(12) STANDARD PATENT
(19) AUSTRALIAN PATENT OFFICE

(11) Application No. **AU 2018218196 B2**

(54) Title
Pre-cooling of natural gas by high pressure compression and expansion

(51) International Patent Classification(s)
F25J 1/00 (2006.01) ***F25J 1/02*** (2006.01)

(21) Application No: **2018218196** (22) Date of Filing: **2018.01.15**

(87) WIPO No: **WO18/147973**

(30) Priority Data

(31) Number	(32) Date	(33) Country
62/458,127	**2017.02.13**	**US**

(43) Publication Date: **2018.08.16**
(44) Accepted Journal Date: **2021.04.08**

(71) Applicant(s)
ExxonMobil Upstream Research Company

(72) Inventor(s)
Pierre Jr., Fritz

(74) Agent / Attorney
Allens Patent & Trade Mark Attorneys, 101 Collins St, MELBOURNE, VIC, 3000, AU

(56) Related Art
CN 102206520 A

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
16 August 2018 (16.08.2018)

WIPO | PCT

(10) International Publication Number
WO 2018/147973 A1

(51) **International Patent Classification:**
F25J 1/00 (2006.01) *F25J 1/02* (2006.01)

(21) **International Application Number:**
PCT/US2018/013701

(22) **International Filing Date:**
15 January 2018 (15.01.2018)

(25) **Filing Language:** English

(26) **Publication Language:** English

(30) **Priority Data:**
62/458,127 13 February 2017 (13.02.2017) US

(71) **Applicant** *(for all designated States except US)*: **EXXONMOBIL UPSTREAM RESEARCH COMPANY** [US/US]; (EMHC-E2-4A-296), 22777 Springwoods Village Parkway, Spring, TX 77389 (US).

(72) **Inventor; and**
(71) **Applicant** *(for US only)*: **PIERRE, Fritz, Jr.** [US/US]; 18011 Bayou Mead Trail, Humble, TX 77346 (US).

(74) **Agent: JENSEN, Nathan, O.** et al.; Exxonmobil Upstream Research Company, (emhc-e2-4a-296), 22777 Springwoods Village Parkway, Spring, TX 77389 (US).

(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV,

(54) **Title:** PRE-COOLING OF NATURAL GAS BY HIGH PRESSURE COMPRESSION AND EXPANSION

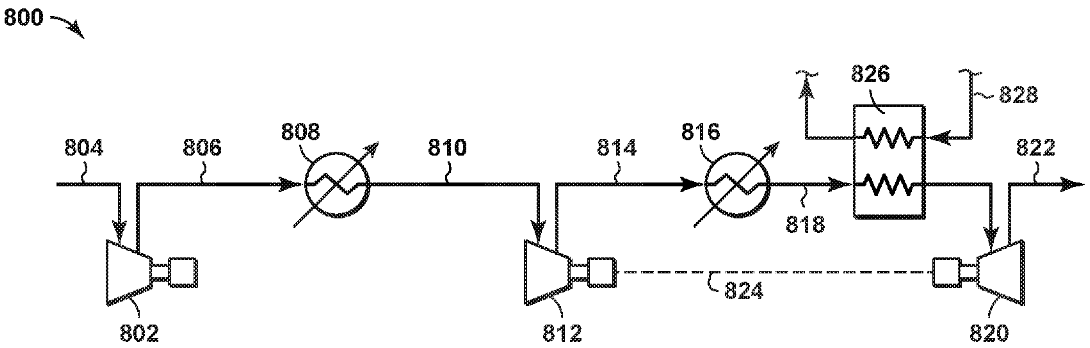

FIG. 8

(57) **Abstract:** A method of producing liquefied natural gas (LNG) is disclosed. A natural gas is compressed in at least two serially arranged compressors to a pressure of at least 2,000 psia and cooled to form a cooled compressed natural gas stream. The cooled compressed natural gas stream is additionally cooled to a temperature below an ambient temperature to form an additionally cooled compressed natural gas stream, which is expanded in at least one work producing natural gas expander to a pressure that is less than 3,000 psia and no greater than the pressure to which the at least two serially arranged compressors compress the natural gas stream, to thereby form a chilled natural gas stream. The chilled natural gas stream is liquefied by indirect heat exchange with a refrigerant to form liquefied natural gas and a warm refrigerant. The cooled compressed natural gas stream is additionally cooled using the warm refrigerant.

WO 2018/147973 A1

[Continued on next page]

MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

- *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*
- *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

Published:

- *with international search report (Art. 21(3))*
- *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

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

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the priority benefit of United States Patent Application 62/458,127 filed February 13, 2017 entitled PRE-COOLING OF NATURAL GAS BY HIGH PRESSURE COMPRESSION AND EXPANSION, the entirety of which is incorporated by reference herein.

[0002] This application is related to U.S. Provisional Patent Application No. 62/458,131, titled "Increasing Efficiency in an LNG Production System by Pre-cooling a Natural Gas Feed Stream," having a common inventor and assignee and filed on an even date herewith, the disclosure of which is incorporated by reference herein in its entirety.

FIELD OF THE INVENTION

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

BACKGROUND

[0004] LNG production is a rapidly growing means to supply natural gas from locations with an abundant supply of natural gas to distant locations with a strong demand for natural gas. The conventional LNG production cycle includes: a) initial treatments of the natural gas resource to remove contaminants such as water, sulfur compounds and carbon dioxide; b) the separation of some heavier hydrocarbon gases, such as propane, butane, pentane, etc. by a variety of possible methods including self-refrigeration, external refrigeration, lean oil, etc.; c) refrigeration of the natural gas substantially by external refrigeration to form liquefied natural gas at near atmospheric pressure and about -160 °C; d) transport of the LNG product in ships or tankers designed for this purpose to a market location; e) re-pressurization and regasification of the LNG at a regasification plant to a pressurized natural gas that may distributed to natural gas consumers. Step (c) of the conventional LNG cycle usually requires the use of large refrigeration compressors often powered by large gas turbine drivers that emit substantial carbon and other emissions. Large capital investment in the billions of US dollars and extensive infrastructure are required as part of the liquefaction plant. Step (e) of the conventional LNG cycle generally includes re-pressurizing the LNG to the required pressure using cryogenic pumps and then re-gasifying the LNG to pressurized natural gas by exchanging heat through an intermediate fluid but ultimately with seawater or by combusting a portion of the natural gas to heat and vaporize the LNG.

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

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

[0007] In contrast to the DMR process, the SMR process has the advantage of allowing all the equipment and bulks associated with the complete liquefaction process to fit within a single FLNG module. The SMR liquefaction module is placed on the topside of the FLNG structure as a complete SMR train. This “LNG-in-a-Box” concept is favorable for FLNG project execution because it allows for the testing and commissioning of the SMR train at a different location from where the FLNG structure is constructed. It may also allow for the reduction in labor cost since it reduces labor hours at ship yards where labor rates tend to be higher than labor rates at conventional fabrication yards. The SMR process has the added advantage of being a relatively efficient, simple, and compact refrigerant process when compared to other mixed refrigerant processes. Furthermore, the SMR liquefaction process is typically 15% to 20% more efficient than expander-based liquefaction processes.

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

[0009] The expander-based process has several advantages that make it well suited for FLNG projects. The most significant advantage is that the technology offers liquefaction without the need for external hydrocarbon refrigerants. Removing liquid hydrocarbon refrigerant inventory, such as propane storage, significantly reduces safety concerns on FLNG projects. An additional advantage of the expander-based process compared to a mixed refrigerant process is that the expander-based process is less sensitive to offshore motions since the main refrigerant mostly remains in the gas phase. However, application of the expander-based process to an FLNG project with LNG production of greater than 2 million tons per year (MTA) has proven to be less appealing than the use of the mixed refrigerant process. The capacity of an expander-based process train is typically less than 1.5 MTA. In contrast, a mixed refrigerant process train, such as that of known dual mixed refrigerant processes, can have a train capacity of greater than 5 MTA. The size of the expander-based process train is limited since its refrigerant mostly remains in the vapor state throughout the entire process and the refrigerant absorbs energy through its sensible heat. For these reasons, the refrigerant volumetric flow rate is large throughout the process, and the size of the heat exchangers and piping are proportionately greater than those of a mixed refrigerant process. Furthermore, the limitations in compander horsepower size results in parallel rotating machinery as the capacity of the expander-based process train increases. The production rate of an FLNG project using an expander-based process can be made to be greater than 2 MTA if multiple expander-based trains are allowed. For example, for a 6 MTA FLNG project, six or more parallel expander-based process trains may be sufficient to achieve the required production. However, the equipment count, complexity and cost all increase with multiple expander trains. Additionally, the assumed process simplicity of the expander-based process compared to a mixed refrigerant process begins to be questioned if multiple trains are required for the expander-based process while the mixed refrigerant process can obtain the required production rate with one or two trains. For these reasons, there is a need to develop a high LNG production capacity FLNG liquefaction process with the advantages of an expander-based process. There is a further need to develop an FLNG technology solution that is better able to handle the challenges that vessel motion has on gas processing.

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

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

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

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

[0014] Thus, there remains a need to develop a pre-cooling process that does not require additional refrigerant and does not introduce a significant amount of extra equipment to the LNG liquefaction process. There is an additional need to develop a pre-cooling process that can be placed in the same module as the liquefaction module. Such a pre-cooling process combined with an SMR process or an expander-based process would be particularly suitable for FLNG applications where topside space and weight significantly impacts the project economics. There remains a specific need to develop an LNG production process with the advantages of an expander-based process and which, in addition, has a high LNG production capacity without significantly increasing facility footprint. There is a further need to develop an LNG technology solution that is better able to handle the challenges that vessel motion has on gas processing. Such a high capacity expander-based liquefaction process would be particularly suitable for FLNG applications where the inherent safety and simplicity of expander-based liquefaction process are greatly valued.

SUMMARY OF THE INVENTION

[0015] The invention provides a method of producing liquefied natural gas (LNG). A natural gas stream is provided from a supply of natural gas. The natural gas stream may be compressed in at least two serially arranged compressors to a pressure of at least 2,000 psia to form a compressed natural gas stream. The compressed natural gas stream may be cooled by indirect heat exchange with an ambient temperature air or water to form a cooled compressed natural gas stream. The cooled compressed natural gas stream may be additionally cooled to a temperature below the ambient temperature to form an additionally cooled compressed natural gas stream. The additionally cooled compressed natural gas stream may be expanded in at least one work producing natural gas expander to a pressure that is less than 3,000 psia and no greater than the pressure to which the at least two serially arranged compressors compress the natural gas stream, to thereby form a chilled natural gas stream. The chilled natural gas stream may then be liquefied by indirect heat exchange with a refrigerant to form liquefied natural gas and a warm refrigerant. The cooled compressed natural gas stream is additionally cooled using the warm refrigerant.

[0016] The invention also provides an apparatus for the liquefaction of natural gas. At least two serially arranged compressors compress a natural gas stream to a pressure greater than 2,000 psia, thereby forming a compressed natural gas stream. A cooling element cools the compressed natural gas stream to form a cooled compressed natural gas stream. A heat exchanger further cools the cooled compressed natural gas stream to a temperature below an ambient temperature to thereby produce an additionally cooled compressed natural gas stream. At least one work-producing expander expands the additionally cooled compressed natural gas stream to a pressure less than 3,000 psia and no greater than the pressure to which the at least two serially arranged compressors compress the natural gas stream, to thereby form a chilled natural gas stream. A liquefaction train liquefies the chilled natural gas stream. A warm refrigerant used by the liquefaction train is directed to the heat exchanger to further cool the cooled compressed natural gas stream.

[0017] The invention further provides a floating LNG structure. At least two serially arranged compressors compress a natural gas stream to a pressure greater than 2,000 psia, thereby forming a compressed natural gas stream. A cooling element cools the compressed natural gas stream to form a cooled compressed natural gas stream. A heat exchanger further cools the cooled compressed natural gas stream to a temperature below an ambient temperature to thereby produce an additionally cooled compressed natural gas stream. At least one work-producing expander expands the additionally cooled compressed natural gas stream to a pressure less than 3,000 psia and no greater than the pressure to which the at least two serially arranged compressors compress the natural gas stream, to thereby form a chilled natural gas stream. A liquefaction train liquefies the chilled natural gas stream. A warm refrigerant used by the liquefaction train is directed to the heat exchanger to further cool the cooled compressed natural gas stream.

BRIEF DESCRIPTION OF THE FIGURES

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

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

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

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

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

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

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

[0025] **Figure 8** is a schematic diagram of a high pressure compression and expansion (HPCE) module according to disclosed aspects.

[0026] **Figure 9** is a schematic diagram of an HPCE module and a feed gas expander-based liquefaction module according to disclosed aspects.

[0027] **Figure 10** is a schematic diagram of an HPCE module and a feed gas expander-based liquefaction module according to disclosed aspects.

[0028] **Figure 11** is a schematic diagram of an HPCE module and a feed gas expander-based liquefaction module according to disclosed aspects.

[0029] **Figure 12** is a flowchart of a method of liquefying natural gas to form LNG according to disclosed aspects.

DETAILED DESCRIPTION

[0030] 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.

[0031] 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.

[0032] As used herein, the term "compressor" means a machine that increases the pressure of a gas by the application of work. A "compressor" or "refrigerant compressor" includes any unit, device, or apparatus able to increase the pressure of a gas stream. This includes compressors having a single compression process or step, or compressors having multi-stage compressions or steps, or more particularly multi-stage compressors within a single casing or shell. Evaporated streams to be compressed can be provided to a compressor at different pressures. Some stages or steps of a cooling process may involve two or more compressors in parallel, series, or both. The present invention is not limited by the type or arrangement or layout of the compressor or compressors, particularly in any refrigerant circuit.

[0033] 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.

[0034] 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.

[0035] The term "gas" is used interchangeably with "vapor," and is defined as a substance or mixture of substances in the gaseous state as distinguished from the liquid or solid state. Likewise, the term "liquid" means a substance or mixture of substances in the liquid state as distinguished from the gas or solid state.

[0036] A "heat exchanger" broadly means any device capable of transferring heat energy or cold energy from one medium to another medium, such as between at least two distinct fluids. Heat exchangers include "direct heat exchangers" and "indirect heat exchangers." Thus, a heat exchanger may be of any suitable design, such as a co-current or counter-current heat exchanger, an indirect heat exchanger (e.g. a spiral wound heat exchanger or a plate-fin heat exchanger such as a brazed aluminum plate fin type), direct contact heat exchanger, shell-and-tube heat exchanger, spiral, hairpin, core, core-and-kettle, printed-circuit, double-pipe or any other type of known heat exchanger. "Heat exchanger" may also refer to any column, tower, unit or other arrangement adapted to allow the passage of one or more streams therethrough, and to affect direct or indirect heat exchange between one or more lines of refrigerant, and one or more feed streams.

[0037] As used herein, the term "indirect heat exchange" means the bringing of two fluids into heat exchange relation without any physical contact or intermixing of the fluids with each other. Core-in-kettle heat exchangers and brazed aluminum plate-fin heat exchangers are examples of equipment that facilitate indirect heat exchange.

[0038] As used herein, the term "natural gas" refers to a multi-component gas obtained from a crude oil well (associated gas) or from a subterranean gas-bearing formation (non-associated gas). The composition and pressure of natural gas can vary significantly. A typical natural gas stream contains methane (C_1) as a significant component. The natural gas stream may also contain ethane (C_2), higher molecular weight hydrocarbons, and one or more acid gases. The natural gas may also contain minor amounts of contaminants such as water, nitrogen, iron sulfide, wax, and crude oil.

[0039] 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.

[0040] 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.

[0041] Aspects disclosed herein describe a process for pre-cooling natural gas to a liquefaction process for the production of LNG by the addition of a high pressure compression and high pressure expansion process to the feed gas. More specifically, the invention describes a process where a pretreated natural gas is compressed to pressure greater than 2,000 psia (13,790 kPa), or more preferably greater than 3,000 psia (20,680 kPa). The hot compressed gas is cooled by exchanging heat with the environment to form a compressed pretreated gas. The cooled compressed gas is additionally cooled to a temperature below the ambient temperature to form an additionally cooled compressed pretreated gas stream. The additionally cooled compressed pretreated gas stream is near-isentropically expanded to a pressure less than 3,000 psia (20,680 kPa), or more preferably to a pressure less than 2,000 psia (13,790 kPa) to form a chilled pretreated gas, where the pressure of the chilled pretreated gas is less than the pressure of the compressed pretreated gas. The chilled pretreated gas may be directed to one or more SMR liquefaction trains, or the chilled pretreated gas may be directed to one or more expander-based liquefaction trains where the gas is further cooled to form LNG. Aspects described herein may be related to and/or further described in one or more of the following patent applications: U.S. Patent Publication number 2017/0167788 titled "Method and System for Separating Nitrogen from Liquefied Natural Gas Using Liquefied Nitrogen;" U.S. Patent Publication No. 2017/0167785 titled "Expander-Based LNG Production Processes Enhanced With Liquid Nitrogen;" U.S. Patent Publication No. 2017/0167787 titled "Method of Natural Gas Liquefaction on LNG Carriers Storing Liquid Nitrogen;" and U.S. Patent Publication 2017/0167786, titled "Pre-cooling of Natural Gas by High Pressure Compression and Expansion;" all having a common assignee and filed on November 10, 2016, the disclosures of which are incorporated by reference herein in their entirety.

[0042] Figure 1 is an illustration of an aspect of the pre-cooling process. The pre-cooling process is referred to herein as a high pressure compression and expansion (HPCE) process **100**. The HPCE process **100** may comprise a first compressor **102** which compresses a pretreated natural gas stream **104** to form an intermediate pressure gas stream **106**. The intermediate pressure gas stream **106** may flow through a first heat exchanger **108** where the intermediate pressure gas stream **106** is cooled by indirectly exchanging heat with the environment to form a cooled intermediate pressure gas stream **110**. The first heat exchanger **108** may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled intermediate pressure gas stream **110** may then be compressed within a second compressor **112** to form a high pressure gas stream **114**. The pressure of the high pressure gas stream **114** may be greater than 2,000 psia (13,790 kPa), or more preferably greater than 3,000 psia (20,680 kPa). The high pressure gas stream **114** may flow through a second heat exchanger **116** where the high pressure gas stream **114** is cooled by indirectly exchanging heat with the environment to form a cooled high pressure gas stream **118**. The second heat exchanger **116** may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled high pressure gas stream **118** may then be expanded within an expander **120** to form a chilled pretreated gas stream **122**. The pressure of the chilled pretreated gas stream **122** may be less than 3,000 psia (20,680 kPa), or more preferably less than 2,000 psia (13,790 kPa), and the pressure of the chilled pretreated gas stream **122** is less than the pressure of the cooled high pressure gas stream **118**. In a preferred aspect, the second compressor **112** may be driven solely by the shaft power produced by the expander **120**, as indicated by the dashed line **124**.

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

[0044] The combination of the HPCE process with SMR trains has several advantages over the conventional SMR process where pretreated natural gas is sent directly to the SMR liquefaction trains. For example, the precooling of the natural gas using the HPCE process allows for an increase in LNG production rate within the SMR trains for a given horsepower within the SMR trains. As described with respect to Figures 3 and 4, SMR trains that are each powered by a gas turbine having an output of about 50 megawatts (MW) can be reduced from five trains producing LNG at 1.5 MTA each to four trains with an increased capacity of 1.9 MTA each. For this given example, the HPCE module has effectively replaced one of the SMR modules. The replacement of one SMR module for an HPCE module is advantageous since the HPCE module is expected to be smaller, of less weight, and having significantly lower cost than the SMR module. Like the SMR module, the HPCE module may have an equivalent size gas turbine to provide compression power, and it will also have an equivalent amount of air or water coolers. Unlike the SMR module, however, the HPCE module does not have an expensive main cryogenic heat exchanger. The vessels and pipes associated with the refrigerant flow within an SMR module are eliminated in the HPCE module. Furthermore, there are no expensive cryogenic pipes in the HPCE module and all the fluid streams remain in a single phase in the HPCE module.

[0045] Another advantage is that the required storage of refrigerant is reduced since the number of SMR trains has been reduced by one. Also, since a large fraction of the warm temperature cooling of the gas occurs in the HPCE module, the heavier hydrocarbon components of the mixed refrigerant can be reduced. For example, the propane component of the mixed refrigerant may be eliminated without any significant reduction in efficiency of the SMR process.

[0046] Another advantage is that for the SMR process which receives chilled pretreated gas from the HPCE process, the volumetric flow rate of the vaporized refrigerant of the SMR process can be more than 25% less than that of a conventional SMR process receiving warm pretreated gas. The lower volumetric flow of refrigerant may reduce the size of the main cryogenic heat exchanger and the size of the low pressure mixed refrigerant compressor. The lower volumetric flow rate of the refrigerant is due to its higher vaporizing pressure compared to that of a conventional SMR process.

[0047] Known propane-precooled mixed refrigeration processes and dual mixed refrigeration (DMR) processes may be viewed as versions of an SMR process combined with a pre-cooling refrigeration circuit, but there are significant differences between such processes and aspects of the present disclosure. For example, the known processes use a cascading propane refrigeration circuit or a warm-end mixed refrigerant to pre-cool the gas. Both these known processes have the advantage of providing 5% to 15% higher efficiency than the SMR process. Furthermore, the capacity of a single liquefaction train using these known processes can be significantly greater than that of a single SMR train. The pre-cooling refrigeration circuit of these technologies, however, comes at the cost of added complexity to the liquefaction process since additional refrigerants and a substantial amount of extra equipment is introduced. For example, the DMR's disadvantage of higher complexity and weight may outweigh its advantages of higher efficiency and capacity when deciding between and DMR process and SMR process for an FLNG application. The known processes have considered the addition of a pre-cooling process upstream of the SMR process as being driven principally by the need for higher thermal efficiencies and higher LNG production capacity for a single train. The HPCE process combined with the SMR process has not been realized previously because it does not provide the higher thermal efficiencies that the refrigerant-based precooling process provides. As described above, the thermal efficiency of the HPCE process with SMR is about the same as a standalone SMR process. The disclosed aspects are believed to be novel based at least in part on its description of a pre-cooling process that aims to reduce the weight and complexity of the liquefaction process rather than increase thermal efficiency, which in the past has been the biggest driver for the addition of a pre-cooling process for onshore LNG applications. For the newer applications of FLNG, footprint, weight, and complexity of the liquefaction process may be a bigger driver of project cost. Therefore the disclosed aspects are of particular value.

[0048] In an aspect, an expander-based liquefaction process may be enhanced by the addition of an HPCE process upstream of the expander-based process. More specifically, in this aspect, a pretreated natural gas stream may be compressed to pressure greater than 2,000 psia (13,790 kPa), or more preferably greater than 3,000 psia (20,680 kPa). The hot compressed gas may then be cooled by exchanging heat with the environment to form a compressed pretreated gas. The compressed pretreated gas may be near-isentropically expanded to a pressure less than 3,000 psia (20,680 kPa), or more preferably to a pressure less than 2,000 psia (13,790 kPa) to form a chilled pretreated gas, where the pressure of the chilled pretreated gas is less than the pressure of the compressed pretreated gas. The chilled pretreated gas is directed to an expander-based process where the gas is further cooled to form LNG. In a preferred aspect, the chilled pretreated gas may be directed to a feed gas expander-based process.

[0049] Figure 2 shows a typical temperature cooling curve **200** for an expander-based liquefaction process. The higher temperature curve **202** is the temperature curve for the natural gas stream. The lower temperature curve **204** is the composite temperature curve of a cold cooling stream and a warm cooling stream. As illustrated, the cooling curve is marked by three temperature pinch-points **206**, **208**, and **210**. Each pinch point is a location within the heat exchanger where the combined heat capacity of the cooling streams is less than that of the natural gas stream. This imbalance in heat capacity between the streams results in reduction in the temperature difference between the cooling streams to the minimally acceptable temperature difference which provides effective heat transfer rate. The lowest temperature pinch-point **206** occurs where the colder of the two cooling streams, typically the cold cooling stream, enters the heat exchanger. The intermediate temperature pinch-point **208** occurs where the second cooling stream, typically the warm cooling stream, enters the heat exchanger. The warm temperature pinch-point **210** occurs where the cold and warm cooling streams exit the heat exchanger. The warm temperature pinch-point **210** causes a need for a high mass flow rate for the warmer cooling stream, which subsequently increases the power demand of the expander-based process.

[0050] One proposed method to eliminate the warm temperature pinch-point **210** is to precool the feed gas with an external refrigeration system such as a propane cooling system or a carbon dioxide cooling system. For example, United States Patent No. 7,386,996 eliminates the warm temperature pinch-point by using a pre-cooling refrigeration process comprising a carbon dioxide refrigeration circuit in a cascade arrangement. This external pre-cooling refrigeration system has the disadvantage of significantly increasing the complexity of the liquefaction process since an additional refrigerant system with all its associated equipment is introduced. Aspects disclosed herein reduce the impact of the warm temperature pinch-point **210** by precooling the feed gas stream by compressing the feed gas to a pressure greater than 2,000 psia (12,790 kPa), cooling the compressed feed gas stream, and expanding the compressed gas stream to a pressure less than 3,000 psia (20,690 kPa), where the expanded pressure of the feed gas stream is less than the compressed pressure of the feed gas stream. This process of cooling the feed gas stream results in a significant reduction in the in the required mass flow rate of the expander-based process cooling streams. It also improves the thermodynamic efficiency of the expander-based process without significantly increasing the equipment count and without the addition of an external refrigerant.

[0051] In a preferred aspect, the expander-based process may be a feed gas expander-based process. The feed gas expander-based process may be an open loop feed gas process where the recycling loop comprises a warm-end expander loop and a cold-end expander loop. The warm-end expander may discharge a first cooling stream and the cold-end expander may discharge the second cooling stream. The temperature of the first cooling stream is higher than the temperature of the second cooling stream. In an aspect, the pressure of the first cooling stream is higher than the pressure of the second cooling stream. In another aspect, the cold-end expander discharges a two-phase stream that is separated into a second cooling stream and a second pressurize LNG stream. Specifically, a produced natural gas stream may be treated to remove impurities, if present, such as water, heavy hydrocarbons, and sour gases, to make the natural gas suitable for liquefaction. The treated natural gas may be directed to the HPCE process where it is compressed to a pressure greater than 2,000 psia (12,790 kPa), or more preferably greater than 3,000 psia (20,680 kPa). The hot compressed gas may then be cooled by exchanging heat with the environment to form a compressed treated natural gas. The compressed treated natural gas may be near-isentropically expanded to a pressure less than

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

[0052] The combination of the HPCE process with the feed gas expander-based process has several advantages over a conventional feed gas expander-based process. Including the HPCE process therewith may increase the efficiency of the of the feed gas expander-based process by 20 to 25%. Thus, the feed-gas expander process of this invention has an efficiency approaching that of an SMR process while still providing the advantages of no external refrigerant use, ease of operation, and reduced equipment count. Furthermore, the refrigerant flow rates and the size of the recycle compressors are expected to be significantly lower for the 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 50% above the production capacity of a similarly sized conventional expander-based liquefaction process.

[0053] Figure 3 is an illustration of an arrangement of SMR liquefaction modules on a FLNG **300**. Natural gas **302** that is pretreated or otherwise suitable for liquefaction may be distributed evenly between five identical or near identical SMR liquefaction modules or trains **304**, **306**, **308**, **310**, **312**. As an example, each SMR liquefaction module may receive approximately 50 MW of compression power from either a gas turbine or an electric motor (not shown) to drive the compressors of the SMR liquefaction modules. Each SMR liquefaction module may produce approximately 1.5 MTA of LNG for a total stream day production of approximately 7.5 MTA of LNG for the FLNG application.

[0054] Figure 4 is an illustration of an arrangement of an HPCE module **404** with the SMR liquefaction modules or trains **406**, **408**, **410**, **412** on a FLNG **400** according to disclosed aspects. Natural gas **402** that is pretreated or otherwise suitable for liquefaction may be directed to the HPCE module **404** to produce a chilled pretreated gas stream **405**. The HPCE module **404** may receive approximately 50 MW of compression power, for example, from either a gas turbine or an electric motor (not shown) to drive one or more compressors within the HPCE module **404**. The chilled pretreated gas may be distributed evenly between the four identical or near identical SMR liquefaction modules **406**, **408**, **410**, **412**. Each SMR liquefaction module may receive approximately 50 MW of compression power from either a gas turbine or an electric motor (not shown) to drive the compressors of the respective SMR liquefaction modules. Each SMR liquefaction module may produce approximately 1.9 MTA of LNG for a total stream day production of approximately 7.6 MTA of LNG for the FLNG application.

[0055] Figure 5 is an illustration of an aspect of the HPCE module **500** referenced in Figure 4. A natural gas stream **502** that has been pretreated to remove impurities, or is otherwise suitable for liquefaction, is fed into a first compressor **504** to form a first intermediate pressure gas stream **506**. The first intermediate pressure gas stream **506** may flow through a first heat exchanger **508** where the first intermediate pressure gas stream **506** is cooled by indirectly exchanging heat with the environment to form a cooled first intermediate pressure gas stream **510**. The first heat exchanger **508** may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled first intermediate pressure gas stream **510** may then be compressed within a second compressor **512** to form a second intermediate pressure gas stream **514**. The second intermediate pressure gas stream **514** may flow through a second heat exchanger **516** where the second intermediate pressure gas stream **514** is cooled by indirectly exchanging heat with the environment to form a cooled second intermediate pressure gas stream **518**. The second heat exchanger **516** may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled second intermediate pressure gas stream **518** may then be compressed within a third compressor **520** to form a high pressure gas stream **522**. The pressure of the high pressure gas stream **522** may be greater than 2,000 psia (13,790 kPa), or more preferably greater than 3,000 psia (20,680 kPa). The high pressure gas stream **522** may flow through a third heat exchanger **524** where the high pressure gas stream **522** is cooled by indirectly exchanging heat with the environment to form a cooled high pressure gas stream **526**. The third heat exchanger **524** may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled high pressure gas stream **526** may then be expanded within an expander **528** to form a chilled pretreated gas stream **530**. The pressure of the chilled pretreated gas stream **530** may be less than 3,000 psia (20,680 kPa), or more preferably less than 2,000 psia (13,790 kPa), and the pressure of the chilled pretreated gas stream **530** may be less than the pressure of the cooled high pressure gas stream **526**. In an aspect, the third compressor **520** may be driven solely by the shaft power produced by the expander **528**, as illustrated by line **532**.

[0056] Figure 6 is an illustration of an HPCE process **601** combined with a feed gas expander-based LNG liquefaction process **600**. Natural gas may be treated to remove impurities, if present, such as water, heavy hydrocarbons, and sour gases, to produce a treated natural gas stream **602** that is suitable for liquefaction. The treated natural gas stream **602** may be mixed with a recycled refrigerant gas stream **604** to form a combined stream **606**. The combined stream **606** may be directed to the HPCE process **601** where the combined streams **606** are compressed within a first compressor **608** to form an intermediate pressure gas stream **610**. The intermediate pressure gas stream **610** may flow through a first heat exchanger **612** where the intermediate pressure gas stream **610** is cooled by indirectly exchanging heat with the environment to form a cooled intermediate pressure gas stream **614**. The first heat exchanger **612** may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled intermediate pressure gas stream **614** may then be compressed within a second compressor **616** to form a high pressure gas stream **618**. The pressure of the high pressure gas stream **618** may be greater than 2,000 psia (13,790 kPa), or more preferably greater than 3,000 psia (20,680 kPa). The high pressure gas stream **618** may flow through a second heat exchanger **620** where the high pressure gas stream **618** is cooled by indirectly exchanging heat with the environment to form a cooled high pressure gas stream **622**. The second heat exchanger **620** may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled high pressure gas stream **622** may then be expanded within an HPCE expander **624** to form a chilled pretreated gas stream **626**. The pressure of the chilled pretreated gas stream **626** is less than 3,000 psia (20,680 kPa), or more preferably less than 2,000 psia (13,790 kPa), and where the pressure of the chilled pretreated gas stream **626** is less than the pressure of the cooled high pressure gas stream **622**. In an aspect, the second compressor **616** may be driven solely by the shaft power produced by the expander **624**, as represented by the dashed line **628**.

[0057] As illustrated in Figure 6, the chilled pretreated gas stream **626** leaves the HPCE process **601** and is directed to a feed gas expander-based process **600**. The chilled pretreated gas stream **626** may be separated into a second chilled pretreated gas stream **630**, a first refrigerant stream **632**, and a second refrigerant stream **634**. The first refrigerant stream **632** may be expanded in a first expander **636** to produce a first cooling stream **638**. The first cooling stream **638** enters at least one cryogenic heat exchanger **640** where it exchanges heat with the second chilled pretreated gas stream **630** and the second refrigerant stream **634** to cool said streams. The first cooling stream **638** exits the at least one cryogenic heat exchanger **640** as a first warm stream **642**. The second refrigerant stream **634**, after being cooled in the at least one cryogenic heat exchanger **640**, may be expanded in a second expander **644** to produce a two-phase stream **646**. The pressure of the two-phase stream **646** may be the same or may be lower than the pressure of the first cooling stream **638**. The two-phase stream **646** may be separated into its vapor component and its liquid component in a first two-phase separator **648** to form a second cooling stream **650** and a second pressurized LNG stream **652**. The temperature of the first cooling stream **638** is higher than the temperature of the second cooling stream **650**. The second cooling stream **650** enters the at least one cryogenic heat exchanger **640** where it exchanges heat with the second chilled pretreated gas stream **630** and the second refrigerant stream **634** to cool said streams. The second cooling stream **650** exits the at least one heat exchanger **640** as a second warm stream **654**. The second chilled pretreated natural gas stream **630** exchanges heat with the first cooling stream **638** and the second cooling stream **650** to produce a first pressurized LNG stream **656**. The first pressurized LNG stream **656** may be reduced in pressure in a hydraulic turbine **658** after exiting the at least one heat exchanger **640**. The first pressurized LNG stream **656** may be mixed with the second pressurized LNG stream **652** to form a combined pressurized LNG stream **660**. The combined pressurized LNG stream **660** may be directed to a second two-phase separator **662** where the pressure of the combined pressurized LNG stream **660** is reduced, and the resulting two-phase stream is separated into an end flash gas stream **664** and a product LNG stream **667**. The end flash gas stream **664** may exchange heat with the first pressurized LNG stream **656** within an end flash gas heat exchanger **668** prior to directing the first pressurized LNG stream **656** to the hydraulic turbine **658**. Additionally, the end flash gas stream **664** may enter the at least one cryogenic heat exchanger **640** to exchange heat with the second chilled pretreated gas stream **630** and the second refrigerant stream **634** to cool said streams. The end flash gas stream **664** exits the at least one heat exchanger **640** as a third warm stream **670**. The third warm stream **670** may be compressed in a first recycle gas compressor **672** and may exchange heat with the environment in a first recycle heat exchanger **674** to form a first recycle gas stream **676**. The first recycle gas stream **676** may be combined with the second warm stream **654** and, together, may be compressed in a second recycle gas compressor **678**, and may exchange heat with the environment in a second recycle heat exchanger **680** to form a second recycle gas stream **682**. The second recycle gas stream **682** may be combined with the first warm stream **642** and, together, may be compressed in third and fourth recycle gas compressors **684**, **686** and may exchange heat with the environment in a third recycle heat exchanger **688** to form the recycle refrigerant gas stream **604**. The third recycle gas compressor **684** may be driven solely by the shaft power produced by the first expander **636**, as shown by the dashed line **690**. The fourth recycle gas compressor **686** may be driven solely by the shaft power produced by the second expander **644**, as shown by the dashed line **692**.

[0058] Figure 7 illustrates a method **700** of producing LNG according to disclosed aspects. At block **702** a natural gas stream may be provided from a supply of natural gas. At block **704** the natural gas stream may be compressed in at least two serially arranged compressors to a pressure of at least 2,000 psia to form a compressed natural gas stream. At block **706** the compressed natural gas stream may be cooled to form a cooled compressed natural gas stream. At block **708** the cooled compressed natural gas stream may be expanded in at least one work producing natural gas expander to a pressure that is less than 3,000 psia and no greater than the pressure to which the at least two serially arranged compressors compress the natural gas stream, to thereby form a chilled natural gas stream. At block **710** the chilled natural gas stream may be liquefied.

[0059] Figure 8 is an illustration of another HPCE process **800** according to disclosed aspects. As with HPCE process **100** shown in Figure 1, HPCE process **800** may comprise a first compressor **802** which compresses a pretreated natural gas stream **804** to form an intermediate pressure gas stream **806**. The intermediate pressure gas stream **806** may flow through a first heat exchanger **808** where the intermediate pressure gas stream **806** is cooled by indirectly exchanging heat with the environment to form a cooled intermediate pressure gas stream **810**. The first heat exchanger **808** may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled intermediate pressure gas stream **810** may then be compressed within a second compressor **812** to form a high pressure gas stream **814**. The pressure of the high pressure gas stream **814** may be greater than 2,000 psia (13,790 kPa), or more preferably greater than 3,000 psia (20,680 kPa). The high pressure gas stream **814** may flow through a second heat exchanger **816** where the high pressure gas stream **814** is cooled by indirectly exchanging heat with the environment to form a cooled high pressure gas stream **818**. The second heat exchanger **816** may be an air cooled heat exchanger or a water cooled heat exchanger. The cooled high pressure gas stream **818** may then be directed to a high pressure heat exchanger **826**, where it is further cooled to a temperature below the ambient temperature by exchanging heat with one or more refrigerant streams **828** from a process external to the HPCE process **800**. In one aspect, the one or more refrigerant streams are refrigerant streams that have cryogenically cooled, chilled, and/or liquefied the chilled, pretreated natural gas stream **822** after it has exited the HPCE process **800**. These refrigerant streams may still be cold enough, even after liquefying natural gas, to cool the cooled high pressure gas stream **818**. The cooled high pressure gas stream **818** exits the high pressure heat exchanger **826** at a temperature below 30 degrees C or below 20 degrees C or below 15 degrees C and is expanded within an expander **820** to form the chilled pretreated gas stream **822**. The pressure of the chilled pretreated gas stream **122** may be less than 3,000 psia (20,680 kPa), or more preferably less than 2,000 psia (13,790 kPa), and the pressure of the chilled pretreated gas stream **822** is less than the pressure of the cooled high pressure gas stream **818**. In a preferred aspect, the second compressor **812** may be driven solely by the shaft power produced by the expander **820**, as indicated by the dashed line **824**.

[0060] Figure 9 depicts an implementation of an HPCE process **901**, similar to HPCE process **601**, and combined with a feed gas expander-based LNG liquefaction process **900**. Those elements in Figure 9 identified by reference numbers found in Figure 6 (e.g., **636, 644, 668)** perform identical or similar functions to the previously described elements and for the sake of brevity will not be further described. HPCE process **901** includes a high pressure heat exchanger **905** that exchanges heat between the cooled high pressure gas stream **622** and the first warm stream **642** that has exited the at least one cryogenic heat exchanger **640**. After passing through the high pressure heat exchanger **905**, the first warm stream **642** is combined with the second recycle gas stream **682** and compressed in the third and fourth recycle gas compressors **684**, **686** as previously described.

[0061] Figure 10 depicts another implementation of an HPCE process **1001**, similar to HPCE process **601**, and combined with a feed gas expander-based LNG liquefaction process **1000**. Those elements in Figure 10 identified by reference numbers found in Figure 6 (e.g., **636, 644, 668)** perform identical or similar functions to the previously described elements and for the sake of brevity will not be further described. HPCE process **1001** includes a high pressure heat exchanger **1005** that exchanges heat between the cooled high pressure gas stream **622** and the second warm stream **654** that has exited the at least one cryogenic heat exchanger **640**. After passing through the high pressure heat exchanger **1005**, the second warm stream **654** is combined with the first recycle gas stream **676** and compressed in the second recycle gas compressor **678** as previously described.

[0062] Figure 11 depicts another implementation of an HPCE process **1101**, similar to HPCE process **601**, and combined with a feed gas expander-based LNG liquefaction process

1100. Those elements in Figure 11 identified by reference numbers found in Figure 6 (e.g., **636, 644, 668**) perform identical or similar functions to the previously described elements and for the sake of brevity will not be further described. HPCE process **1101** includes a high pressure heat exchanger **1105** that exchanges heat between the cooled high pressure gas stream **622** and both the first warm stream **642** and the second warm stream **654** that have exited the at least one cryogenic heat exchanger **640**. After passing through the high pressure heat exchanger **1105**, the first warm stream **642** is combined with the second recycle gas stream **682** and compressed in the third and fourth recycle gas compressors **684**, **686** as previously described. After passing through the high pressure heat exchanger **1105**, the second warm stream **654** is combined with the first recycle gas stream **676** and compressed in the second recycle gas compressor **678** as previously described.

[0063] The disclosed aspects that include a high pressure heat exchanger in the HPCE module (i.e., Figures 8-11) take advantage of refrigerant streams are still cold enough, after an initial use, to increase the pre-cooling of a natural gas stream in the HPCE module. An advantage of using such a high pressure heat exchanger in the HPCE module is that the efficiency of the overall liquefaction process shown in Figure 9, for example, may improve as much as approximately 3% compared to the efficiency of the liquefaction process shown in Figure 6.

[0064] Figure 12 is a method **1200** of producing LNG according to disclosed aspects. At block **1202** a natural gas stream may be provided from a supply of natural gas. At block **1204** the natural gas stream may be compressed in at least two serially arranged compressors to a pressure of at least 2,000 psia to form a compressed natural gas stream. At block **1206** the compressed natural gas stream may be cooled to form a cooled compressed natural gas stream. At block **1208** the cooled compressed natural gas stream is additionally cooled to a temperature below the ambient temperature to form an additionally cooled compressed natural gas stream. At block **1210** the cooled compressed natural gas stream may be expanded in at least one work producing natural gas expander to a pressure that is less than 3,000 psia and no greater than the pressure to which the at least two serially arranged compressors compress the natural gas stream, to thereby form a chilled natural gas stream. At block **1212** the chilled natural gas stream may be liquefied.

[0065] Disclosed aspects may include any combinations of the methods and systems shown in the following numbered paragraphs. This is not to be considered a complete listing of all possible aspects, as any number of variations can be envisioned from the description above.

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

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

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

cooling the compressed natural gas stream by indirect heat exchange with an ambient temperature air or water to form a cooled compressed natural gas stream;

additionally cooling the cooled compressed natural gas stream to a temperature below the ambient temperature to form an additionally cooled compressed natural gas stream;

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

liquefying the chilled natural gas stream by indirect heat exchange with a refrigerant to form liquefied natural gas and a warm refrigerant;

wherein the cooled compressed natural gas stream is additionally cooled using the warm refrigerant.

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

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

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

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

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

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

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

wherein the first temperature is higher than the second temperature.

6. The method of paragraph 5, further comprising:

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

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

7. The method of paragraph 4, further comprising:

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

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

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

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

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

8. The method of any of paragraphs 5-7, wherein a pressure of the first cooling stream is one of

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

higher than a pressure of the second cooling stream.

9. The method of any of paragraphs 5-7, wherein the liquefying step comprises cooling the second chilled natural gas stream to form a second pressurized LNG stream by

exchanging heat with the first cooling stream and the second cooling stream to form a first warm cooling stream and a second warm cooling stream.

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

11. The method of paragraph 9, further comprising:

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

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

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

12. The method of paragraph 11, further comprising:

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

13. The method of paragraph 11, further comprising:

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

14. The method of paragraph 9, wherein the first warm cooling stream is used as the warm refrigerant to additionally cool the cooled compressed natural gas stream to form the additionally cooled compressed natural gas stream.

15. The method of paragraph 9, wherein the second warm cooling stream is used as the warm refrigerant to additionally cool the cooled compressed natural gas stream to form the additionally cooled compressed natural gas stream.

16. The method of paragraph 3, wherein the expander-based liquefaction module comprises:

a first expanded refrigerant within a first gas phase refrigeration cycle; and

a second expanded refrigerant within a second gas phase refrigeration cycle.

17. The method of paragraph 16, wherein the first expanded refrigerant is feed gas.

18. The method of paragraph 16 or paragraph 17, wherein the first gas phase refrigeration cycle is a closed loop refrigeration cycle.

19. The method of any of paragraphs 16-18, wherein the second expanded refrigerant is nitrogen.

20. The method of any of paragraphs 16-19, wherein the second gas phase refrigeration cycle is a closed loop refrigeration cycle.

21. The method of any of paragraphs 1-20 wherein the at least two compressors compress the natural gas stream to a pressure greater than 3,000 psia.

22. The method of any of paragraphs 1-21, wherein the natural gas expander is a work producing expander that expands the additionally cooled compressed natural gas stream to a pressure less than 2,000 psia.

23. The method of any of paragraphs 1-22, further comprising:

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

24. The method of any of paragraphs 1-23, wherein the temperature of the additionally cooled compressed natural gas stream is less than 30 °C.

25. The method of any of paragraphs 1-24, wherein the temperature of the additionally cooled compressed natural gas stream is less than 15 °C.

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

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

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

a heat exchanger configured to further cool the cooled compressed natural gas stream to a temperature below an ambient temperature to thereby produce an additionally cooled compressed natural gas stream;

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

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

wherein a warm refrigerant used by the liquefaction train is directed to the heat exchanger to further cool the cooled compressed natural gas stream.

27. The apparatus of paragraph 26, wherein the liquefaction train comprises one of a nitrogen gas expander-based liquefaction module and an open loop feed gas expander-based liquefaction module, and further comprising, when the liquefaction train comprises an open loop feed gas expander-based module, a recycle refrigerant stream of the open loop feed gas expander-based module that is combined with the natural gas stream prior to the natural gas stream being compressed by the two or more serially-arranged compressors, wherein the chilled natural gas stream is a first chilled natural gas stream that is separated into a second chilled natural gas stream, a first refrigerant stream, and a second refrigerant stream.

28. The apparatus of paragraph 27, wherein the feed gas expander-based liquefaction module comprises:

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

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

wherein the first temperature is higher than the second temperature.

29. The apparatus of any of paragraphs 26-28, wherein the natural gas expander is a work producing expander configured to expand the cooled compressed natural gas stream to a pressure less than 2,000 psia.

30. The apparatus of any of paragraphs 26-29, wherein the at least two serially arranged compressors, the cooling element, the heat exchanger, the at least one work-producing expander, and the liquefaction train are disposed on a floating LNG structure.

31. The apparatus of paragraph 30, wherein the at least two serially arranged compressors, the cooling element, the heat exchanger, and the at least one work-producing expander are disposed within a single module on a topside of the floating LNG structure.

32. A floating LNG structure, comprising:

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

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

a heat exchanger configured to further cool the cooled compressed natural gas stream to a temperature below an ambient temperature to thereby produce an additionally cooled compressed natural gas stream;

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

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

wherein a warm refrigerant used by the liquefaction train is directed to the heat exchanger to further cool the cooled compressed natural gas stream.

[0066] While the foregoing is directed to aspects of the present disclosure, other and further aspects of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

CLAIMS

What is claimed is:

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

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

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

cooling the compressed natural gas stream by indirect heat exchange with an ambient temperature air or water to form a cooled compressed natural gas stream;

additionally cooling the cooled compressed natural gas stream to a temperature below the ambient temperature to form an additionally cooled compressed natural gas stream;

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

liquefying the chilled natural gas stream by indirect heat exchange with a refrigerant to form liquefied natural gas and a warm refrigerant;

wherein the cooled compressed natural gas stream is additionally cooled using the warm refrigerant;

wherein liquefying the chilled natural gas stream is performed in one or more expander-based liquefaction modules, and wherein the expander-based liquefaction module is a feed gas expander-based liquefaction module, wherein the chilled natural gas stream is a first chilled natural gas stream, and further comprising:

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

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

wherein the first temperature is higher than the second temperature.

2. The method of claim 1, wherein the feed gas expander-based liquefaction module is an open loop feed gas expander-based liquefaction module, and wherein a recycle refrigerant stream of the open loop feed gas expander-based process is combined with the natural gas stream prior to the compressing step.

3. The method of claim 1 or 2, further comprising:

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

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

4. The method of any one of claims 1-3, wherein a pressure of the first cooling stream is one of:

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

higher than a pressure of the second cooling stream.

5. The method of any one of claims 1-3, wherein the liquefying step comprises cooling the second chilled natural gas stream to form a second pressurized LNG stream by exchanging heat with the first cooling stream and the second cooling stream to form a first warm cooling stream and a second warm cooling stream.

6. The method of claim 5, wherein the second pressurized LNG stream is mixed with the first pressurized LNG stream prior to expanding the second pressurized LNG stream.

7. The method of claim 5, further comprising:

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

separating the reduced-pressure second pressurized LNG stream into an end-flash gas stream and an LNG stream; and cooling the second pressurized LNG stream and the second chilled natural gas stream using the end-flash gas stream.

8. The method of claim 7, further comprising:

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

mixing the compressed end-flash gas stream with one or more recycling refrigerant streams, or

using the compressed end-flash gas stream as fuel.

9. The method of claim 5, wherein the first warm cooling stream or the second warm cooling stream is used as the warm refrigerant to additionally cool the cooled compressed natural gas stream to form the additionally cooled compressed natural gas stream.

10. The method of any one of claims 1-9, wherein the natural gas expander is a work producing expander that expands the additionally cooled compressed natural gas stream to a pressure less than 2,000 psia.

11. The method of any one of claims 1-10, further comprising:

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

12. The method of any one of claims 1-11, wherein the temperature of the additionally cooled compressed natural gas stream is less than 30 °C or less than 15 °C.

13 An apparatus for the liquefaction of natural gas, comprising:

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

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

a heat exchanger configured to further cool the cooled compressed natural gas stream to a temperature below an ambient temperature to thereby produce an additionally cooled compressed natural gas stream;

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

a liquefaction train configured to liquefy the chilled natural gas stream, wherein the liquefaction train comprises a feed gas expander-based liquefaction module;

wherein a warm refrigerant used by the liquefaction train is directed to the heat exchanger to further cool the cooled compressed natural gas stream,

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

and wherein the feed gas expander-based liquefaction module comprises:

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

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

wherein the first temperature is higher than the second temperature.

14. The apparatus of claim 13, wherein the at least two serially arranged compressors, the cooling element, the heat exchanger, the at least one work-producing expander, and the liquefaction train are disposed on

a floating LNG structure or

a single module on a topside of the floating LNG structure.

15. A floating LNG structure, comprising:

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

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

a heat exchanger configured to further cool the cooled compressed natural gas stream to a temperature below an ambient temperature to thereby produce an additionally cooled compressed natural gas stream;

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

a liquefaction train configured to liquefy the chilled natural gas stream, the liquefaction train comprising a feed gas expander-based liquefaction module;

wherein a warm refrigerant used by the liquefaction train is directed to the heat exchanger to further cool the cooled compressed natural gas stream,

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

and wherein the feed gas expander-based liquefaction module comprises:

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

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

wherein the first temperature is higher than the second temperature.

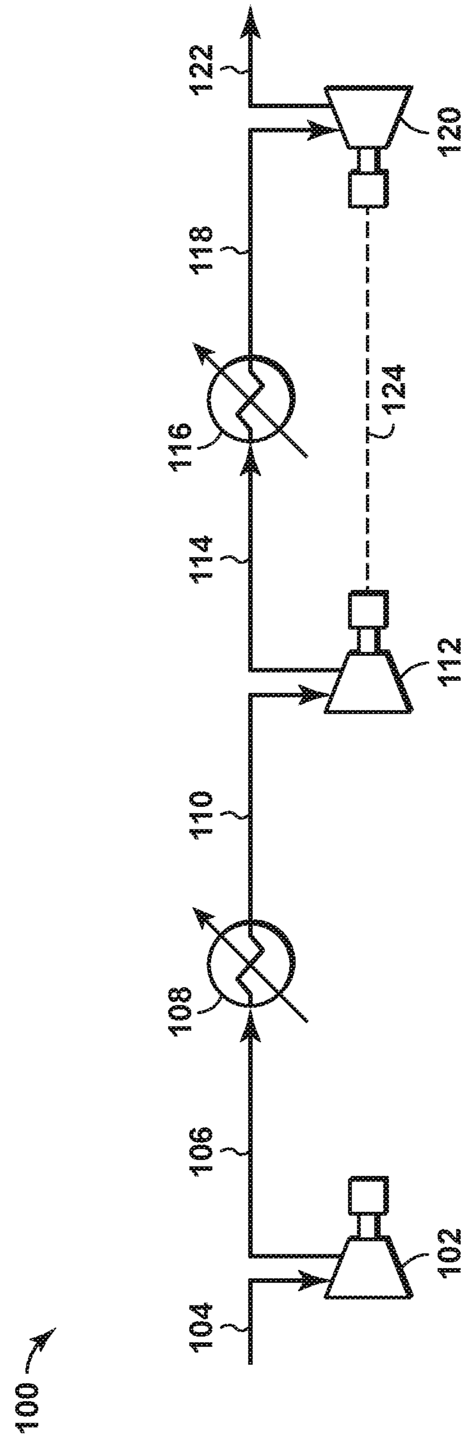

FIG. 1

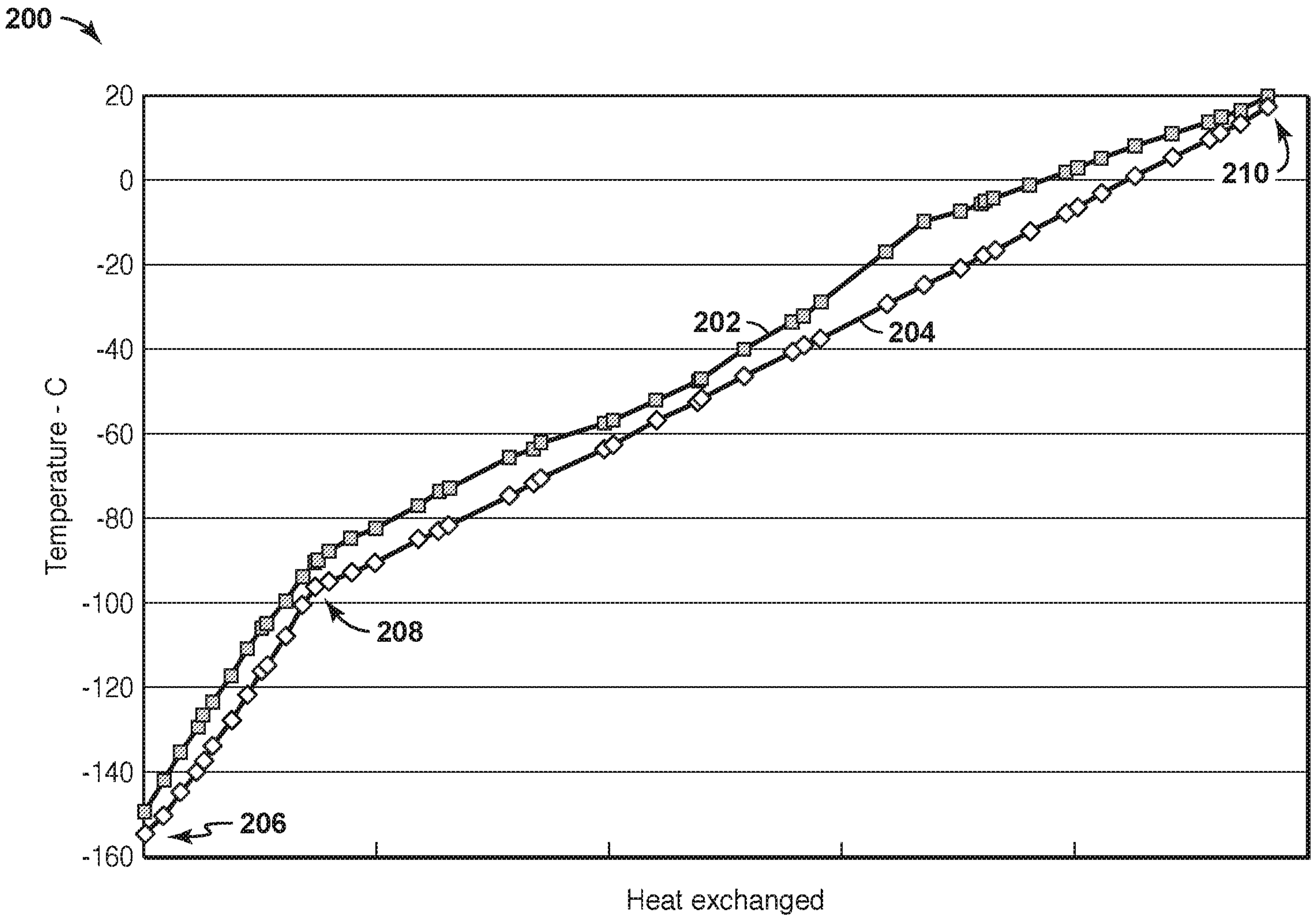
200
Temperature - C
20
0
-20
-40
-60
-80
-100
-120
-140
-160
Heat exchanged
202
204
206
208
210

FIG. 2

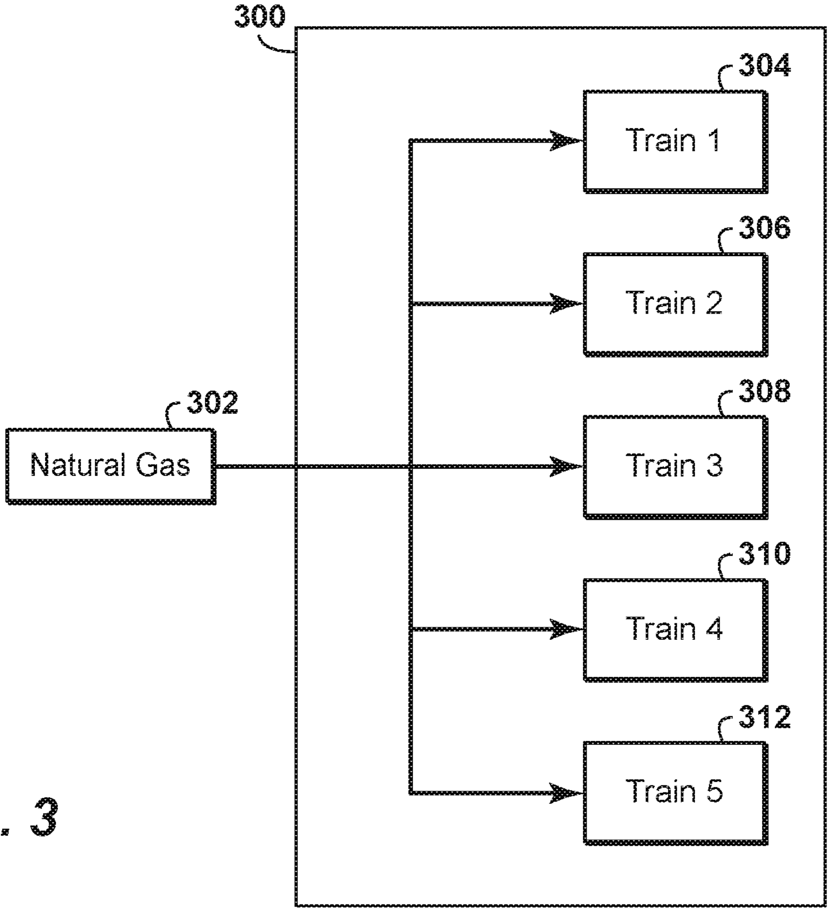
300
302
Natural Gas
304
Train 1
306
Train 2
308
Train 3
310
Train 4
312
Train 5

FIG. 3

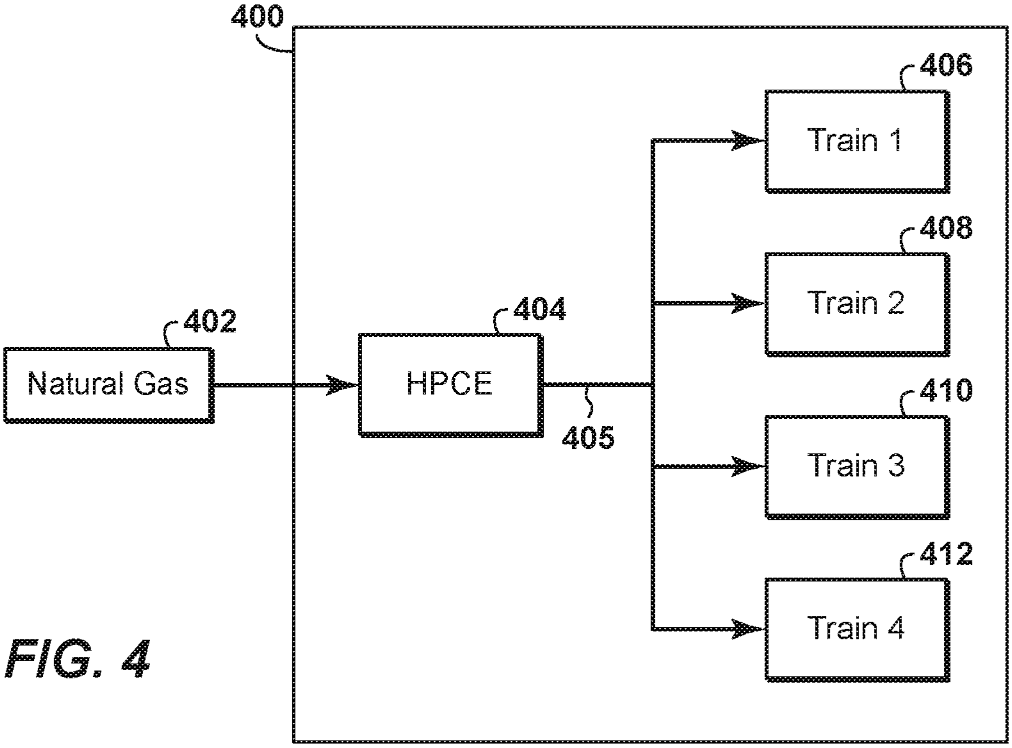
400
402
Natural Gas
404
HPCE
405
406
Train 1
408
Train 2
410
Train 3
412
Train 4

FIG. 4

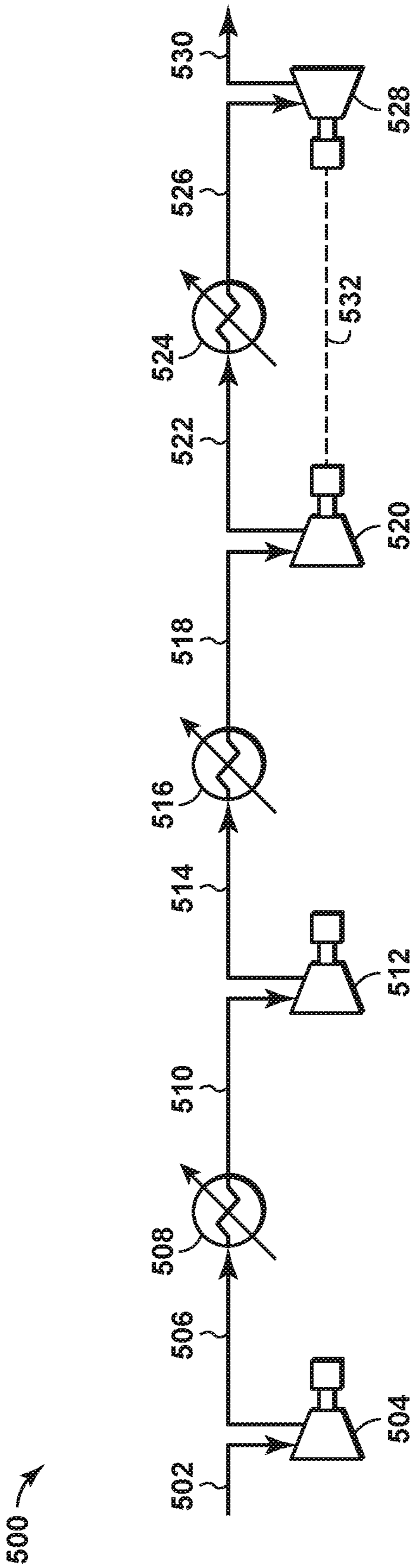
500
502
504
506
508
510
512
514
516
518
520
522
524
526
528
530
532

FIG. 5

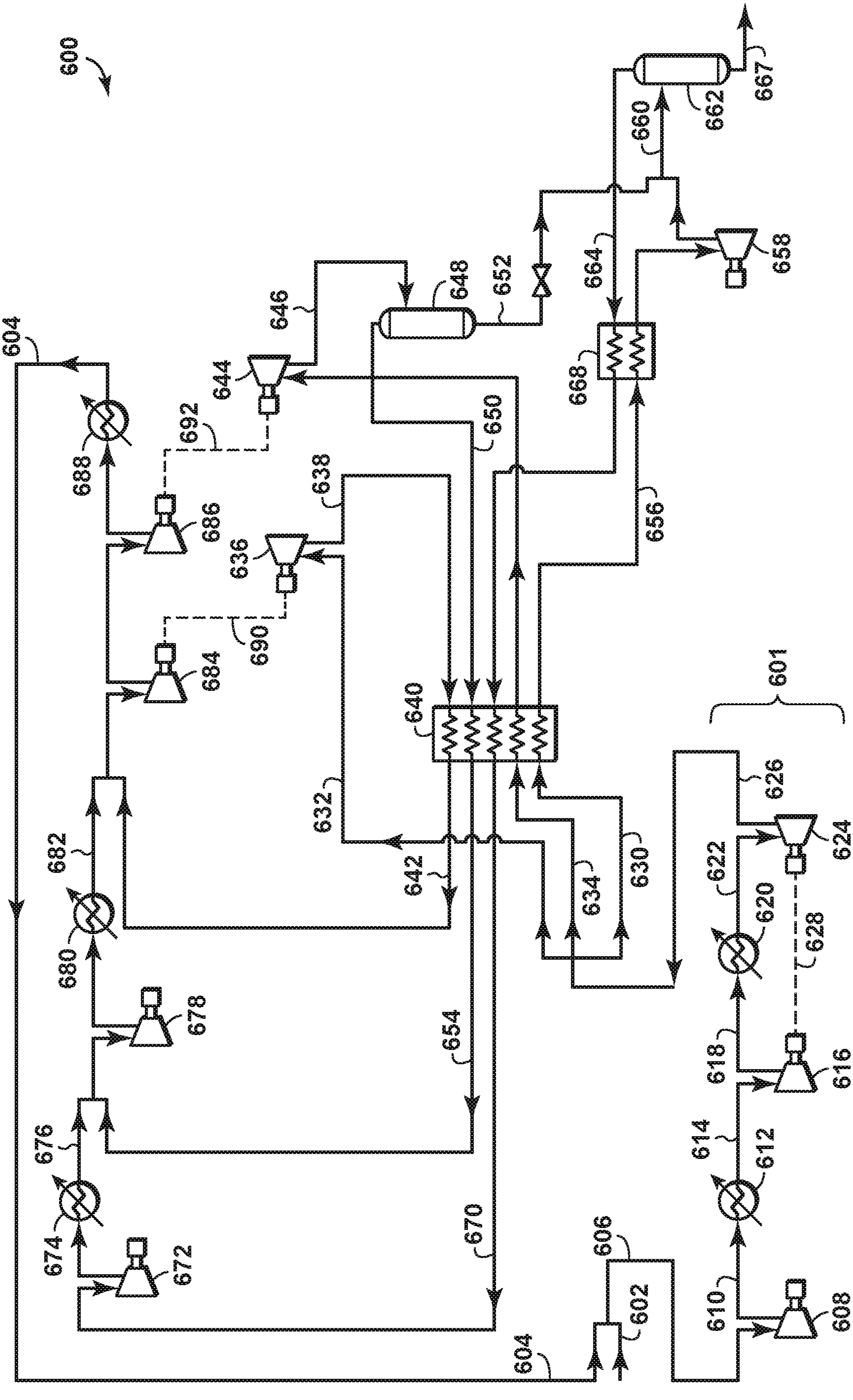
600
601
602
604
604
606
608
610
612
614
616
618
620
622
624
626
628
630
632
634
636
638
640
642
644
646
648
650
652
654
656
658
660
662
664
667
668
670
672
674
676
678
680
682
684
686
688
690
692

FIG. 6

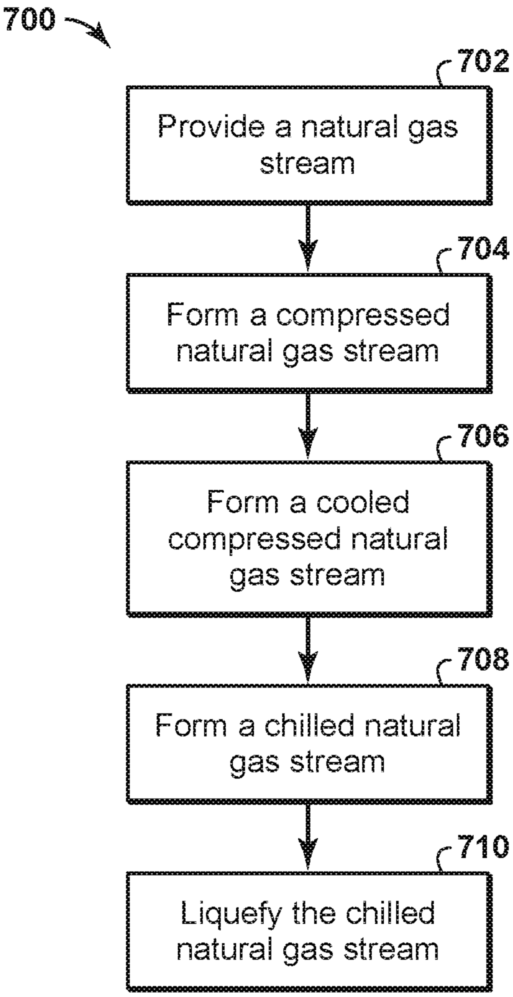
700
702
Provide a natural gas stream
704
Form a compressed natural gas stream
706
Form a cooled compressed natural gas stream
708
Form a chilled natural gas stream
710
Liquefy the chilled natural gas stream

FIG. 7

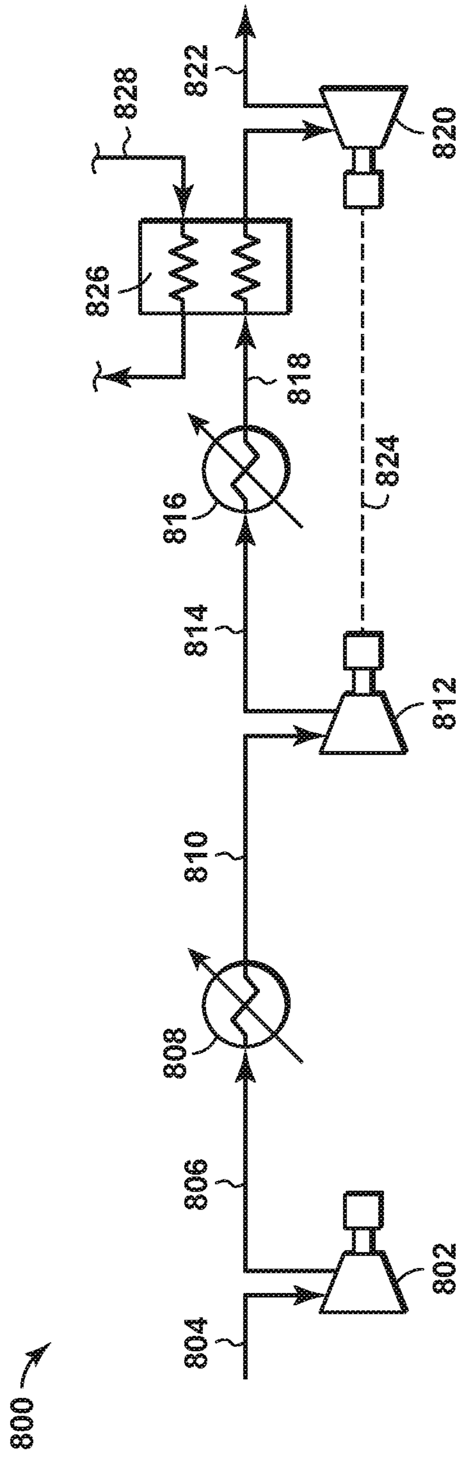

FIG. 8

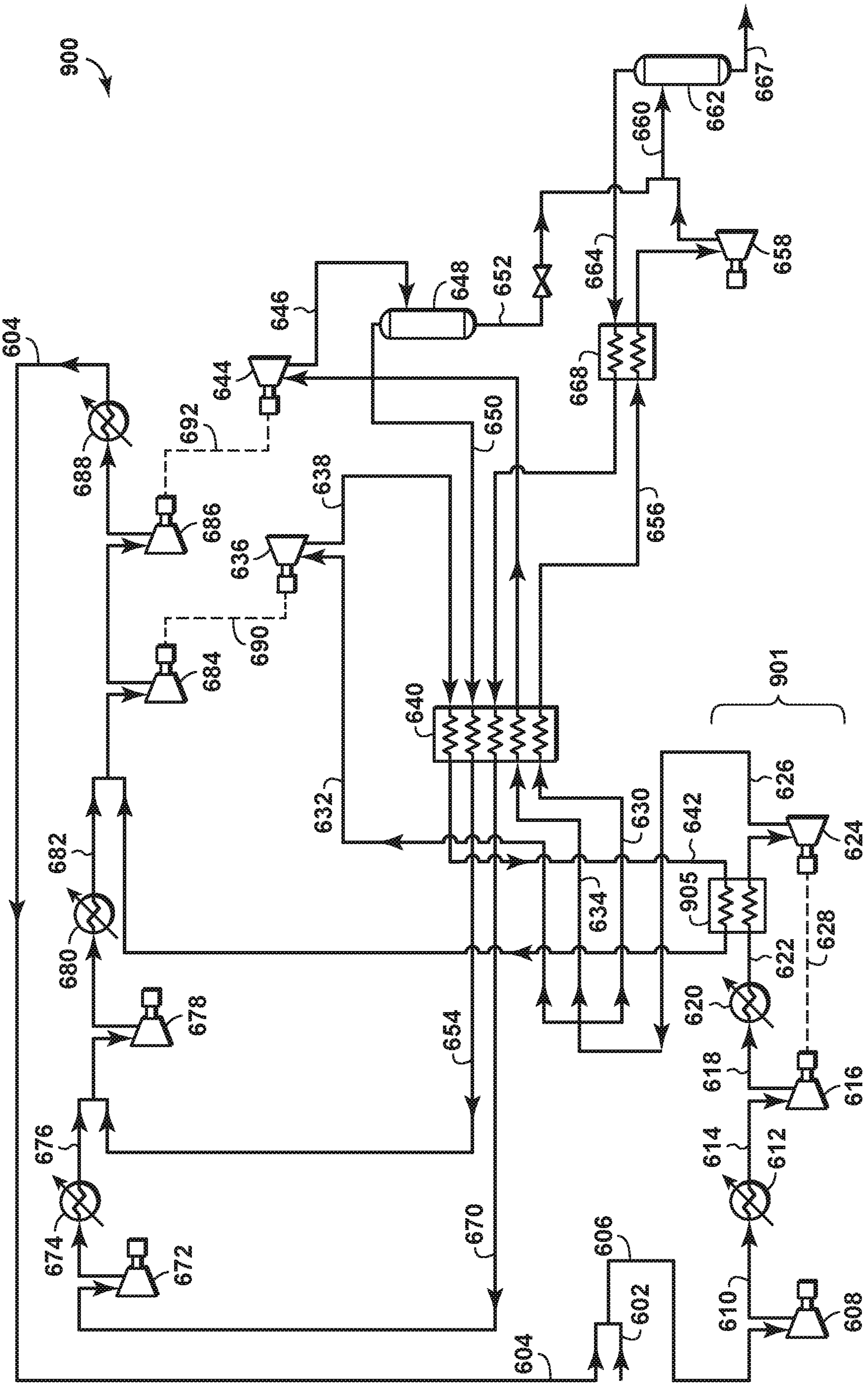
900
604
646
648
652
644
692
688
650
664
658
668
660
662
667
638
686
636
656
690
684
640
901
632
630
642
626
624
682
680
634
905
628
622
620
678
654
618
616
676
614
612
674
672
670
606
602
610
608
604

FIG. 9

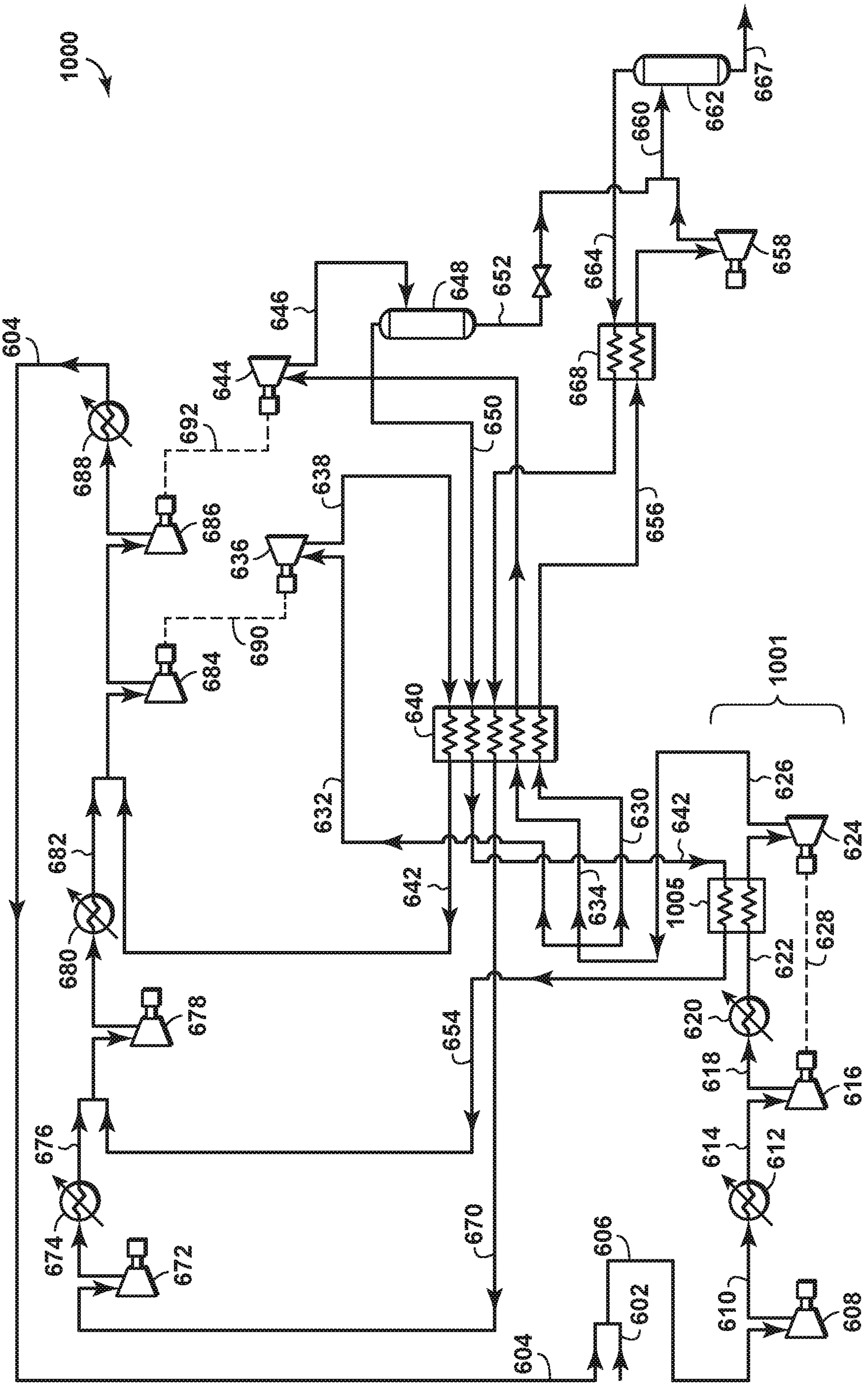
1000
604
692
646
648
652
667
662
660
688
644
650
664
658
638
668
686
636
656
690
684
1001
640
632
630
642
626
682
642
634
1005
624
680
628
622
654
678
620
618
616
676
614
612
674
670
606
672
602
610
608
604

FIG. 10

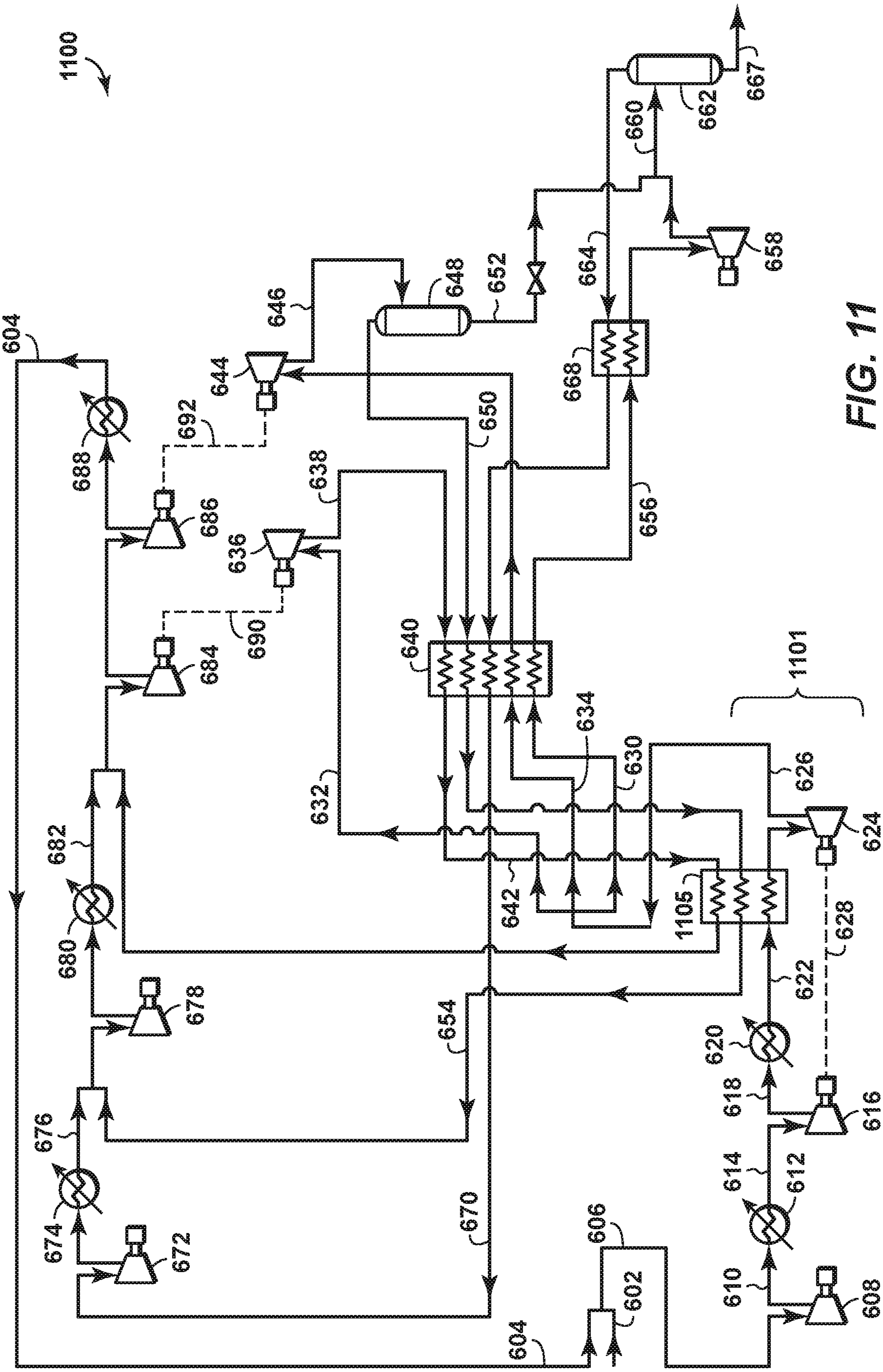
1100
604
602
606
608
610
612
614
616
618
620
622
624
626
628
630
632
634
636
638
640
642
644
646
648
650
652
654
656
658
660
662
664
667
668
670
672
674
676
678
680
682
684
686
688
690
692
1101
1105

FIG. 11

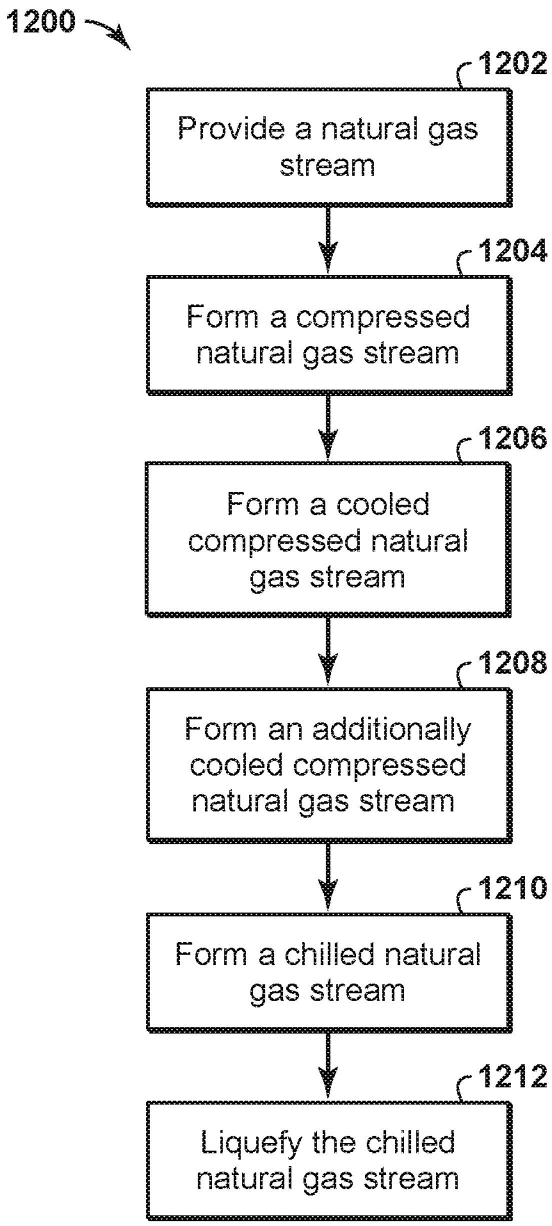
1200
1202
Provide a natural gas stream
1204
Form a compressed natural gas stream
1206
Form a cooled compressed natural gas stream
1208
Form an additionally cooled compressed natural gas stream
1210
Form a chilled natural gas stream
1212
Liquefy the chilled natural gas stream

FIG. 12