

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

CROSS REFERENCE TO RELATED APPLICATIONS

- 5 **[0001]** This application claims the priority benefit of United States Provisional Patent Application No. 62/902460, filed September 19, 2019, entitled PRETREATMENT AND PRE-COOLING OF NATURAL GAS BY HIGH PRESSURE COMPRESSION AND EXPANSION.

FIELD OF THE INVENTION

- 10 **[0002]** 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

- 15 **[0003]** 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
20 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
25 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
30 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.

[0004] Although LNG production in general is well known, technology improvements may still provide an LNG producer 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.

[0005] 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.

[0006] 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.

- [0007] 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. Also, to remove heavy hydrocarbons and recover the necessary natural gas liquids for refrigerant makeup, a scrub column is often used. **Figure 1** illustrates a typical LNG liquefaction system **100** integrating a simple SMR process with a scrub column **104**. A SMR refrigerant loop **106** cools and liquefies a feed gas stream **102** in one or more heat exchangers **108a**, **108b**, **108c**. Specifically, the SMR refrigerant loop **106** cools the feed gas stream **102** before it is sent to the scrub column **104**. Heavy hydrocarbons are removed from a bottom stream **110** of the scrub column **104**, and a cooled vapor stream **112** is removed from the top of the scrub column **104**. The cooled vapor stream **112** is then cooled and partially condensed in heat exchanger **108b** through heat exchange with the SMR refrigerant loop **106**. The cooled vapor stream is sent to a separating vessel **114**, where the condensed portion of the cooled vapor stream is returned to the scrub column as a liquid reflux stream **116**, and the vapor portion **118** of the cooled vapor stream is liquefied through heat exchange with the SMR refrigerant loop **106** in the heat exchanger **108c**. An LNG stream **120** exits the LNG liquefaction system **100** for storage and/or transport.
- [0008] The integrated scrub column design, such as the one depicted in **Figure 1** and described above, is usually the lowest cost option for heavy hydrocarbon removal. However, this design has the disadvantage of reducing train capacity because some of the refrigeration of the SMR train is used in heat exchanger **108b** to produce the column reflux. It also has the disadvantage of increasing the equipment count of an SMR train, which may limit the ability to place the SMR train within a single FLNG module. Furthermore, for FLNG applications of greater than 1.5 MTA, multiple SMR trains are required, with each train having its own integrated scrub column. 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. There remains an additional need to develop a heavy hydrocarbon removal process capable of increasing train capacity while also reducing overall equipment count for high production FLNG applications.

[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 compressor 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. An integrated scrub column design may also be used to remove heavy hydrocarbons for an expander-based liquefaction process. The advantages and disadvantages of its use is similar to that of an SMR process. The use of an integrated scrub column design limits the liquefaction pressure to a value below the cricondenbar of the feed gas. This fact is a particular disadvantage for expander-based processes since its process efficiency is more negatively impacted by lower liquefaction pressures than mixed refrigerant processes. 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. There remains

a further need to develop a heavy hydrocarbon removal process better suited for expander based process by eliminating the efficiency and production loss associated with conventional technologies.

[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 an increased equipment count and increased complexity due to its requirement for two independent refrigeration loops and the compression of the feed gas.

[0012] GB 2,486,036 describes a feed gas expander-based process that is an open loop refrigeration cycle including a pre-cooling 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. Furthermore, there is an additional need to develop a pre-cooling process that can easily integrate with a heavy hydrocarbon removal process and provide auxiliary cooling upstream of liquefaction. 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] According to disclosed aspects, a method and apparatus are provided for producing liquefied natural gas (LNG) from a natural gas stream. A portion of the natural gas stream is cooled in a first heat exchanger to generate a cooled natural gas stream. The cooled natural gas stream and the natural gas stream are combined to generate a combined natural gas stream, and heavy hydrocarbons are removed therefrom in a separator to thereby generate a separated natural gas stream and a separator bottom stream. Liquids are separated from the separator bottom stream to form an overhead stream, which is cooled and separated to form a recycle gas stream. The recycle gas stream is compressed in a recycle compressor to form a compressed recycle gas stream. A first portion of the compressed recycle gas stream is directed through the first heat exchanger to form a cooled compressed recycle stream therefrom, and the cooled compressed recycle stream is directed to the separator as a column reflux stream. The separated natural gas stream is used as a coolant in the first heat exchanger to thereby generate a pretreated natural gas stream. A second portion of the compressed recycle gas stream and the pretreated natural gas stream are compressed in at least one compressor to a pressure of at least 1,500 psia to form a compressed natural gas stream, and the compressed natural gas stream is cooled to form a cooled compressed natural gas stream. The cooled compressed natural gas stream is expanded, in at least one work producing natural gas expander, to a pressure that is less than 2,000 psia and no greater than the pressure to which the at least one compressor compresses the pretreated natural gas stream, to thereby form a chilled pretreated gas stream. The chilled pretreated gas stream is recycled to exchange heat with one or more process streams comprising at least a portion of the natural gas stream, the separated natural gas stream, and the second portion of the compressed recycle gas stream, thereby generating a warmed refrigerant stream. The warmed refrigerant stream is liquefied to form LNG.

[0016] According to still other disclosed aspects, a method and apparatus are provided for producing liquefied natural gas (LNG) from a natural gas stream. A portion of the natural gas stream is cooled in a first heat exchanger to generate a cooled natural gas stream. The cooled natural gas stream and the natural gas stream are combined to generate a combined natural gas stream, and heavy hydrocarbons are removed therefrom in a separator to thereby generate a separated natural gas stream and a separator bottom stream. Liquids are separated from the separator bottom stream to form an stream, which is cooled and separated to form a recycle gas

stream. The recycle gas stream is compressed in a recycle compressor to form a compressed recycle gas stream. A first portion of the compressed recycle gas stream is directed through the first heat exchanger to form a cooled compressed recycle stream therefrom, and the cooled compressed recycle stream is directed to the separator as a column reflux stream. A pressure and a temperature of the separated natural gas stream are reduced in a pressure reducing device, and the separated natural gas stream is then used as a coolant in the first heat exchanger to thereby generate a pretreated natural gas stream. A second portion of the compressed recycle gas stream and the pretreated natural gas stream are compressed in a feed compressor to a pressure of at least 1,500 psia to form a compressed natural gas stream, which is cooled to form a cooled high pressure gas stream. The cooled high pressure gas stream is liquefied to form LNG.

BRIEF DESCRIPTION OF THE FIGURES

- [0017] **Figure 1** is a schematic diagram of a SMR process with an integrated scrub column for heavy hydrocarbon removal according to known principles.
- 15 [0018] **Figure 2** is a schematic diagram of a high pressure compression and expansion (HPCE) module with heavy hydrocarbon removal according to disclosed aspects.
- [0019] **Figure 3** is a schematic diagram showing an arrangement of single-mixed refrigerant (SMR) liquefaction modules according to known principles.
- [0020] **Figure 4** is a schematic diagram showing an arrangement of SMR liquefaction modules according to disclosed aspects.
- 20 [0021] **Figure 5** is a graph showing a heating and cooling curve for an expander-based refrigeration process.
- [0022] **Figure 6** is a schematic diagram of an HPCE module with heavy hydrocarbon removal according to disclosed aspects.
- 25 [0023] **Figure 7** is a schematic diagram of an HPCE module with heavy hydrocarbon removal and a feed gas expander-based liquefaction module according to disclosed aspects.
- [0024] **Figure 8** is a flowchart of a method of liquefying natural gas to form LNG according to disclosed aspects.
- [0025] **Figure 9** is a flowchart of a method of liquefying natural gas to form LNG according to disclosed aspects.
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[0026] **Figure 10** is a schematic diagram of a natural gas pretreatment apparatus as well as a portion of a liquefaction module, according to disclosed aspects.

[0027] **Figure 11** is a schematic diagram of a natural gas pretreatment apparatus and a liquefaction module according to disclosed aspects.

5 [0028] **Figure 12** is a schematic diagram of a natural gas pretreatment apparatus and a liquefaction module according to disclosed aspects.

[0029] **Figure 13** is a schematic diagram of a natural gas pretreatment apparatus and a liquefaction module according to disclosed aspects.

[0030] **Figure 14** is a schematic diagram of a natural gas pretreatment apparatus and a
10 liquefaction module according to disclosed aspects.

[0031] **Figure 15** is a schematic diagram of a natural gas pretreatment apparatus and a liquefaction module according to disclosed aspects.

[0032] **Figure 16A** is a schematic diagram of a natural gas pretreatment apparatus and a liquefaction module according to disclosed aspects.

15 [0033] **Figure 16B** is a schematic diagram of a natural gas pretreatment apparatus and a liquefaction module according to disclosed aspects.

[0034] **Figure 17** is a flowchart depicting a method of producing liquefied natural gas according to disclosed aspects.

[0035] **Figure 18** is a flowchart depicting a method of producing liquefied natural gas
20 according to disclosed aspects.

[0036] **Figure 19** is a flowchart depicting a method of producing liquefied natural gas according to disclosed aspects.

[0037] **Figure 20** is a flowchart depicting a method of producing liquefied natural gas according to disclosed aspects.

25 [0038] **Figure 21** is a flowchart depicting a method of producing liquefied natural gas according to disclosed aspects.

DETAILED DESCRIPTION

[0039] 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.

[0040] 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.

[0041] 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. Reference herein to more than one compressor includes more than one single-stage compressor, one or more multi-stage compressors, and any combination thereof. 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.

[0042] 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.

[0043] As used herein, the term "environment" refers to ambient local conditions, e.g., temperatures and pressures, in the vicinity of a process.

[0044] 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.

[0045] The term "gas" is used interchangeably herein 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.

[0046] 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
5 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.

[0047] As used herein, the term "heavy hydrocarbons" refers to hydrocarbons having more
10 than four carbon atoms. Principal examples include pentane, hexane and heptane. Other examples include benzene, aromatics, or diamondoids.

[0048] 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
15 examples of equipment that facilitate indirect heat exchange.

[0049] 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
20 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.

[0050] As used herein, the term "separation device" or "separator" refers to any vessel configured to receive a fluid having at least two constituent elements and configured to produce
25 a gaseous stream out of a top portion and a liquid (or bottoms) stream out of the bottom of the vessel. The separation device/separator may include internal contact-enhancing structures (e.g. packing elements, strippers, weir plates, chimneys, etc.), may include one, two, or more sections (e.g. a stripping section and a reboiler section), and/or may include additional inlets and outlets. Exemplary separation devices/separators include bulk fractionators, stripping
30 columns, phase separators, scrub columns, and others.

[0051] As used herein, the term "scrub column" refers to a separation device used for the removal of heavy hydrocarbons from a natural gas stream.

[0052] 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.

[0053] 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.

[0054] Aspects disclosed herein describe a process for pretreating and 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 prior to liquefying the natural gas. A portion of the compressed and expanded gas is used to cool one or more process streams associated with pretreating the feed gas. More specifically, the invention describes a process where heavy hydrocarbons are removed from a natural gas stream to form a pretreated natural gas stream.

The pretreated natural gas is compressed to pressure greater than 1,500 psia (10,340 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 first chilled pretreated gas, where the pressure of the first chilled pretreated gas is less than the pressure of the compressed pretreated gas. The first chilled pretreated gas is separated into at least one refrigerant stream and a non-refrigerant stream. The at least one refrigerant stream is directed to at least one heat exchanger where it acts to cool a process stream and form a warmed refrigerant stream. The warmed refrigerant stream is mixed with the non-refrigerant stream to form a second chilled pretreated gas. The second chilled pretreated gas may be directed to one or more SMR liquefaction trains, or the second chilled pretreated gas may be directed to one or more expander-based liquefaction trains where the gas is further cooled to form LNG.

[0055] **Figure 2** is an illustration of a pretreatment apparatus **200** for pretreating and pre-cooling a natural gas stream **201**, followed by a high pressure compression and expansion (HPCE) process module **212**. A natural gas stream **201** may flow into a separation device, such as a scrub column **202**, where the natural gas stream **201** is separated into a column overhead stream **203** and a column bottom stream **204**. The column overhead stream **203** may flow through a first heat exchanger **205**, known as a ‘cold box’, where the column overhead stream

203 is partially condensed to form a two-phase stream 206. The two-phase stream 206 may flow into another separation device, such as a separator 207, to form cold pretreated gas stream 208 and a liquid stream 209. The cold pretreated gas stream 208 may flow through the first heat exchanger 205 where the cold pretreated gas stream 208 is warmed by indirectly exchanging heat with the column overhead stream 203, thereby forming a pretreated natural gas stream 210. The liquid stream 209 may be pressurized within a pump 211 and then directed to the scrub column 202 as a column reflux stream.

[0056] The HPCE process module 212 may comprise a first compressor 213 which compresses the pretreated natural gas stream 210 to form an intermediate pressure gas stream 214. The intermediate pressure gas stream 214 may flow through a second heat exchanger 215 where the intermediate pressure gas stream 214 is cooled by indirectly exchanging heat with the environment to form a cooled intermediate pressure gas stream 216. The second heat exchanger 215 may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled intermediate pressure gas stream 216 may then be compressed within a second compressor 217 to form a high pressure gas stream 218. The pressure of the high pressure gas stream 218 may be greater than 1,500 psia (10,340 kPa), or more preferably greater than 3,000 psia (20,680 kPa). The high pressure gas stream 218 may flow through a third heat exchanger 219 where the high pressure gas stream 218 is cooled by indirectly exchanging heat with the environment to form a cooled high pressure gas stream 220. The third heat exchanger 219 may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled high pressure gas stream 220 may then be expanded within an expander 221 to form a first chilled pretreated gas stream 222. The pressure of the first chilled pretreated gas stream 222 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 first chilled pretreated gas stream 222 is less than the pressure of the cooled high pressure gas stream 220. In a preferred aspect, the second compressor 217 may be driven solely by the shaft power produced by the expander 221, as indicated by the dashed line 223. The first chilled pretreated gas stream 222 may be separated into a refrigerant stream 224 and a non-refrigerant stream 225. The refrigerant stream 224 may flow through the first heat exchanger 205 where the refrigerant stream 224 is partially warmed by indirectly exchanging heat with the column overhead stream 203, thereby forming a warmed refrigerant stream 226. The warmed refrigerant stream 226 may mix with the non-refrigerant stream 225 to form a second chilled pretreated gas stream 227. The second chilled pretreated gas stream 227 may then be liquefied in, for example, an SMR liquefaction train 240 through indirect heat exchange with an SMR

refrigerant loop **228** in a fourth heat exchanger **229**. The resultant LNG stream **230** may then be stored and/or transported as needed.

[0057] It should be noted that the refrigerant stream **224** may be used to cool or chill any of the process streams associated with the pretreatment apparatus **200**. For example, one or more of the column overhead stream **203**, the two-phase stream **206**, the cold pretreated gas stream **208**, the liquid stream **209**, and the pretreated natural gas stream **210** may be configured to exchange heat with the refrigerant stream **224**. Furthermore, other process streams not associated with the pretreatment apparatus **200** may be cooled through heat exchange with the refrigerant stream **224**. The refrigerant stream **224** may be split into two or more sub-streams that are used to cool various process streams.

[0058] 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 1,500 psia (10,340 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 first chilled pretreated gas, where the pressure of the first chilled pretreated gas is less than the pressure of the compressed pretreated gas. The first chilled pretreated gas stream is separated into a refrigerant stream and a non-refrigerant stream. The refrigerant stream is warmed by exchanging heat with a column overhead stream in order to help partially condense the column overhead stream and produce a warmed refrigerant stream. The warmed refrigerant stream is mixed with the non-refrigerant stream to produce a second chilled pretreated gas. The second chilled pretreated gas may then be directed to multiple SMR liquefaction trains, arranged in parallel, where the chilled pretreated gas is further cooled therein to form LNG.

[0059] The combination of the HPCE process with pretreatment of the natural gas and liquefaction within multiple SMR liquefaction trains has several advantages over the conventional SMR process where natural gas is sent directly to the SMR liquefaction trains for both heavy hydrocarbon removal (final pretreatment step) and liquefaction. For example, the pre-cooling of the natural gas using the HPCE process allows for an increase in LNG production rate within the SMR liquefaction trains for a given horsepower within the SMR liquefaction trains. **Figures 3 and 4** demonstrate how the disclosed aspects provide such an LNG production increase. **Figure 3** is an illustration of an arrangement of liquefaction modules

or trains, such as SMR liquefaction trains, on an LNG production facility such as an FLNG unit **300** according to known principles. A natural gas stream **302** that is pretreated to remove sour gases and water to make the natural gas suitable for cryogenic treatment may be distributed between five identical or nearly identical SMR liquefaction trains **304, 306, 308, 310, 312** arranged in parallel. As an example, each SMR liquefaction train may receive approximately 50 megawatts (MW) of compression power from either a gas turbine or an electric motor (not shown) to drive the compressors of the respective SMR liquefaction train. Each SMR liquefaction module comprises an integrated scrub column to remove heavy hydrocarbons from the natural gas stream and to recover a sufficient amount of natural gas liquids to provide refrigerant make-up. Each SMR liquefaction module may produce approximately 1.5 million tons per year (MTA) of LNG for a total stream production of approximately 7.5 MTA for the entire FLNG unit **300**.

[0060] In contrast, **Figure 4** schematically depicts an LNG liquefaction facility such as an FLNG unit **400** according to disclosed aspects. FLNG unit **400** includes four SMR liquefaction trains **406, 408, 410, 412** arranged in parallel. Unlike the SMR liquefaction trains shown in Figure 3, none of the SMR liquefaction trains **406, 408, 410, 412** include a scrub column. Instead, a natural gas stream **402**, which is pretreated to remove sour gases and water to make the gas suitable for cryogenic treatment, may be directed to a HPCE module **404** to produce a chilled pretreated gas stream **405**. As previously explained, the HPCE module is integrated with a heavy hydrocarbon removal process therein (including a scrub column or similar separator) to remove any hydrocarbons that may form solids during the liquefaction of the natural gas stream **402**. The HPCE module **404** may receive approximately 55 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 stream **405** may be distributed between the 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 production of approximately 7.6 MTA of LNG for the FLNG unit **400**. If the FLNG unit **400** uses the disclosed HPCE process module integrated with a single scrub column and cold box (referred to collectively as the HPCE process module **404**), only a single scrub column is required to remove heavy hydrocarbons from the natural gas stream **402**. The replacement of one SMR liquefaction train with the disclosed HPCE module **404** is

advantageous since the HPCE module is expected to be smaller, of less weight, and having significantly lower cost than the replaced SMR liquefaction train. Like the replaced SMR liquefaction train, the HPCE module **404** 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 replaced SMR liquefaction train, however, the HPCE module **404** 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 replaced HPCE liquefaction train. Furthermore, the amount of expensive cryogenic pipes in the HPCE module **404** is significantly reduced.

10 **[0061]** The disclosed HPCE module comprises a single scrub column used to remove the heavy hydrocarbons from the natural gas that is then fed to all the liquefaction trains. This design increases the required power of the HPCE module by 10 to 15% compared to a design where heavy hydrocarbon removal is not included. However, integrating the heavy hydrocarbon removal within the HPCE module instead of within each SMR liquefaction train
15 reduces the weight of each SMR liquefaction train and may result in a total reduction in equipment count and overall topside weight of an FLNG system. Another advantage is that the liquefaction pressure can be greater than the cricondenbar of the feed gas, which results in increased liquefaction efficiency. Furthermore, the proposed design is more flexible to feed gas changes than the integrated scrub column design.

20 **[0062]** Another advantage of the disclosed HPCE module is that the required storage of refrigerant is reduced since the number of SMR liquefaction 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
25 significant reduction in efficiency of the SMR liquefaction process.

[0063] Another advantage is that for a SMR liquefaction process which receives chilled pretreated gas from the disclosed HPCE module, the volumetric flow rate of the vaporized refrigerant of the SMR liquefaction process can be more than 25% less than that of a conventional SMR liquefaction process receiving warm pretreated gas. The lower volumetric
30 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 liquefaction process.

[0064] Known propane-precooled mixed refrigeration processes and dual mixed refrigeration (DMR) processes may be viewed as versions of an SMR liquefaction 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 liquefaction process. Furthermore, the capacity of a single liquefaction train using these known processes can be significantly greater than that of a single SMR liquefaction 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 liquefaction process's disadvantage of higher complexity and weight may outweigh its advantages of higher efficiency and capacity when deciding between a DMR liquefaction process and an SMR liquefaction process for an FLNG application. The known processes have considered the addition of a pre-cooling process upstream of the SMR liquefaction process as being driven principally by the need for higher thermal efficiencies and higher LNG production capacity for a single liquefaction train. The disclosed HPCE process combined with the SMR liquefaction process has not been realized previously because it does not provide the higher thermal efficiencies that the refrigerant-based pre-cooling process provides. As described herein, the thermal efficiency of the HPCE process with the SMR liquefaction is about the same as a standalone SMR liquefaction 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. As an additional point, the integrated scrub column design is traditionally seen as the lowest cost option for heavy hydrocarbon removal of natural gas to liquefaction. However, the integration of heavy hydrocarbon removal with a HPCE process, as disclosed herein, provides a previously unrealized advantage of potentially reducing total equipment count and weight when multiple liquefaction trains is the preferred design methodology. For the newer applications of FLNG and remote onshore application, footprint, weight, and complexity of the liquefaction process may be a bigger driver of project cost. Therefore the disclosed aspects are of particular value.

[0065] 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 1,500 psia (10,340 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 first chilled pretreated gas, where the pressure of the first chilled pretreated gas is less than the pressure of the compressed pretreated gas. The first chilled pretreated gas stream is separated into refrigerant stream and a non-refrigerant stream. The refrigerant stream is warmed by exchanging heat with a column overhead stream in order to help partially condense the column overhead stream and produce a warmed refrigerant stream. The warmed refrigerant stream is mixed with the non-refrigerant stream to produce a second chilled pretreated gas. The second chilled pretreated gas is directed to an expander-based process where the gas is further cooled to form LNG. In a preferred aspect, the second chilled pretreated gas may be directed to a feed gas expander-based process.

[0066] Figure 5 shows a typical temperature cooling curve **500** for an expander-based liquefaction process. The higher temperature curve **502** is the temperature curve for the natural gas stream. The lower temperature curve **504** is the composite temperature curve of a cold cooling stream and a warm cooling stream. The natural gas is liquefied at pressure above its cricondenbar which allows for the close matching of the natural gas cooling curve (shown at **502**) with the composite temperature curve of the cold and warm cooling streams (shown at **504**) to maximize thermal efficiency. As illustrated, the cooling curve is marked by three temperature pinch-points **506**, **508**, and **510**. 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 a reduction of the temperature difference between the cooling stream to the minimally acceptable temperature difference which provides effective heat transfer rate. The lowest temperature pinch-point **506** occurs where the colder of the two cooling streams, typically the cold cooling stream, enters the heat exchanger. The intermediate temperature pinch-point **508** occurs where the second cooling stream, typically the warm cooling stream, enters the heat exchanger. The warm temperature pinch-point **510** occurs where the cold and warm cooling streams exit the heat exchanger. The warm temperature pinch-point **510** 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.

[0067] One proposed method to eliminate the warm temperature pinch-point 510 is to pre-cool 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 510 by pre-cooling the feed gas stream by compressing the feed gas to a pressure greater than 1,500 psia (10,340 kPa), cooling the compressed feed gas stream, and expanding the compressed gas stream to a pressure less than 2,000 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. This process may also be integrated with heavy hydrocarbon removal in order to remove the heavy hydrocarbon upstream of the liquefaction process. Since the gas is now free of heavy hydrocarbons that would form solids, the pretreated gas can be liquefied at a pressure above its cricondenbar in order to improve liquefaction efficiency.

[0068] In a preferred aspect, the expander-based process may be a feed gas expander-based process. This feed gas expander process comprises a first closed expander-based refrigeration loop and a second closed expander-based refrigeration loop. The first expander-based refrigeration loop may be principally charged with methane from a feed gas stream. The first expander-based refrigeration loop liquefies the feed gas stream. The second expander-based refrigeration loop may be charged with nitrogen as the refrigerant. The second expander-based refrigeration loop sub-cools the LNG streams. Specifically, a produced natural gas stream may be treated to remove impurities, if present, such as water, and sour gases, to make the natural gas suitable for cryogenic treatment. The treated natural gas stream may be directed to a scrub column where the treated natural gas stream is separated into a column overhead stream and a column bottom stream. The column overhead stream may be partially condensed within a first heat exchanger by indirectly exchanging heat with a cold pretreated gas stream and a refrigerant stream to thereby form a two phase stream. The two phase stream may be directed to a separator

where the two phase stream is separated into the cold pretreated gas stream and a liquid stream. The cold pretreated gas stream may be warmed within the first heat exchanger by exchanging heat with the column overhead stream to form a pretreated natural gas stream. The liquid stream may be pressurized within a pump and then directed to the scrub column to provide reflux to the scrub column. The pretreated natural gas stream may be directed to an HPCE process as disclosed herein, where it is compressed to a pressure greater than 1,500 psia (10,340 kPa), or more preferably greater than 3,000 psia (20,680 kPa). The hot compressed gas stream may then be cooled by exchanging heat with the environment to form a compressed treated natural gas stream. The compressed treated natural gas stream 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 first chilled treated natural gas stream, where the pressure of the first chilled treated natural gas stream is less than the pressure of the compressed treated natural gas stream. The first chilled natural gas stream may be separated into the refrigerant stream and a non-refrigerant stream. The refrigerant stream may be partially warmed within the first heat exchanger by exchanging heat with the column overhead stream to form a warmed refrigerant stream. The warmed refrigerant stream may mix with the non-refrigerant stream to form a second chilled natural gas stream. The second chilled treated natural gas may be directed to the feed gas expander process where the first expander-based refrigeration loop acts to liquefy the second chilled treated natural gas to form a pressurized LNG stream. The second expander refrigeration loop then acts to subcool the pressurized LNG stream. The subcooled pressurized LNG stream may then be expanded to a lower pressure in order to form an LNG stream.

[0069] The combination of the HPCE process with pretreatment of the natural gas and liquefaction of the pretreated gas within an expander-based process has several advantages over a conventional expander-based process. Including the HPCE process therewith may increase the efficiency of the expander-based process by 5 to 25% depending of the type of expander-based process employed. The feed gas expander process described herein may have a liquefaction efficiency similar to 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 expander-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 30 to 50% above the production capacity of a similarly sized conventional expander-based liquefaction process. The combination of HPCE process with heavy

hydrocarbon removal upstream of an expander-based liquefaction process has the additional benefit of providing the option to liquefy the gas at pressures above its cricondenbar to improve liquefaction efficiency. Expander-based liquefaction processes are particularly sensitive to liquefaction pressures. Therefore, the HPCE process described herein is well suited for removing heavy hydrocarbons while also increasing the liquefaction efficiency and production capacity of expander-based liquefaction processes.

[0070] Figure 6 is an illustration of an aspect of an HPCE module 600 with an integrated scrub column according to another aspect of the disclosure. A natural gas stream 601, which has been pretreated to remove sour gases and water to make the gas suitable for cryogenic treatment, is fed into a separation device, such as a scrub column 602, where the natural gas stream 601 is separated into a column overhead stream 603 and a column bottom stream 604. The column overhead stream 603 may flow through a first heat exchanger 605 where the column overhead stream 603 is partially condensed to form a two-phase stream 606. The two-phase stream 606 may be directed to another separation device, such as a separator 607, to form a cold pretreated gas stream 608 and a liquid stream 609. The cold pretreated gas stream 608 may flow through the first heat exchanger 605 where the cold pretreated gas stream 608 is warmed by indirect heat exchange with the column overhead stream 603 to form a pretreated natural gas stream 610 therefrom. The liquid stream may be pressurized within a pump 611 and then directed to the scrub column 602 as a column reflux stream. The pretreated natural gas stream 610 is directed to a first compressor 612 and compressed therein to form a first intermediate pressure gas stream 613. The first intermediate pressure gas stream 613 may flow through a second heat exchanger 614 where the first intermediate pressure gas stream 613 is cooled by indirect heat exchange with the environment to form a cooled first intermediate pressure gas stream 615. The second heat exchanger 614 may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled first intermediate pressure gas stream 615 may then be compressed within a second compressor 616 to form a second intermediate pressure gas stream 617. The second intermediate pressure gas stream 617 may flow through a third heat exchanger 618 where the second intermediate pressure gas stream 617 is cooled by indirect heat exchange with the environment to form a cooled second intermediate pressure gas stream 619. The third heat exchanger 618 may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled second intermediate pressure gas stream 619 may then be compressed within a third compressor 620 to form a high pressure gas stream 621. The pressure of the high pressure gas stream 621 may be greater than 1,500 psia (10,340 kPa), or more preferably greater

than 3,000 psia (20,680 kPa). The high pressure gas stream **621** may flow through a fourth heat exchanger **622** where the high pressure gas stream **621** is cooled by indirectly exchanging heat with the environment to form a cooled high pressure gas stream **623**. The fourth heat exchanger **622** may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled high pressure gas stream **623** may then be expanded within an expander **624** to form a first chilled pretreated gas stream **625**. The pressure of the first chilled pretreated gas stream **625** 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 first chilled pretreated gas stream **625** may be less than the pressure of the cooled high pressure gas stream **623**. In an aspect, the third compressor **620** may be driven solely by the shaft power produced by the expander **624**, as illustrated by line **624a**. The first chilled pretreated gas stream **625** may be separated into a refrigerant stream **626** and a non-refrigerant stream **627**. The refrigerant stream **626** may flow through the first heat exchanger **605** where the refrigerant stream **626** is partially warmed by indirectly exchanging heat with the column overhead stream **603** to form a warmed refrigerant stream **628** therefrom. The warmed refrigerant stream **628** may mix with the non-refrigerant stream **627** to form a second chilled pretreated gas stream **629**, which may then be liquefied by an SMR liquefaction process as previously explained. As with pretreatment apparatus **200**, the refrigerant stream **626** may be used to cool any process stream associated or not associated with the HPCE module **600**.

[0071] **Figure 7** is an illustration of an HPCE module **700** with an integrated scrub column and combined with a feed gas expander-based LNG liquefaction process according to disclosed aspects. A natural gas stream **701**, which has been pretreated to remove sour gases and water to make the gas suitable for cryogenic treatment, is fed into a separation device, such as a scrub column **702**, where the treated natural gas stream **701** is separated into a column overhead stream **703** and a column bottom stream **704**. The column overhead stream **703** may flow through a first heat exchanger **705** where the column overhead stream **703** is partially condensed to form a two-phase stream **706**. The two-phase stream **706** may be directed to another separation device, such as a separator **707**, to form a cold pretreated gas stream **708** and a liquid stream **709**. The cold pretreated gas stream **708** may flow through the first heat exchanger **705** where the cold pretreated gas stream **708** is warmed by indirect heat exchange with the column overhead stream **703** to form a pretreated natural gas stream **710** therefrom. The liquid stream **709** may be pressurized within a pump **711** and then directed to the scrub column **702** as a column reflux. The pretreated natural gas stream **710** is directed to a first compressor **713** and compressed therein to form an intermediate pressure gas stream **714**. The

intermediate pressure gas stream **714** may flow through a second heat exchanger **715** where the intermediate pressure gas stream **714** is cooled by indirect heat exchange with the environment to form a cooled intermediate pressure gas stream **716**. The second heat exchanger **715** may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled intermediate pressure gas stream **716** may then be compressed within a second compressor **717** to form a high pressure gas stream **718**. The pressure of the high pressure gas stream **718** may be greater than 1,500 psia (10,340 kPa), or more preferably greater than 3,000 psia (20,680 kPa). The high pressure gas stream **718** may flow through a third heat exchanger **719** where the high pressure gas stream **718** is cooled by indirect heat exchange with the environment to form a cooled high pressure gas stream **720**. The third heat exchanger **719** may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled high pressure gas stream **720** may then be expanded within an expander **721** to form a first chilled pretreated gas stream **722**. The pressure of the first chilled pretreated gas stream **722** 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 first chilled pretreated gas stream **722** is less than the pressure of the cooled high pressure gas stream **720**. In an aspect, the second compressor **717** may be driven solely by the shaft power produced by the expander **721**, as represented by the dashed line **723**. The first chilled pretreated gas stream **722** may be separated into a refrigerant stream **724** and a non-refrigerant stream **725**. The refrigerant stream **724** may flow through the first heat exchanger **705** where the refrigerant stream **724** is partially warmed by indirect heat exchange with the column overhead stream **703** to form a warmed refrigerant stream **726** therefrom. The warmed refrigerant stream **726** may mix with the non-refrigerant stream **725** to form a second chilled pretreated gas stream **727**. As with pretreatment apparatus **200** and HPCE module **600**, the refrigerant stream **724** may be used to cool any process stream associated or not associated with the HPCE module **700**.

[0072] As illustrated in **Figure 7**, the second chilled pretreated gas stream **727** is directed to a feed gas expander-based LNG liquefaction process **730**. The feed gas expander-based process **730** includes a primary cooling loop **732**, which is a closed expander-based refrigeration loop that may be charged with components from the feed gas stream. The liquefaction system also includes a subcooling loop **734**, which is also a closed expander-based refrigeration loop preferably charged with nitrogen as the sub-cooling refrigerant. Within the primary cooling loop **732**, an expanded, cooled refrigerant stream **736** is directed to a first heat exchanger zone **738** where it exchanges heat with the second chilled pretreated gas stream **727** to form a first warm refrigerant stream **740**. The first warm refrigerant **740** is directed to a

second heat exchanger zone **742** where it exchanges heat with a compressed, cooled refrigerant stream **744** to additionally cool the compressed, cooled refrigerant stream **744** and form a second warm refrigerant stream **746** and a compressed, additionally cooled refrigerant stream **748**. The second heat exchanger zone **742** may comprise one or more heat exchangers where the one or more heat exchangers may be of a printed circuit heat exchanger type, a shell and tube heat exchanger type, or a combination thereof. The heat exchanger types within the second heat exchanger zone **742** may have a design pressure of greater than 1,500 psia, or more preferably, a design pressure of greater than 2,000 psia, or more preferably, a design pressure of greater than 3,000 psia.

[0073] The second warm refrigerant stream **746** is compressed in one or more compression units **750**, **752** to a pressure greater than 1,500 psia, or more preferably, to a pressure of approximately 3,000 psia, to thereby form a compressed refrigerant stream **754**. The compressed refrigerant stream **754** is then cooled against an ambient cooling medium (air or water) in a cooler **756** to produce the compressed, cooled refrigerant stream **744**. The compressed, additionally cooled refrigerant stream **748** is near isentropically expanded in an expander **758** to produce the expanded, cooled refrigerant stream **736**. The expander **758** may be a work expansion device, such as a gas expander, which produces work that may be extracted and used for compression.

[0074] The first heat exchanger zone **738** may include a plurality of heat exchanger devices, and in the aspects shown in **Figure 7**, the first heat exchanger zone includes a main heat exchanger **760** and a sub-cooling heat exchanger **762**. These heat exchangers may be of a brazed aluminum heat exchanger type, a plate fin heat exchanger type, a spiral wound heat exchanger type, or a combination thereof.

[0075] Within the sub-cooling loop **734**, an expanded sub-cooling refrigerant stream **764** (preferably comprising nitrogen) is discharged from an expander **766** and drawn through the sub-cooling heat exchanger **762** and the main heat exchanger **760**. The expanded sub-cooling refrigerant stream **764** is then sent to a compression unit **768** where it is re-compressed to a higher pressure and warmed. After exiting compression unit **768**, the resulting recompressed sub-cooling refrigerant stream **770** is cooled in a cooler **772**. After cooling, the recompressed sub-cooling refrigerant stream **770** is passed through the main heat exchanger **760** where it is further cooled by indirect heat exchange with the expanded, cooled refrigerant stream **736** and the expanded sub-cooling refrigerant stream **764**. After exiting the first heat exchanger area **738**, the re-compressed and cooled sub-cooling refrigerant stream is expanded through the

expander **766** to provide the expanded sub-cooling refrigerant stream **764** that is re-cycled through the first heat exchanger zone as described herein. In this manner, the second chilled pretreated gas stream **727** is further cooled, liquefied and sub-cooled in the first heat exchanger zone **738** to produce a sub-cooled gas stream **774**. The sub-cooled gas stream **774** may be expanded to a lower pressure to produce the LNG stream (not shown).

[0076] **Figure 8** illustrates a method **800** of producing LNG according to disclosed aspects. At block **802** heavy hydrocarbons are removed from the natural gas stream to thereby generate a separated natural gas stream. At block **804** the separated natural gas stream is partially condensed in a first heat exchanger to thereby generate a partially condensed natural gas stream. At block **806** liquids are separated from the partially condensed natural gas stream to thereby generate a pretreated natural gas stream. At block **808** the pretreated natural gas stream is compressed in at least two serially arranged compressors to a pressure of at least 1,500 psia to form a compressed natural gas stream. At block **810** the compressed natural gas stream is cooled to form a cooled compressed natural gas stream. At block **812** the cooled natural gas stream is expanded to a pressure that is less than 2,000 psia and no greater than the pressure to which the at least two serially arranged compressors compress the pretreated natural gas stream, to thereby form a chilled natural gas stream. At block **814** the chilled natural gas stream is separated into a refrigerant stream and a non-refrigerant stream. At block **816** the refrigerant stream is warmed through heat exchange with one or more process streams comprising the natural gas stream, the separated natural gas stream, the partially condensed natural gas stream, and the pretreated natural gas stream, thereby generating a warmed refrigerant stream. At block **818** the warmed refrigerant stream and the non-refrigerant stream are liquefied.

[0077] **Figure 9** illustrates a method **900** of producing LNG according to disclosed aspects. At block **902** the natural gas stream is pretreated to generate a pretreated natural gas stream. At block **904** the pretreated natural gas stream is compressed in at least two serially arranged compressors to a pressure of at least 1,500 psia. At block **906** the compressed natural gas stream is cooled. At block **908** the cooled compressed natural gas stream is expanded in at least one work producing natural gas expander to a pressure that is less than 2,000 psia and no greater than the pressure to which the at least two serially arranged compressors compress the pretreated natural gas stream, to thereby form a chilled natural gas stream. At block **910** the chilled natural gas stream is separated into a refrigerant stream and a non-refrigerant stream. At block **912** the refrigerant stream is warmed in a heat exchanger through heat exchange with one or more process streams associated with pretreating the natural gas stream, thereby

generating a warmed refrigerant stream. At block **914** the warmed refrigerant stream and the non-refrigerant stream are liquefied.

[0078] Figure 10 is an illustration of a pretreatment apparatus 1000 for pretreating and pre-cooling a natural gas stream 1001, followed by a high pressure compression and expansion (HPCE) process module 1012, according to another aspect of the disclosure. Pretreatment apparatus 1000 may include a system for removing water or moisture from a natural gas stream, such as a molecular sieve dehydrator 1000a. While only shown in Figure 10, it is to be understood that the aspects depicted in Figures 11-16 may also use some type of water/moisture removal systems, such as dehydrator 1000a. The natural gas stream 1001 then flows into a separation device, such as a scrub column 1002, where the natural gas stream 1001 is separated into a column overhead stream 1003 and a column bottom stream 1004. The column overhead stream 1003 flows through a first heat exchanger 1005, where the column overhead stream 1003 is partially condensed to form a two-phase stream 1006. The two-phase stream 1006 may flow into another separation device, such as a separator 1007, where a cold pretreated gas stream 1008 is separated from a liquid stream 1009. The cold pretreated gas stream 1008 may flow through the first heat exchanger 1005 where the cold pretreated gas stream 1008 is warmed by indirectly exchanging heat with the column overhead stream 1003, thereby forming a pretreated natural gas stream 1010. The liquid stream 1009 may be pressurized within a pump (not shown) and then directed to the scrub column 1002 as a column reflux stream. A reboiler 1074 heats a portion 1075 of the liquids extracted from the bottom of scrub column 1002 and returns the heated liquids and associated gases to the scrub column, thereby generating a stripping gas 1076 for the column. Alternatively, a stripping gas stream for the reboiler operation may be sourced from the natural gas stream 1001, as shown by dashed line 1076a.

[0079] To control the temperature of the natural gas stream 1001 entering the scrub column, a side stream 1011 of the natural gas stream 1001 may be directed to the first heat exchanger 1005 to be cooled therein and generate a cooled natural gas stream 1011a. The cooled natural gas stream 1011a is combined with the natural gas stream upstream of the scrub column 1002 to form a combined natural gas stream 1001a, as depicted in Figure 10. The side stream may comprise 1% to 100%, or 10% to 90%, or 25% to 75%, or 40% to 60% of the natural gas stream 1001, depending on the temperature of the natural gas stream 1001 and the desired input temperature of the natural gas stream into the scrub column.

[0080] The HPCE process module 1012 may comprise a first compressor 1013 which compresses the pretreated natural gas stream 1010 to form an intermediate pressure gas stream

1014. The intermediate pressure gas stream 1014 may flow through a second heat exchanger (not shown) where the intermediate pressure gas stream 1014 is cooled by indirectly exchanging heat with the environment. The second heat exchanger may be an air cooled heat exchanger or a water cooled heat exchanger. The intermediate pressure gas stream 1014 may then be compressed within a second compressor 1017 to form a high pressure gas stream 1018. The pressure of the high pressure gas stream 1018 may be greater than 1,500 psia (10,340 kPa), or more preferably greater than 3,000 psia (20,680 kPa). The high pressure gas stream 1018 may flow through a third heat exchanger 1019 where the high pressure gas stream 1018 is cooled by indirectly exchanging heat with the environment to form a cooled high pressure gas stream 1020. The third heat exchanger 1019 may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled high pressure gas stream 1020 may then be expanded within an expander 1021 to form a first chilled pretreated gas stream 1022. The pressure of the first chilled pretreated gas stream 1022 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 first chilled pretreated gas stream 1022 is less than the pressure of the cooled high pressure gas stream 1020. In a preferred aspect, the second compressor 1017 may be driven solely by the shaft power produced by the expander 1021. In other disclosed aspects, including those aspects in which the HPCE process module 1012 includes only one compressor, the expander 1021 may be connected to a generator (not shown) to generate power. The first chilled pretreated gas stream 1022 may be separated into a refrigerant stream 1024 and a non-refrigerant stream 1025. The refrigerant stream 1024 may comprise between 10% and 90%, or between 25% and 75%, or between 40% or 60% of the first pre-treated gas stream 1022. The refrigerant stream 1024 is recycled to flow through the first heat exchanger 1005 where the refrigerant stream 1024 is partially warmed by indirectly exchanging heat with the column overhead stream 1003, thereby forming a warmed refrigerant stream 1026. The warmed refrigerant stream 1026 may mix with the non-refrigerant stream 1025 to form a second chilled pretreated gas stream 1027. The second chilled pretreated gas stream 1027 may then be liquefied in, for example, a feed gas expander-based liquefaction module 1040. The feed gas expander-based liquefaction module 1040 includes a primary cooling loop, which is a closed expander-based refrigeration loop that may be charged with components from the feed gas stream. The second chilled pre-treated gas stream 1027 is liquefied through indirect heat exchange with a refrigerant stream 1042 in a cryogenic heat exchanger 1029. While the primary cooling loop of the feed gas expander-based liquefaction module is shown, it is to be understood that other portions of the liquefaction module, while not depicted, are included with the disclosure herein. The resultant LNG stream 1030 may then

be stored and/or transported as needed.

[0081] Refrigerant stream 1042 is cooled in a heat exchanger 1044 and compressed in first and second refrigerant compressors 1046, 1048 to produce a compressed refrigerant stream 1050. The compressed refrigerant stream 1050 is cooled in an pre-compression heat exchanger 1052, which employs ambient-temperature air, water, or other coolant as is known in the art. The compressed refrigerant stream is then further compressed in a third refrigerant compressor 1054 and becomes a further compressed refrigerant stream 1056. Additional refrigerant compressors 1054a may be employed if necessary. In an aspect the third refrigerant compressor is powered by a gas turbine 1056. The further compressed refrigerant stream may be cooled by an intercooling heat exchanger 1058 and a post-compression heat exchanger 1060, and used to warm refrigerant stream 1042 in heat exchanger 1044. The cooled compressed refrigerant stream 1062 is then expanded in first and second refrigerant expanders 1064, 1066, to produce an expanded refrigerant stream 1068. In an aspect the first and second refrigerant expanders are connected to first and second refrigerant compressors 1046, 1048, respectively. In a preferred aspect, the first and second refrigerant compressors 1046, 1048 may be driven solely by the shaft power produced by the first and second refrigerant expanders 1064, 1066, respectively. The expanded refrigerant stream 1068 is directed to the cryogenic heat exchanger 1029, where it provides the cooling energy necessary to liquefy the second chilled pre-treated gas stream 1027 to produce the LNG stream 1030. The expanded refrigerant stream 1068 is warmed inside the cryogenic heat exchanger 1029 to form the refrigerant stream 1042, which is cycled through the feed gas expander-based liquefaction module 1040 in a closed-loop fashion as described herein and depicted in Figure 10.

[0082] The refrigerant stream 1024 may be used to cool or chill any of the process streams associated with the pretreatment apparatus 1000. For example, one or more of the column overhead stream 1003, the two-phase stream 1006, the cold pretreated gas stream 1008, the liquid stream 1009, and the pretreated natural gas stream 1010 may be configured to exchange heat with the refrigerant stream 1024. Furthermore, other process streams or cooling needs not associated with the pretreatment apparatus 1000, and represented symbolically at 1072, may be cooled through heat exchange with the refrigerant stream 1024 as desired in terms of process location and/or cost. For example, the cooling need 1072 may include pre-chilling the natural gas stream prior to the natural gas stream entering the dehydrator 1000a to assist in dehydration operations. This is advantageous because it is not necessary to take a slipstream from liquefaction module 1040 to perform the same function, and the liquefaction module 1040 and

the pretreatment apparatus 1000 can be independently controlled. As an additional benefit, the refrigerant stream 1024 may be used during start-up operations to cool the pretreatment apparatus 1000. The refrigerant stream 1024 may be split into two or more sub-streams that are used to cool various process streams.

5 **[0083]** Figure 11 is an illustration of a pretreatment apparatus 1100 for pretreating and pre-cooling a natural gas stream 1101, followed by a high pressure compression and expansion (HPCE) process module 1112, according to another aspect of the disclosure. Apparatus 1100 is similar to apparatus 1000, and similar elements are labeled with similar reference numbers. Like apparatus 1000, apparatus 1100 includes a scrub column 1102, a first heat exchanger
10 1105, and a separator 1107. To control the temperature of the natural gas stream 1101 entering the scrub column, a side stream 1111 of the natural gas stream 1101 may be directed to the first heat exchanger 1105 to be cooled therein and form a cooled natural gas stream 1111a. The cooled natural gas stream 1111a is combined with the natural gas stream upstream of the scrub column 1102 to form a combined natural gas stream 1101a, as depicted in Figure 11. The side
15 stream may comprise 1% to 100%, or 10% to 90%, or 25% to 75%, or 40% to 60% of the natural gas stream 1101, depending on the temperature of the natural gas stream 1101 and the desired input temperature of the natural gas stream into the scrub column.

[0084] The combined natural gas stream 1101a flows into scrub column 1102 and is separated into a column overhead stream 1103 and a column bottom stream 1104. The column
20 overhead stream 1103 flows through first heat exchanger 1105 to be partially condensed and forming a two-phase stream 1106. The two-phase stream 1106 flows into separator 1107 and is separated into a cold pretreated gas stream 1108 and a liquid stream 1109. The cold pretreated gas stream 1108 flows through the first heat exchanger 1105 and is warmed by indirectly exchanging heat with the column overhead stream 1103, thereby forming a pretreated natural
25 gas stream 1110. The liquid stream 1109 may be pressurized within a pump (not shown) and then directed to the scrub column 1102 as a column reflux stream. A stripping gas stream 1176 for the reboiler operation may be sourced from the natural gas stream 1001; alternatively, a reboiler as shown in Figure 10 may be used to provide the stripping gas for the scrub column.

[0085] Pretreated natural gas stream 1110 is input into an HPCE process module 1112,
30 which is similar to HPCE process module 1012 and will not be further described. The output of HPCE process module 1112 is a first chilled pretreated gas stream 1122, which is separated into a refrigerant stream 1124 and a non-refrigerant stream 1125. The refrigerant stream 1124 may comprise between 10% and 90%, or between 25% and 75%, or between 40% or 60% of

the first pre-treated gas stream 1122. The refrigerant stream 1124 is recycled to flow through the first heat exchanger 1105 to be warmed by indirectly exchanging heat with the column overhead stream 1103, thereby forming a warmed refrigerant stream 1126. A side stream 1124a of the refrigerant stream 1124 may be directed to a pressure-reducing and temperature-reducing device such as a Joule-Thomson valve 1124b to produce a further cooled refrigerant stream, which is also directed to flow through the first heat exchanger 1105 to cool the column overhead stream 1103 and any other process streams flowing therethrough. The resulting warmed side stream 1124c is combined with the pretreated natural gas stream 1110. The warmed refrigerant stream 1126 may mix with the non-refrigerant stream 1125 to form a second chilled pretreated gas stream 1127. The second chilled pretreated gas stream 1127 may then be liquefied in, for example, a feed gas expander-based liquefaction module 1140, to produce an LNG stream 1130. Module 1140 may be similar to module 1040, and therefore will not be further described. An expander 1171 may be employed to reduce the pressure and temperature of LNG stream 1130, to thereby produce a sub-cooled LNG stream suitable for storage and transport.

[0086] The refrigerant stream 1124 may be used to cool or chill any of the process streams associated with the pretreatment apparatus 1100. For example, one or more of the column overhead stream 1103, the two-phase stream 1106, the cold pretreated gas stream 1108, the liquid stream 1109, and the pretreated natural gas stream 1110 may be configured to exchange heat with the refrigerant stream 1124. Furthermore, other process streams or cooling needs not associated with the pretreatment apparatus 1100, and represented symbolically at 1172, may be cooled through heat exchange with the refrigerant stream 1124 as desired in terms of process location and/or cost. The refrigerant stream 1124 may be split into two or more sub-streams that are used to cool various process streams.

[0087] Figure 12 depicts a pretreatment apparatus 1200 for pretreating and pre-cooling a natural gas stream 1201, followed by a high pressure compression and expansion (HPCE) process module 1212 (similar to module 1112) and a feed gas expander-based liquefaction module 1240 (similar to module 1140), to produce an LNG stream 1230. Apparatus 1200 is similar to apparatus 1100, and similar elements are labeled with similar reference numbers. A natural gas stream 1201 flows into a first heat exchanger 1205 to be partially condensed, and is then sent to a scrub column 1202 to be separated into a column overhead stream 1203 and a column bottom stream 1204. The column overhead stream 1203 flows through the first heat exchanger 1205 to be partially condensed and forming a two-phase stream 1206. The two-

phase stream 1206 flows into a separator 1207 and is separated into a cold pretreated gas stream 1208 and a liquid stream 1209. The cold pretreated gas stream 1208 optionally flows through a Joule-Thompson (J-T) valve 1208a, and then flows through the first heat exchanger 1205, where it is warmed by indirectly exchanging heat with the column overhead stream 1203 to form a pretreated natural gas stream 1210. The liquid stream 1209 may be pressurized within a pump 1209a and then directed to the scrub column 1202 as a column reflux stream. A stripping gas stream 1276 for the reboiler operation may be sourced from the natural gas stream; alternatively, a reboiler as shown in Figure 10 may be used to provide the stripping gas for the scrub column.

10 [0088] Pretreated natural gas stream 1210 is input into an HPCE process module 1212, which is similar to HPCE module 1012 and will not be further described. The output of HPCE process module 1212 is a first chilled pretreated gas stream 1222, which is separated into a refrigerant stream 1224 and a non-refrigerant stream 1225. The refrigerant stream 1224 may comprise between 10% and 90%, or between 25% and 75%, or between 40% or 60% of the first chilled pre-treated gas stream 1222. The refrigerant stream 1224 is recycled to flow through the first heat exchanger 1205 to be warmed by indirectly exchanging heat with the column overhead stream 1203, thereby forming a warmed refrigerant stream 1226. The warmed refrigerant stream 1226 may mix with the non-refrigerant stream 1225 to form a second chilled pretreated gas stream 1227. The second chilled pretreated gas stream 1227 may then be liquefied in, for example, a feed gas expander-based liquefaction module 1240, to produce an LNG stream 1230. The J-T valve 1208a is used when the temperature of 1224 is not low enough to provide sufficient cooling energy to the heat exchanger 1205.

[0089] Figure 13 depicts a pretreatment apparatus 1300 for pretreating and pre-cooling a natural gas stream 1301, followed by a high pressure compression and expansion (HPCE) process module 1312 (similar to modules 1012, 1112, and 1212) and a feed gas expander-based liquefaction module 1340 (similar to modules 1040, 1140, and 1240), to produce an LNG stream 1330. Apparatus 1300 is similar to apparatus 1000, and similar elements are labeled with similar reference numbers. Like apparatus 1000, apparatus 1300 includes a scrub column 1302, a first heat exchanger 1305, and a separator 1307. To control the temperature of the natural gas stream 1301 entering the scrub column, a side stream 1311a of the natural gas stream 1301 may be directed to the first heat exchanger 1305 to be cooled therein and form a cooled natural gas stream 1311a. The cooled natural gas stream 1311a is combined with the natural gas stream upstream of the scrub column 1302 to form a combined natural gas stream

1301a, as depicted in Figure 13. The side stream may comprise 1% to 100%, or 10% to 90%, or 25% to 75%, or 40% to 60% of the natural gas stream 1301, depending on the temperature of the natural gas stream 1301/1301a and the desired input temperature of said natural gas stream into the scrub column.

5 [0090] The combined natural gas stream 1301a flows into scrub column 1302 and is separated into a column overhead stream 1303 and a column bottom stream 1304. The column overhead stream 1303 flows through first heat exchanger 1305 to be partially condensed and forming a two-phase stream 1306. The two-phase stream 1306 flows into separator 1307 and is separated into a cold pretreated gas stream 1308 and a liquid stream 1309. The cold pretreated
10 gas stream 1308 flows through the first heat exchanger 1305 and is warmed by indirectly exchanging heat with the column overhead stream 1303, thereby forming a pretreated natural gas stream 1310. The liquid stream 1309 may be pressurized within a pump (not shown) and then directed to the scrub column 1302 as a column reflux stream. A reboiler 1374 heats a portion 1375 of the liquids extracted from the bottom of scrub column 1302 and returns the
15 heated liquids and associated gases to the scrub column, thereby generating a stripping gas 1376 for the column. Alternatively, a stripping gas stream for the reboiler operation may be sourced from the natural gas stream 1001, as previously described.

[0091] Pretreated natural gas stream 1310 is input into an HPCE process module 1312, which is similar to HPCE process module 1012 and will not be further described. The output
20 of HPCE process module 1312 is a chilled pretreated gas stream 1322, all of which is recycled to flow through the first heat exchanger 1305 to be warmed by indirectly exchanging heat with the column overhead stream 1303, thereby forming a warmed refrigerant stream 1326. The warmed refrigerant stream 1326 may then be liquefied in, for example, a feed gas expander-based liquefaction module 1340, to produce an LNG stream 1330. Module 1340 may be similar
25 to module 1040, and therefore will not be further described. An expander 1371 may be employed to reduce the pressure and temperature of LNG stream 1330 and produce a sub-cooled LNG stream suitable for storage and transport.

[0092] Figure 14 depicts a pretreatment apparatus 1400 for pretreating and pre-cooling a natural gas stream 1401, followed by a high pressure compression and expansion (HPCE)
30 process module 1412, according to another aspect of the disclosure. Apparatus 1400 is similar to apparatus 1100, and similar elements will be labeled with similar reference numbers. Like apparatus 1100, apparatus 1400 includes a scrub column 1402, a first heat exchanger 1405, and a separator 1407. A natural gas stream 1401 is expanded and cooled by a feed gas expander

1478 to form an expanded natural gas stream 1479. The expanded natural gas stream flows into scrub column 1402 and is separated into a column overhead stream 1403 and a column bottom stream 1404. The column overhead stream 1403 flows through first heat exchanger 1405 to be partially condensed and forming a two-phase stream 1406. The two-phase stream 1406 flows into separator 1407 and is separated into a cold pretreated gas stream 1408 and a liquid stream 1409. The cold pretreated gas stream 1408 flows through the first heat exchanger 1405 and is warmed by indirectly exchanging heat with the column overhead stream 1403, thereby forming a pretreated natural gas stream 1410. The liquid stream 1409 may be pressurized within a pump (not shown) and then directed to the scrub column 1402 as a column reflux stream. A stripping gas stream 1476 for the reboiler operation may be sourced from the natural gas stream 1401; alternatively, a reboiler as shown in Figure 10 may be used to provide the stripping gas for the scrub column.

[0093] Pretreated natural gas stream 1410 is compressed in a feed gas compressor 1480 to form a compressed pretreated natural gas stream 1481, which is input into an HPCE process module 1412. The HPCE process module 1412 is similar to HPCE process module 1012 and will not be further described. Feed gas compressor 1480 may be powered by a gas turbine, or preferably, may be powered by a power output of the feed gas expander 1478. The output of HPCE process module 1412 is a chilled pretreated gas stream 1422, all of which is recycled to flow through the first heat exchanger 1405 to be warmed by indirectly exchanging heat with the column overhead stream 1403, and thereby forming a warmed refrigerant stream 1426. The warmed refrigerant stream 1426 then be liquefied in, for example, a feed gas expander-based liquefaction module 1140, to produce an LNG stream 1430. Module 1440 may be similar to module 1040 and therefore will not be further described. An expander 1471 may be employed to reduce the pressure and temperature of LNG stream 1430, to thereby produce a sub-cooled LNG stream suitable for storage and transport.

[0094] To control the temperature of the natural gas stream 1401 entering the scrub column, a side stream 1411 of the natural gas stream 1401 (or expanded natural gas stream 1479) may be directed to the first heat exchanger 1405 to be cooled therein and form a cooled natural gas stream 1411a. The cooled natural gas stream 1411a is combined with the natural gas stream upstream of the scrub column 1402 to form a combined natural gas stream 1401a, as depicted in Figure 14. The side stream may comprise 1% to 100%, or 10% to 90%, or 25% to 75%, or 40% to 60% of the natural gas stream 1401/expanded natural gas stream 1479, depending on the temperature of the natural gas stream 1401/expanded natural gas stream 1479 and the

desired input temperature of the natural gas stream into the scrub column.

[0095] Figure 15 depicts a pretreatment apparatus 1500 for pretreating and pre-cooling a natural gas stream 1501, followed by a high pressure compression and expansion (HPCE) process module 1512, according to another aspect of the disclosure. Apparatus 1500 is similar in some respects to apparatus 1100, and similar elements are labeled with similar reference numbers. Like apparatus 1100, apparatus 1500 includes a scrub column 1502 and a first heat exchanger 1505 but does not include a separator to which a cooled vapor stream from the scrub column is directed. Instead, a side stream 1511 of the natural gas stream 1501 may be directed to the first heat exchanger 1505 to be cooled therein and form a cooled natural gas stream 1511a. The cooled natural gas stream 1511a is combined with the natural gas stream upstream of the scrub column 1502 to produce a combined natural gas stream 1501a, as depicted in Figure 15. The side stream may comprise 1% to 100%, or 10% to 90%, or 25% to 75%, or 40% to 60% of the natural gas stream 1501, depending on the temperature of the natural gas stream 1501 and the desired input temperature of the natural gas stream into the scrub column 1502. The combined natural gas stream 1501a flows into scrub column 1502 and is separated into a column overhead stream 1503, which may be called a separated natural gas stream, and a column bottom stream 1504. The column bottom stream 1504 is directed to a stabilizer 1584. The stabilizer removes light hydrocarbons from the column bottom stream 1504, which is separated into a stabilizer overhead stream 1586 and a stabilized hydrocarbons liquid stream 1585. The stabilized hydrocarbons liquid stream 1585 is stable at normal storage conditions and is salable as stabilized condensate. The stabilizer overhead stream 1586 is cooled in a reflux cooler 1587 and directed to a reflux separator 1588, where it is separated into a reflux liquid stream 1589 and a recycle gas stream 1590. The reflux liquid stream 1589 may be pumped by pump 1589a, and is returned to the stabilizer 1584. The reflux liquid stream functions to wash down any heavy hydrocarbons from upflowing gas in the stabilizer. The recycle gas stream 1590 is compressed in a recycle compressor 1591 to form a compressed recycle gas stream 1592. According to disclosed aspects the recycle compressor 1591 has a much smaller capacity (e.g., 0.5 MW) than the compressors in the HPCE process module 1512. In other words, the recycle compressor 1591 may have a compression capacity of less than or equal to 0.5%, or greater than 0.5% but less than or equal to 1%, or greater than 1% but less than or equal to 5%, of the total compression power of the LNG plant. A first portion 1593 of the compressed recycle gas stream 1592 passes through the first heat exchanger 1505, where it is cooled to be partially or fully condensed, thereby forming a cooled compressed recycle gas stream 1594.

The cooled compressed recycle gas stream 1594 is directed to the scrub column 1502 as a column reflux stream. A reflux drum (not shown) may be placed in line 1594 to provide a buffer for the column reflux stream entering the scrub column. A stripping gas stream 1576 for the reboiler operation may be sourced from the natural gas stream 1001; alternatively, a reboiler as shown in Figure 10 may be used to provide the stripping gas for the scrub column.

[0096] The column overhead stream 1503 flows through first heat exchanger 1505, thereby forming a pretreated natural gas stream 1510. The pretreated natural gas stream 1510 is combined with a second portion 1592a of the compressed recycle gas stream 1592 and input into an HPCE process module 1512, which is similar to HPCE process module 1012 and will not be further described. The output of HPCE process module 1512 is a chilled pretreated gas stream 1522, all of which is recycled to flow through the first heat exchanger 1505 to be warmed by indirectly exchanging heat with the first portion 1593, thereby forming a warmed refrigerant stream 1526. The warmed refrigerant stream 1526 may then be liquefied in, for example, a feed gas expander-based liquefaction module 1540, to produce an LNG stream 1530. Module 1540 may be similar to module 1040 in Figure 10 and therefore will not be further described.

[0097] Figure 16 depicts a pretreatment apparatus 1600 for pretreating and pre-cooling a natural gas stream 1601, followed by a high pressure compression and expansion (HPCE) process module 1612, according to another aspect of the disclosure. Apparatus 1600 is similar in some respects to apparatus 1500, and similar elements are labeled with similar reference numbers. Like apparatus 1500, apparatus 1600 includes a scrub column 1602 and a first heat exchanger 1605 but does not include a separator to which a cooled vapor stream from the scrub column is directed. Instead, a side stream 1611 of the natural gas stream 1601 may be directed to the first heat exchanger 1605 to be cooled therein and form a cooled natural gas stream 1611a. The cooled natural gas stream 1611a is combined with the natural gas stream upstream of the scrub column 1602 to produce a combined natural gas stream 1601a, as depicted in Figure 16. The side stream may comprise 1% to 100%, or 10% to 90%, or 25% to 75%, or 40% to 60% of the natural gas stream 1601, depending on the temperature of the natural gas stream 1601 and the desired input temperature of the natural gas stream into the scrub column 1602. The combined natural gas stream 1601a flows into scrub column 1602 and is separated into a column overhead stream 1603, which may be called a separated natural gas stream, and a column bottom stream 1604. The column bottom stream 1604 is directed to a stabilizer 1684. The stabilizer removes light hydrocarbons from the column bottom stream 1604, which is

separated into a stabilizer overhead stream 1686 and a stabilized hydrocarbons liquid stream 1685. The stabilized hydrocarbons liquid stream 1685 is stable at normal storage conditions and is salable as stabilized condensate. The stabilizer overhead stream 1686 is cooled in a reflux cooler 1687 and directed to a reflux separator 1688, where it is separated into a reflux liquid stream 1689 and a recycle gas stream 1690. The reflux liquid stream 1689 may be pumped by pump 1689a, and is returned to the stabilizer 1684. The reflux liquid stream functions to wash down any heavy hydrocarbons from upflowing gas in the stabilizer. The recycle gas stream 1690 is compressed in a recycle compressor 1691 to form a compressed recycle gas stream 1692. According to disclosed aspects the recycle compressor 1691 has a much smaller capacity (e.g., 0.5 MW) than the compressors in the HPCE process module 1612. In other words, the recycle compressor 1691 may have a compression capacity of less than or equal to 0.5%, or greater than 0.5% but less than or equal to 1%, or greater than 1% but less than or equal to 5%, of the total compression power of the LNG plant. A first portion 1693 of the compressed recycle gas stream 1692 passes through the first heat exchanger 1605, where it is cooled to be partially or fully condensed, thereby forming a cooled compressed recycle gas stream 1694. The cooled compressed recycle gas stream 1694 is directed to the scrub column 1602 as a column reflux stream. A reflux drum (not shown) may be placed in line 1694 to provide a buffer for the column reflux stream entering the scrub column. A stripping gas stream 1676 for the reboiler operation may be sourced from the natural gas stream 1001; alternatively, a reboiler as shown in Figure 10 may be used to provide the stripping gas for the scrub column.

[0098] The pressure of the column overhead stream 1603 is reduced using a pressure-reducing device such as a Joule-Thomson valve 1603a, and the column overhead stream 1603 then flows through first heat exchanger 1605, thereby forming a pretreated natural gas stream 1610. The pretreated natural gas stream 1610 is combined with a second portion 1692a of the compressed recycle gas stream 1692 and is compressed in a feed gas compressor 1680 to form a compressed pretreated natural gas stream 1681. The feed gas compressor 1680 may be turbine-driven or motor-driven. The compressed pretreated natural gas stream 1681 may flow through a second heat exchanger 1619 to be cooled by indirectly exchanging heat with the ambient environment to form a cooled high pressure gas stream 1622. The second heat exchanger may be an air cooled heat exchanger or a water cooled heat exchanger. Because the Joule-Thomson valve 1603a reduces the pressure of the column overhead stream 1603, no expander (such as expander 1021) is required as disclosed in Figure 15. Instead, the cooled high pressure gas stream 1622 is liquefied in, for example, a feed gas expander-based

liquefaction module 1640, to produce an LNG stream 1630. Module 1640 may be similar to module 1040 in Figure 10 and therefore will not be further described. Alternatively, as shown in Figure 17, an HPCE module 1712 may be employed to compress and cool the pretreated natural gas stream 1610 prior to liquefying the cooled high pressure gas stream 1622 in the liquefaction module 1640. HPCE module 1712 is similar in structure to HPCE module 1012 and will not be further described.

[0099] It should be noted that in some circumstances, the first portion 1693 of the compressed recycle gas stream may have a higher concentration of heavy hydrocarbons (i.e., C₅₊) than the column overhead stream 1603, and in such cases it would not be necessary to reduce the pressure of the column overhead stream 1603 with a Joule-Thomson valve 1603a. Disclosed aspects may include eliminating Joule-Thomson valve 1603a, or alternatively, including a valve bypass line 1603b that selectively bypasses the Joule-Thomson valve as desired.

[0100] While the aspects disclosed in Figures 15-17 and described above may require a small additional compressor (e.g., 1591, 1691) and may not work well for very lean gas (i.e., less than 2% contaminants), the aspects disclosed in Figures 15-17 provide for higher LNG production than various other disclosed aspects. Furthermore, the separator shown in Figures 10-14 by reference numbers 1007, 1107, 1207, 1307, 1407 may be used in Figures 15-17 as a reflux drum (not shown), receiving stream 1594, 1694 before connecting to the scrub column 1502, 1602. Such a reflux drum provides buffering time and control for reflux liquid feeding the scrub column. The stabilizer, which is not shown in the other disclosed aspects but may nonetheless used in any of the disclosed aspects to produce stabilized condensate as a salable stream, is additionally employed in Figure 16 to obtain a reflux stream for the scrub column.

[0101] The aspects depicted in Figures 10-17 and described herein have employed feed gas expander-based liquefaction technologies or trains as an example technology that can be used to liquefy the natural gas. However, the disclosed aspects are equally effective when employing other types of liquefaction trains or technologies, such as single mixed refrigerant (SMR), dual mixed refrigerant (DMR), expander-based technologies using nitrogen, or other liquefaction techniques. Such liquefaction techniques are considered to be within the scope of the disclosed aspects. Additionally, the aspects disclosed herein can be used in any LNG liquefaction location, they have especial utility in circumstances where space is at a premium for LNG liquefaction, such as offshore liquefaction, onshore remote facilities, and the like. Additionally, any of the disclosed aspects may provide additional cooling for the first heat exchanger

generated by reducing the pressure and temperature of part or all of the recycled refrigerant stream using, for example, a Joule-Thomson valve, as shown in Figure 11 at 1124b.

[0102] Figure 17 is a flowchart depicting a method 1700 of producing liquefied natural gas (LNG) from a natural gas stream according to disclosed aspects. At block 1702 a portion of the natural gas stream is cooled in a first heat exchanger to generate a cooled natural gas stream. At block 1704 the cooled natural gas stream and the natural gas stream are combined to generate a combined natural gas stream, and heavy hydrocarbons are removed therefrom to thereby generate a separated natural gas stream. At block 1706 the separated natural gas stream is partially condensed in the first heat exchanger to thereby generate a partially condensed natural gas stream, and liquids are separated therefrom to thereby generate a cold pretreated gas stream and a liquid stream. At block 1708 the cold pretreated gas stream is warmed in the first heat exchanger and then compressed in at least one compressor to a pressure of at least 1,500 psia to form a compressed natural gas stream. At block 1710 the compressed natural gas stream is cooled to form a cooled compressed natural gas stream that is expanded, in at least one work producing natural gas expander, to a pressure that is less than 2,000 psia and no greater than the pressure to which the at least one compressor compresses the pretreated natural gas stream, to thereby form a chilled natural gas stream. At block 1712 the chilled natural gas stream is separated into a refrigerant stream and a non-refrigerant stream, and the refrigerant stream is recycled to exchange heat in the first heat exchanger with one or more process streams comprising at least a portion of the natural gas stream, the separated natural gas stream, and the cold pretreated gas stream, thereby generating a warmed refrigerant stream. At block 1714 the warmed refrigerant stream and the non-refrigerant stream are liquefied to form LNG.

[0103] Figure 18 is a flowchart depicting a method 1800 of producing liquefied natural gas (LNG) from a natural gas stream according to disclosed aspects. At block 1802 the natural gas stream is cooled in a first heat exchanger to generate a cooled natural gas stream. At block 1804 heavy hydrocarbons are removed from the cooled natural gas stream to thereby generate a separated natural gas stream. At block 1806 the separated natural gas stream is partially condensed in the first heat exchanger to thereby generate a partially condensed natural gas stream, and liquids are separated therefrom to thereby generate a cold pretreated gas stream and a liquid stream. At block 1808 the cold pretreated gas stream is warmed in the first heat exchanger and then compressed in at least one compressor to a pressure of at least 1,500 psia to form a compressed natural gas stream. At block 1810 the compressed natural gas stream is cooled to form a cooled compressed natural gas stream that is expanded, in at least one work

producing natural gas expander, to a pressure that is less than 2,000 psia and no greater than the pressure to which the at least one compressor compresses the pretreated natural gas stream, to thereby form a chilled natural gas stream. At block 1812 the chilled natural gas stream is separated into a refrigerant stream and a non-refrigerant stream, and the refrigerant stream is recycled to exchange heat with one or more process streams comprising the natural gas stream, the separated natural gas stream, and the cold pretreated gas stream, thereby generating a warmed refrigerant stream. At block 1814 the warmed refrigerant stream and the non-refrigerant stream are liquefied to form LNG.

[0104] Figure 19 is a flowchart depicting a method 1900 of producing liquefied natural gas (LNG) from a natural gas stream according to disclosed aspects. At block 1902 a portion of the natural gas stream is cooled in a first heat exchanger to generate a cooled natural gas stream. At block 1904 the cooled natural gas stream and the natural gas stream are combined to generate a combined natural gas stream, and heavy hydrocarbons are removed therefrom to thereby generate a separated natural gas stream. At block 1906 the separated natural gas stream is partially condensed in the first heat exchanger to thereby generate a partially condensed natural gas stream, and liquids are separated therefrom to thereby generate a cold pretreated gas stream and a liquid stream. At block 1908 the cold pretreated gas stream is warmed in the first heat exchanger and then compressed in at least one compressor to a pressure of at least 1,500 psia to form a compressed natural gas stream. At block 1910 the compressed natural gas stream is cooled to form a cooled compressed natural gas stream that is expanded, in at least one work producing natural gas expander, to a pressure that is less than 2,000 psia and no greater than the pressure to which the at least one compressor compresses the pretreated natural gas stream, to thereby form a chilled natural gas stream. At block 1912 the chilled natural gas stream is recycled through heat exchange with one or more process streams comprising the portion of the natural gas stream, the separated natural gas stream, and the cold pretreated gas stream, thereby generating a warmed refrigerant stream. At block 1914 the warmed refrigerant stream is liquefied to form LNG.

[0105] Figure 20 is a flowchart showing a method 2000 of producing liquefied natural gas (LNG) from a natural gas stream according to disclosed aspects. At block 2002 a portion of the natural gas stream is cooled in a first heat exchanger to generate a cooled natural gas stream. At block 2004 the cooled natural gas stream and the natural gas stream are combined to generate a combined natural gas stream, and heavy hydrocarbons are removed therefrom in a separator to thereby generate a separated natural gas stream and a separator bottom stream. At

block 2006 liquids are separated from the separator bottom stream to form an overhead stream, which is cooled and separated to form a recycle gas stream. At block 2008 the recycle gas stream is compressed in a recycle compressor to form a compressed recycle gas stream. At block 2010 a first portion of the compressed recycle gas stream is directed through the first
5 heat exchanger to form a cooled compressed recycle stream therefrom, and the cooled compressed recycle stream is directed to the separator as a column reflux stream. At block 2012 the separated natural gas stream is used as a coolant in the first heat exchanger to thereby generate a pretreated natural gas stream. At block 2014 a second portion of the compressed recycle gas stream and the pretreated natural gas stream are compressed in at least one
10 compressor to a pressure of at least 1,500 psia to form a compressed natural gas stream, and the compressed natural gas stream is cooled to form a cooled compressed natural gas stream. At block 2016 the cooled compressed natural gas stream is expanded, in at least one work producing natural gas expander, to a pressure that is less than 2,000 psia and no greater than the pressure to which the at least one compressor compresses the pretreated natural gas stream,
15 to thereby form a chilled pretreated gas stream. At block 2018 the chilled pretreated gas stream is recycled to exchange heat with one or more process streams comprising at least a portion of the natural gas stream, the separated natural gas stream, and the first portion of the compressed recycle gas stream, thereby generating a warmed refrigerant stream. At block 2020 the warmed refrigerant stream is liquefied to form LNG.

20 **[0106]** Figure 21 is a flowchart depicting a method 2100 of producing liquefied natural gas (LNG) from a natural gas stream according to disclosed aspects. At block 2102 a portion of the natural gas stream is cooled in a first heat exchanger to generate a cooled natural gas stream. At block 2104 the cooled natural gas stream and the natural gas stream are combined to generate a combined natural gas stream, and heavy hydrocarbons are removed therefrom in a
25 separator to thereby generate a separated natural gas stream and a separator bottom stream. At block 2106 liquids are separated from the separator bottom stream to form an overhead stream, which is cooled and separated to form a recycle gas stream. At block 2108 the recycle gas stream is compressed in a recycle compressor to form a compressed recycle gas stream. At block 2110 a first portion of the compressed recycle gas stream is directed through the first
30 heat exchanger to form a cooled compressed recycle stream therefrom, and the cooled compressed recycle stream is directed to the separator as a column reflux stream. At block 2112 a pressure and a temperature of the separated natural gas stream are reduced in a pressure reducing device, and the separated natural gas stream is then used as a coolant in the first heat

exchanger to thereby generate a pretreated natural gas stream. At block 2114 a second portion of the compressed recycle gas stream and the pretreated natural gas stream are compressed in a feed compressor to a pressure of at least 1,500 psia to form a compressed natural gas stream, which is cooled to form a cooled high pressure gas stream. At block 2116 the cooled high pressure gas stream is liquefied to form LNG.

[0107] 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.