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(72) **Inventor:** VINCENNELLI, Jorge; 119 Benjis Pl, Spring, TX 77380 (US).

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(74) **Agent: HASENBERG, Lisa, M.** et al.; ExxonMobil Upstream Research Company, 22777 Springwood Village Parkway, (EMHC-N1-4A-607), Spring, TX 77389 (US).

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(71) Applicant: EXXONMOBIL UPSTREAM RESEARCH COMPANY [US/US]; 22777 Springwoods Village Parkway, (EMHC-N1-4A-607), Spring, TX 77389 (US).

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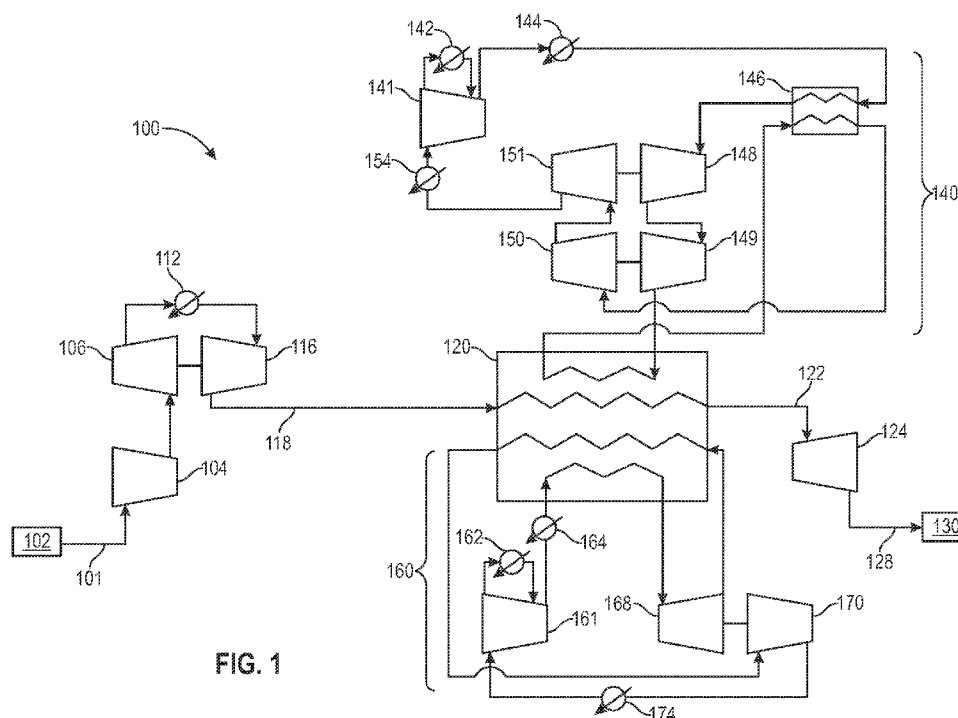


FIG. 1

(S7) Abstract: Natural gas liquefaction processes may be facilitated by incorporating secondary liquid cooling to facilitate an overall pressure decrease and improved throughput at a fixed compressor power. Natural gas processing methods may comprise: providing a natural gas stream to a first compressor, compressing the natural gas stream in the first compressor and, performing air cooled heat exchange, conveying the resulting cooled, compressed natural gas stream to a multiple stream heat exchanger cooled by first and second gaseous refrigerants in first and second closed refrigerant loops and cooling to form a chilled, compressed natural gas stream, expanding the chilled, compressed natural gas stream to form a chilled natural gas stream, and converted the chilled natural gas stream into liquefied natural gas. Secondary liquid cooling is incorporated in at least one of the first or second closed refrigerant loops, and/or upstream from the multiple stream heat exchanger and downstream from the first compressor.

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NATURAL GAS LIQUEFACTION METHODS AND SYSTEMS FEATURING SECONDARY LIQUID COOLING

CROSS REFERENCE TO RELATED APPLICATIONS

- 5 [0001] This application claims the priority benefit of United States Provisional Patent Application No. 63/199443, filed December 29, 2020, entitled NATURAL GAS LIQUEFACTION METHODS AND SYSTEMS FEATURING SECONDARY LIQUID COOLING, the entirety of which is incorporated by reference herein.

FIELD

- 10 [0002] The present disclosure relates to natural gas liquefaction.

BACKGROUND

- [0003] Natural gas, a hydrocarbon resource comprising predominantly methane, has become an increasingly important energy source in recent years. Natural gas is often processed
15 into liquefied natural gas (LNG) to facilitate transport from production fields to a locale having a strong commercial or consumer need for natural gas. Conventional LNG processing techniques may include: (a) initial treatments of the natural gas to remove contaminants such as water, sulfur compounds and carbon dioxide; (b) separation of heavier hydrocarbon gases (*e.g.*, propane, butane, pentane, and the like), such as through self-refrigeration, external
20 refrigeration, lean oil, and the like; (c) refrigeration of the natural gas, such as through external refrigeration to form LNG at near atmospheric pressure and about -160°C; (d) transportation of the LNG to a market location in specially designed ships or tankers; and (e) conversion of the LNG into pressurized natural gas at a site for processing or distribution to consumers.

- 25 [0004] Refrigeration and/or cryogenic fluids may be employed to cool an incoming natural gas stream prior to liquefaction. Illustrative natural gas liquefaction processes employing liquid nitrogen or other cryogenic fluids are described in U.S. Patent 3,878,689, for example, wherein liquefaction takes place at ambient pressure. One disadvantage of such cryogenic fluid approaches, particularly those employing hydrocarbon cryogenic fluids (*e.g.*, ethane, propane,
30 and the like), is that significant reservoirs of cryogenic fluids may need to be maintained at a natural gas production site. The undesired aspects associated with external cryogenic hydrocarbon fluids may be addressed by employing one or more closed refrigerant loops to promote cooling of a natural gas stream. U.S. Patent 6,412,302 describes a natural gas liquefaction process in which two closed refrigerant loops, one utilizing nitrogen and the other

utilizing natural gas, may be employed to cool an incoming natural gas stream prior to expansion to promote further cooling. U.S. Patent 8,616,012 describes a natural gas liquefaction process featuring a closed refrigerant loop employing a portion of a natural gas feed.

5 [0005] Another approach for facilitating production of LNG is to compress and expand an incoming natural gas stream prior to promoting further cooling through refrigeration. U.S. Patent Application Publications 2017/0167787 and 20180231303 describe natural gas liquefaction processes employing a compression-expansion cycle prior to promoting further cooling through refrigeration. The refrigerant in these cases is a portion of the natural gas feed
10 that is maintained in an open refrigerant loop. U.S. Patent Application Publications 20190101327, 20190101328, and 20190376740 describe natural gas liquefaction processes employing a compression-expansion cycle prior to promoting further cooling with separate closed refrigerant loops, one employing natural gas and the other employing nitrogen. In the foregoing types of natural gas liquefaction processes, discharge pressure thresholds, which may
15 be constrained by commonly used metal grades and compressor designs employed during natural gas processing, may limit throughput. Excessive pressure in the refrigerant loops may also be problematic in some instances.

SUMMARY

20 [0006] In some aspects, the present disclosure provides natural gas liquefaction methods employing secondary liquid cooling. The methods comprise: providing a natural gas stream to a first compressor; compressing the natural gas stream with the first compressor to form a compressed natural gas stream having a pressure higher than that of the natural gas stream; performing air cooled heat exchange upon the compressed natural gas stream to form a cooled,
25 compressed natural gas stream; conveying the cooled, compressed natural gas stream to a multiple stream heat exchanger that is cooled with a first gaseous refrigerant and a second gaseous refrigerant, the first and second gaseous refrigerants differing from one another; wherein the first gaseous refrigerant is provided to the multiple stream heat exchanger by a first closed refrigerant loop and the second gaseous refrigerant is provided to the multiple stream
30 heat exchanger by a second closed refrigerant loop; cooling the cooled, compressed natural gas stream in the multiple stream heat exchanger to a temperature lower than that of the cooled, compressed natural gas stream to form a chilled, compressed natural gas stream; expanding the chilled, compressed natural gas stream in a downstream expander to form a chilled natural gas stream; and converting the chilled natural gas stream into liquefied natural gas; wherein

secondary liquid cooling is incorporated in at least one of the first closed refrigerant loop, the second closed refrigerant loop, and/or upstream from the multiple stream heat exchanger and downstream from the first compressor.

[0007] In some or other aspects, natural gas liquefaction systems employing secondary liquid cooling comprise: a natural gas stream in fluid communication with an inlet of a first compressor; an air cooled heat exchanger in fluid communication with an outlet of the first compressor; a multiple stream heat exchanger having a first inlet in fluid communication with an outlet of the air cooled heat exchanger and that is cooled with a first gaseous refrigerant and a second gaseous refrigerant, the first and second gaseous refrigerants differing from one another, and the first gaseous refrigerant being provided to the multiple stream heat exchanger from a first closed refrigerant loop and the second gaseous refrigerant being provided to the multiple stream heat exchanger from a second closed refrigerant loop; and a downstream expander having an inlet in fluid communication with a first outlet of the multiple stream heat exchanger; wherein secondary liquid cooling is incorporated in at least one of the first closed refrigerant loop, the second closed refrigerant loop, and/or upstream from the multiple stream heat exchanger and downstream from the first compressor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The following figures are included to illustrate certain aspects of the present disclosure, and should not be viewed as exclusive embodiments. The subject matter disclosed is capable of considerable modifications, alterations, combinations, and equivalents in form and function, as will occur to one having ordinary skill in the art and having the benefit of this disclosure.

[0009] FIG. 1 is a diagram of a natural gas liquefaction system and method employing two closed refrigerant loops and no additional incorporation of secondary liquid cooling.

[0010] FIG. 2 is a diagram of a natural gas liquefaction system and method employing two closed refrigerant loops having gaseous refrigerants, with incorporation of secondary liquid cooling in at least one of the two closed refrigerant loops, preferably in both of the two closed refrigerant loops.

[0011] FIG. 3 is a diagram of a first configuration of a natural gas liquefaction system and method employing two closed refrigerant loops having gaseous refrigerants, with incorporation of secondary liquid cooling upstream from a multiple stream heat exchanger, preferably in combination with secondary liquid cooling incorporated in at least one of the closed refrigerant loops.

[0012] FIG. 4 is a diagram of a second configuration of a natural gas liquefaction system and method employing two closed refrigerant loops having gaseous refrigerants, with incorporation of secondary liquid cooling upstream from a multiple stream heat exchanger, preferably in combination with secondary liquid cooling incorporated in at least one of the closed refrigerant loops.

[0013] FIG. 5 is a diagram of a first configuration of a natural gas liquefaction system and method employing two closed refrigerant loops having gaseous refrigerants, with incorporation of secondary liquid cooling upstream from a multiple stream heat exchanger and in both of the closed refrigerant loops.

[0014] FIG. 6 is a diagram of a second configuration of a natural gas liquefaction system and method employing two closed refrigerant loops having gaseous refrigerants, with incorporation of secondary liquid cooling upstream from a multiple stream heat exchanger and in both of the closed refrigerant loops.

DETAILED DESCRIPTION

[0015] The present disclosure relates to natural gas liquefaction and systems therefor and, more particularly, natural gas liquefaction methods and systems featuring at least one closed refrigerant loop and secondary liquid cooling in one or more locations to promote natural gas liquefaction. Preferably, the natural gas liquefaction systems and methods employ two closed refrigerant loops having different gaseous refrigerants in each refrigerant loop, such as natural gas and nitrogen, wherein the secondary liquid cooling may be present in at least one of the closed refrigerant loops and/or in one or more additional locations to promote more efficient natural gas liquefaction.

[0016] Liquefied natural gas (LNG) is a convenient form for transportation of natural gas from a production location to a distribution or processing location. In the course of producing liquefied natural gas, a natural gas stream may undergo various processing operations in addition to heat exchange to lower the natural gas below its boiling point. Since large volumes of natural gas are usually processed into LNG, it may be desirable to increase throughput of a natural gas stream. Even incremental improvements in throughput may afford significant increases in process efficiency. Increased throughput may be realized by promoting lower temperatures and pressures during natural gas liquefaction. In addition to promoting increased throughput at a fixed compressor power, lower pressures may also decrease capital expenditures by facilitating simpler process designs with fewer components and/or allowing less costly metal grades to be employed for component fabrication.

[0017] The present disclosure describes methods and systems for processing a natural gas stream, preferably compression or compression-expansion methods and systems, in which compression or compression-expansion takes place upstream from a multiple stream heat exchanger, two closed refrigerant loops are employed to promote natural gas cooling and secondary liquid cooling is employed in one or more locations, as described further herein. The refrigerant loops employed in the disclosure herein may maintain the refrigerants in a gaseous state throughout the cooling process, without becoming at least partially condensed to a liquid state. By maintaining the refrigerants in a gaseous state throughout the cooling process, the design of the refrigerant loops may be simplified by avoiding gas-liquid separation. Pressure in the refrigerant loops may be lowered by incorporating secondary liquid cooling according to the present disclosure, which may afford one or more advantages discussed further herein.

[0018] Another advantage of employing refrigerant loops having the refrigerants maintained in a gaseous state is that the refrigerants are usually near room temperature at some point in the loop, particularly following compression and after being cooled by an air cooled heat exchanger. This feature allows a secondary liquid coolant, such as chilled water, to be employed for promoting further cooling of the refrigerant and lowering the pressure within the refrigerant loop, including prior to expansion, thereby reducing the required compressor power. As used herein, the term “chilled water” refers to water, solutions of water and salt (including sea water), and solutions of water and water-miscible organic compounds, such as water-glycol solutions. Chilled water may have a temperature from about 10°C to about -15°C or about 5°C to about -15°C, depending on whether substantially pure water, water-salt or water-glycol solutions are being chilled and the starting temperature of the water prior to chilling. The chilled water may be produced from an external chilled water system employing conventional refrigerants (*e.g.*, fluorocarbons or propane), or may be obtained from a natural source, if readily available (*e.g.*, deep sea water).

[0019] By incorporating secondary liquid cooling as a supplemental cooling element in at least one of the closed refrigerant loops used in conjunction with natural gas liquefaction (*e.g.*, through indirect gas-liquid cooling), the refrigerants may reach lower temperatures than otherwise achievable through compression-expansion alone, thereby allowing deeper cooling of an incoming natural gas stream to be realized. Decreased pressures in the refrigerant loops may be realized as well, thereby allowing preset refrigerant temperatures to be reached at a lower compressor power. The deeper cooling may allow natural gas processing to occur at lower pressures as well, thereby facilitating simpler equipment designs and avoiding the use of

expensive metal grades having a higher pressure ratings. Further, at a fixed compressor power for compressing a natural gas stream, the lower natural gas pressures achievable through use of the disclosure herein may facilitate increased natural gas throughput when forming liquefied natural gas.

5 **[0020]** At least some of the foregoing benefits may be realized by employing secondary liquid cooling in at least one of the closed refrigerant loops (*e.g.*, as a supplemental cooling element to promote indirect gas-liquid cooling). In the case of a first refrigerant loop circulating methane and a second refrigerant loop circulating nitrogen, it may be particularly beneficial to incorporate secondary liquid cooling in at least the methane refrigerant loop,
10 which tends to operate at a higher initial pressure. However, additive benefits may be realized by incorporating secondary liquid cooling in the nitrogen refrigerant loop as well. Providing secondary liquid cooling to multiple locations may be readily accomplished, as discussed further below.

15 **[0021]** In addition to or as an alternative to providing secondary liquid cooling to one or more of the closed refrigerant loops, secondary liquid cooling may also be utilized for cooling an incoming natural gas stream prior to undergoing heat exchange with the closed refrigerant loops described above but after undergoing initial compression or compression-expansion. By providing secondary liquid cooling to an incoming natural gas stream in this manner, benefits such as a decreased multiple stream heat exchanger size and/or simpler processing equipment
20 designs may be realized. These benefits may be realized separately or in addition to those afforded by providing secondary liquid cooling to one or more of the closed refrigerant loops.

25 **[0022]** In the case of secondary liquid cooling being provided by an external refrigeration system, the bulk of the capital expenditure is in the refrigeration system itself. To optimize benefits of the external refrigeration system and better justify its cost, secondary liquid cooling may be provided to as many locations as possible wherein it may provide benefits. Advantageously, secondary liquid cooling may be readily distributed to multiple locations within a natural gas liquefaction system with limited additional capital investment and engineering difficulty. Accordingly, it can be particularly advantageous to provide secondary liquid cooling to both closed refrigerant loops, or the incoming natural gas stream and one of
30 the closed refrigerant loops, or the incoming natural gas stream and both of the closed refrigerant loops. All of these possibilities are encompassed within the scope of the present disclosure. If the capacity of a system providing a secondary liquid coolant is limited, advantages may be realized by providing secondary liquid cooling to one of the closed refrigerant loops and to the incoming natural gas stream following compression. For example,

if limited secondary liquid coolant is present, it can be advantageous to provide secondary liquid cooling to the refrigerant loop employing methane (natural gas) and to the natural gas stream following initial compression thereof.

[0023] As a further advantage, secondary liquid cooling need not necessarily be provided
5 totally from an external refrigeration system when producing LNG according to the disclosure herein. Many large natural gas beds are found in subsea locations, from which LNG is produced onsite on an LNG transport ship. At depths below about 1000 meters, ocean water has a temperature of about 0-4°C, which may be pumped to the surface and provided as a secondary liquid coolant according to the disclosure herein. Alternately, sea water taken from
10 shallower depths (*e.g.*, below about 300 meters) may afford lower chilled water temperatures with conventional refrigeration systems to provide secondary liquid cooling for processing of LNG on a LNG transport ship. The foregoing approaches may avoid the capital investment needed for providing external refrigeration and/or lower the size and capacity of external refrigeration needed, which may be particularly advantageous in a space-limited LNG transport
15 ship. Because chilled water may be produced more easily when starting from already cold sea water, potential capacity constraints may be alleviated. In other words, it may be more feasible to provide chilled water to all available secondary liquid cooling locations when producing chilled water from sea water. In addition, as discussed above, employing secondary liquid cooling in one or more suitable locations may also allow simpler equipment designs to be realized in some cases, thereby allowing additional footprint reductions to be realized.

[0024] 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 as a significant component, sometimes as a primary
25 component. A natural gas stream may also contain ethane, higher molecular weight hydrocarbons (*e.g.*, propane), and/or one or more acid gases. Minor amounts of contaminants such as water, nitrogen, iron sulfide, wax, and crude oil, for example, may also be present. One or more of these components may be removed and/or lessened in concentration prior to processing a natural gas stream according to the disclosure herein. Liquefied natural gas (LNG)
30 may comprise predominantly methane after undergoing processing. The natural gas stream fed to the systems and methods described herein may be pre-processed to remove one or more components therefrom. Preferably, pre-processed natural gas is substantially free of water and carbon dioxide. More preferably, pre-processed natural gas has a maximum C₅₊ content of

about 1000 ppmv (parts per million by volume) and a benzene content of less than about 1 ppmv.

[0025] As used herein, the term "compressor" refers to a machine, unit, device, or apparatus that increases the pressure of a gas stream by the application of work. Compressors may feature a single compression process or step, or compressors may feature multi-stage compressions or steps, more particularly multi-stage compressors located within a single casing or shell. Gas streams to be compressed may be provided to a compressor at different pressures. Some stages or steps of a gas cooling process may involve two or more compressors in parallel, series, or both.

[0026] As used herein, the term "expander" refers to a machine, unit, device or apparatus suitable for increasing the volume of a gas, accompanied by decreasing the gas temperature and gas pressure. Unless a particular type of expander is specifically stated herein, expanders used in the present disclosure may operate by (1) at least partially by isenthalpic means, or (2) at least partially by isentropic means, or (3) a combination of both isentropic means and isenthalpic means. As such, the term "expander" may refer to a hydraulic turbine or any alternative constructs for promoting expansion of a gas. Suitable devices for promoting isenthalpic expansion of natural gas may 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 promoting isentropic expansion of natural gas may include equipment such as expanders or compressor-expanders, including turboexpander-compressor assemblies, that extract or derive work from such expansion. An expander may comprise a hydraulic turbine effective to increase the volume of a gas from a first volume to a larger second volume. Some stages or steps of a gas cooling process may involve two or more expanders in parallel, series, or both.

[0027] As used herein, the term "compressor-expander" refers to a machine in which an expander provides shaft power to drive a compressor. Some types of "turboexpanders" are representative of a compressor-expander operatively coupled together on a single (common) shaft. Other types of turboexpanders may be coupled to a generator to promote production of electrical power.

[0028] As used herein, the term "cooling" refers to lowering and/or dropping the 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, at least about 50°C, at least about 75°C, at least about 85°C, at least about 95°C, or at least about 100°C. The cooling may

be promoted by direct or indirect contact with any suitable heat sink, including air or a cooling liquid, for lowering the temperature. Preferably, cooling may take place through indirect contact with a heat sink. Cooling may also take place by expansion as well.

[0029] As used herein, the term "heat exchanger" refers to any device capable of
5 transferring thermal energy from one medium to another medium. Heat exchangers may 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, a plate-fin heat exchanger such as a brazed aluminum plate fin type a shell-and-tube heat exchanger, spiral, hairpin, core, core-and-kettle,
10 printed-circuit, or double-pipe heat exchanger), a direct contact heat exchanger, or any other type of heat exchanger. Preferably, heat exchange in the present disclosure takes place through indirect heat exchange. "Heat exchangers" may also refer to any column, tower, unit or other arrangement adapted to allow the passage of one or more streams for promoting direct or indirect heat exchange between one or more lines of refrigerant. "Air cooled heat exchangers"
15 may cool a gas stream against ambient atmosphere, which may include air or any other enriched atmospheric or inert gas.

[0030] As used herein, the term "closed refrigerant loop" means a refrigerant does not leave the refrigerant loop and then re-enter another stream in a process (*e.g.*, a natural gas stream undergoing liquefaction according to the disclosure herein). A refrigerant loop may be
20 connected to another process stream (*e.g.*, a natural gas stream or a source of nitrogen) to provide makeup refrigerant on an as-needed basis.

[0031] As used herein, the term "upstream" refers to an element in a flow scheme which is located prior to or before a reference point or reference element relative to the direction of fluid flow. For example, a compressor that is positioned in a flow scheme upstream of an expander
25 is located on the side of the expander that fluid enters into the expander.

[0032] As used herein, the term "downstream" refers to an element in a flow scheme which is located after a reference point or reference element relative to the direction of fluid flow. For example, a compressor that is positioned in a flow scheme downstream of an expander is located on the side of the expander that fluid exits the expander.

30 [0033] As used herein, the term "room temperature" refers to about 23°C.

[0034] As used herein, the term "secondary liquid cooling" refers to cooling a process stream (*e.g.*, a natural gas stream or refrigerant) using a liquid coolant subsequent to a prior cooling of the process stream (*e.g.*, via air cooled heat exchange).

[0035] Non-limiting embodiments of the present disclosure will now be described with reference to the drawings.

[0036] FIG. 1 is a diagram of a natural gas liquefaction system and method employing two closed refrigerant loops and no additional incorporation of secondary liquid cooling. As shown in FIG. 1, system and method 100 provides natural gas stream 102 to first compressor 104 via feed line 101. In first compressor 104, natural gas stream 102 is pressurized to a pressurization state higher than that of the natural gas stream. Additional pressurization then may take place in second compressor 106, which may be further coupled to expander 116 by a common drive shaft, thereby defining a compressor-expander or turboexpander-compressor assembly. Optionally, intermediate heat exchange (not shown) may take place while conveying the natural gas from first compressor 104 to second compressor 106. In second compressor 106, the natural gas undergoes further compression, and cooling then takes place in air cooled heat exchanger 112 while conveying the natural gas to first expander 116. Expansion of the natural gas in first expander 116 may lower the temperature after the two compression cycles prior to provide a cooled, expanded natural gas stream in line 118. The cooled, expanded natural gas stream is conveyed via line 118 to multiple stream heat exchanger 120 for further cooling, as described in additional detail hereinafter.

[0037] Multiple stream heat exchanger 120 may employ two different gaseous refrigerants that remain separate in a gaseous state in closed refrigerant loops 140 and 160, described hereinafter, which afford further indirect heat exchange to the cooled, expanded natural gas stream entering from line 118. The two different refrigerants also undergo heat exchange with each other in multiple stream heat exchanger 120, which may comprise a printed circuit heat exchanger, brazed aluminum heat exchanger, or similar heat exchanger in particular system and method embodiments. Heat exchange of the cooled, expanded natural gas stream with the two different refrigerants in multiple stream heat exchanger 120 may result in further lowering of the temperature of the natural gas. After exiting multiple stream heat exchanger 120 via line 122, the cooled, expanded natural gas stream may undergo further expansion in downstream expander 124, preferably a hydraulic turbine. Expansion of the cooled, expanded natural gas stream in downstream expander 124 affords a chilled natural gas stream having an even lower temperature and pressure in line 128. The chilled natural gas stream may then have a suitable temperature and entropic state for conversion into LNG 130. At least partial liquefaction to form LNG 130 may occur upon the cooled, expanded natural gas stream exiting downstream expander 124.

[0038] As referenced above, system and method 100 employs closed refrigerant loops 140 and 160, which provide two different gaseous refrigerants to multiple stream heat exchanger 120. In preferred embodiments, closed refrigerant loop 140 circulates gaseous methane or predominantly gaseous methane, preferably pre-processed natural gas, and closed refrigerant
5 loop 160 circulates gaseous nitrogen or predominantly gaseous nitrogen. These two refrigerants are particularly convenient due to their physical properties and the ease with which they can be obtained, for example, methane or natural gas may be drawn from a processed natural gas stream, and nitrogen may be obtained from a conventional air separation unit. As shown in FIG. 1, closed refrigerant loop 140 transits multiple stream heat exchanger 120 once,
10 whereupon a first gaseous refrigerant therein may undergo heat exchange with the cooled, expanded natural gas stream and a second gaseous refrigerant in closed refrigerant loop 160. Closed refrigerant loop 160, in contrast, transits multiple stream heat exchanger 120 twice, wherein the second gaseous refrigerant may undergo initial heat exchange with the first gaseous refrigerant during a first pass, and more extensive heat exchange with the cooled, expanded
15 natural gas stream may occur during a second pass. Closed refrigerant loop 160 transits multiple stream heat exchanger 120 twice, since the refrigerant therein (*e.g.*, nitrogen) is cooled to a lower temperature than is the refrigerant in closed refrigerant loop 140. Interaction of the refrigerant in closed refrigerant loop 160 with the refrigerant in closed refrigerant loop 140 may afford an intermediate temperature state that allows a desired refrigerant temperature to
20 be reached more readily in closed refrigerant loop 160. Additional details regarding closed refrigerant loops 140 and 160 and the interaction of the first and second gaseous refrigerants in multiple stream heat exchanger 120 are provided hereinafter.

[0039] Closed refrigerant loop 140 provides a first gaseous refrigerant to multiple stream heat exchanger 120. In particular, closed refrigerant loop 140 may circulate gaseous methane
25 or gaseous natural gas as the first gaseous refrigerant. Referring to FIG. 1, main refrigerant compressor 141, which may be single-stage or multi-stage, compresses the first gaseous refrigerant to a higher pressure state. When main refrigerant compressor 141 is multi-stage, interstage heat exchange may take place via air cooled heat exchanger 142. Additional rejection of excess heat may then take place downstream from main refrigerant compressor
30 141 at air cooled heat exchanger 144 and then further downstream in supplemental heat exchanger 146, such as a printed circuit heat exchanger or brazed aluminum heat exchanger. After undergoing additional heat exchange in supplemental heat exchanger 146, the first gaseous refrigerant is conveyed to expanders 148 and 149, which are linked in series and are respectively coupled to compressors 150 and 151 via separate common drive shafts, thereby

defining two turboexpander-compressor assemblies. Stepwise expansion is conducted in expanders 148 and 149, since the pressure of the first gaseous refrigerant (*e.g.*, methane or natural gas) is usually too high to undergo complete expansion to afford a desired pressure and temperature in a single expander. After undergoing expansion sequentially in expanders 148 and 149, the first gaseous refrigerant may be sufficiently cooled to promote heat exchange and passes through multiple stream heat exchanger 120, wherein the first gaseous refrigerant may promote cooling of the cooled, expanded natural gas stream and a second gaseous refrigerant, preferably gaseous nitrogen, as discussed hereinbelow.

[0040] After promoting heat exchange in multiple stream heat exchanger 120, the first gaseous refrigerant may still be at a sufficiently low temperature to provide additional heat exchange before being recirculated to main refrigerant compressor 141. As shown in FIG. 1, the first gaseous refrigerant leaving multiple stream heat exchanger 120 may be conveyed to supplemental heat exchanger 146, wherein the temperature of incoming first gaseous refrigerant may be lowered before being conveyed to expander 148. Optionally, supplemental heat exchanger 146 and additional heat exchange with the first gaseous refrigerant therein may be omitted. If additional heat exchange of the first gaseous refrigerant is omitted, the first refrigerant may be returned directly from multiple stream heat exchanger 120 to compressor 150. After being returned to supplemental heat exchanger 146 and promoting additional heat exchange, the first gaseous refrigerant may be re-pressurized through sequential passage through compressors 150 and 151, followed by rejection of excess heat via air cooled heat exchanger 154 prior to re-entering main refrigerant compressor 141 and beginning the refrigeration cycle anew. In the case of methane (natural gas) as the first gaseous refrigerant, the methane may be maintained at about -91°C , thereby allowing the methane to promote cooling of nitrogen in closed refrigerant loop 160 to a temperature of about -89°C before further expansive cooling takes place to about -155°C . As a result, the first gaseous refrigerant is pressurized to a very high pressure (~ 200 bar) to afford a sufficient pressure drop to achieve this temperature. Nitrogen, once chilled to -89°C , only needs one additional expansion in closed refrigerant loop 160 to achieve a temperature of -155°C .

[0041] Closed refrigerant loop 160 provides a second gaseous refrigerant to multiple stream heat exchanger 120, wherein the second gaseous refrigerant differs from the first gaseous refrigerant. In particular, closed refrigerant loop 160 may preferably circulate gaseous nitrogen. Referring still to FIG. 1, main refrigerant compressor 161, which may be single-stage or multi-stage, compresses the second gaseous refrigerant to a higher pressure state. When main refrigerant compressor 161 is multi-stage, interstage heat exchange may take place via

air cooled heat exchanger 162. Additional rejection of excess heat may take place downstream from main refrigerant compressor 161 at air cooled heat exchanger 164 before the second gaseous refrigerant enters multiple stream heat exchanger 120. As shown, after undergoing expansion and heat exchange, the second gaseous refrigerant transits multiple stream heat exchanger 120 a first time, wherein additional cooling may be afforded by the first gaseous refrigerant. In the case of nitrogen as the second gaseous refrigerant, the first transit of multiple stream heat exchanger 120 may lower the nitrogen temperature to about -89°C, and additional expansion may lower the nitrogen temperature to about -155°C. Optionally, the additional transit of multiple stream heat exchanger 120 by closed refrigerant loop 160 may be omitted if sufficient heat exchange may otherwise take place, however. After transiting multiple stream heat exchanger 120 a first time, the second gaseous refrigerant exits multiple stream heat exchanger 120 and undergoes expansion in expander 168, after which the second gaseous refrigerant is in a lower temperature state. Expander 168 may be coupled to compressor 170 via a common drive shaft, thereby defining a compressor-expander or turboexpander-compressor assembly. After undergoing expansion in expander 168, the second gaseous refrigerant is returned to multiple stream heat exchanger 120, wherein it may afford further and more effective cooling of the cooled, expanded natural gas stream. After promoting further cooling of the cooled, expanded natural gas stream, the second gaseous refrigerant is conveyed to compressor 170 and re-compressed to a higher pressure state. Following re-pressurization, heat exchange of the second gaseous refrigerant may take place via air-cooled heat exchanger 174 prior to the second gaseous refrigerant re-entering main refrigerant compressor 161 and beginning the refrigeration cycle anew.

[0042] As referenced in brief hereinabove, the present disclosure incorporates secondary liquid cooling within at least one of closed refrigerant loops 140 and 160 (*i.e.*, as a separate gas-liquid cooling element) and/or upstream from multiple stream heat exchanger 120 and downstream from compressor 104. FIGS. 2-6 show diagrams of various system and method configurations incorporating secondary liquid cooling in at least one location. Preferably, secondary liquid cooling is incorporated both upstream from multiple stream heat exchanger 120 and within at least one of closed refrigerant loops 140 and 160, and even more preferably, secondary liquid cooling is incorporated upstream from multiple stream heat exchanger 120 and within both of closed refrigerant loops 140 and 160. Additional details are provided hereinafter in reference to FIGS. 2-6. Identical reference characters are used in FIGS. 2-6 for describing in-common elements having similar features to those described above in FIG. 1. Moreover, in the interest of brevity, elements in FIGS. 2-6 having similar operational

characteristics to those described above in FIG. 1 are not described again in detail. It is additionally noted that in several of the system and method configurations depicted in FIGS. 2-6 and described hereinafter, the configuration shown is identical to that provided in FIG. 1, except for the introduction of the secondary liquid cooling in one or more locations. As noted above, through the introduction of secondary liquid cooling, certain elements present in system and method 100 may be omitted, if desired, in the systems and methods described hereinafter. As such, elements that are present in FIG. 1 and remain depicted in FIGS. 2-6, but which may be omitted as a consequence of introducing secondary liquid cooling, are described hereinafter as optional elements.

10 [0043] FIG. 2 is a diagram of a natural gas liquefaction system and method employing two closed refrigerant loops employing gaseous refrigerants, with incorporation of secondary liquid cooling in at least one of the two closed refrigerant loops, preferably in both of the two closed refrigerant loops. Referring to FIG. 2, system and method 200 differs from system and method 100 in the incorporation of secondary liquid cooling 210 (*e.g.*, chilled water) upstream from supplemental heat exchanger 146 and expander 148. The first gaseous refrigerant in this location is usually at or near room temperature, and secondary liquid cooling 210 can considerably lower the temperature of the first gaseous refrigerant entering expander 148. Optionally, secondary liquid cooling 210 may be incorporated downstream from supplemental heat exchanger 146 instead and/or secondary liquid cooling 210 may be incorporated as a third stream on supplemental heat exchanger 146 to afford an even more efficient heat exchange. By lowering the temperature of the first gaseous refrigerant in this location, the operating pressure within closed refrigerant loop 140 may be lowered from about 200 bar relative to ambient pressure to about 125 bar relative to ambient pressure (*i.e.*, a pressure decrease of about 37.5%). Although FIG. 2 shows both expanders 148 and 149 and compressors 150 and 151 being present, as in FIG. 1, the decreased operating pressure within closed refrigerant loop 140 may allow one compressor-expander to become an optional design element (*e.g.*, expander 149 and compressor 150). Specifically, the decreased operating pressure may allow the compressed gaseous refrigerant (*e.g.*, methane) within closed refrigerant loop 140 to undergo expansion and subsequent re-compression in a single step, rather than stepwise expansion and re-compression needed when working at higher operating pressures.

20 25 30 [0044] In addition, secondary liquid cooling may be provided within closed refrigerant loop 160 as well. As shown in FIG. 2, secondary liquid cooling 220 may be incorporated downstream from air cooled heat exchanger 164 and upstream from multiple stream heat exchanger 120, thereby additionally lowering the temperature of the second gaseous refrigerant

just prior to initially entering multiple stream heat exchanger 120. Again, the temperature of the second gaseous refrigerant may be near room temperature at this location within closed refrigerant loop 160, thereby allowing secondary liquid cooling 220 to be particularly effective. Lowering the temperature of the second gaseous refrigerant just prior to its entry into multiple stream heat exchanger 120 allows the second gaseous refrigerant to undergo more effective initial cooling when transiting multiple stream heat exchanger, thereby allowing the size of multiple stream heat exchanger 120 to be decreased, if desired. In non-limiting examples, introduction of secondary liquid cooling 220 into closed refrigerant loop 160 may allow the operating pressure within closed refrigerant loop 160 to be lowered from about 100 bar relative to ambient pressure (*e.g.*, in the system and method configuration shown in FIG. 1) to about 90 bar relative to ambient pressure (*i.e.*, a pressure decrease of about 10%).

[0045] Secondary liquid cooling 220 in closed refrigerant loop 160 may be optionally omitted even when secondary liquid cooling 210 is present in closed refrigerant loop 140. Preferably, both secondary liquid cooling 210 and secondary liquid cooling 220 are both present.

[0046] FIG. 3 is a diagram of a first configuration of a natural gas liquefaction system and method employing two closed refrigerant loops employing gaseous refrigerants, with incorporation of secondary liquid cooling upstream from a multiple stream heat exchanger, preferably in combination with secondary liquid cooling in at least one of the closed refrigerant loops. Referring to FIG. 3, system and method 300 differs from system and method 100 in the incorporation of secondary liquid cooling 310 (*e.g.*, chilled water) downstream from air cooled heat exchanger 112 and upstream from expander 116. The compressed natural gas stream in this location has not yet undergone extensive cooling and may remain at or near room temperature, and secondary liquid cooling 310 can considerably lower the gas temperature prior to expansion taking place in expander 116. Thus, by introducing secondary liquid cooling 310 upstream from multiple stream heat exchanger 120 in the depicted location, deeper cooling of the cooled, expanded natural gas stream exiting multiple stream heat exchanger 120 may be realized prior to additional expansion. Accompanying the temperature decrease of the cooled, expanded natural gas stream, a pressure decrease from about 110 bar relative to ambient pressure to about 70 bar to about 90 bar relative to ambient pressure may be realized by incorporating secondary liquid cooler 310 upstream from multiple stream heat exchanger 120 in the depicted location (18-36% pressure decrease). The pressure decrease may allow increased natural gas throughput to be realized at a fixed compressor power.

[0047] System and method 300 may contain or omit secondary liquid cooling within closed refrigerant loops 140 and 160. As shown in FIG. 3, secondary liquid cooler 220 is present in closed refrigerant loop 160, and a secondary liquid cooler is absent from closed refrigerant loop 140. However, when secondary liquid cooling 310 is employed in the depicted location, it is to be appreciated that secondary liquid cooling 220 may be optionally omitted from closed refrigerant loop 160 or secondary liquid cooling may be added to closed refrigerant loop 140 in a similar location to that described above for secondary liquid cooling 210. FIG. 5 shows system and method 500, which is analogous in configuration to system and method 300, with each of secondary liquid cooling 210, 220 and 310 all in place. By employing chilled water in the upstream location depicted in FIG. 3, the natural gas stream may reach a temperature of about 10°C or below, assuming a chilled water temperature of about 5°C. For example, in the depicted configuration, the discharge temperature from expander 116 may be about -20°C under these conditions. In contrast, without secondary liquid cooling being used, the incoming natural gas stream may be at a temperature of about 0°C or above when provided to multiple stream heat exchanger 120.

[0048] FIG. 4 is a diagram of a second configuration of a natural gas liquefaction system and method employing two closed refrigerant loops employing gaseous refrigerants, with incorporation of secondary liquid cooling upstream from a multiple stream heat exchanger, preferably in combination with secondary liquid cooling in at least one of the closed refrigerant loops. System and method 400 depicted in FIG. 4 differs from system and method 300 shown in FIG. 3 in that the upstream location of secondary liquid cooling 310, as well as that of air cooled heat exchanger 112, have shifted further downstream toward multiple stream heat exchanger 120. More significantly, by providing effective secondary liquid cooling downstream from compressor 104 and upstream from multiple stream heat exchanger 120 (*i.e.*, in line 410), compressor 106 and expander 116 may be eliminated, since they may no longer be necessary to bring an incoming natural gas stream into a temperature and pressure state suitable to undergo further cooling in multiple stream heat exchanger 120. As such system and method 400 shown in FIG. 4 has omitted these elements, which may afford significant capital expenditure savings. It is to be appreciated, of course, that still other alternative configurations may retain compressor 106 and expander 116 with air cooled heat exchanger 112 located in between, while still incorporating air cooled heat exchanger 112 and secondary liquid cooling 310 in line 410 downstream from expander 116 and upstream from multiple stream heat exchanger 120. By employing chilled water in the upstream location depicted in FIG. 4, the

natural gas stream may reach a temperature of about 0°C to about 10°C before being provided to multiple stream heat exchanger 120.

[0049] Like system and method 300, system and method 400 may similarly contain or omit secondary liquid cooling within closed refrigerant loops 140 and 160. As shown in FIG. 4, secondary liquid cooling 220 is present in closed refrigerant loop 160, and secondary liquid cooling is absent from closed refrigerant loop 140. However, when secondary liquid cooling 310 is incorporated in the depicted location, it is to be appreciated that secondary liquid cooling 220 may be optionally omitted from closed refrigerant loop 160 or secondary liquid cooling may be added to closed refrigerant loop 140 in a similar location to that described above for secondary liquid cooling 210. FIG. 6 shows system and method 600, which is analogous in configuration to system and method 400, with each of secondary liquid coolers 210, 220 and 310 all in place.

[0050] Accordingly, methods of the present disclosure may comprise: providing a natural gas stream to a first compressor; compressing the natural gas stream with the first compressor to form a compressed natural gas stream having a pressure higher than that of the natural gas stream; performing air cooled heat exchange upon the compressed natural gas stream to form a cooled, compressed natural gas stream; conveying the cooled, compressed natural gas stream to a multiple stream heat exchanger that is cooled with a first gaseous refrigerant and a second gaseous refrigerant that differ from one another; cooling the cooled, compressed natural gas stream in the multiple stream heat exchanger to a temperature lower than that of the cooled, compressed natural gas stream to form a chilled, compressed natural gas stream; expanding the chilled, compressed natural gas stream in a downstream expander to form a chilled natural gas stream; and converting the chilled natural gas stream into liquefied natural gas. The first gaseous refrigerant is provided to the multiple stream heat exchanger by a first closed refrigerant loop, and the second gaseous refrigerant is provided to the multiple stream heat exchanger by a second closed refrigerant loop. Secondary liquid cooling is incorporated in at least one of the first closed refrigerant loop, the second closed refrigerant loop, and/or upstream from the multiple stream heat exchanger and downstream from the first compressor.

[0051] Likewise, systems suitable for liquefying natural gas according to the disclosure herein may comprise: a natural gas stream in fluid communication with an inlet of a first compressor; an air cooled heat exchanger in fluid communication with an outlet of the first compressor; a multiple stream heat exchanger having a first inlet in fluid communication with an outlet of the air cooled heat exchanger and that is cooled with a first gaseous refrigerant and a second gaseous refrigerant that differ from each other; and a downstream expander having

an inlet in fluid communication with a first outlet of the multiple stream heat exchanger. The first gaseous refrigerant is provided to the multiple stream heat exchanger by a first closed refrigerant loop, and the second gaseous refrigerant is provided to the multiple stream heat exchanger by a second closed refrigerant loop. Secondary liquid cooling is incorporated in at least one of the first closed refrigerant loop, the second closed refrigerant loop, or upstream from the multiple stream heat exchanger.

[0052] As indicated above, the first gaseous refrigerant and the second gaseous refrigerant differ from each other. Preferably, the first gaseous refrigerant comprises or consists essentially of methane, and the second gaseous refrigerant comprises or consists essentially of nitrogen.

[0053] The first closed refrigerant loop, which may contain methane or predominantly methane as a first gaseous refrigerant, may comprise: a main compressor; an air cooled heat exchanger having an inlet in fluid communication with an outlet of the main compressor; a supplemental heat exchanger (*e.g.*, a printed circuit heat exchanger or a brazed aluminum heat exchanger) having a first inlet in fluid communication with an outlet of the air cooled heat exchanger; at least one expander having an inlet in fluid communication with a first refrigerant outlet of the supplemental heat exchanger and an outlet in fluid communication with a first refrigerant inlet of the multiple stream heat exchanger; and at least one compressor having an inlet in fluid communication with a first refrigerant outlet of the multiple stream heat exchanger and an outlet in fluid communication with the main compressor. Preferably, the first refrigerant outlet of the multiple stream heat exchanger is in fluid communication with a second inlet of the supplemental heat exchanger and a second outlet of the supplemental heat exchanger is in fluid communication with the inlet of the at least one compressor.

[0054] When present, secondary liquid cooling in the first closed refrigerant loop may be located upstream from the supplemental heat exchanger and the at least one expander. Optionally, the secondary liquid cooling may be downstream from the supplemental heat exchanger and upstream from the at least one expander and/or the secondary liquid cooling may be located within the supplemental heat exchanger (*e.g.*, by incorporating a third flow line within a printed circuit heat exchanger or brazed aluminum heat exchanger). Preferably, secondary liquid cooling is present in at least the first closed refrigerant loop in the systems and methods disclosed herein.

[0055] The second closed refrigerant loop, which may contain nitrogen or predominantly nitrogen as a second gaseous refrigerant may comprise: a main compressor; an air cooled heat exchanger having an inlet in fluid communication with an outlet of the main compressor and

an outlet in fluid communication with a second refrigerant inlet of the multiple stream heat exchanger; an expander having an inlet in fluid communication with a second refrigerant outlet of the multiple stream heat exchanger and an outlet in fluid communication with a third refrigerant inlet of the multiple stream heat exchanger; and a compressor having an inlet in fluid communication with a third refrigerant outlet of the multiple stream heat exchanger and an outlet in fluid communication with the main compressor.

[0056] When present, secondary liquid cooling in the second closed refrigerant loop may be located downstream from the air cooled heat exchanger and upstream from the multiple stream heat exchanger.

[0057] In preferred system and method configuration, secondary liquid cooling may be present in both the first closed refrigerant loop and the second closed refrigerant loop. More specifically, secondary liquid cooling in the first closed refrigerant loop may be located downstream from the supplemental heat exchanger and upstream from the at least one expander, and secondary liquid cooling in the second closed refrigerant loop may be located downstream from the air cooled heat exchanger and upstream from the multiple stream heat exchanger.

[0058] Secondary liquid cooling may also be present upstream from the multiple stream heat exchanger. When secondary liquid cooling is present upstream from the multiple stream heat exchanger, secondary liquid cooling may also be present in the first closed refrigerant loop and/or the second closed refrigerant loop, preferably in both the first and second closed refrigerant loops.

[0059] Secondary liquid cooling of the natural gas stream upstream from the multiple stream heat exchanger may be conducted with or without additional compression beyond that provided by the first compressor. In some system and method configurations, compression of the natural gas stream takes place with just the first compressor, and air cooled heat exchange and secondary liquid cooling take place as the natural gas is conveyed to the multiple stream heat exchanger. That is, such system and method configurations may omit a compressor-expander downstream from the main compressor. Other system and method configurations may include those in which a second compressor and an upstream expander are present, preferably as a compressor-expander operatively coupled by a common drive shaft, and each of which is upstream from the multiple stream heat exchanger; and an air cooled heat exchanger is present downstream from the second compressor and upstream from the upstream expander. In such system and method configurations, secondary liquid cooling may be located downstream from the air cooled heat exchanger and upstream from the upstream expander.

[0060] Secondary liquid cooling in the present disclosure may be provided from any suitable liquid, which may be obtained via external refrigeration, from a natural source or any combination thereof. Preferably, secondary liquid cooling may be provided by chilled water, wherein the chilled water may include substantially pure water, solutions of water and salt (including sea water), or solutions of water and water-miscible organics (*e.g.*, water-glycol solutions). The chilled water employed in the disclosure herein may have a temperature ranging from about 10°C to about -15°C or about 5°C to about -15°C. In the present disclosure, suitable chilled water may be obtained from a chilled water supply system, suitable variations for which will be familiar to persons having ordinary skill in the art. Alternately, chilled water may be obtained from a natural source, such as deep sea ocean water, which may represent a viable option when forming liquefied natural gas at offshore locations. Shallow ocean water having a slightly higher temperature may also be chilled with external refrigeration to obtain a lower chilled water temperature than that realizable by cooling water substantially from room temperature. Yet alternatively, the chilled water may be obtained using a vapor absorption chilling machine (VAM). Any heat source at the required temperature may be employed for VAM energy input. Preferably, waste heat may be employed in the VAM to produce the chilled water, such as surplus heat available from gas turbine exhaust recovered in the form of steam. For example, in preferred aspects, heat recovered from the gas turbine exhaust in the form of steam is routed to a steam turbine for power generation, and steam extracted from the steam turbine (generally at a pressure of about 8 barg) is employed as the heating medium in the VAM for the generation of chilled water. Alternatively, waste heat can be recovered and integrated with the VAM system through a hot oil circuit from any heat generating process including gas turbine combustion. Waste heat in the form of combustion exhaust gas may also be direct-coupled to the VAM system without an intermediate medium such as steam or hot oil. Yet alternatively, in certain aspects, a higher grade energy source, *e.g.*, process off-gases, may be used to supply heat to the VAM system through combustion.

[0061] Embodiments disclosed herein include:

[0062] A. Methods for forming LNG. The methods comprise: providing a natural gas stream to a first compressor; compressing the natural gas stream with the first compressor to form a compressed natural gas stream having a pressure higher than that of the natural gas stream; performing air cooled heat exchange upon the compressed natural gas stream to form a cooled, compressed natural gas stream; conveying the cooled, compressed natural gas stream to a multiple stream heat exchanger that is cooled with a first gaseous refrigerant and a second gaseous refrigerant, the first and second gaseous refrigerants differing from one another;

wherein the first gaseous refrigerant is provided to the multiple stream heat exchanger by a first closed refrigerant loop and the second gaseous refrigerant is provided to the multiple stream heat exchanger by a second closed refrigerant loop; cooling the cooled, compressed natural gas stream in the multiple stream heat exchanger to a temperature lower than that of the cooled, compressed natural gas stream to form a chilled, compressed natural gas stream; expanding the chilled, compressed natural gas stream in a downstream expander to form a chilled natural gas stream; and converting the chilled natural gas stream into liquefied natural gas; wherein secondary liquid cooling is incorporated in at least one of the first closed refrigerant loop, the second closed refrigerant loop, and/or upstream from the multiple stream heat exchanger and downstream from the first compressor.

[0063] B. Systems for forming LNG. The systems comprise: a natural gas stream in fluid communication with an inlet of a first compressor; an air cooled heat exchanger in fluid communication with an outlet of the first compressor; a multiple stream heat exchanger having a first inlet in fluid communication with an outlet of the air cooled heat exchanger and that is cooled with a first gaseous refrigerant and a second gaseous refrigerant, the first and second gaseous refrigerants differing from one another, and the first gaseous refrigerant being provided to the multiple stream heat exchanger from a first closed refrigerant loop and the second gaseous refrigerant being provided to the multiple stream heat exchanger from a second closed refrigerant loop; and a downstream expander having an inlet in fluid communication with a first outlet of the multiple stream heat exchanger; wherein secondary liquid cooling is incorporated in at least one of the first closed refrigerant loop, the second closed refrigerant loop, and/or upstream from the multiple stream heat exchanger and downstream from the first compressor.

[0064] Embodiments A and B may have one or more of the following additional elements in any combination:

[0065] Element 1: wherein the first gaseous refrigerant comprises methane and the second gaseous refrigerant comprises nitrogen.

[0066] Element 2: wherein the first closed refrigerant loop comprises: a main compressor; an air cooled heat exchanger having an inlet in fluid communication with an outlet of the main compressor; a supplemental heat exchanger having a first inlet in fluid communication with an outlet of the air cooled heat exchanger; at least one expander having an inlet in fluid communication with a first refrigerant outlet of the supplemental heat exchanger and an outlet in fluid communication with a first refrigerant inlet of the multiple stream heat exchanger; and at least one compressor having an inlet in fluid communication with a first refrigerant outlet of

the multiple stream heat exchanger and an outlet in fluid communication with the main compressor.

[0067] Element 3: wherein the supplemental heat exchanger comprises a printed circuit heat exchanger or a brazed aluminum heat exchanger.

5 [0068] Element 4: wherein the first refrigerant outlet of the multiple stream heat exchanger is in fluid communication with a second inlet of the supplemental heat exchanger and a second outlet of the supplemental heat exchanger is in fluid communication with the inlet of the at least one compressor.

10 [0069] Element 5: wherein secondary liquid cooling is present in the first closed refrigerant loop, and the secondary liquid cooling is located upstream from the supplemental heat exchanger and the at least one expander, or the secondary liquid cooling is incorporated within the supplemental heat exchanger.

15 [0070] Element 6: wherein the second closed refrigerant loop comprises: a main compressor; an air cooled heat exchanger having an inlet in fluid communication with an outlet of the main compressor and an outlet in fluid communication with a second refrigerant inlet of the multiple stream heat exchanger; an expander having an inlet in fluid communication with a second refrigerant outlet of the multiple stream heat exchanger and an outlet in fluid communication with a third refrigerant inlet of the multiple stream heat exchanger; and a compressor having an inlet in fluid communication with a third refrigerant outlet of the multiple stream heat exchanger and an outlet in fluid communication with the main compressor.

[0071] Element 7: wherein secondary liquid cooling is present in the second closed refrigerant loop, and the secondary liquid cooling is located downstream from the air cooled heat exchanger and upstream from the multiple stream heat exchanger.

25 [0072] Element 8: wherein secondary liquid cooling is present in both the first closed refrigerant loop and the second closed refrigerant loop.

[0073] Element 9: wherein secondary liquid cooling is present upstream from the multiple stream heat exchanger and downstream from the first compressor.

30 [0074] Element 10: wherein secondary liquid cooling is present upstream from the multiple stream heat exchanger and downstream from the first compressor, and secondary liquid cooling is present in both the first closed refrigerant loop and the second closed refrigerant loop.

[0075] Element 11: wherein the compressed natural gas stream is further compressed with a second compressor and subsequently expanded with an upstream expander, each of which is upstream from the multiple stream heat exchanger; wherein the air cooled heat exchange is

performed with an air cooled heat exchanger downstream from the second compressor and upstream from the upstream expander, and secondary liquid cooling is located downstream from the air cooled heat exchanger and upstream from the upstream expander.

[0076] Element 11A: wherein the system further comprises: a second compressor and an upstream expander, each of which is upstream from the multiple stream heat exchanger; wherein the air cooled heat exchanger is downstream from the second compressor and upstream from the upstream expander; and wherein secondary liquid cooling is located downstream from the air cooled heat exchanger and upstream from the upstream expander.

[0077] Element 12: wherein the second compressor and the upstream expander are operatively coupled by an in-common drive shaft.

[0078] Element 13: wherein the secondary liquid cooling is provided by chilled water, the chilled water optionally being provided by a chilled water supply system.

[0079] Illustrative combinations applicable to A and B may include, but are not limited to, 1 and 2; 1-3; 1-4; 1-5; 1 and 6; 1, 6 and 7; 1-7; 1-8; 1, and 6-8; 1, and 6-9; 1, and 6-10; 1 and 8; 1, 8 and 9; 1 and 10; 1, 10, and 11 or 11A; 1, and 11 or 11A; 1, 11 or 11A, and 12; 1 and 13; 2 and 3; 2-4; 2-5; 2 and 6; 2, 6 and 7; 2-7; 2-8; 2, and 6-8; 2, and 6-9; 2, and 6-10; 2 and 8; 2, 8 and 9; 2 and 10; 2, 10, and 11 or 11A; 2, and 11 or 11A; 2, 11 or 11A, and 12; 2 and 13; 6 and 7; 6-8; 6-9; 6-10; 6 and 8; 6 and 9; 6, 8 and 9; 6 and 10; 6, 10, and 11 or 11A; 6, and 11 or 11A; 6, 11 or 11A, and 12; 6 and 13; 8 and 9; 8 and 10; 8-10; 8, 10, and 11 or 11A; 8, and 11 or 11A; 8, 11 or 11A, and 12; 8 and 13; 9 and 10; 9, 10, and 11 or 11A; 9, and 11 or 11A; 9, 11 or 11A, and 12; 10, and 11 or 11A; 10, 11 or 11A, and 12; 10 and 13; 11 or 11A, and 12; 11 or 11A, and 13; and 12 and 13. Any of the foregoing may contain secondary liquid cooling in the first cooling loop only; the second cooling loop only; upstream of the multiple stream heat exchanger and downstream of the first compressor only; in the first cooling loop and in the second cooling loop only; in the first cooling loop and upstream of the multiple stream heat exchanger and downstream of the first compressor only; in the second cooling loop and upstream of the multiple stream heat exchanger and downstream of the first compressor only; and in each of the first cooling loop, the second cooling loop, and upstream of the multiple stream heat exchanger and downstream of the first compressor.

[0080] All documents described herein are incorporated by reference herein for purposes of all jurisdictions where such practice is allowed, including any priority documents and/or testing procedures to the extent they are not inconsistent with this text. As is apparent from the foregoing general description and the specific embodiments, while forms of the disclosure have been illustrated and described, various modifications can be made without departing from the

spirit and scope of the disclosure. Accordingly, it is not intended that the disclosure be limited thereby. For example, the compositions described herein may be free of any component, or composition not expressly recited or disclosed herein. Any method may lack any step not recited or disclosed herein. Likewise, the term “comprising” is considered synonymous with the term “including.” Whenever a method, composition, element or group of elements is preceded with the transitional phrase “comprising,” it is understood that we also contemplate the same composition or group of elements with transitional phrases “consisting essentially of,” “consisting of,” “selected from the group of consisting of,” or “is” preceding the recitation of the composition, element, or elements and vice versa.

10 [0081] One or more illustrative incarnations incorporating one or more invention elements are presented herein. Not all features of a physical implementation are described or shown in this application for the sake of clarity. It is understood that in the development of a physical embodiment incorporating one or more elements of the present invention, numerous implementation-specific decisions must be made to achieve the developer's goals, such as compliance with system-related, business-related, government-related and other constraints, which vary by implementation and from time to time. While a developer's efforts might be time-consuming, such efforts would be, nevertheless, a routine undertaking for those of ordinary skill in the art and having benefit of this disclosure.

20 [0082] Unless otherwise indicated, all numbers expressing quantities of ingredients, properties such as molecular weight, reaction conditions, and so forth used in the present specification and associated claims are to be understood as being modified in all instances by the term “about.” Accordingly, unless indicated to the contrary, the numerical parameters set forth in the following specification and attached claims are approximations that may vary depending upon the desired properties sought to be obtained by the embodiments of the present invention. At the very least, and not as an attempt to limit the application of the doctrine of equivalents to the scope of the claim, each numerical parameter should at least be construed in light of the number of reported significant digits and by applying ordinary rounding techniques.

25 [0083] Whenever a numerical range with a lower limit and an upper limit is disclosed, any number and any included range falling within the range is specifically disclosed, including the lower limit and upper limit. In particular, every range of values (of the form, “from about a to about b,” or, equivalently, “from approximately a to b,” or, equivalently, “from approximately a-b”) disclosed herein is to be understood to set forth every number and range encompassed within the broader range of values. Also, the terms in the claims have their plain, ordinary meaning unless otherwise explicitly and clearly defined by the patentee. Moreover, the

indefinite articles “a” or “an,” as used in the claims, are defined herein to mean one or more than one of the element that it introduces.

[0084] Therefore, the present disclosure is well adapted to attain the ends and advantages mentioned as well as those that are inherent therein. The particular embodiments disclosed
5 above are illustrative only, as the present disclosure may be modified and practiced in different but equivalent manners apparent to one having ordinary skill in the art and having the benefit of the teachings herein. Furthermore, no limitations are intended to the details of construction or design herein shown, other than as described in the claims below. It is therefore evident that the particular illustrative embodiments disclosed above may be altered, combined, or
10 modified and all such variations are considered within the scope and spirit of the present disclosure. The embodiments illustratively disclosed herein suitably may be practiced in the absence of any element that is not specifically disclosed herein and/or any optional element disclosed herein.

CLAIMS

What is claimed is:

1. A method comprising:
 - 5 providing a natural gas stream to a first compressor;
compressing the natural gas stream with the first compressor to form a compressed natural gas stream having a pressure higher than that of the natural gas stream;
performing air cooled heat exchange upon the compressed natural gas stream to
10 form a cooled, compressed natural gas stream;
conveying the cooled, compressed natural gas stream to a multiple stream heat exchanger that is cooled with a first gaseous refrigerant and a second gaseous refrigerant, the first and second gaseous refrigerants differing from one another;
wherein the first gaseous refrigerant is provided to the multiple stream
15 heat exchanger by a first closed refrigerant loop and the second gaseous refrigerant is provided to the multiple stream heat exchanger by a second closed refrigerant loop;
cooling the cooled, compressed natural gas stream in the multiple stream heat exchanger to a temperature lower than that of the cooled, compressed natural gas stream to form a chilled, compressed natural gas stream;
20 expanding the chilled, compressed natural gas stream in a downstream expander to form a chilled natural gas stream; and
converting the chilled natural gas stream into liquefied natural gas;
wherein secondary liquid cooling is incorporated in at least one of the first closed refrigerant loop, the second closed refrigerant loop, and/or upstream from
25 the multiple stream heat exchanger and downstream from the first compressor.
2. The method of claim 1, wherein the first gaseous refrigerant comprises methane and the second gaseous refrigerant comprises nitrogen.
- 30 3. The method of claim 1 or claim 2, wherein the first closed refrigerant loop comprises:
a main compressor;
an air cooled heat exchanger having an inlet in fluid communication with an outlet of
the main compressor;

a supplemental heat exchanger having a first inlet in fluid communication with an outlet of the air cooled heat exchanger;

at least one expander having an inlet in fluid communication with a first refrigerant outlet of the supplemental heat exchanger and an outlet in fluid communication with a first
5 refrigerant inlet of the multiple stream heat exchanger; and

at least one compressor having an inlet in fluid communication with a first refrigerant outlet of the multiple stream heat exchanger and an outlet in fluid communication with the main compressor.

10 4. The method of claim 3, wherein the supplemental heat exchanger comprises a printed circuit heat exchanger or a brazed aluminum heat exchanger.

5. The method of claim 3 or claim 4, wherein the first refrigerant outlet of the multiple stream heat exchanger is in fluid communication with a second inlet of the supplemental heat
15 exchanger and a second outlet of the supplemental heat exchanger is in fluid communication with the inlet of the at least one compressor.

6. The method of any one of claims 3-5, wherein secondary liquid cooling is present in the first closed refrigerant loop, and the secondary liquid cooling is located upstream from the
20 supplemental heat exchanger and the at least one expander, or the secondary liquid cooling is incorporated within the supplemental heat exchanger.

7. The method of any one of claims 1-6, wherein the second closed refrigerant loop comprises:

25 a main compressor;

an air cooled heat exchanger having an inlet in fluid communication with an outlet of the main compressor and an outlet in fluid communication with a second refrigerant inlet of the multiple stream heat exchanger;

an expander having an inlet in fluid communication with a second refrigerant outlet of
30 the multiple stream heat exchanger and an outlet in fluid communication with a third refrigerant inlet of the multiple stream heat exchanger; and

a compressor having an inlet in fluid communication with a third refrigerant outlet of the multiple stream heat exchanger and an outlet in fluid communication with the main compressor.

35

8. The method of claim 7, wherein secondary liquid cooling is present in the second closed refrigerant loop, and the secondary liquid cooling is located downstream from the air cooled heat exchanger and upstream from the multiple stream heat exchanger.
- 5 9. The method of any one of claims 5-8, wherein secondary liquid cooling is present in both the first closed refrigerant loop and the second closed refrigerant loop.
10. The method of any one of claims 1-9, wherein secondary liquid cooling is present upstream from the multiple stream heat exchanger and downstream from the first compressor.
- 10 11. The method of claim 9 or claim 10, wherein secondary liquid cooling is present upstream from the multiple stream heat exchanger and downstream from the first compressor, and secondary liquid cooling is present in both the first closed refrigerant loop and the second closed refrigerant loop.
- 15 12. The method of any one of claims 1-11, wherein the compressed natural gas stream is further compressed with a second compressor and subsequently expanded with an upstream expander, each of which is upstream from the multiple stream heat exchanger;
wherein the air cooled heat exchange is performed with an air cooled heat exchanger
20 downstream from the second compressor and upstream from the upstream expander, and secondary liquid cooling is located downstream from the air cooled heat exchanger and upstream from the upstream expander.
- 25 13. The method of claim 12, wherein the second compressor and the upstream expander are operatively coupled by an in-common drive shaft.
14. The method of any one of claims 1-13, wherein the secondary liquid cooling is provided by chilled water, the chilled water optionally being provided by a chilled water supply system.
- 30 15. A system comprising:
a natural gas stream in fluid communication with an inlet of a first compressor;
an air cooled heat exchanger in fluid communication with an outlet of the first compressor;
a multiple stream heat exchanger having a first inlet in fluid communication with an
35 outlet of the air cooled heat exchanger and that is cooled with a first gaseous refrigerant and a second gaseous refrigerant, the first and second gaseous refrigerants differing from one

another, and the first gaseous refrigerant being provided to the multiple stream heat exchanger from a first closed refrigerant loop and the second gaseous refrigerant being provided to the multiple stream heat exchanger from a second closed refrigerant loop; and

5 a downstream expander having an inlet in fluid communication with a first outlet of the multiple stream heat exchanger;

wherein secondary liquid cooling is incorporated in at least one of the first closed refrigerant loop, the second closed refrigerant loop, and/or upstream from the multiple stream heat exchanger and downstream from the first compressor.

10 16. The system of claim 15, wherein the first gaseous refrigerant comprises methane and the second gaseous refrigerant comprises nitrogen.

17. The system of claim 15 or claim 16, wherein the first closed refrigerant loop comprises:
a main compressor;
15 an air cooled heat exchanger having an inlet in fluid communication with an outlet of the main compressor;
a supplemental heat exchanger having a first inlet in fluid communication with an outlet of the air cooled heat exchanger;
at least one expander having an inlet in fluid communication with a first
20 refrigerant outlet of the supplemental heat exchanger and an outlet in fluid communication with a first refrigerant inlet of the multiple stream heat exchanger; and
at least one compressor having an inlet in fluid communication with a first refrigerant outlet of the multiple stream heat exchanger and an outlet in fluid communication with the main compressor.

25 18. The system of claim 17, wherein the supplemental heat exchanger comprises a printed circuit heat exchanger or a brazed aluminum heat exchanger.

19. The system of claim 17 or claim 18, wherein the first refrigerant outlet of the multiple
30 stream heat exchanger is in fluid communication with a second inlet of the supplemental heat exchanger and a second outlet of the supplemental heat exchanger is in fluid communication with the inlet of the at least one compressor.

20. The system of any one of claims 17-19, wherein secondary liquid cooling is present in the first closed refrigerant loop, and the secondary liquid cooling is located upstream from the supplemental heat exchanger and the at least one expander, or the secondary liquid cooling is incorporated within the supplemental heat exchanger.

5

21. The system of any one of claims 15-20, wherein the second closed refrigerant loop comprises:

a main compressor;

10 an air cooled heat exchanger having an inlet in fluid communication with an outlet of the main compressor and an outlet in fluid communication with a second refrigerant inlet of the multiple stream heat exchanger;

an expander having an inlet in fluid communication with a second refrigerant outlet of the multiple stream heat exchanger and an outlet in fluid communication with a third refrigerant inlet of the multiple stream heat exchanger; and

15 a compressor having an inlet in fluid communication with a third refrigerant outlet of the multiple stream heat exchanger and an outlet in fluid communication with the main compressor.

22. The system of claim 21, wherein secondary liquid cooling is present in the second closed refrigerant loop, and the secondary liquid cooling is located downstream from the air cooled heat exchanger and upstream from the multiple stream heat exchanger.

20

23. The system of any one of claims 20-22, wherein secondary liquid cooling is present in both the first closed refrigerant loop and the second closed refrigerant loop.

25

24. The system of any one of claims 15-23, wherein secondary liquid cooling is present upstream from the multiple stream heat exchanger and downstream from the first expander.

25. The system of claim 23 or claim 24, wherein secondary liquid cooling is present upstream from the multiple stream heat exchanger and downstream from the first expander and secondary liquid cooling is present in both the first closed refrigerant loop and the second closed refrigerant loop.

30

26. The system of any one of claims 15-25, further comprising:

35 a second compressor and an upstream expander, each of which is upstream from the multiple stream heat exchanger;

wherein the air cooled heat exchanger is downstream from the second compressor and upstream from the upstream expander; and

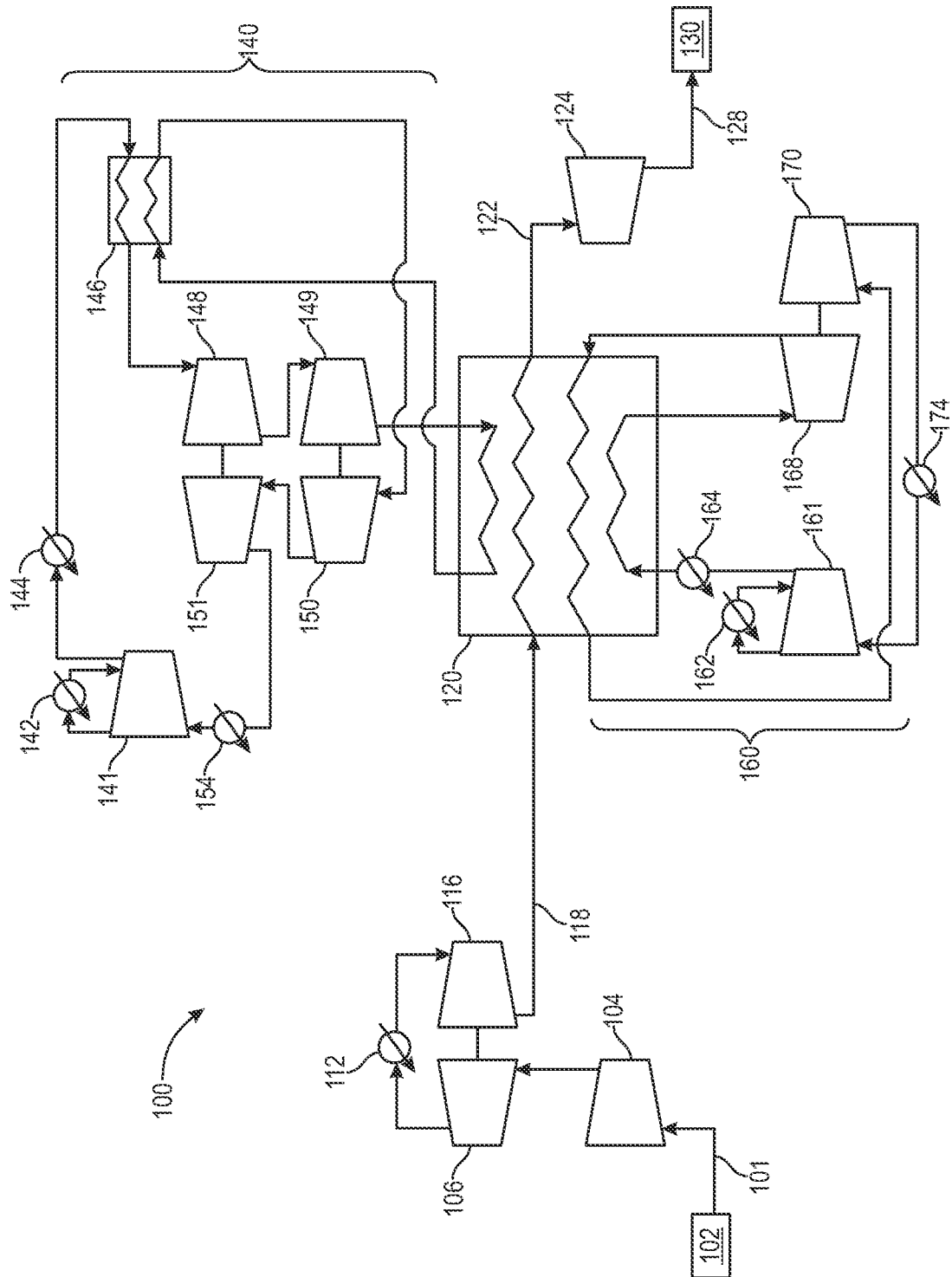
wherein secondary liquid cooling is located downstream from the air cooled heat exchanger and upstream from the upstream expander.

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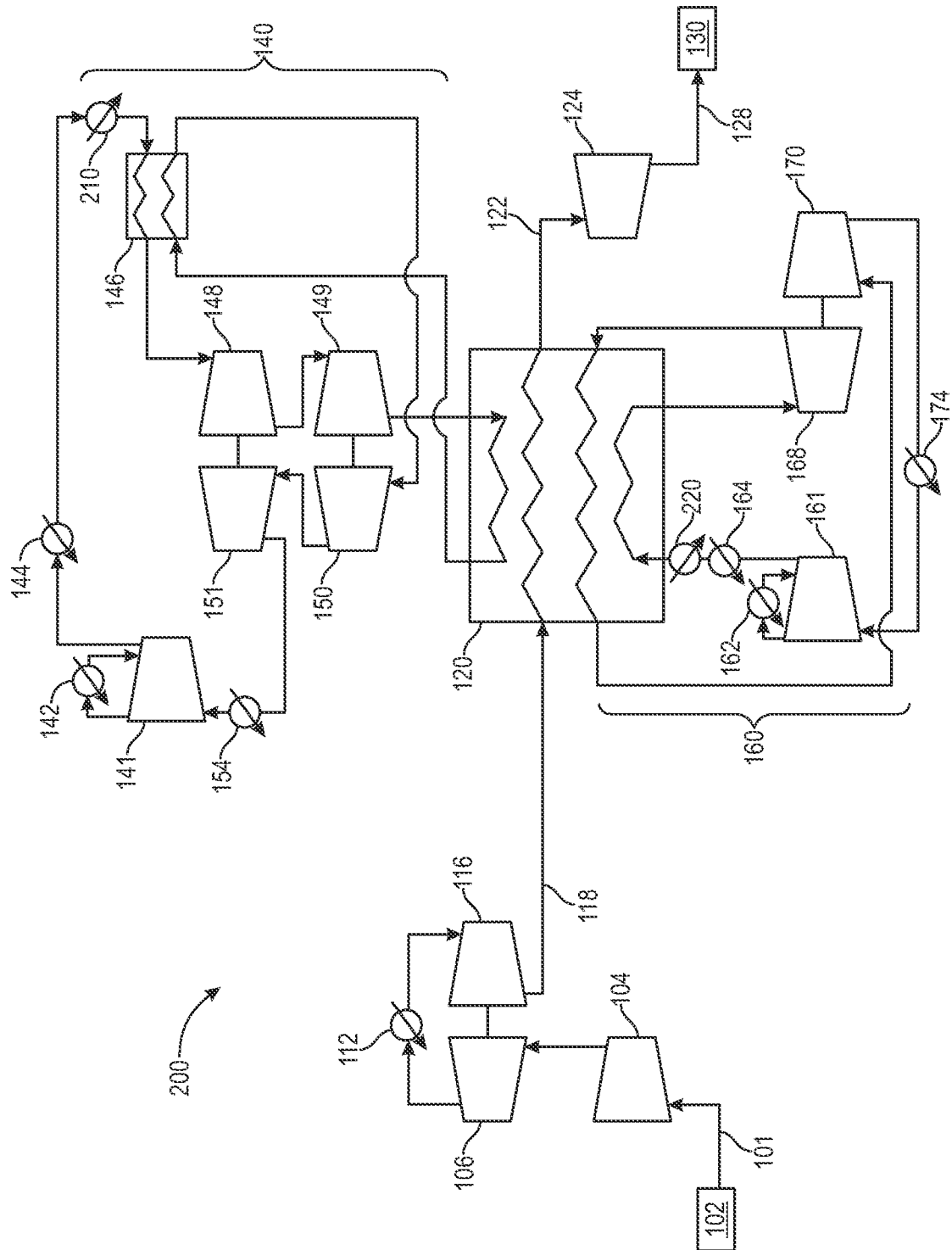
27. The system of claim 26, wherein the second compressor and the upstream expander are operatively coupled by an in-common drive shaft.

28. The system of any one of claims 15-27, wherein the secondary liquid cooling is provided by chilled water, the chilled water optionally being provided by a chilled water supply system.

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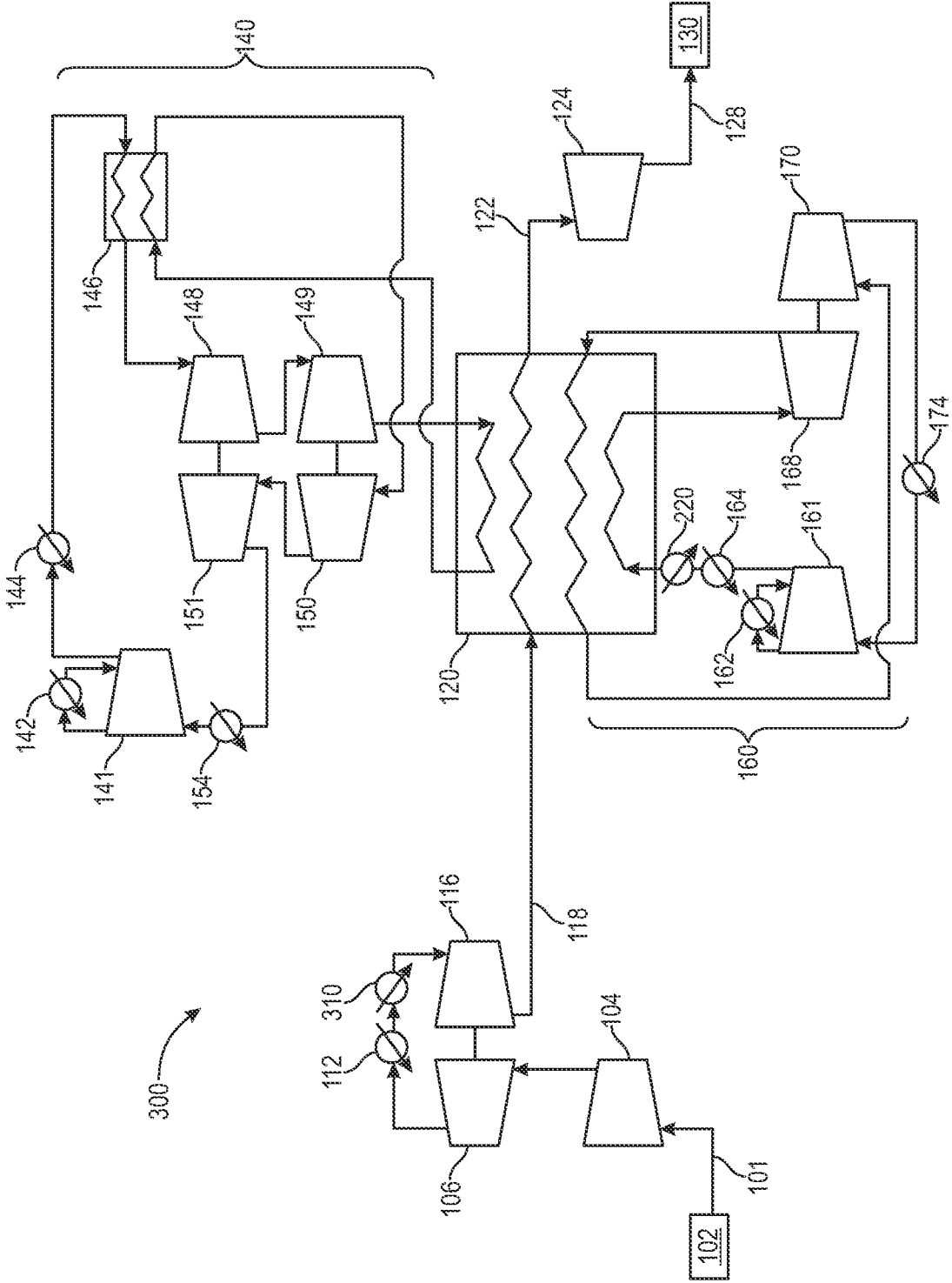


FIG. 3

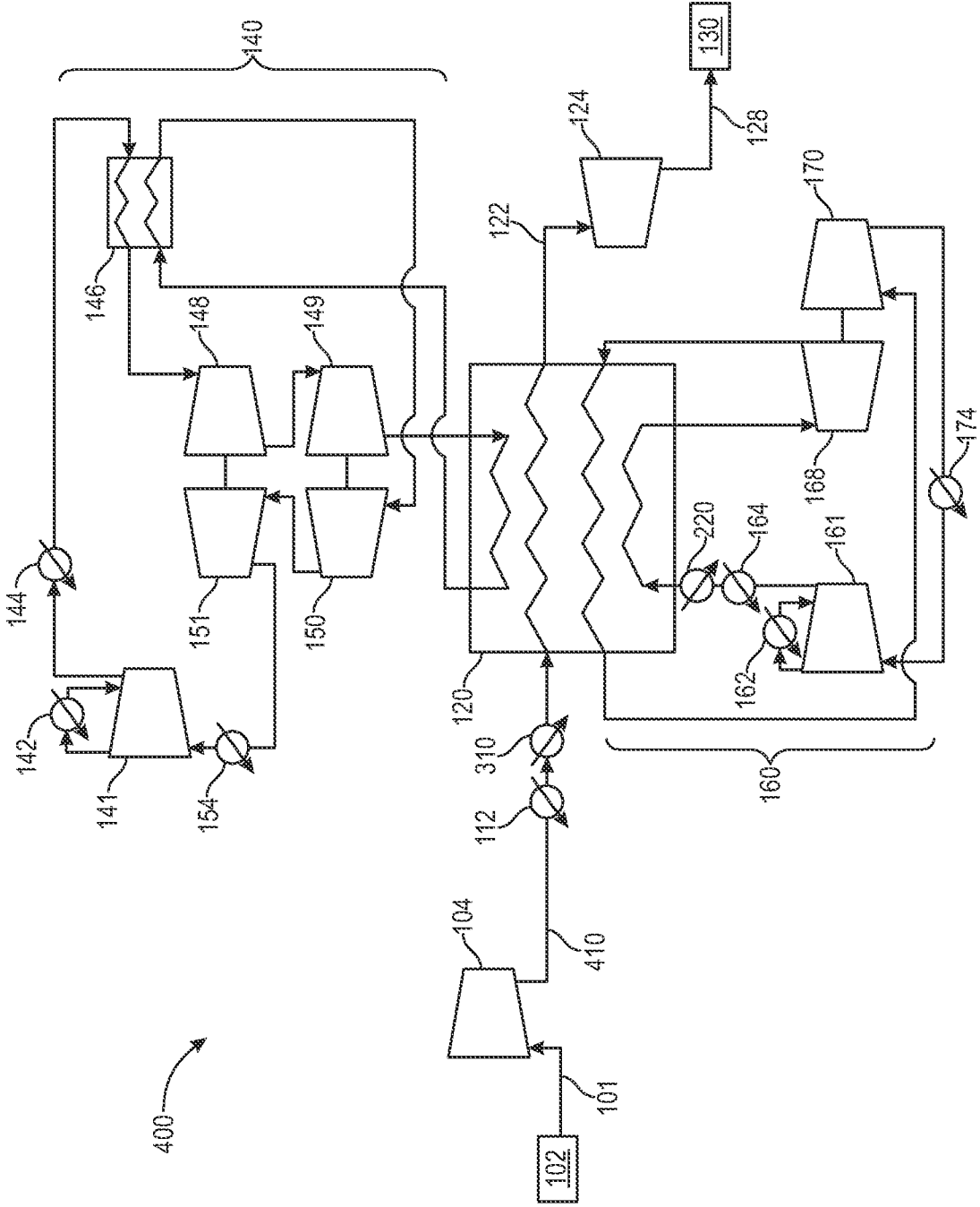
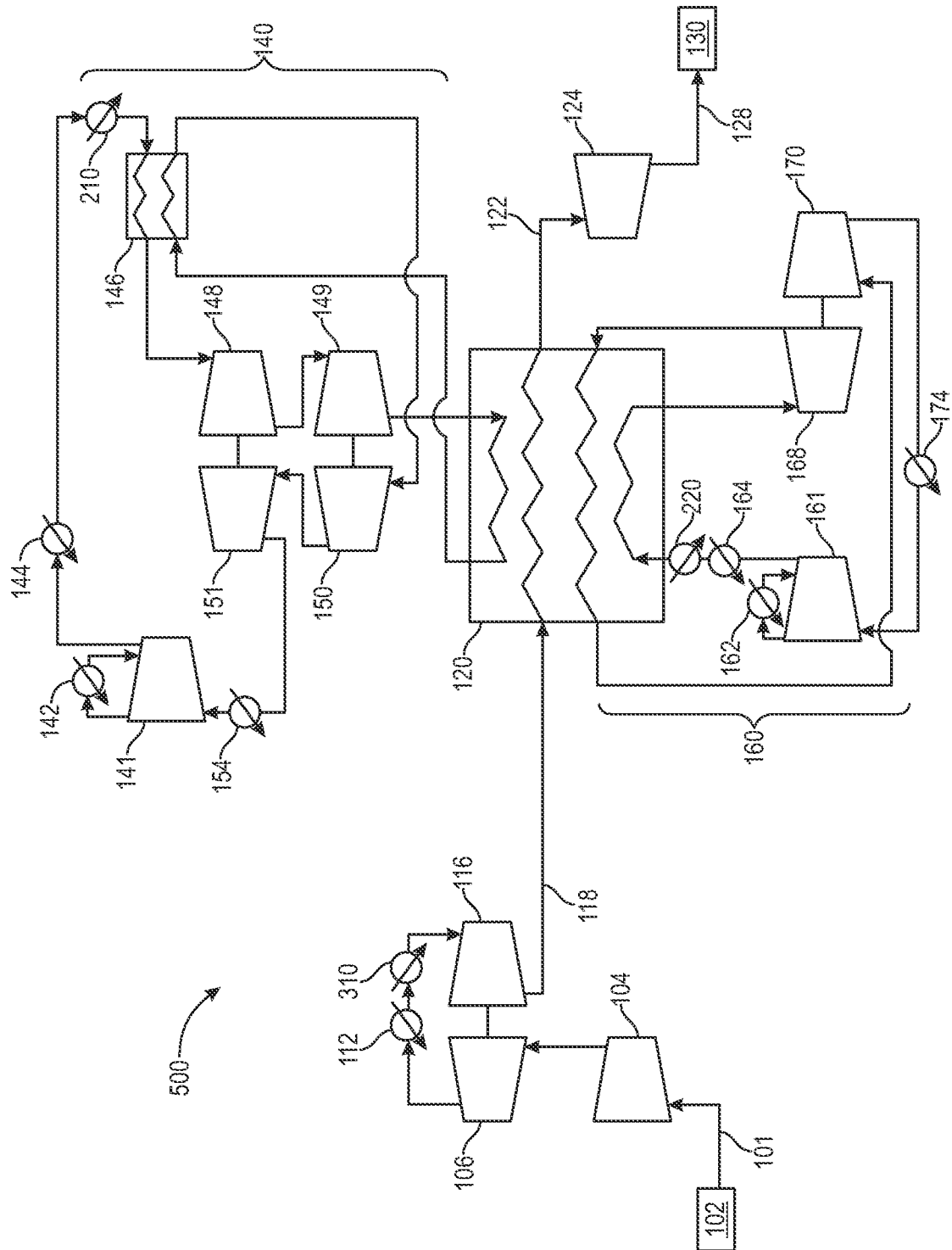
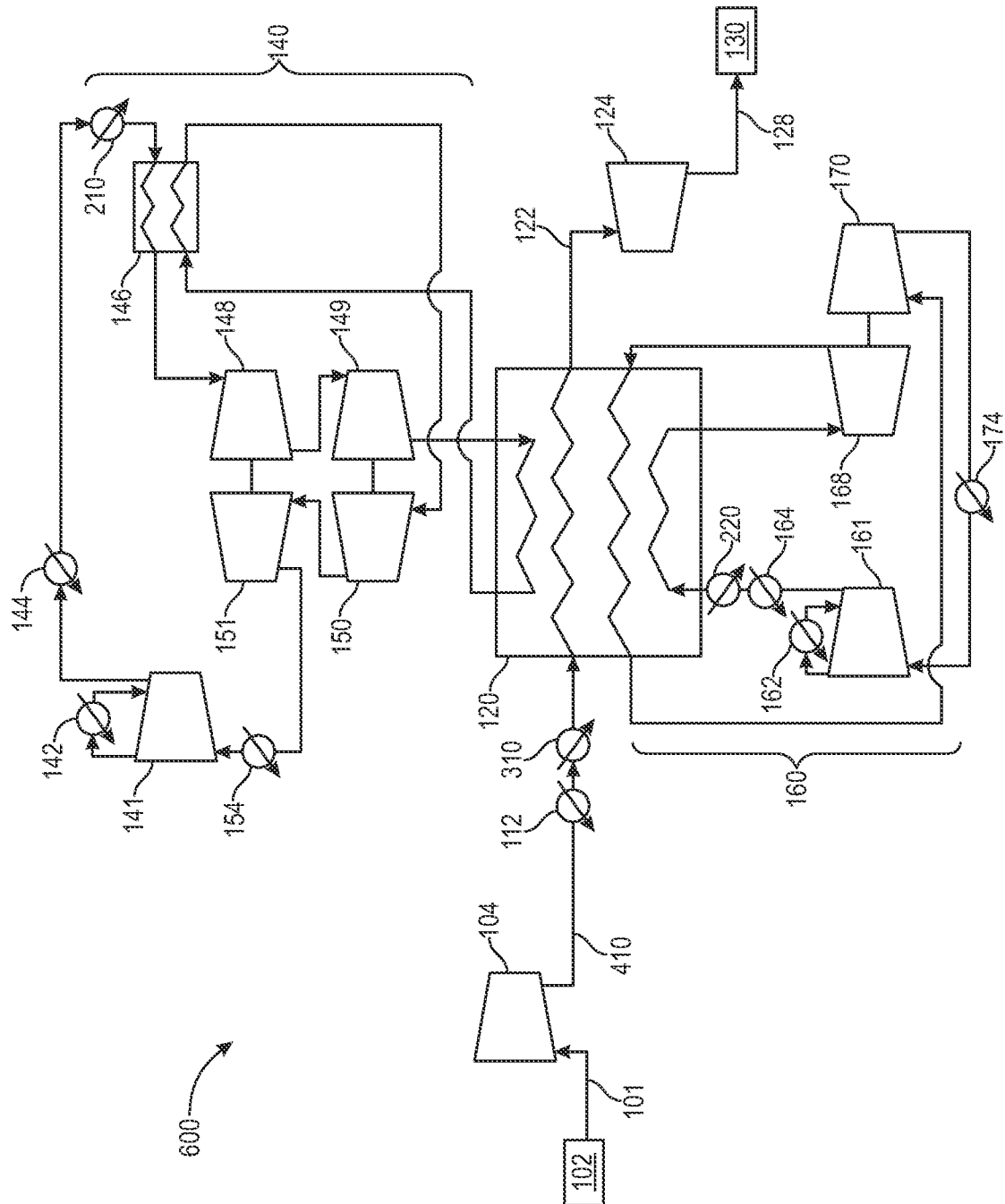


FIG. 4



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INTERNATIONAL SEARCH REPORT

International application No
PCT/US2021/072398

A. CLASSIFICATION OF SUBJECT MATTER

INV. F25J1/00

ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F25J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2020/064061 A1 (LIU YIJUN [US] ET AL) 27 February 2020 (2020-02-27) paragraphs [0057], [0063], [0055], [0065], [0013]; figures 7,5 -----	1-9, 14-23, 28
X	US 2019/101328 A1 (PIERRE JR FRITZ [US]) 4 April 2019 (2019-04-04) paragraphs [0012], [0013], [0015]; figure 2 -----	1, 15
A	CN 106 123 486 B (CHENGDU SEPMEM SCI & TECH CO LTD) 7 June 2019 (2019-06-07) figures 1,2 -----	14, 28

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

2 March 2022

Date of mailing of the international search report

09/05/2022

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Schopfer, Georg

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2021/072398

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims;; it is covered by claims Nos.:
2-9, 14, 16-23, 28 (completely); 1, 15 (partially)

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 2-9, 14, 16-23, 28(completely); 1, 15(partially)

Refrigerant cooling by secondary liquid cooling

2. claims: 10-13, 24-27(completely); 1, 15(partially)

Feedgas cooling by secondary liquid cooling

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2021/072398

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CN 106123486 B	07-06-2019	NONE	