US 20220404094A1

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2022/0404094 A1**

Prosser et al. (43) **Pub. Date: Dec. 22, 2022**

(54) **SYSTEM AND M ETHOD FOR SUPPLYING CRYOGENIC REFRIGERATION**

(71) Applicant: **PRAXAIR TECHNOLOGY, INC.**, Danbury, CT (US)

(72) Inventors: **Neil M. Prosser**, Lockport, NY (US); **James R. Handley**, East Amherst, NY (US); **Ricardo Dutra de Castro Costa**, Clarence Center, NY (US); **John F. Billingham**, East Amherst, NY (US); **David R. Parsnick**, Amherst, NY (US)

(21) Appl. No.: **17/251,408**

(22) PCT Filed: **Dec. 1, 2020**

(86) PCT No.: **PCT/US2020/062665**

§ 371 (c)(1),
(2) Date: **Dec. 11, 2020**

Related U.S. Application Data

(60) Provisional application No. 62/950,198, filed on Dec. 19, 2019.

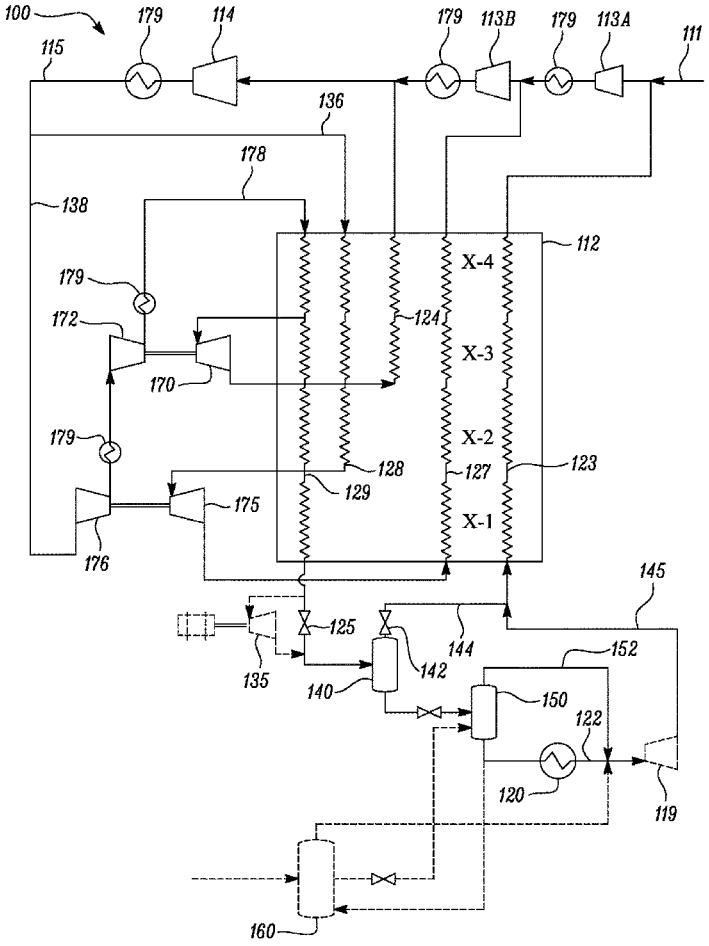
Publication Classification

(51) **Int. Cl.**
F25J 1/00 (2006.01)
F25J 1/02 (2006.01)

(52) **U.S. Cl.**
CPC ***F25J 1/0015*** (2013.01); ***F25J 1/0057*** (2013.01); ***F25J 1/0237*** (2013.01); *F25J 2210/42* (2013.01); *F25J 2210/40* (2013.01); *F25J 2230/08* (2013.01); *F25J 2290/12* (2013.01); *F25J 2230/24* (2013.01)

(57) **ABSTRACT**

Various systems and methods for suppling cryogenic refrigeration to supercomputing applications such as quantum computing operations are provided. The disclosed systems and methods are flexible, efficient and scaleable to meet the cryogenic refrigeration requirements of many supercomputing applications. The disclosed systems and methods include: (i) a liquid nitrogen based integrated refrigeration system that integrates a nitrogen refrigerator with a refrigeration load circuit; (ii) a closed loop liquid nitrogen based refrigerator that provides cooling to the refrigeration load circuit via indirect heat exchange between liquid nitrogen in a nitrogen refrigerator and a separate refrigerant in a closed-loop refrigeration load circuit; and (iii) a liquid air based integrated refrigeration system that integrates an air intake system with a refrigerator and a refrigeration load circuit.



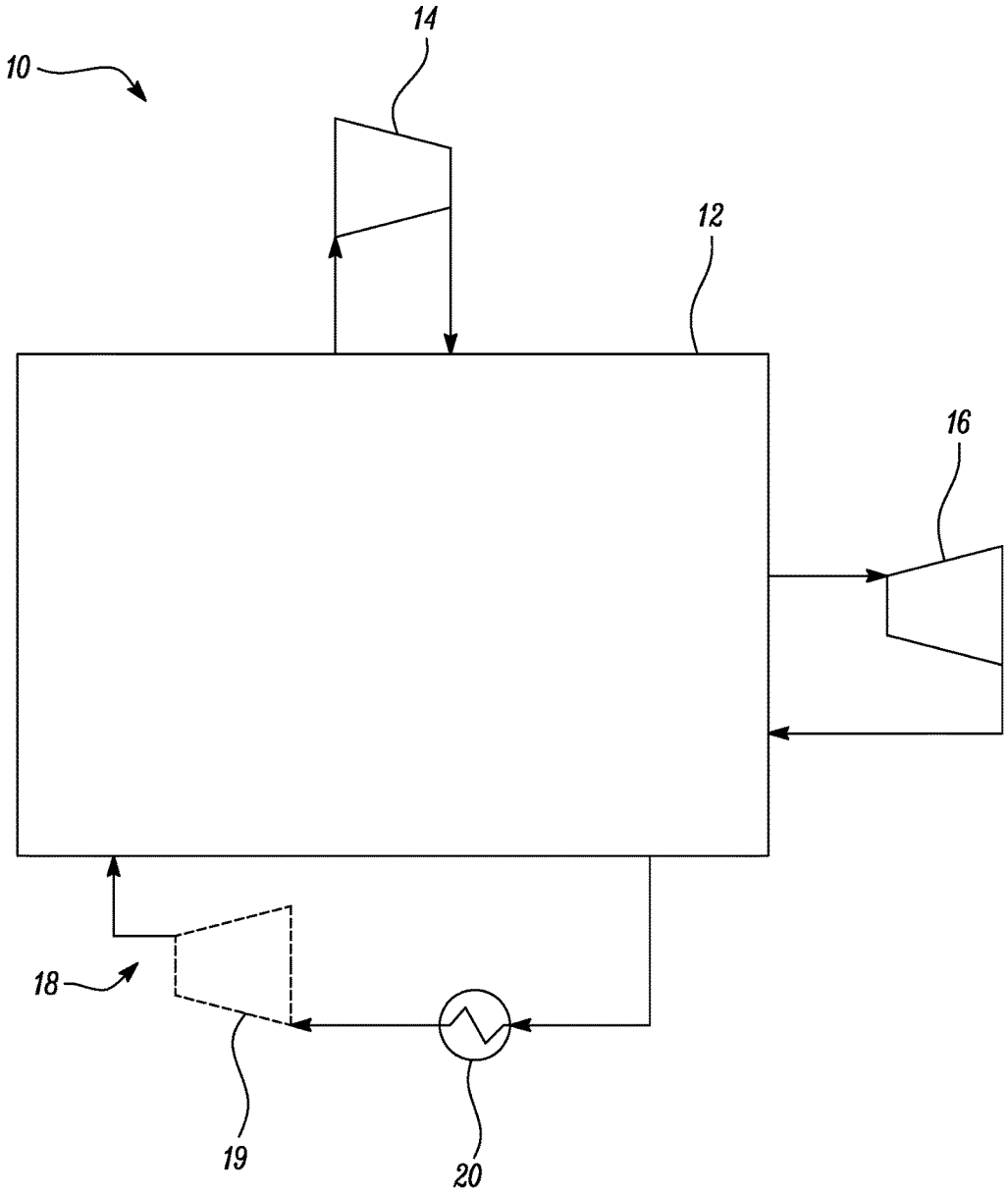


FIG. 1

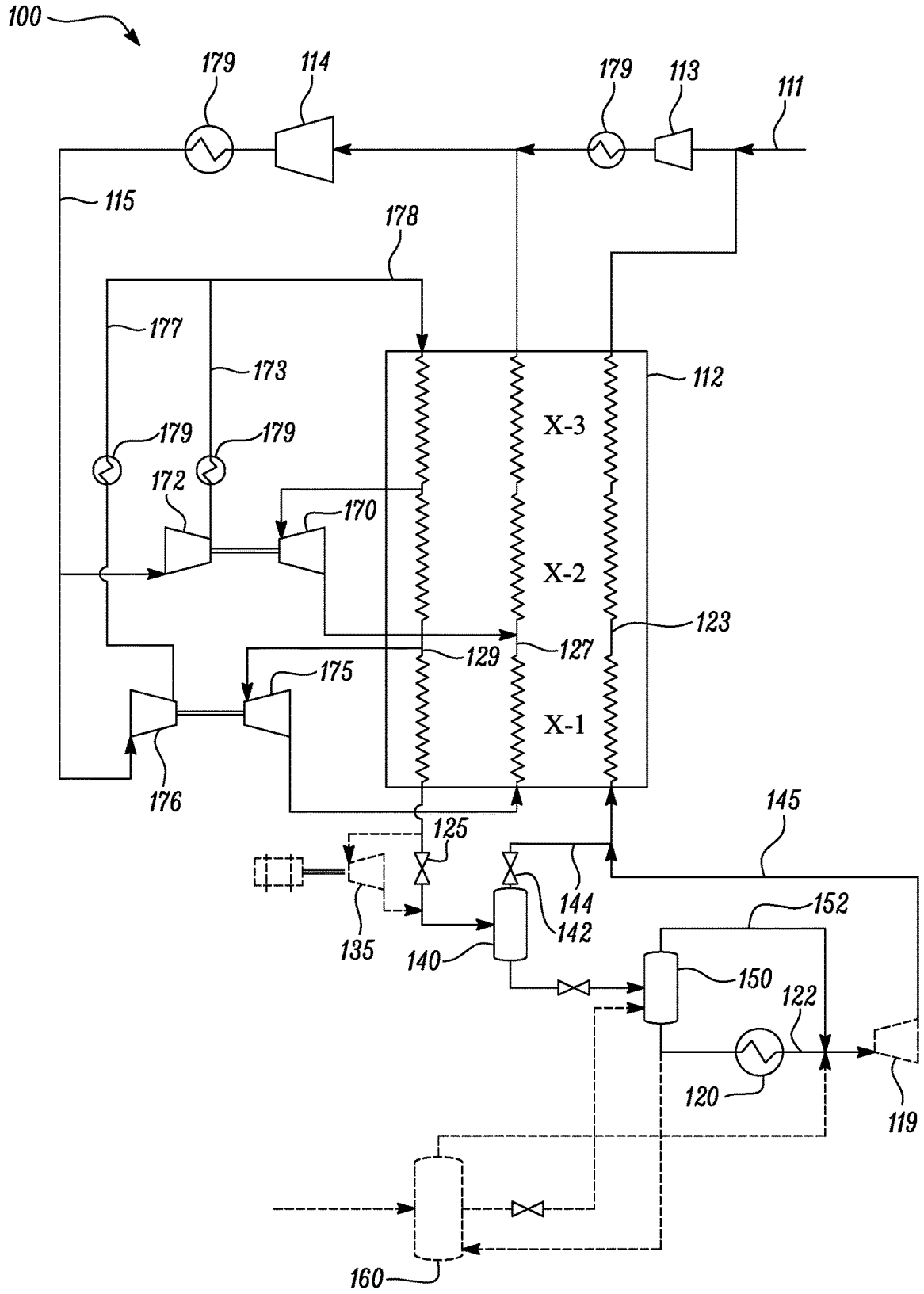

100
179
114
179
113
111
115
178
177
173
112
179
179
172
170
X-3
X-2
123
129
127
175
X-1
176
145
125
144
142
152
135
140
150
122
120
119
160

FIG. 2

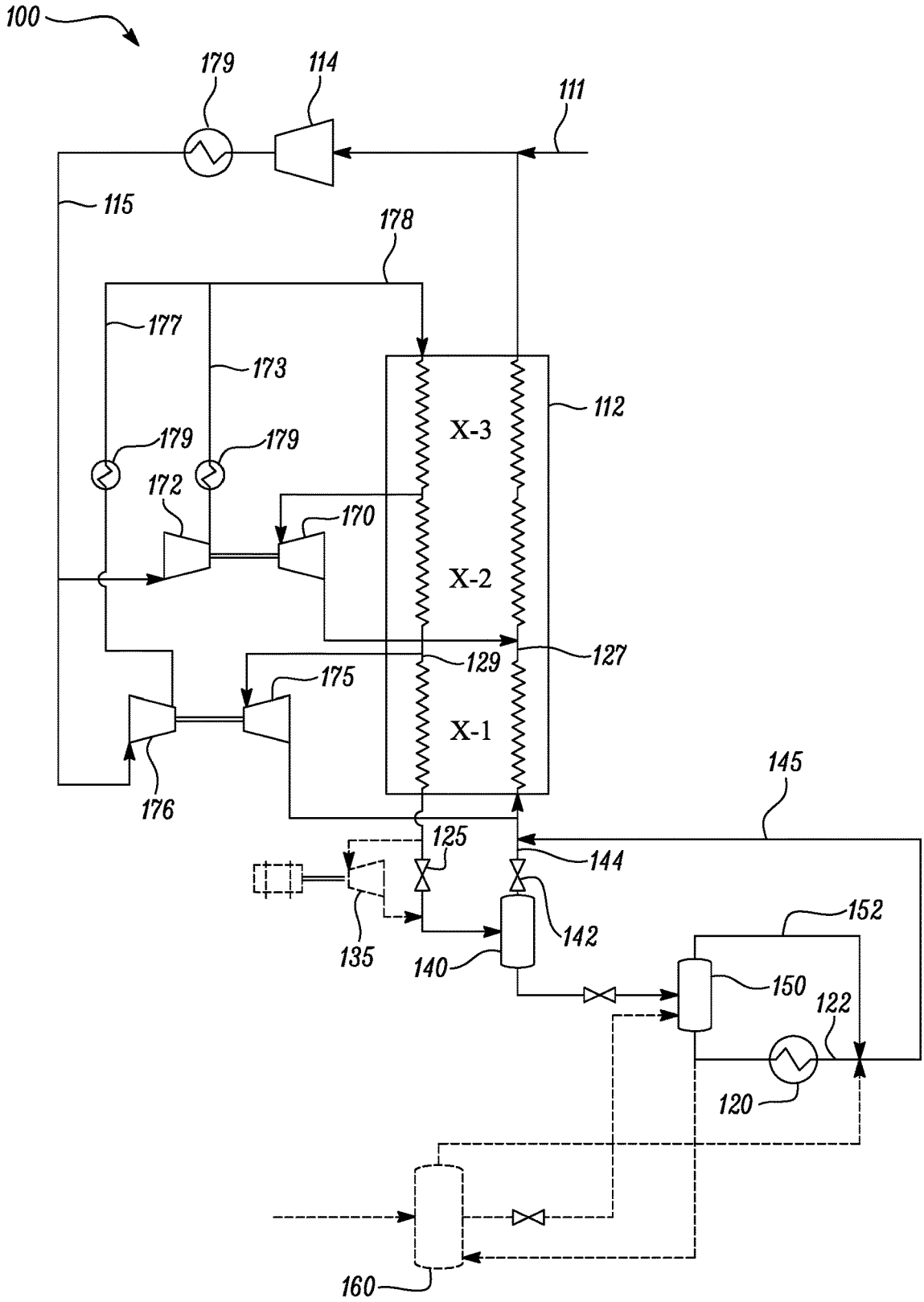

100
179
114
111
115
178
177
173
112
X-3
179
179
172
170
X-2
129
127
175
X-1
176
145
125
144
152
142
135
140
150
122
120
160

FIG. 3

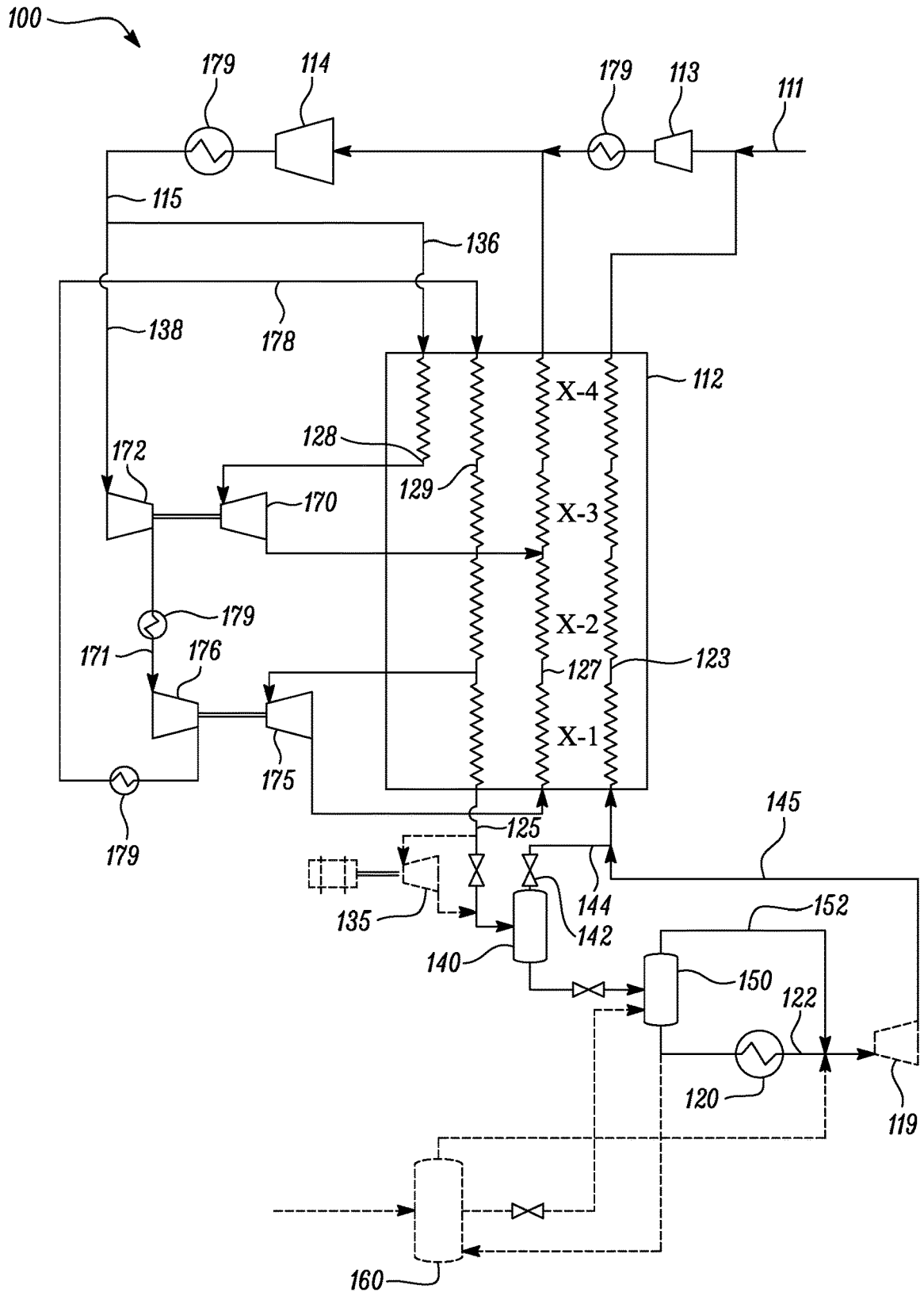

100
179
114
179
113
111
115
136
138
178
112
X-4
128
172
129
170
X-3
179
171
176
X-2
123
127
X-1
175
179
125
145
135
144
142
152
140
150
122
120
119
160

FIG. 4

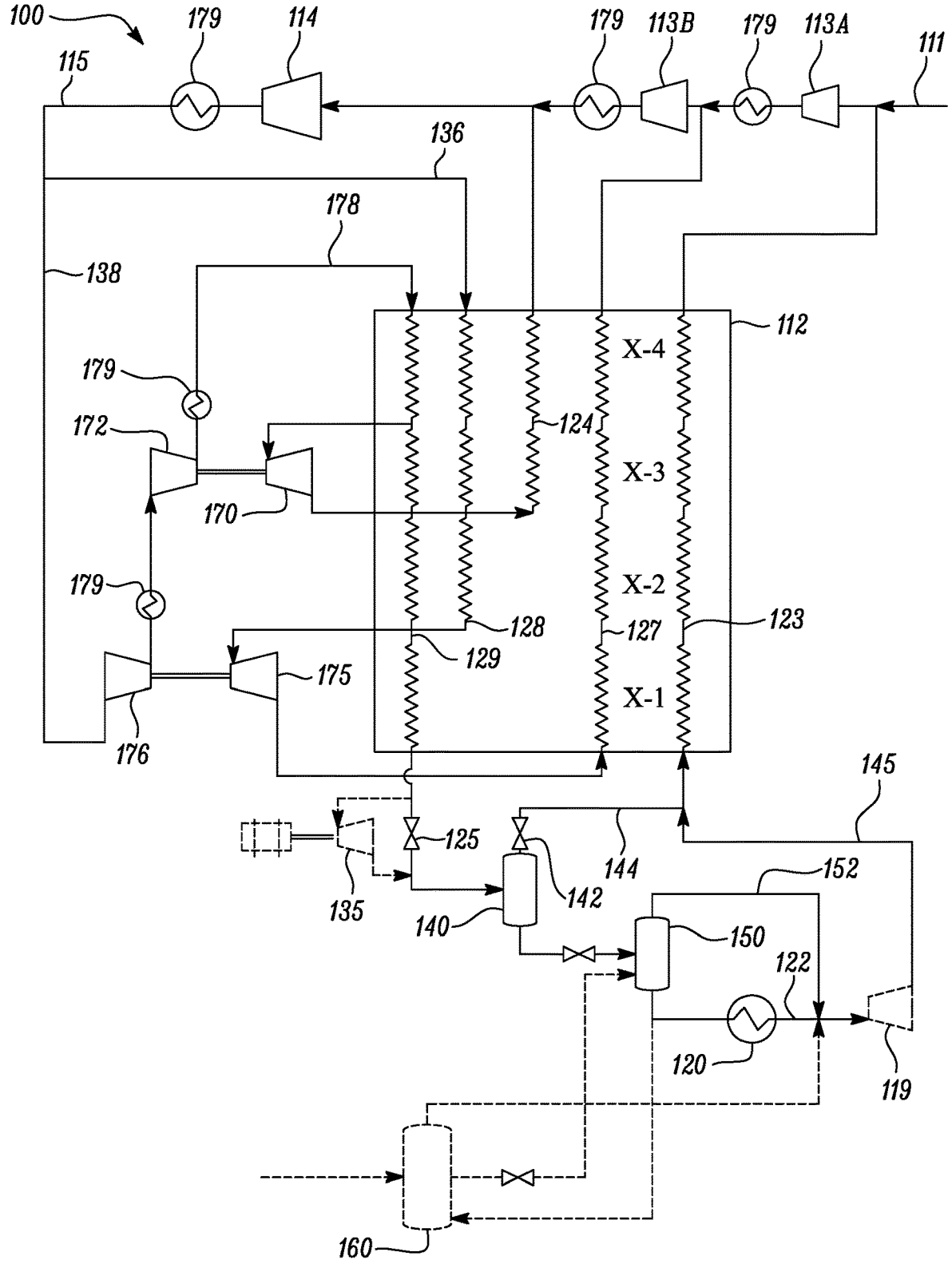

100
179
114
179
113B
179
113A
111
115
136
178
138
112
X-4
X-3
X-2
X-1
179
172
124
170
179
128
127
123
129
175
176
145
125
144
152
135
142
140
150
122
120
119
160

FIG. 5

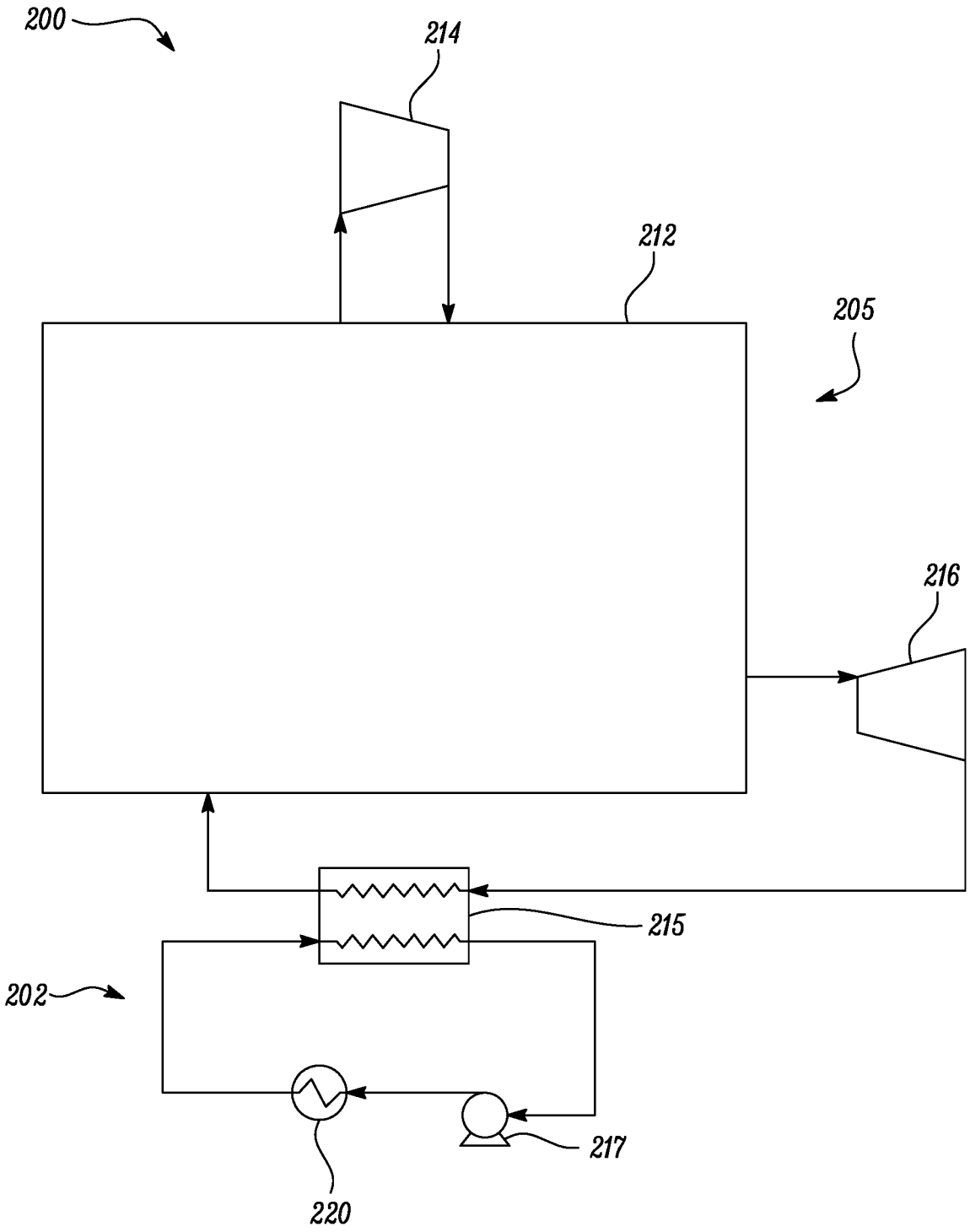


FIG. 6

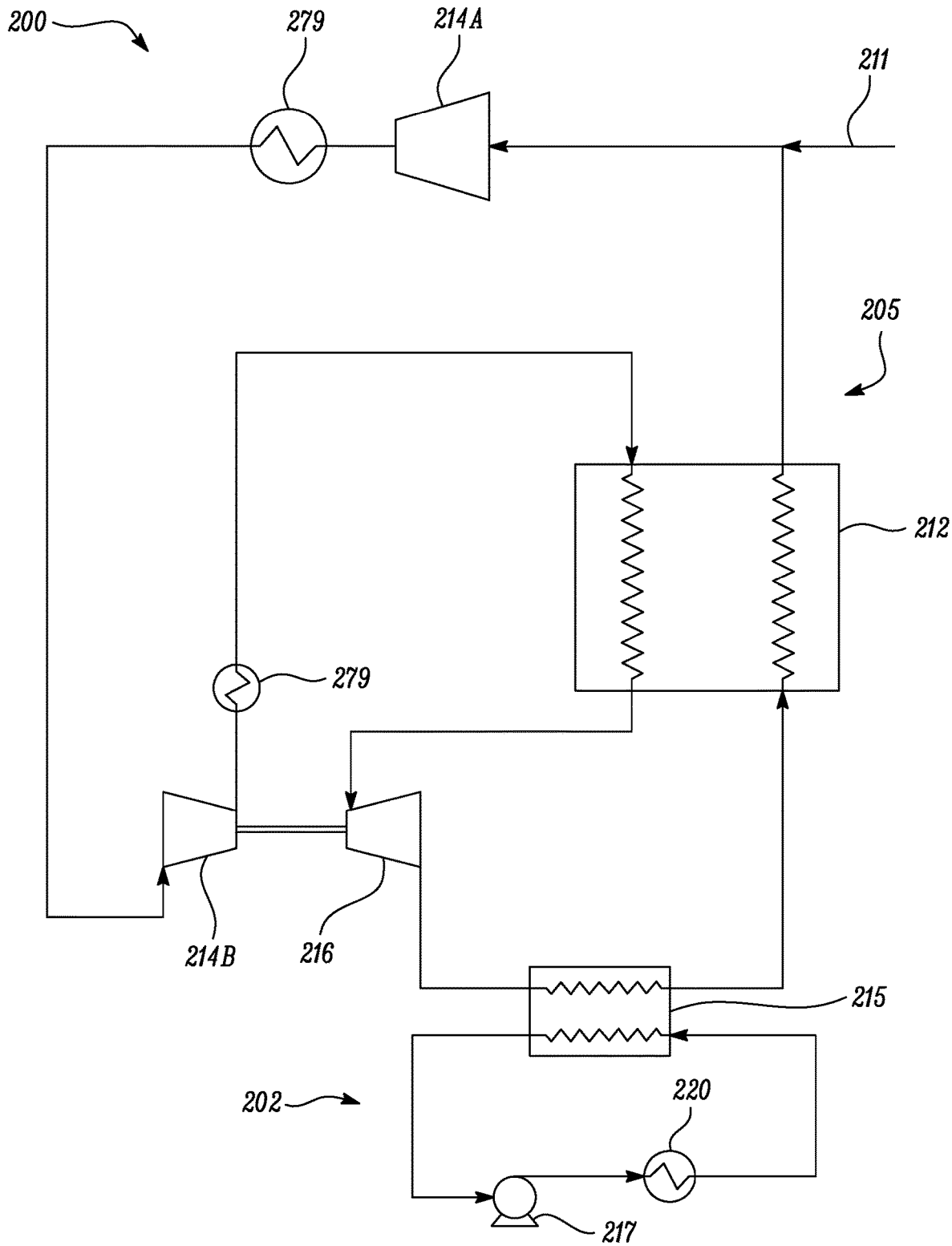


FIG. 7

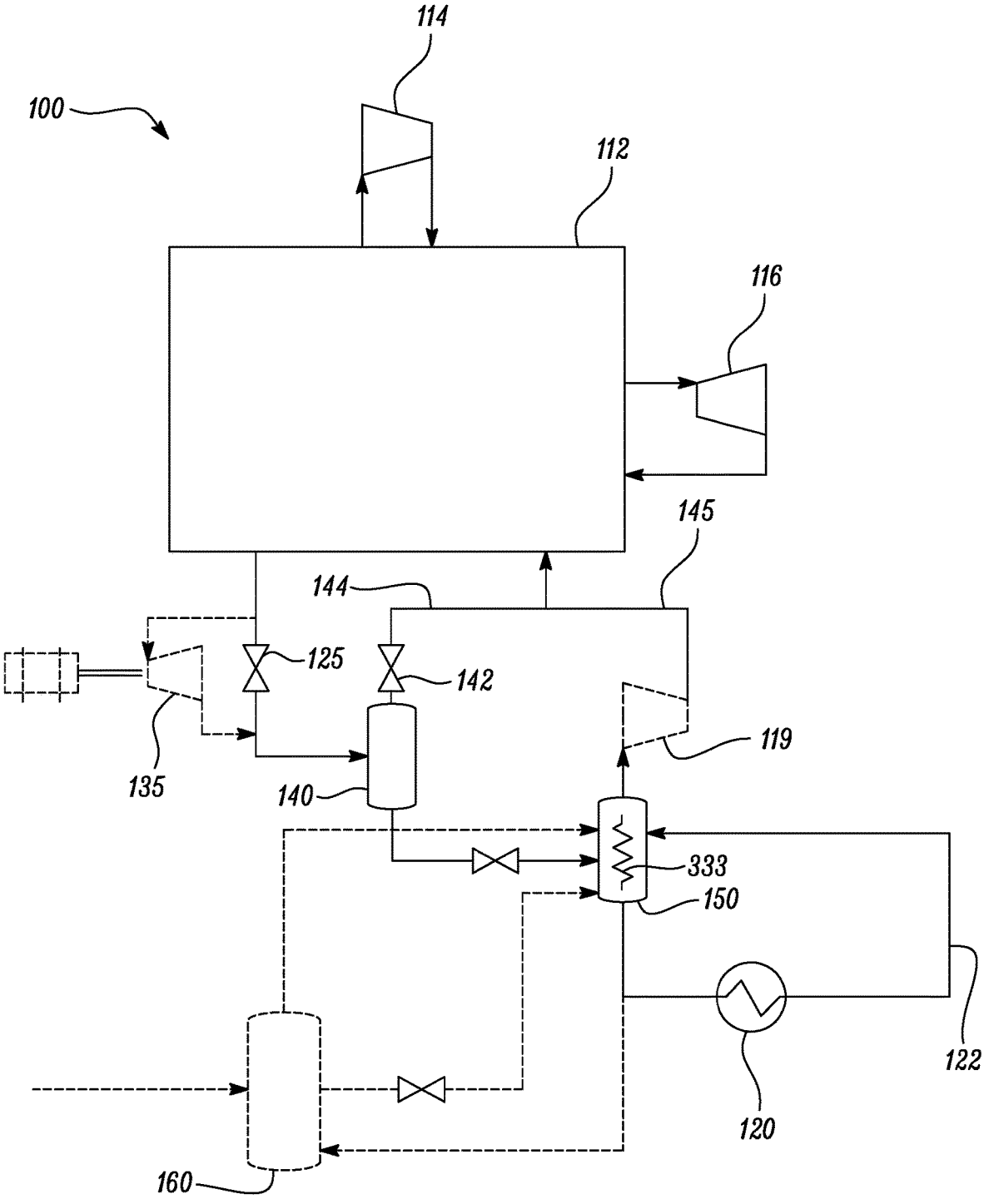


FIG. 8

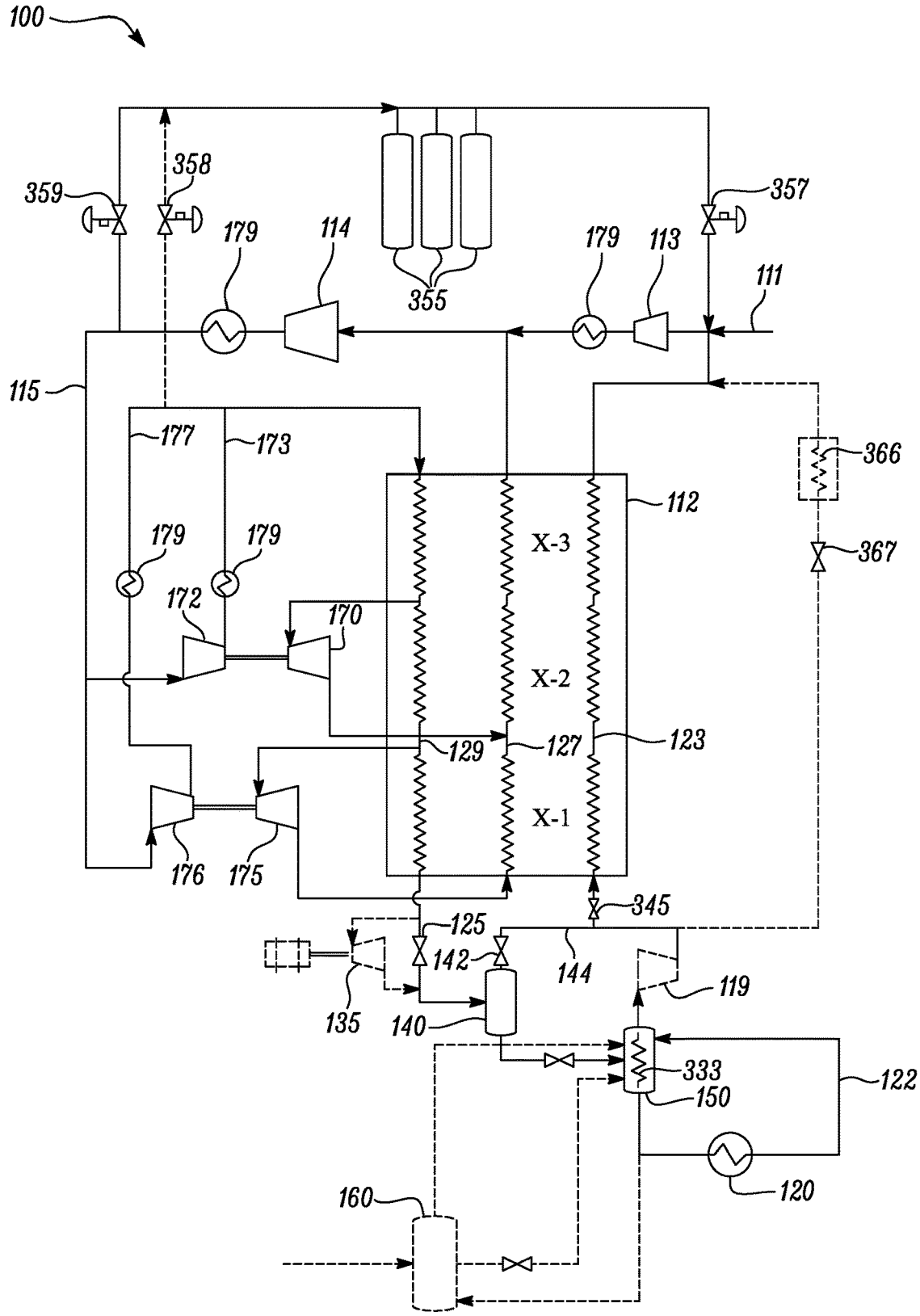

100
358
359
357
179
114
179
113
355
111
115
177
173
366
112
179
179
X-3
367
172
170
X-2
129
127
123
X-1
176
175
345
125
142
144
119
135
140
333
122
150
120
160

FIG. 9

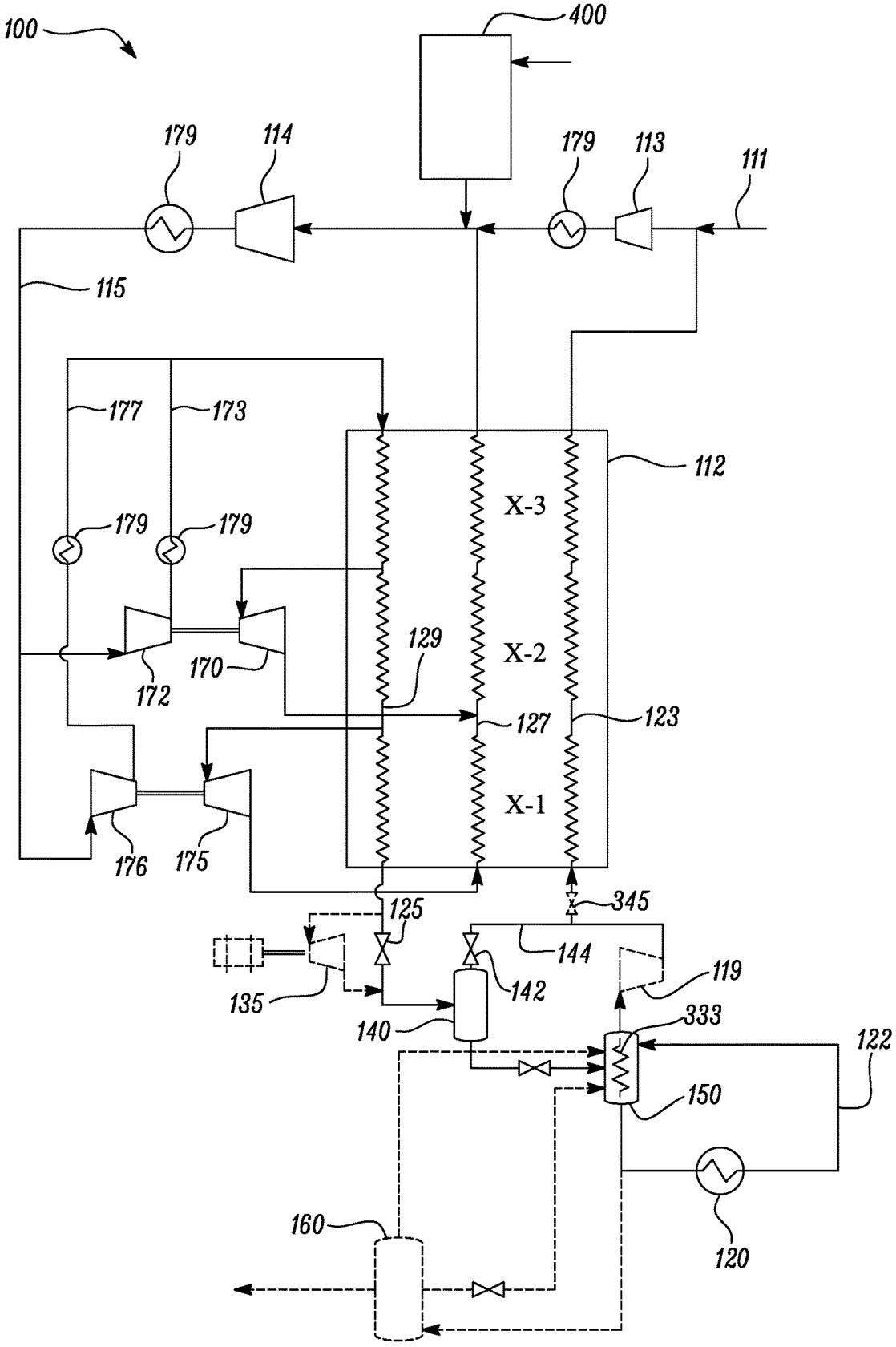

100
400
179
114
179
113
111
115
177
173
112
179
179
X-3
129
X-2
170
172
127
123
X-1
176
175
125
345
144
119
135
142
140
333
122
150
160
120

FIG. 10

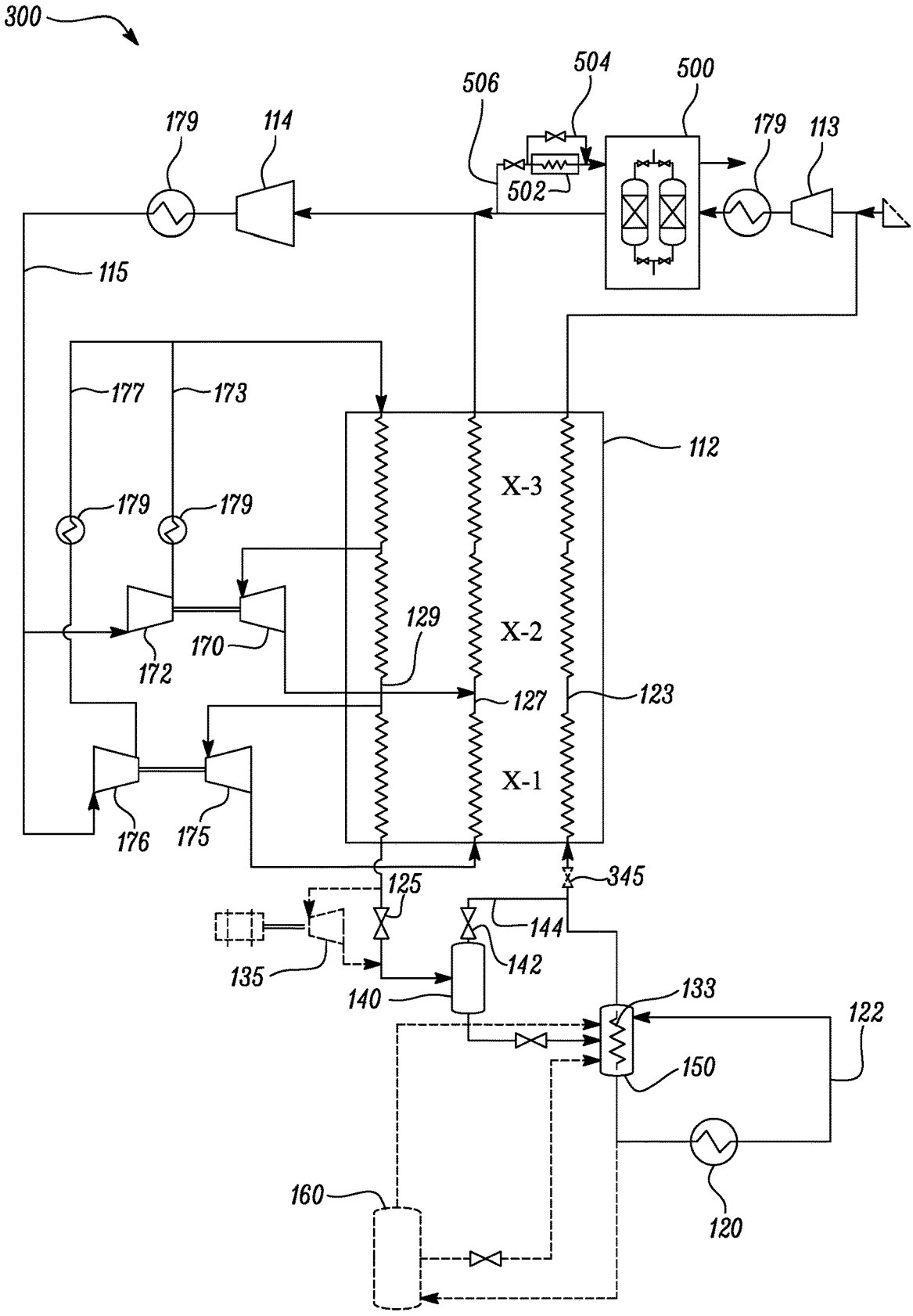

300
504
500
506
179
114
179
113
502
115
177
173
112
179
179
X-3
129
X-2
170
172
127
123
X-1
176
175
125
345
144
142
135
140
133
122
150
160
120

FIG. 11

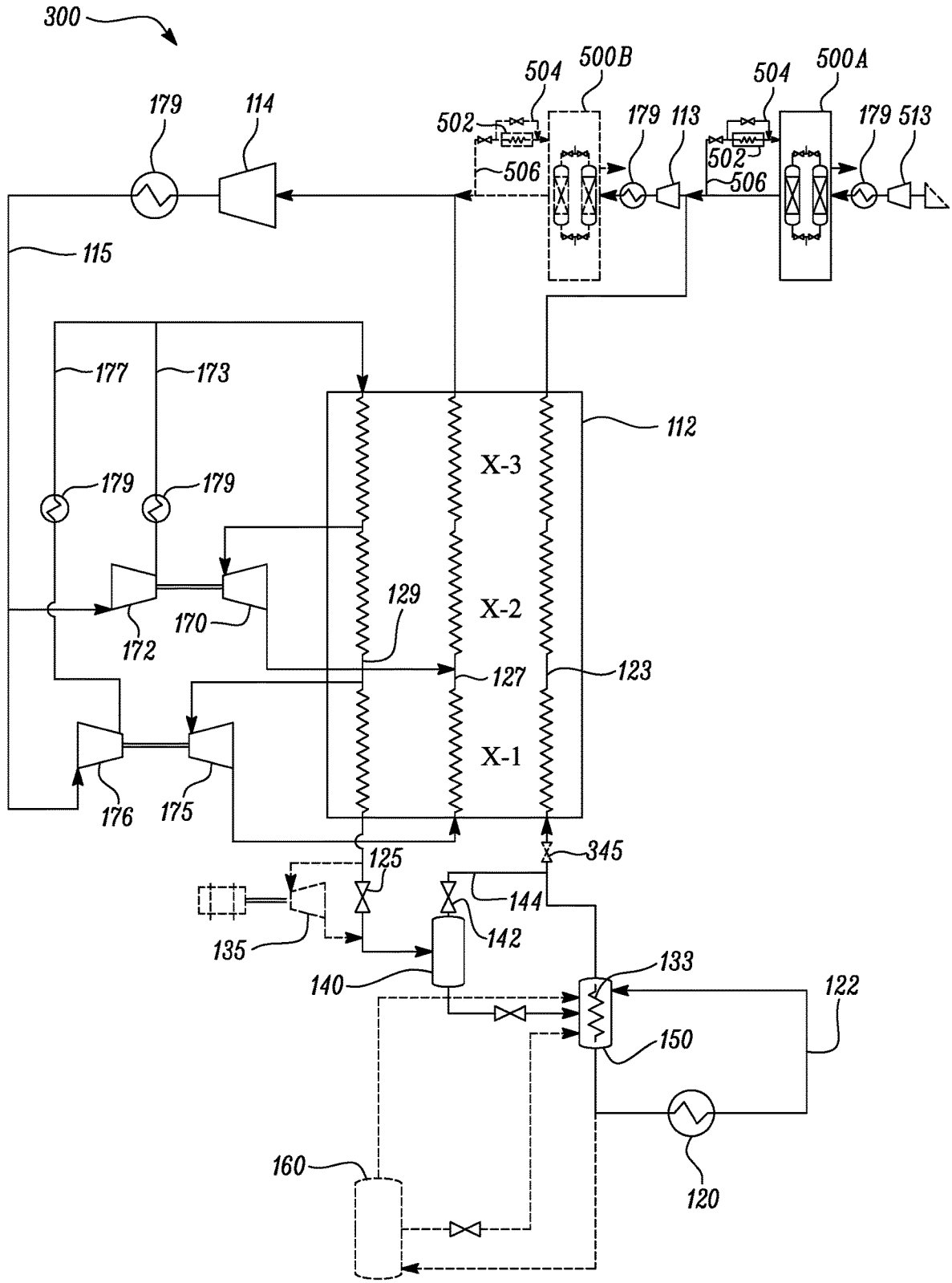

300
179
114
504
500B
502
506
179
113
504
500A
502
506
179
513
115
177
173
112
179
179
X-3
129
X-2
170
172
127
123
X-1
176
175
125
345
144
142
135
140
133
122
150
160
120

FIG. 12

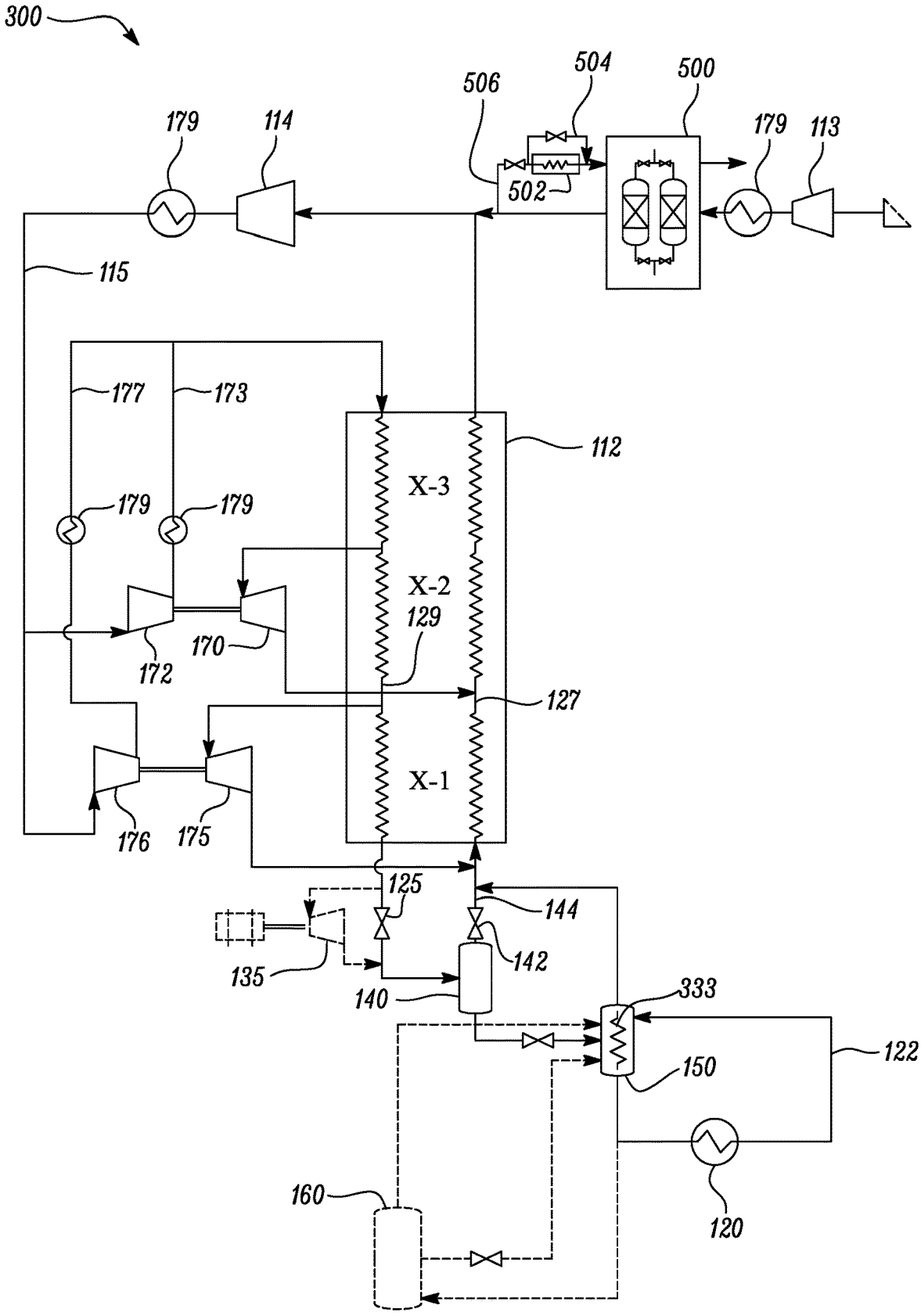

300
504
500
506
179
114
179
113
502
115
177
173
112
179
179
X-3
X-2
129
170
172
127
X-1
176
175
125
144
142
135
140
333
122
150
160
120

FIG. 13

SYSTEM AND M ETHOD FOR SUPPLYING CRYOGENIC REFRIGERATION

RELATED APPLICATIONS

[0001] This application claims the benefit of International Application No. PCT/US2020/062665, filed on Dec. 1, 2020, and U.S. Provisional Application Serial No. 62/950,198, filed on Dec. 19, 2019, which is incorporated herein by reference.

TECHNICAL FIELD

[0002] The present invention relates to liquid nitrogen refrigeration, and more particularly, to a liquid nitrogen refrigerator configured to provide cryogenic refrigeration to a nitrogen refrigerator, directly or indirectly.

BACKGROUND

[0003] There are various industrial gas business opportunities for cryogenic refrigeration systems tailored for supercomputing applications, such as quantum computing operations performed at large data centers. Quantum computer memory and processing requirements must be operated at cryogenic temperatures, which often require the refrigeration to be supplied at or near liquid nitrogen temperatures.

[0004] What is needed, therefore is an efficient and flexible refrigeration system and method for suppling cryogenic refrigeration to a refrigeration load circuit in supercomputing applications either directly via an integrated arrangement including with a liquid nitrogen based refrigerator integrated with the refrigeration load circuit or indirectly via a closed loop liquid nitrogen based refrigerator.

SUMMARY OF THE INVENTION

[0005] In one aspect, the present invention may be broadly characterized as a liquid nitrogen based refrigeration system integrated with a refrigeration load circuit and associated methods comprising: (1) a nitrogen refrigerator having one or more recycle compressors, a warm booster compressor, a cold booster compressor, a warm turbine, a cold turbine, and a heat exchanger with at least one cooling passage and at least one recycle passage; and (2) a refrigeration load circuit having an expansion valve or a liquid turbine; a separator, a buffer tank, and a refrigeration load. The nitrogen refrigerator is configured to receive a source of nitrogen gas as well as a cold nitrogen gas return stream and produce a liquid nitrogen refrigerant stream. The refrigeration load circuit is configured to: (a) receive the nitrogen refrigerant stream; (b) expand the nitrogen refrigerant stream in the expansion valve or the liquid turbine; (c) separate the expanded nitrogen refrigerant stream in the separator into liquid and vapor portions; (d) cool a refrigeration load with the liquid portion of the expanded nitrogen refrigerant stream while vaporizing the liquid portion of the expanded refrigerant stream; and (e) return the vaporized stream and the vapor portion of the nitrogen refrigerant stream as the nitrogen return stream to the nitrogen refrigerator. The present integrated liquid nitrogen based refrigeration system and associated methods may include various optional elements and advantages features as generally shown and described below with reference to the embodiments illustrated in FIGS. **1-5** and **8-10** of the accompanying drawings. Incorporation of one or more of the preferred optional elements and advantages features very much depend on the cooling requirements of the refrigeration load including the target refrigeration temperature and operating pressures of the refrigeration system.

[0006] In another aspect, the present invention may also be broadly characterized as a closed loop liquid nitrogen based refrigerator comprising: (1) a recycle compressor; (2) a cold booster compressor; (3) a cold turbine; (4) a primary heat exchanger with at least one cooling passage and at least one recycle passage; and (5) an auxiliary heat exchanger to cool a separate refrigerant in a closed-loop refrigeration load circuit in via indirect heat exchange between liquid nitrogen in the refrigerator and the separate refrigerant in a closed-loop refrigeration load circuit. The closed loop liquid nitrogen based refrigerator and associated methods may include elements and features as generally shown and described below with reference to the embodiments illustrated in FIGS. **6-7** of the accompanying drawings.

[0007] Finally, the present invention may further be broadly characterized as a liquid air based refrigeration system integrated with a refrigeration load circuit and associated methods comprising: (1) an air intake system having a main air compressor and/or a recycle compressor and a pre-purifier; (2) a refrigerator having one or more recycle compressors, a warm booster compressor, a cold booster compressor, a warm turbine, a cold turbine, and a heat exchanger with at least one cooling passage and at least one recycle passage; and (3) a refrigeration load circuit having an expansion valve or a liquid turbine; a separator, a buffer tank, and a refrigeration load. The refrigerator is configured to receive a pre-purified and compressed source of air as well as a cold air return stream and produces a liquid air refrigerant stream. The refrigeration load circuit is configured to: (a) receive the liquid air refrigerant stream; (b) expand the liquid air refrigerant stream in an expansion valve or a liquid turbine; (c) separate the expanded air refrigerant stream in the separator into a liquid portion and a vapor portion; (d) cool a refrigeration load with the liquid portion of the expanded air refrigerant stream while vaporizing the liquid portion of the expanded air refrigerant stream; and (e) return the vaporized air stream and the vapor portion of the air refrigerant stream as the air return stream to the refrigerator. The present integrated liquid air based refrigeration system and associated methods also may include various optional elements and advantages features as generally shown and described below with reference to the embodiments depicted in FIGS. **11-13** of the accompanying drawings. As indicated above, use of the optional elements and advantages features in any given embodiment very much depends on the cooling requirements of the refrigeration load including the target refrigeration temperature and operating pressures of the refrigeration system.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] While the present application concludes with claims distinctly pointing out the subject matter that Applicants regard as the invention, it is believed that the invention will be better understood when taken in connection with the accompanying drawings in which:

[0009] FIG. **1** is a schematic diagram of an integrated nitrogen refrigeration system configured to provide cryogenic refrigeration to a refrigeration load in supercomputing applications at or near the minimum achievable temperature;

[0010] FIG. **2** is an illustration of an embodiment of the integrated nitrogen refrigeration system of FIG. **1** depicting a medium pressure nitrogen liquefier arrangement;

[0011] FIG. **3** is an illustration of another embodiment of the integrated nitrogen refrigeration system of FIG. **1** depicting another medium pressure nitrogen liquefier arrangement suitable for supplying nitrogen refrigeration at temperatures warmer than the minimum achievable temperature;

[0012] FIG. **4** is an illustration of yet another embodiment of the integrated nitrogen refrigeration system of FIG. **1** depicting a low pressure nitrogen liquefier arrangement;

[0013] FIG. **5** is an illustration of yet another embodiment of the integrated nitrogen refrigeration system of FIG. **1** depicting a high pressure nitrogen liquefier arrangement;

[0014] FIG. **6** is a schematic diagram of a closed loop nitrogen refrigeration system configured to provide cryogenic refrigeration to a refrigeration load in supercomputing applications at temperatures warmer than the minimum achievable temperature;

[0015] FIG. **7** is an illustration of an embodiment of the closed loop nitrogen refrigeration system of FIG. **6**;

[0016] FIG. **8** is a simplified schematic diagram of an integrated nitrogen refrigeration system with a trim heater for stabilization of the return gas flow to the nitrogen refrigerator;

[0017] FIG. **9** is an illustration of an embodiment of the integrated nitrogen refrigeration system of FIG. **8**;

[0018] FIG. **10** is an illustration of another embodiment of the integrated nitrogen refrigeration system of FIG. **8** and shown coupled to an air separation unit as the source of gaseous nitrogen;

[0019] FIG. **11** is a schematic diagram of a medium pressure integrated liquid air based refrigeration system configured to provide cryogenic refrigeration to a refrigeration load in supercomputing applications at or near the minimum achievable temperature;

[0020] FIG. **12** is an illustration of another embodiment of a medium pressure integrated liquid air based refrigeration system configured to supply cryogenic refrigeration at temperatures warmer than the minimum achievable temperature; and

[0021] FIG. **13** is an illustration of yet another embodiment of a medium pressure integrated liquid air based refrigeration system configured to supply cryogenic refrigeration at temperatures warmer than the minimum achievable temperature.

DETAILED DESCRIPTION

[0022] Turning now to the drawings, multiple embodiments of the present system and method for supplying cryogenic refrigeration to a refrigeration load circuit in supercomputing applications, such as quantum computing operations are shown. Most of the embodiments may be characterized as an integrated arrangement with a liquid nitrogen based refrigerator (See FIGS. **1-5** and **8-10**) or with a liquid air based refrigerator (See FIGS. **11-13**). Alternatively, cryogenic refrigeration system may be configured as a closed loop refrigeration arrangement (See FIGS. **6-7**). In each of the illustrated embodiments, a common and key feature is the scalability of the depicted system wherein the systems can be sized to provide from as low as about 20 kW of refrigeration to 2000 kW of refrigeration or more. The specific configuration or arrangement of the nitrogen refrigerator or liquid air refrigerator can be optimized depending on the temperature requirements needed to cool the refrigeration load in the supercomputing application or other cryogenic refrigeration applications.

[0023] Turning now to FIG. **1**, there is shown a simplified schematic of the present system and method for supplying cryogenic refrigeration to a refrigeration load in supercomputing applications. The illustrated system is a liquid nitrogen based refrigeration system **10** integrated with the end-use application (i.e. refrigeration load) **20** and includes a heat exchanger **12**, recycle compressor(s) **14**, turboexpander (s) **16**, and a return gas circuit **18**. The specific arrangement of the nitrogen refrigerator (i.e. heat exchanger **12**, recycle compressor(s) **14**, and turboexpander(s) **16**) as well as the return gas circuit **18** is highly dependent on the temperature requirements needed to cool the refrigeration load **20**, which in turn dictates the operating pressures of the nitrogen refrigerator **10**.

[0024] The most efficient and most cost effective manner of providing the cryogenic refrigeration would be to configure the integrated liquid nitrogen based refrigerator to supply nitrogen refrigerant at minimum achievable temperature. The minimum achievable temperature is typically tied to the pressure of the liquid nitrogen in the refrigeration loop, and which is preferably attained by reducing the pressure of the in the cryogenic refrigeration loop to at or near ambient pressure. At ambient pressure (i.e. about 14.7 psia) the liquid nitrogen is at a temperature of about 77.3 K, which is generally the minimum available temperature for a nitrogen refrigerator that is configured to operate at ambient or higher pressures. Operation of a nitrogen refrigerator at sub-ambient pressures is not practical nor desired as the potential for air in-leakage could lead to freezing of any moisture, carbon dioxide, and other air contaminants which could lead to failure or under-performance of the nitrogen refrigerator.

[0025] If minimum temperature operation of the nitrogen refrigerator is desired, the nitrogen refrigeration system must be controlled so that the temperature of the vaporized nitrogen exiting the refrigerator is the minimum available temperature which, as indicated above, occurs when the liquid nitrogen is at or near ambient pressure. To motivate the vaporized nitrogen from the cryogenic refrigerator to and through the low pressure gas return circuit **18** downstream of the refrigeration load, a cold compressor **19** is optionally used. To perform efficiently, the nitrogen refrigerator produces cold liquid nitrogen at high pressure. The most efficient nitrogen refrigerator design would provide the cold nitrogen at high pressures, and in some applications the nitrogen is supplied at or above the critical pressure. For refrigeration supply temperatures of between about 77.5 K to 79.1 K the nitrogen pressure exiting the refrigeration load is between about 15 psia to about 18 psia. At these low pressure levels, a cold blower (not shown) will likely be necessary Alternatively, if cryogenic refrigeration at temperatures of about 80.1 K is acceptable for the intended application, the pressure can be about 20 psia. In this case, or in similar applications where the temperature nitrogen refrigeration supply can be even warmer, the vaporized nitrogen can be returned to the nitrogen refrigerator without a cold compressor.

[0026] The nitrogen stream returning or recycling back to the nitrogen refrigerator is at its lowest pressure at the warm end of the heat exchanger just before it enters the recycle compressor(s). As indicated above, this recycled nitrogen stream should be at or more preferably above atmospheric pressure in order to avoid the possibility of air in-leakage, as this would lead to freezing in the nitrogen refrigerator, and

possibly create operational problems in the refrigeration load system. The optional cold blowers raise the pressure of the vaporized nitrogen as it exits the refrigeration load system such that the return circuit pressure to ensure maintained above atmospheric pressure. Depending on the intended application, multiple, redundant cold blowers may be required to achieve a high reliability often required of cryogenic refrigeration systems.

[0027] Table 1 shows the approximate power consumption to provide refrigeration with cryogenic liquid at varying design temperatures based on computer based simulations and models. The relationship between temperature and pressure exiting the refrigeration load is shown in Table 1. As the target refrigeration temperature rises, the relative refrigerator power demand (i.e. relative power consumption) decreases as is expected from the Second Law of Thermodynamics. However, as the nitrogen refrigerant approaches its critical point, its latent heat begins to decrease rapidly. Note that the critical point temperature of nitrogen is 126.2 K and its corresponding critical point pressure is 493 psia. This decrease in latent heat in the nitrogen refrigerant means that the refrigerant flow needed to balance the refrigeration load increases commensurately, which explains why the power demand of the refrigeration system is higher for a target refrigeration temperature of 118 K than it is for a target refrigeration temperature of 111 K. Hence, the integrated liquid nitrogen refrigeration system of FIGS. **1-5** is preferred where the target refrigeration temperature is below about 115 K.

[0028] In addition to the operational cost savings realized from the reduced power requirement, there may also be modest capital cost savings in the integrated refrigeration system of FIGS. **1-5** as the target refrigeration temperature is raised above the lowest design values. The lower power requirement of the refrigeration system generally means the recycle compressor(s), the motor(s), the turbine(s), and the heat exchanger will decrease in load and/or size, which translates to possible capital cost savings. However, where the higher pressure nitrogen stream directly provides cooling to the refrigeration load require that the maximum allowable working pressure rating of the equipment in the refrigeration load circuit must be higher, possibly resulting in increased capital costs.

[0029] Above a target refrigeration temperature of 115 K, a different refrigeration concept such as that shown in FIGS. **6-7** should be used. Sensible heat could be provided in addition to latent heat so that the liquid nitrogen flow is decreased in an attempt to reduce the power consumption at target refrigeration temperatures above 111 K, but introduction of sensible heat will introduce other efficiency penalties and is generally not beneficial. The concept for providing higher temperature refrigeration, preferably above about 115 K, is shown in the embodiments shown in FIG. **6** and FIG. **7** and described in more detail below.

TABLE 1

Total Refrigerator Power Demand for Warmer Temperature Refrigeration

Refrigerant Fluid	Refrigerant Temp (K)	Refrigerant Pressure (psia)	Relative Refrigerator Power Demand (%)
Nitrogen	77.7	15.3	100 (baseline)
	81.8	1.655	94
	89.5	50	81
	96.8	90	74
	110.9	225	60
	117.7	325	75
Alternate Fluid	150	—	51
Alternate Fluid	200	—	33

[0030] As seen in Table 1, the relative refrigerator power demand associated with providing refrigeration at 150 K using a refrigerant other than nitrogen is 51% which is only modestly lower in power consumption than the relative refrigerator power demand of 60% associated with providing nitrogen refrigeration at 110.9 K. The primary reason for this narrow difference is the thermodynamic penalty for cooling the alternate refrigerant using the sensible heat of gas nitrogen in the auxiliary heat exchanger. In other words, the heat transfer in the auxiliary heat exchanger is thermodynamically very irreversible due to the large temperature difference at the cold end and small temperature difference at the warm end. Other less important efficiency penalties also result from the need for a discrete or separate refrigeration circuit for these warmer refrigeration temperatures. Conversely, the relative refrigerator power demand associated with providing refrigeration at 200 K using a refrigerant other than nitrogen is 33% which represents a somewhat large power savings compared to the case providing refrigeration at 150 K using a refrigerant other than nitrogen (i.e. relative refrigerator power demand of 51%). This substantial power savings is indicative of the benefit of the associated with warmer target refrigeration temperatures. Both these cases bear the thermodynamic irreversibility penalty resulting from the auxiliary heat exchanger and the indirect heat transfer compared to the direct liquid nitrogen refrigeration systems shown in FIGS. **1-5** that are designed or configured to be used at colder target refrigeration temperatures, specifically colder than about 115 K.

[0031] A key feature of the embodiments shown in FIGS. **1-5** is the nitrogen refrigeration circuit is integrated with the refrigeration production system. The refrigeration production system in the illustrated embodiments produces liquid nitrogen at the cold end of the heat exchanger. The liquid nitrogen is then supplied directly to the refrigeration load, where it is vaporized and returned to the cold end of the nitrogen refrigerator. By integrating the liquid nitrogen directly from the refrigerator with the refrigeration load the need for an auxiliary heat exchanger is avoided that would otherwise be required to cool a refrigerant in the separate refrigeration circuit. The finite temperature difference realized in the auxiliary heat exchanger would result in the actual temperature of the separate refrigerant being supplied at the refrigeration load being higher than the temperature of the liquid nitrogen being supplied directly to the refrigeration load in the integrated arrangement. Avoiding this penalty is especially important in cryogenic refrigeration applications having very low temperature requirements.

[0032] Turning now to FIGS. **2-5**, the embodiments shown in FIGS. **2** and **3** depict cryogenic refrigeration systems **100** employing medium pressure nitrogen liquefier arrangements, whereas FIG. **4** shows an embodiment of the cryogenic refrigeration system **200** employing a low pressure

nitrogen liquefier arrangement and FIG. **5** depicts another embodiment having a high pressure nitrogen liquefier arrangement **300**. The liquefaction cycles shown in FIGS. **2-5** appear very similar to conventional nitrogen liquefiers. For example, the liquefaction cycle depicted in FIG. **2** is much like the medium pressure liquefier disclosed in U.S. Pat. No. 4,778,497 while the liquefaction cycle depicted in FIG. **4** is similar to the low pressure liquefier described in U.S. Pat. No. 6,220,053 and the liquefaction cycle depicted in FIG. **5** is similar to high pressure liquefier described in U.S. Pat. No. 5,231,835.

[0033] The disclosed embodiments of the nitrogen refrigerator differ from the conventional nitrogen liquefiers in that they lack a warm nitrogen feed gas supply and the nitrogen refrigerators also have no liquid nitrogen subcooler. Unlike a conventional nitrogen liquefier, the nitrogen refrigerators shown in FIGS. **2-5** are configured for a full recycle of the liquid nitrogen refrigerant, albeit in the vapor phase, such that the liquid nitrogen subcooler would provide little or no benefit.

[0034] Common features of the nitrogen refrigerators illustrated in FIGS. **2-5** include a configuration wherein the nitrogen refrigerators produce cold nitrogen at high pressure at the cold end of the heat exchanger **112**. In each of the illustrated embodiments, the nitrogen refrigerant exiting the heat exchanger **112** is let down in pressure through a throttle valve **125** or optional liquid turbine **135**. The nitrogen refrigerant is then directed to a separator **140** where the minor flashed gas flow **144** is returned at low or medium pressure to the heat exchanger **112**. The nitrogen vapor from the separator is let down in pressure through a valve **142** only slightly so the separator **140** operates at a slightly higher pressure than the buffer tank **150** and refrigeration load circuit. The liquid nitrogen is passed from the separator **140** to a buffer tank **150**, which directly supplies the liquid nitrogen refrigerant to the refrigeration load **120**. The liquid nitrogen level in the buffer tank is controlled to balance the refrigeration load **120**. This control is preferably adjusted by adjusting the nitrogen refrigerant production of the refrigerator system **100**. The return stream **122** from the refrigeration load **120** is saturated vapor or slightly superheated nitrogen vapor. As previously described, the optional cold compressor **119** is needed only when the refrigeration supply temperature is required to be near its minimum available temperature, between about 77.5 K to about 79.1 K. The return stream **122** from the refrigeration load **120** is combined with the nitrogen vapor **152** from the separator **150** and introduced into a low pressure return circuit **123** (FIGS. **2** and **4**) or a medium pressure return circuit **127** (FIG. **3**) of the heat exchanger **112**. Note the heat exchanger include a high pressure nitrogen circuit **129** or passage for the high pressure feed stream **178**. Also, a plurality of aftercoolers **179** may be employed downstream of compressors, as required.

[0035] An optional liquid storage tank **160** is also shown in the various embodiments including those embodiments shown in FIGS. **2-5**. The purpose of the optional liquid storage tank **160** is to hold externally supplied liquid nitrogen or to hold liquid nitrogen produced from the liquefier of the nitrogen refrigerator. Depending on the cooling requirements of the intended application, liquid nitrogen could be produced by the nitrogen refrigerator in a modal operating method that produces excess liquid nitrogen part of the time and/or consumes the stored liquid nitrogen part of the time. This modal operating method may be advantageous in situations where power costs vary as a function of time. Alternatively, excess liquid nitrogen could be produced by the nitrogen refrigerator for export as a merchant liquid or for other uses at the customer site in addition to meeting the cooling requirements of the intended application.

[0036] In some cryogenic refrigeration applications, the use of a modal operating method for excess liquid nitrogen production and/or liquid nitrogen consumption may require substantial gas storage at the warm end of the cryogenic refrigeration system. Preferably, a plurality of gas receivers (See e.g. FIG. **9**) would be configured to store nitrogen molecules when the liquid nitrogen tank is emptying; and the gas receivers would supply the nitrogen molecules when the liquid nitrogen tank is filling. In some operating scenarios, including operating scenarios where excess liquid nitrogen is exported a nitrogen producing air separation unit (See e.g. FIG. **10**) may be required, particularly during modal operation when the gas receiver volume or capacity could become impractically or uneconomically large.

[0037] Another beneficial feature of the embodiments shown in FIGS. **2-5** is the use of radial inflow turbines **170**, **175**. The radial inflow turbines **170**, **175** used in the illustrated embodiments are capable of high efficiency without compromising operating rangeability and are configured to operate at a pressure ratio of between about 8.5 to 10.0. In order to cool the high pressure nitrogen stream exiting the cold end of the heat exchanger **112** sufficiently for supply of refrigeration at a target temperature of 95 K to 100 K or below, the nitrogen stream exiting the cold turbine **175** must be lower than about 90 psia and more preferably between 80 psia and 90 psia. Preferably, the nitrogen stream exiting the turbine is nearly a saturated vapor or it can be up to 10% liquid or even several degrees superheated.

[0038] With the desired pressure ratio of the cold turbine **175** between about 8.5 to 10.0, the high pressure feed stream **178** is approximately 800 psia. This high pressure feed stream **178** enhances the efficiency of the refrigeration system **100** for two thermodynamically based reasons. First, the higher pressure stream results in a straighter cooling curve. As its pressure gets higher above the nitrogen critical pressure of 493 psia, the change in heat capacity as it cools is reduced, resulting in less severe "kinks" in the cooling curve. In the lower direction, as its pressure becomes subcritical, the cooling curve then has a constant temperature latent heat zone which creates a very uneven cooling curve and is very thermodynamically irreversible. Second, higher pressure streams to the turbine are beneficial thermodynamically simply because they have higher heat capacities. This simply means they are better able to recover refrigeration with lower flows, which results in lower flow and power consumption in the recycle compressors.

[0039] In the refrigeration cycle depicted in FIG. **2**, both the warm turbine **170** and the cold turbine **175** operate at similar pressures. In a conventional nitrogen liquefier, the warm turbine flow is typically about one-half of the cold turbine flow for this cycle. In this case, though, with essentially all the liquid nitrogen produced at the cold end is returned to the nitrogen refrigerator as a cold gas, the refrigeration demand for the warm turbine is comparatively lower. So, the warm turbine flow in the embodiment of FIG. **2** is preferably only between about 10% to about 20% of the cold turbine flow. Because of this reduced warm turbine flow, elimination of the warm turbine and booster may even

be considered or contemplated for this embodiment. The discharge stream **115** from the medium pressure recycle compressor **114** is fed to the warm booster **172** and cold booster **176** in parallel, and their respective discharge streams **173** and **177** are recombined to form combined stream **178** at the highest pressure in the cycle before they enter the heat exchanger **112**, which is preferably a brazed aluminum heat exchanger. The low pressure recycle compressor **113** raises the pressure of the combined feed stream made up of the warmed low pressure flash gas stream **144** and return stream **145** from the refrigeration load **120**. A small make-up flow **111** may be required to compensate for leakage losses in the turbomachinery. Very low leakage seals, such as dry gas seals, can be employed if desired to minimize this flow. The low pressure recycle compressor **113** and the medium pressure recycle compressor **114** can be combined into a single machine with one motor and one bull-gear, if desired. As the requirements for the target refrigeration temperature are raised, the corresponding pressure of nitrogen for the refrigeration load circuit also becomes higher. For example, as shown above in Table 1, if the target refrigeration temperature is 89.5 K, the pressure of nitrogen exiting the refrigeration load circuit is about 50 psia. The separator **150**, if it is used, will also be commensurately higher in pressure. This means that the low pressure circuit is higher in pressure and the power needed from the low pressure recycle compressor **113** is reduced. In this situation, the number of compression stages needed in the low pressure recycle compressor **113** may also be reduced.

[0040] In the refrigeration cycle depicted in FIG. **3**, the target refrigeration temperature is preferably about 95 K to about 97 K. The pressure from gas return stream **145** exiting the refrigeration load circuit is as high as the pressure in the exhaust stream from the cold turbine **175**. Unlike the embodiment shown in FIG. **2**, the embodiment of FIG. **3** has no low pressure gas return stream and no low pressure recycle compressor.

[0041] Yet another embodiment and refrigeration cycle is shown in FIG. **4**. There are two main differences in this configuration compared to the embodiment depicted in FIG. **3**. First, the feed nitrogen **136** to the warm turbine **170** is piped from the recycle compressor discharge **115** rather than the warm and cold booster streams. Second, the warm booster **172** and cold booster **176** operate in series rather than parallel, with a portion of the recycle compressor discharge shown as stream **138** first compressed in the warm booster **172**, then in the cold booster **176**. The high pressure stream **178** from the cold booster discharge supplies the cold turbine **175** and the cold liquid nitrogen product stream exiting passage **129** at the cold end of the heat exchanger **112**. The configuration shown in FIG. **4**, with its lower pressure ratio across the warm turbine **170**, and lower pressure ratio with higher flow across the warm booster **172** will lead to a lower speed, larger size impeller design for the warm turbine **170** and warm booster **172**. This configuration also makes use of an additional heat exchange zone (shown as X-**2**) between the cold turbine takeoff and the warm turbine return that is not needed in the embodiments depicted in FIG. **2** and FIG. **3**. This is due to the lower temperature range of the warm turbine **170** in FIG. **4** resulting from its lower pressure ratio.

[0042] FIG. **5** shows yet another alternative embodiment of the cryogenic refrigerator having a liquefaction cycle that provides improved efficiency compared to conventional liquefaction systems. To accomplish this, the warm turbine inlet and the cooling product are designed to operate at a very high pressure such as about 1300 psia, although the optimum operating pressure likely depends on the heat exchanger **112** and turbomachinery design tradeoffs. The higher pressure within the liquefaction cycle improves the thermodynamic efficiency of the nitrogen refrigerator by improving the reversibility of the heat exchanger temperature profile and because of the higher heat capacity of the feed streams. In the embodiment disclosed in FIG. **5**, the cold turbine **175** must operate with an exhaust pressure approximately the same as it is for other liquefiers, so that it is sufficiently cold to cool the liquid nitrogen product stream exiting passage **129** at the cold end of the heat exchanger **112** to the desired target refrigeration temperature. This means that the cold turbine **175** must have a lower pressure feed and preferably the lower pressure feed **136** is supplied as a portion from the discharge stream **115** from high pressure recycle compressor **114**.

[0043] Because the pressure ratio would be too high if the warm turbine exhausted into the cold turbine exhaust circuit, the warm turbine exhaust in the embodiment of FIG. **5** is supplied to a separate, intermediate pressure circuit **124** or passage within the heat exchanger **112**. This feature provides some design freedom in selecting the desired exhaust pressure of the warm turbine **170**, and the corresponding return pressure between the medium pressure recycle compressors **113**A, **113**B and the high pressure recycle compressor **114**.

[0044] Similar to the embodiment shown in FIG. **4**, the warm booster **172** and cold booster **176** are fed in series, albeit in reverse order, with the portion of feed stream **138** first directed to the cold booster **176** and subsequently directed to the warm booster **172**. The additional heat exchange zone, shown as X-**2** is preferably disposed between the warm turbine exhaust and cold turbine draw in a manner similar to that of the nitrogen refrigerator of FIG. **4**.

[0045] As indicated above, if applications where the design requirements dictate a target refrigeration temperature above 111K and more preferably at or above 115 K, a closed loop refrigeration concept such as that shown in FIGS. **6**-**7** should be used. As seen in FIG. **6**, a separate refrigeration circuit **202** containing an alternate refrigerant is used to cool the refrigeration load **220**. A closed loop nitrogen based refrigerator **205** is used to generate the refrigeration that is indirectly transferred to the separate refrigeration load circuit **202**. This is done using vapor nitrogen exiting the turboexpander **216**, which is passed through an auxiliary heat exchanger **215** to cool the alternate refrigerant in separate refrigerant circuit **202**.

[0046] The alternate refrigerant fluid is selected such that it provides constant temperature refrigeration using its latent heat. The preferred alternate refrigerant(s) will have its normal boiling point slightly below the target refrigeration temperature so that the separate refrigeration circuit pressure is modestly above ambient pressure, avoiding concerns for air in-leakage. In addition, the critical temperature of the alternate refrigerant must be higher than the target refrigeration temperature, preferably by a large margin. Circulating the alternate refrigerant at temperatures well below the critical temperature means the refrigeration circuit can be operated at a moderate pressure, and the flow rate within the refrigeration circuit would be relatively low. The preferred alternate refrigerant is non-toxic and inflammable. It is also

desirable that the alternate refrigerant has the lowest possible greenhouse warming potential. Potential alternate refrigerants and the normal boiling points include: Krypton (119.9 K); R-14 (145.4 K); nitrous oxide (184.7 K); R-23 (191.1 K); R-41 (195.0 K); and R-116 (195.0 K).

[0047] FIG. **6** shows a simplified schematic of the closed loop liquid nitrogen based refrigeration system **200** that includes a main heat exchanger **212**, an auxiliary heat exchanger **215**, recycle compressor(s) **214**, and turbine(s) **216**, and as well as the associated gas circuits. The separate alternate refrigerant based system **202** is also a closed loop refrigeration system incorporating the auxiliary heat exchanger **215**, one or more pumps **217**, and the refrigeration load **220**. The pump **217** is used raise the pressure of the alternate refrigerant after it is condensed in the auxiliary heat exchanger **215** so that it can be recirculated. A pump is preferred instead of a gas phase blower because the pump is generally lower cost, requires less power, and generally causes less of a thermodynamic penalty. For cryogenic refrigeration applications requiring a high degree of reliability and/or availability, as well as extended rangeability of the refrigeration supply, multiple pumps may be employed.

[0048] The gas nitrogen exiting the turboexpander (i.e. turbine) **216** is the lowest temperature stream in the refrigerator. It directly provides the refrigeration to balance the refrigerant circuit. The flow of the turbine exhaust stream in the liquid nitrogen based refrigerator must be sufficiently high and the temperature must be sufficiently cold to provide the necessary cooling in the auxiliary heat exchanger **215**. The auxiliary heat exchanger **215** is preferably a counter-current heat exchanger that exhibits a large temperature difference at its cold end, where the turbine exhaust stream enters the auxiliary heat exchanger **215**. The temperature difference of the counter flowing streams in the auxiliary heat exchanger **215** progressively decreases and is tightest at the auxiliary heat exchanger warm end, where the turbine exhaust stream exits the auxiliary heat exchanger **215**. So, the temperature of the turbine exhaust stream exiting the warm end of the heat exchanger limits the operating temperatures of the refrigeration system **200**.

[0049] A more detailed embodiment of the closed-loop nitrogen refrigerator is shown in FIG. **7**. Due to the higher temperature level of the refrigeration load circuit **202**, the cold turbine **216** supplies sufficient refrigeration so there is generally no need for a warm turbine. The turbine exhaust temperature and flow are optimized to achieve the lowest power and capital solution. Reduction in cold turbine flow means that the cold turbine exhaust temperature must also be reduced in order to provide the refrigeration demand. The lowest power solution will have a small temperature difference at the warm end of the heat exchanger **212**, which indicates minimized wasted refrigeration. The selection of pressure levels is very unconstrained, since there is no liquid generated in the refrigerator **205**. As for the other systems, higher pressures will tend to improve efficiency. Also, the turbine pressure ratio should not exceed 8.5-10.0. For this system **200**, a turbine pressure ratio lower than about 10.0 yields a significant power savings. The lower pressure ratio requires increased flow, which gives a more uniform cooling curve in the heat exchanger **212** and improved efficiency (reduces the temperature difference at the cold end). In turndown of this and the other refrigeration systems previously described, the pressure levels are decreased. For the best turndown the pressures of the recycle compressor and the turbine are decreased such that the pressure ratio across each are held constant and the volumetric flows are also constant. In this way the recycle compressor **214**A, **214**B and turbine **216** each maintain their design aerodynamic efficiencies. As shown in FIG. **7**, a plurality of aftercoolers **279** may be employed downstream of compressors and a small make-up flow **211** may be required to compensate for leakage losses in the turbomachinery.

[0050] For extensive, efficient turndown it is also desirable that the cold turbine exhaust pressure is maintained well above atmospheric pressure. With such a design, the lowest pressure of the system **200** will remain above atmospheric at turndown. There is no liquid nitrogen handling for this system, which adds simplicity. A liquid buffer tank, or multiple tanks will probably be needed for control and operation of the refrigerant circuit. The refrigeration output of the present system and method is primarily be controlled by modulating the refrigerant flow rate and the nitrogen refrigerator should be modulated to balance the refrigeration load.

Additional Features of the Nitrogen Refrigeration Systems

[0051] Additional design features in the present cryogenic refrigeration systems and methods may prove beneficial to enhance the operability and flexibility of the above-described embodiments. One important feature is the ability of the cryogenic refrigeration system to handle small variations in refrigeration loads, and more particularly variations in the nitrogen return gas as the refrigeration load changes. For large supercomputing applications, it is foreseeable if not likely that the refrigeration loads may be in disparate locations within the large data centers or even at separate facilities. As a result, the flow and other characteristics of the nitrogen return gas may also vary due to operational changes in the refrigeration loads or refrigeration load circuits, even if the net total refrigeration load does not change.

[0052] A decrease in the nitrogen return gas from the refrigeration load circuits may lead to a drop in the pressure of the nitrogen return gas/flash gas line in the nitrogen refrigerator. Depending on the pressure of the low pressure circuit, a relatively minor decrease in the return gas flow may cause the pressure of this line to drop below atmospheric pressure. Any drop in pressure below atmospheric pressure needs to be avoided so that air incursions into the refrigeration system and/or refrigeration load circuits does not occur. Even if the low pressure circuit pressure is higher a decrease in return flow that is extreme enough, or long lasting enough may cause the pressure in the gas return circuit to fall too low. Also, if the return gas decrease continues for any extended time, the entire refrigeration system pressure will drop, and the refrigeration output will decrease, which in turn may introduce a large instability in the refrigeration system.

[0053] To mitigate these problems, variations to the integrated nitrogen refrigeration systems described with reference to FIGS. **1-5** are illustrated in the integrated nitrogen refrigeration systems of FIGS. **8** through **10**. Many of the components and features shown in FIGS. **8-10** are the same as described above with reference to FIGS. **1-5** and for the sake of brevity will not be repeated. Rather, the following discussion of the embodiments shown in FIGS. **8-10** focuses on various additional components and features.

[0054] For example, as seen in FIGS. **8-10** a trim heater **333** is included in the refrigeration load circuits. Specifically, an electric trim heater **333** is used to maintain a constant nitrogen return flow of saturated vapor from the refrigeration load circuit. The trim heater **333** is shown installed in the buffer tank **150** but could also be installed in an additional liquid tank or elsewhere in the nitrogen return gas circuit. To compensate for an unplanned reduction in gas return vapor, the trim heater load would be increased.

[0055] Any reduction in gas return vapor may be sensed by a flow meter or a pressure transducer in the nitrogen return gas circuit or conduit. The trim heater **333** is preferably always on at a low output in order to ensure its ability to respond quickly. Another important feature is the ability of the cryogenic refrigeration system to handle intentional changes in operation of the refrigeration system in an effort to manage power consumption to reduce operating costs of the refrigeration system. An example of such imposing intentional changes in operation is operation in a modal operating mode that produces and stores excess liquid nitrogen part of the time when power costs are generally lower and/or consumes the stored liquid nitrogen as required by the application and associated refrigeration loads. As discussed above, this modal operating mode may be advantageous in situations where power costs vary as a function of time and where the refrigerator may be turned down or shut off entirely during high power cost periods. These may be regular "time of day" power cost changes, or more variable time of use power cost changes driven by electric grid capacity demands. Alternatively, excess liquid nitrogen could be produced by the nitrogen refrigerator for export as a merchant liquid or for other uses at the customer site in addition to meeting the cooling requirements of the intended application.

[0056] Variable production of excess liquid nitrogen and/or variable consumption of liquid nitrogen requires substantial gas storage at the warm end of the cryogenic refrigeration system. As the refrigeration output of the nitrogen refrigerator is modulated, the pressures within the refrigeration system will change. The most efficient turndown method of the nitrogen refrigerator is preferably the same as turndown in nitrogen liquefiers. During such turndowns, all the pressure levels within the liquefier/refrigerator fall in concert so that the turbines and the recycle compressor pressure ratios and volumetric flow rates stay nearly constant. In this way these turbomachines continue to operate at or near their design point efficiencies. This turndown method also enables a very large turndown range. Generally, the turbine inlet nozzle positions are fixed in this method. The pressure at the suction of the low pressure recycle compressor will necessarily decrease when turndown is affected using this method.

[0057] FIG. **9** shows an example refrigeration configuration similar to the embodiment of FIG. **2** but with an optional throttle valve **345** disposed in the low pressure return circuit **123** near the cold end of the heat exchanger **112** that would be used if the turndown method allowed the low pressure recycle compressor suction pressure to decrease. Us e of the optional throttle valve **345** keeps the refrigeration load circuit at constant pressure and refrigeration temperature, rather than allowing it to fall with the pressure of the low pressure recycle compressor **113**. Locating this optional throttle valve **345** at the cold end of the heat exchanger **112** is thermodynamically better than locating the throttle valve at the warm end of the heat exchanger **112**. However, the optional throttle valve **345** and installation thereof is generally less costly if it is configured or located at the warm end. In order to make use of this method of turndown, the pressure of the low pressure recycle compressor **113** must be elevated above atmospheric. The greater degree to which it is elevated, the greater the extent of efficient turndown that can be accomplished. An alternative approach to refrigeration turndown that will likely be acceptable in most cases is to decrease the pressure ratios of the turbines **170**, **175** and consequently the recycle compressor(s) **113**, **114** by opening the turbine inlet nozzles. This turndown method will be less efficient and less rangeable than the former method, as all the turbomachinery will move away from their design operating points and design efficiencies. But the low pressure recycle compressor **113** suction pressure need not decrease.

[0058] In either turndown method at least some of the system pressure levels will decrease, then need to increase again when the refrigeration rate is turned back up. This means that, without any nitrogen gas supply from a nitrogen producing air separation unit, the nitrogen gas must be captured and then recovered. Very small ranges in capacity can be handled with an externally supplied liquid tank. For larger capacity changes a receiver, or multiple of receivers **355** (i.e. a receiver bank), as shown in FIG. **9** will capture the nitrogen gas molecules at the warm end. When the refrigeration capacity is being turned down, the system pressures decrease, and nitrogen gas is supplied at pressure from the discharge of the medium pressure recycle compressor **114** or the discharge of the warm booster **172** or cold booster **176**.

[0059] When the capacity is increased, the stored gas in the receiver bank **355** is returned via valve **357** to the refrigeration system **100** at the lowest pressure location of the refrigeration system, namely the low pressure recycle compressor **113** suction end. The high pressure supply of nitrogen gas to the receiver bank **355** via valve **358** is optionally from discharge of the boosters **172**, **176**, rather than the discharge of the recycle compressor(s) **114** via valve **359**. This is beneficial in that it requires less receiver bank volume but may require a higher design pressure for the receiver bank **355**.

[0060] Another feature of the refrigeration system shown in FIG. **9** is an optional start-up heater **366**. The purpose of the optional start-up heater **366** is to provide nitrogen gas to the refrigeration system upon restart after a shutdown. During a restart it is conceivable that the introduction of cold return flow to the nitrogen refrigerator will not be balanced by a sufficient feed flow from the compressors when the refrigeration system is started up. This would mean that gas exiting the warm end of the nitrogen refrigerator is unacceptably cold. This start-up heater **366** would provide a relatively low flow of warmed nitrogen gas via valve **367** to enable start-up of the nitrogen refrigerator at low capacity.

[0061] For the anticipated normal capacity modulations needed to respond to refrigeration load and typical weather variations, a refrigeration system with a receiver bank is likely to provide a satisfactory solution. If, on the other hand, substantial capacity modulation is expected or planned, the volume of return gas storage to be provided by the receiver bank may be excessive. In this case, a nitrogen producing air separation unit **400** is preferably coupled to the nitrogen refrigeration system as shown in FIG. **10**.

Liquid Air Refrigeration Systems

[0062] An alternative to the nitrogen refrigeration system having a large receiver bank or that requires a nitrogen producing air separation unit may be to operate the cryogenic refrigeration system with liquid air rather than nitrogen. A liquid air based refrigeration system offers a design that has many operational advantages and is much more sustainable. Ultimately, the atmosphere provides an infinite gas supply so that a liquid air based refrigeration system obviates any need for a receiver bank or a gas producing air separation unit. In addition, the rangeability of the air-based cryogenic refrigeration system is not limited by the gas supply and concerns relating to avoiding sub-ambient pressures are no longer relevant.

[0063] However, using liquid air as the refrigerant in the integrated refrigeration system limits the minimum achievable temperature to 82.0 K rather than the of 77.5 K target refrigeration temperature that can be provided with a liquid nitrogen based refrigeration system. Also, the use of liquid air could lead to a genuine safety concern due to the potential for oxygen enrichment that may occur within the system, which can generally be avoided with a design that avoids or minimizes 'dead' legs in the refrigeration circuit, and with operating criteria specifying periodic or measurement based liquid drainage from tanks and associated circuits, including any such 'dead' legs.

[0064] FIGS. **11-13** show various embodiments of a liquid air based refrigeration system **300**. Many of the individual components and features shown in FIGS. **11-13** are the same or similar to those described above with reference to FIGS. **8-10** and for the sake of brevity will not be repeated. Rather, the following discussion of the embodiments shown in FIGS. **11-13** focuses on the differences between the liquid air based integrated refrigeration system and the nitrogen based integrated refrigeration systems **100** described with reference to FIGS. **8-10**.

[0065] FIG. **11** shows a liquid air based refrigeration system based similar to that shown in FIG. **2** and FIG. **9**, although any of the embodiments shown in FIGS. **2-5** and **8-10** could also be modified to use liquid air. Comparing the embodiment of FIG. **11** to that of FIGS. **2** and **9**, the optional cold compressor **119** of the nitrogen based system is removed as it is not needed even when the design calls for the coldest refrigeration temperatures possible. Also, there will be no liquid withdrawal from the optional storage tank **160**.

[0066] The key additions to the embodiment of the liquid air based system shown in FIG. **11** compared to that of the liquid nitrogen based system of FIGS. **2** and is the addition of an air pre-purifier **500** after the low pressure recycle compressor **113** to remove contaminants that would freeze out contaminants such as carbon dioxide, moisture, oxides of nitrogen, and some heavy hydrocarbons that are undesirable for process safety. The pre-purifier **500** is preferably a temperature swing adsorption (TSA) based unit that minimizes the required regeneration flow. The regeneration heater **502** is most likely electrically heated, although it could as well be natural gas fired or steam heated. The bypass circuit **504** around the heater **502** is for the cooling step that is a normal part of the TSA pre-purifier operating cycle. A portion of the cleaned pre-purifier outlet stream **506** is returned for regeneration. Low pressure return gas from the refrigerator warm end could be considered as a gas source for the regeneration flow. However, the pre-purifier outlet gas is a better choice.

[0067] FIG. **12** shows yet another alternative embodiment of the liquid air based refrigeration system **300** configured for applications that has a somewhat higher target refrigeration temperature and where the low pressure return stream is elevated in pressure. In this case air compression stages are required to feed fresh air into the system, when it is needed. The location of the pre-purifier **500**A is shown to be after the main air compressor **513** and upstream of the return of the low pressure stream. This is based on a design scenario where the maximum feed air flow is relatively low compared to the low pressure return flow. Alternatively, the pre-purifier **500**B can be located after the low pressure recycle compressor **113**. The choice of location depends on the maximum feed air flow, the air compressor discharge pressure, and whether the liquefier turndown method allows the low pressure circuit to decrease in pressure. These factors affect the sizing of the pre-purifier **500**A, **500**B. For example, if the air compressor discharge pressure is relatively low and the feed air flow is high enough that additional compression in the low pressure recycle compressor would result in more moisture condensation and a lower volumetric flow, then the alternative pre-purifier **500**B location would be preferred. Also, if the turndown method entails reducing the pressure of the low pressure return gas circuit, that would mean the pre-purifier would operate at lower pressure upon recharging the system with air and increasing the refrigeration capacity. This would require larger beds or throttling of the air after the pre-purifier. So, this would also tend to make the alternative pre-purifier **500**B location preferable. It is not shown in the drawing, but there also will need to be a vent of air to atmosphere in the system so that the liquid air based refrigeration system **300** pressures can be reduced when the refrigerator capacity is being unloaded. To minimize the wasted power during this operation the venting stream should be at the lowest pressure possible. It can be located after the low pressure recycle compressor, or better, after the first stage of the low pressure recycle compressor.

[0068] When the refrigeration temperature is high enough, the return gas from the refrigeration load will be similar in pressure to the design exhaust pressure of the cold turbine. In this case a separate low pressure return stream is not needed. For a nitrogen based refrigerator this occurs when the refrigeration temperature is about 95-97 K, and higher. For an air based refrigerator this will occur when the refrigeration temperature is at least about 99.5 K-101.5 K. FIG. **13** shows a liquid air based refrigeration system **300** with a warm enough refrigeration temperature so that there is no low pressure return stream (See **123**, **345** in FIGS. **2**, **4**, **5**, **9** and **10**). In this case, the air compression and air pre-purification are always entirely separate from the gas recycle circuit.

[0069] While the present systems and methods for cryogenic refrigeration have been described with reference to several preferred embodiments, it is understood that numerous additions, changes and omissions can be made without departing from the spirit and scope of the present system and method as set forth in the appended claims. Specifically, alternative cold end configurations of the integrated nitrogen refrigeration system are contemplated. For example, the buffer tank may be used for liquid nitrogen addition or liquid nitrogen manufacture in lieu of a separate storage tank. In

such arrangement, the buffer tank would probably be sized larger to satisfy the dual functions. Another contemplated variant would be to combine the separator and buffer tank function in a single liquid vessel. Some further contemplated alternatives include arrangements where the optional liquid turbine is loaded by a compressor that raises the pressure of another stream or it could be loaded by an energy dissipating brake instead of loading by a generator. Of course, the optional liquid turbine is a power saving feature that may be used in applications where the additional capital costs are justified.

[0070] The contemplated designs of the presently disclosed refrigeration systems and methods are readily scaleable in size by increasing or decreasing the size of the various compressor(s), turbine(s), heat exchanger(s) and associate equipment and piping circuits. It is expected that the disclosed cryogenic refrigeration systems would be suitable for use in applications providing between about 20 kW of refrigeration to about 2000 kW of refrigeration or more to the refrigeration load circuits.

What is claimed is:

1. A liquid nitrogen based integrated refrigeration system comprising:

a nitrogen refrigerator having one or more recycle compressors, a warm booster compressor, a cold booster compressor, a warm turbine, a cold turbine, and a heat exchanger with at least one cooling passage and at least one recycle passage;

wherein the nitrogen refrigerator is configured to receive a source of nitrogen gas and a nitrogen return stream and produce a nitrogen refrigerant stream;

a refrigeration load circuit having an expansion valve or a liquid turbine, a separator, a buffer tank, and a refrigeration load;

wherein the refrigeration load circuit is configured to: (a) receive the nitrogen refrigerant stream; (b) expand the nitrogen refrigerant stream in the expansion valve or the liquid turbine; (c) separate the expanded nitrogen refrigerant stream in the separator into a liquid portion and a vapor portion; (d) cool a refrigeration load with the liquid portion of the expanded nitrogen refrigerant stream while vaporizing the liquid portion of the expanded nitrogen refrigerant stream; and (e) return the vaporized stream and the vapor portion of the nitrogen refrigerant stream as the nitrogen return stream to the nitrogen refrigerator.

2. The liquid nitrogen based integrated refrigeration system of claim **1**, further comprising an optional cold compressor disposed downstream of the refrigeration load and configured to boost the pressure of the nitrogen return stream.

3. The liquid nitrogen based integrated refrigeration system of claim **1**, wherein the heat exchanger is configured with: (i) one cooling passage and two recycle passages; (ii) one cooling passage and one recycle passage; (iii) two cooling passages and two recycle passages; or (iv) two cooling passages and three recycle passages.

4. The liquid nitrogen based integrated refrigeration system of claim **1**, wherein the one or more recycle compressors further comprises: (i) a low pressure recycle compressor and a medium pressure recycle compressor; (ii) a low pressure recycle compressor, a medium pressure recycle compressor, and a high pressure recycle compressor.

5. The liquid nitrogen based integrated refrigeration system of claim **1**, wherein the warm booster and the cold booster are arranged is series.

6. The liquid nitrogen based integrated refrigeration system of claim **1**, wherein the warm booster and the cold booster are arranged is parallel.

7. The liquid nitrogen based integrated refrigeration system of claim **1**, wherein the warm turbine is a warm boosted loaded turbine operatively coupled to the warm booster and the cold turbine is a cold boosted loaded turbine operatively coupled to the cold booster.

8. The liquid nitrogen based integrated refrigeration system of claim **1**, wherein the warm turbine and the cold turbine are configured as radial inflow turbines and have a pressure ratio of between about 8.5 to 10.0.

9. The liquid nitrogen based integrated refrigeration system of claim **1**, further comprising an optional liquid storage tank disposed in operative association with the refrigeration load circuit.

10. The liquid nitrogen based integrated refrigeration system of claim **1**, further comprising a trim heater disposed within the buffer tank and configured to modulate the nitrogen return stream recycled to the heat exchanger.

11. The liquid nitrogen based integrated refrigeration system of claim **1** further comprising an optional throttle valve configured to throttle the nitrogen return stream.

12. The liquid nitrogen based integrated refrigeration system of claim **1** further comprising an optional start-up heater.

13. The liquid nitrogen based integrated refrigeration system of claim **1** further comprising one or more gas receivers configured to modulate the nitrogen gas fed to the nitrogen refrigerator.

14. The liquid nitrogen based integrated refrigeration system of claim **1** wherein the refrigeration system is operatively coupled to a nitrogen producing air separation unit to control the nitrogen gas fed to the nitrogen refrigerator.

15. A liquid air based integrated refrigeration system comprising:

an air intake system having a compressor and a pre-purifier;

a refrigerator having one or more recycle compressors, a warm booster compressor, a cold booster compressor, a warm turbine, a cold turbine, and a heat exchanger with at least one cooling passage and at least one recycle passage;

wherein the refrigerator is configured to receive a source of compressed, pre-purified air and a cold return stream and produce a liquid air refrigerant stream;

a refrigeration load circuit having an expansion valve or a liquid turbine, a separator, a buffer tank, and a refrigeration load;

wherein the refrigeration load circuit is configured to: (a) receive the liquid air refrigerant stream; (b) expand the liquid air refrigerant stream in the expansion valve or the liquid turbine; (c) separate the expanded refrigerant stream in the separator into a liquid portion and a vapor portion; (d) cool a refrigeration load with the liquid portion of the expanded refrigerant stream while vaporizing the liquid portion of the expanded refrigerant stream; and (e) return the vaporized stream and the vapor portion of the expanded refrigerant stream as the cold return stream to the refrigerator.

* * * * *