a pressure less than 3,000 psia and no greater than the pressure to which the at least two serially arranged compressors compress the natural gas stream, to thereby form a chilled natural gas stream; and

a liquefaction train configured to liquefy the chilled natural gas stream.