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(54) **HIGH TEMPERATURE SUPERCONDUCTOR REFRIGERATION SYSTEM**

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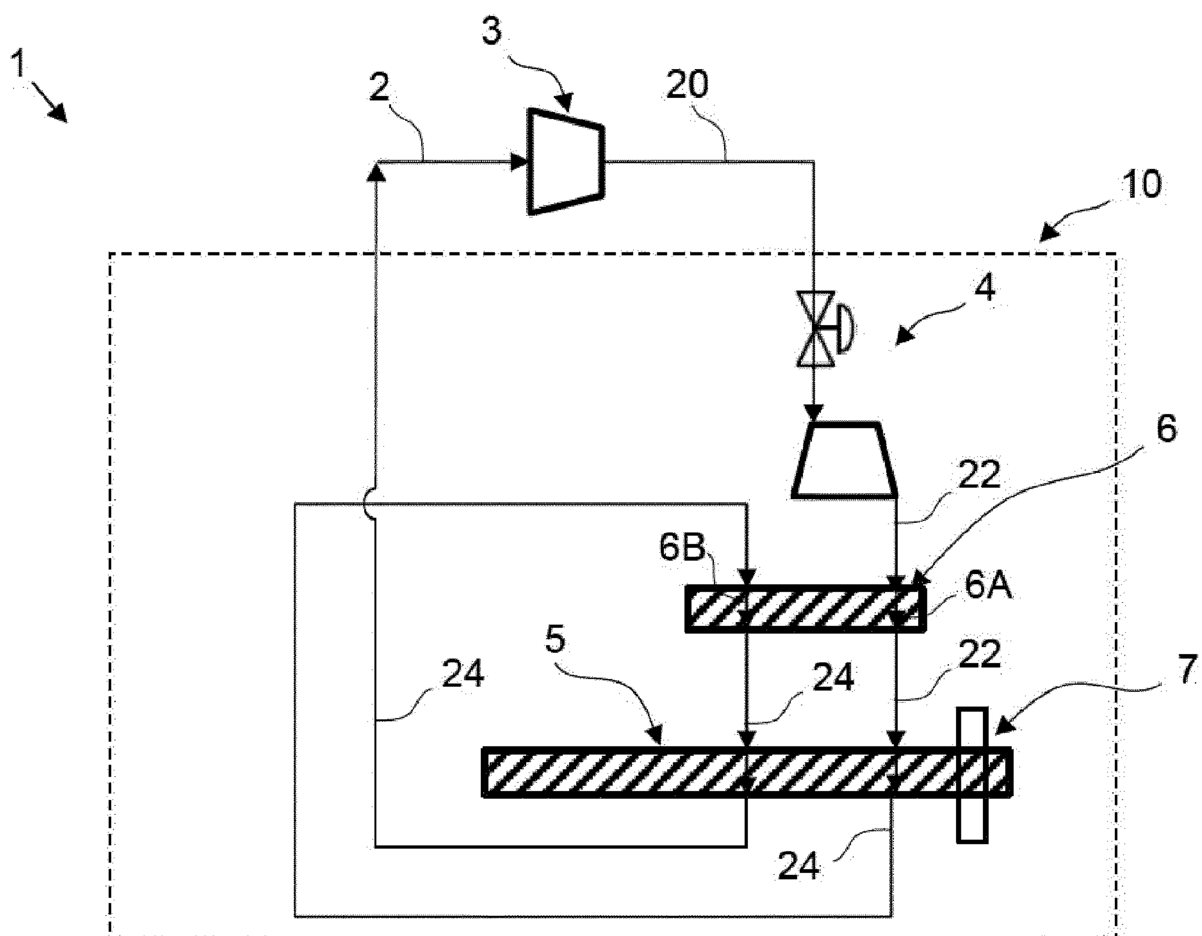
(57) **ABSTRACT**

A cryogenic refrigeration system and a corresponding method for increasing the cooling efficiency of the system, preferably the cooling of a thermally coupled load. Accordingly, the system comprises a supply means for providing a supply flow of a cryogenic refrigerant, a compressor fluidly coupled to said supply means and configured to compress the supplied cryogenic refrigerant, and a cold box fluidly coupled to the compressor, said cold box comprising a first expansion device and a first heat exchanger, wherein the first expansion device is configured to receive the compressed cryogenic refrigerant from the compressor and expand it and provide the expanded refrigerant to the first heat exchanger, and wherein the first heat exchanger is configured to be thermally coupled to a load. The system furthermore comprises a second heat exchanger arranged in the cold box comprising at least a first and second heat exchanging section.



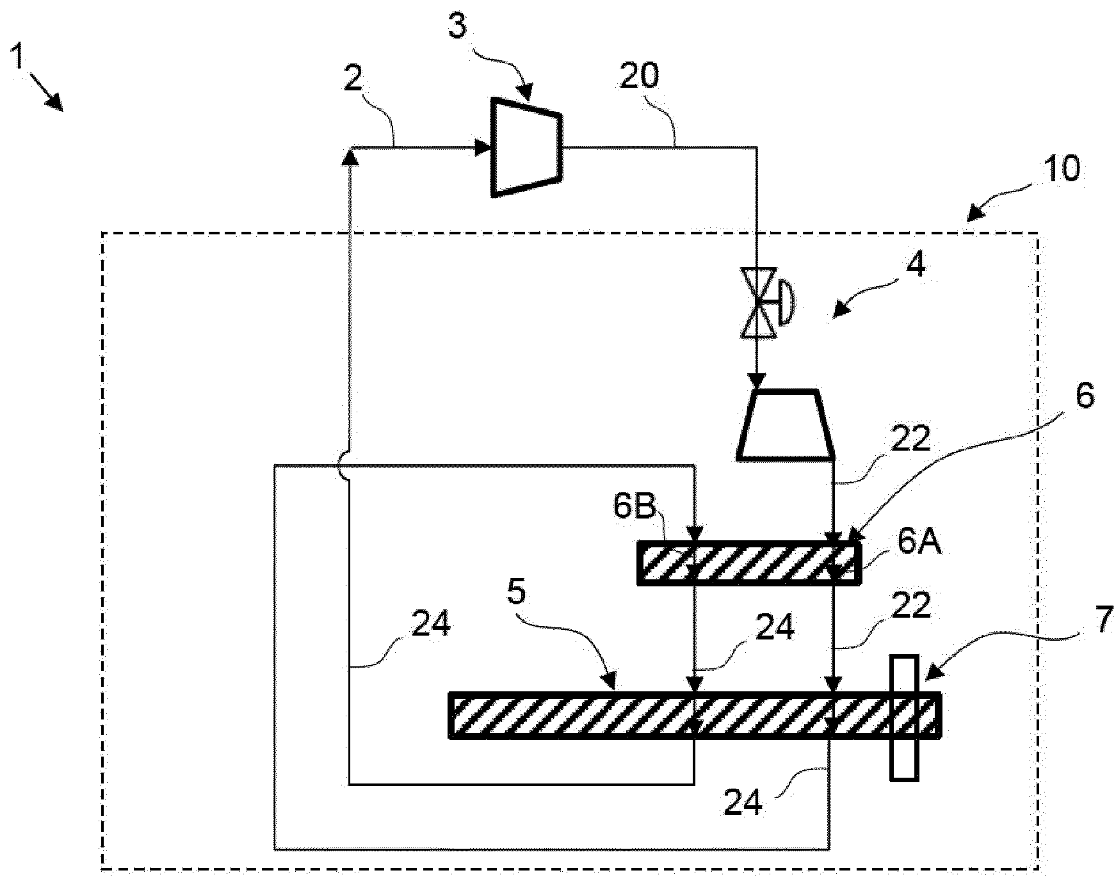


Fig. 1

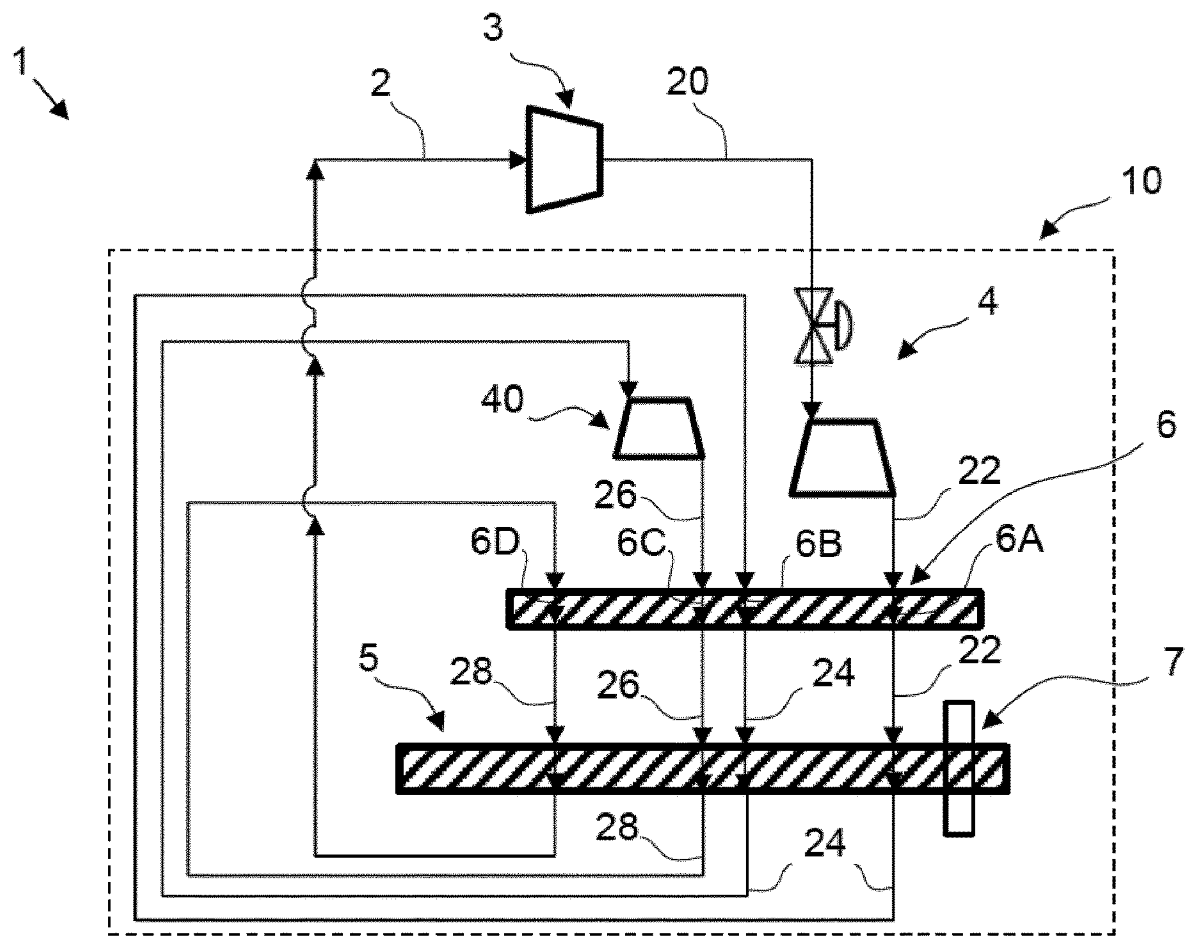


Fig. 2

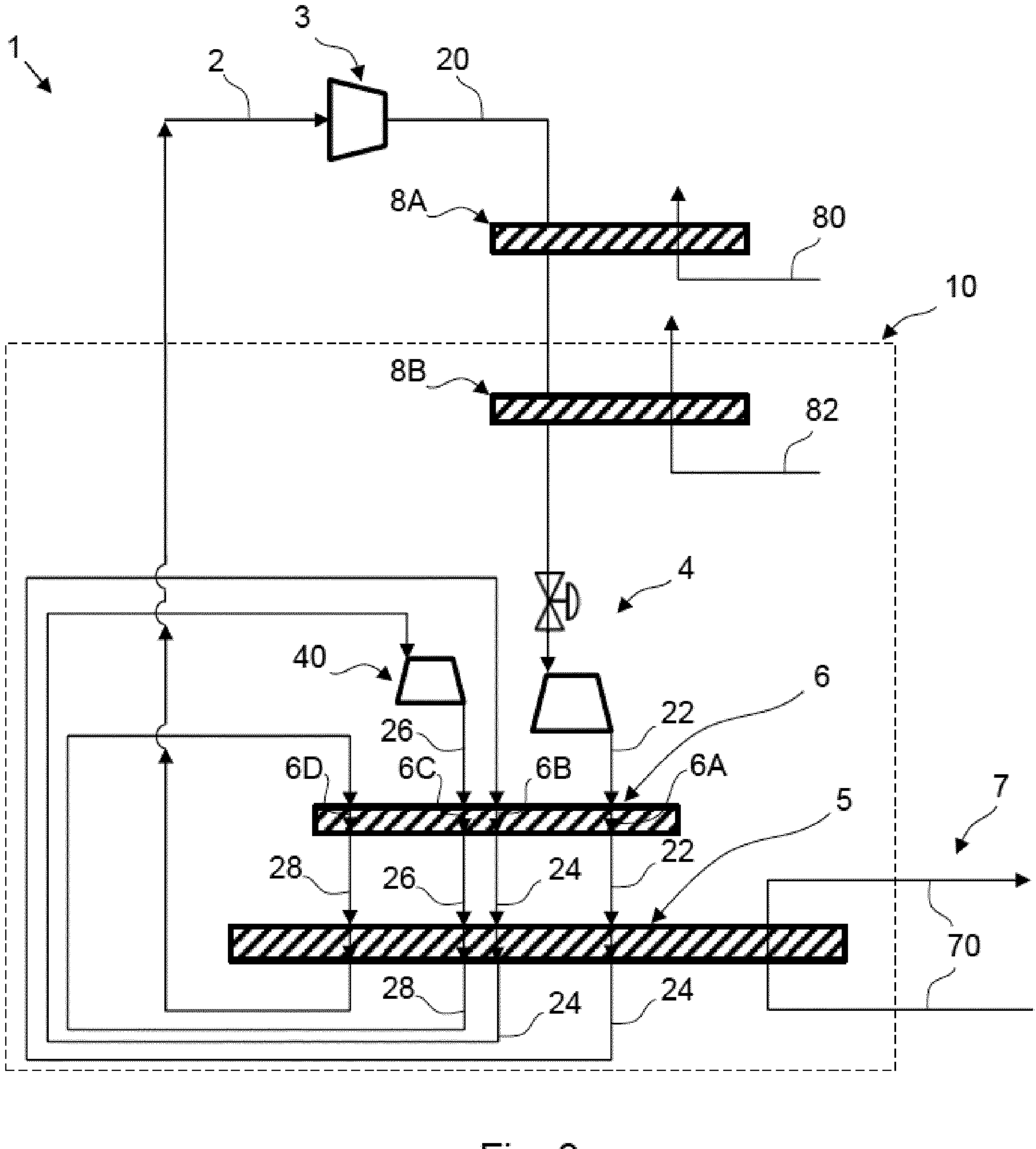
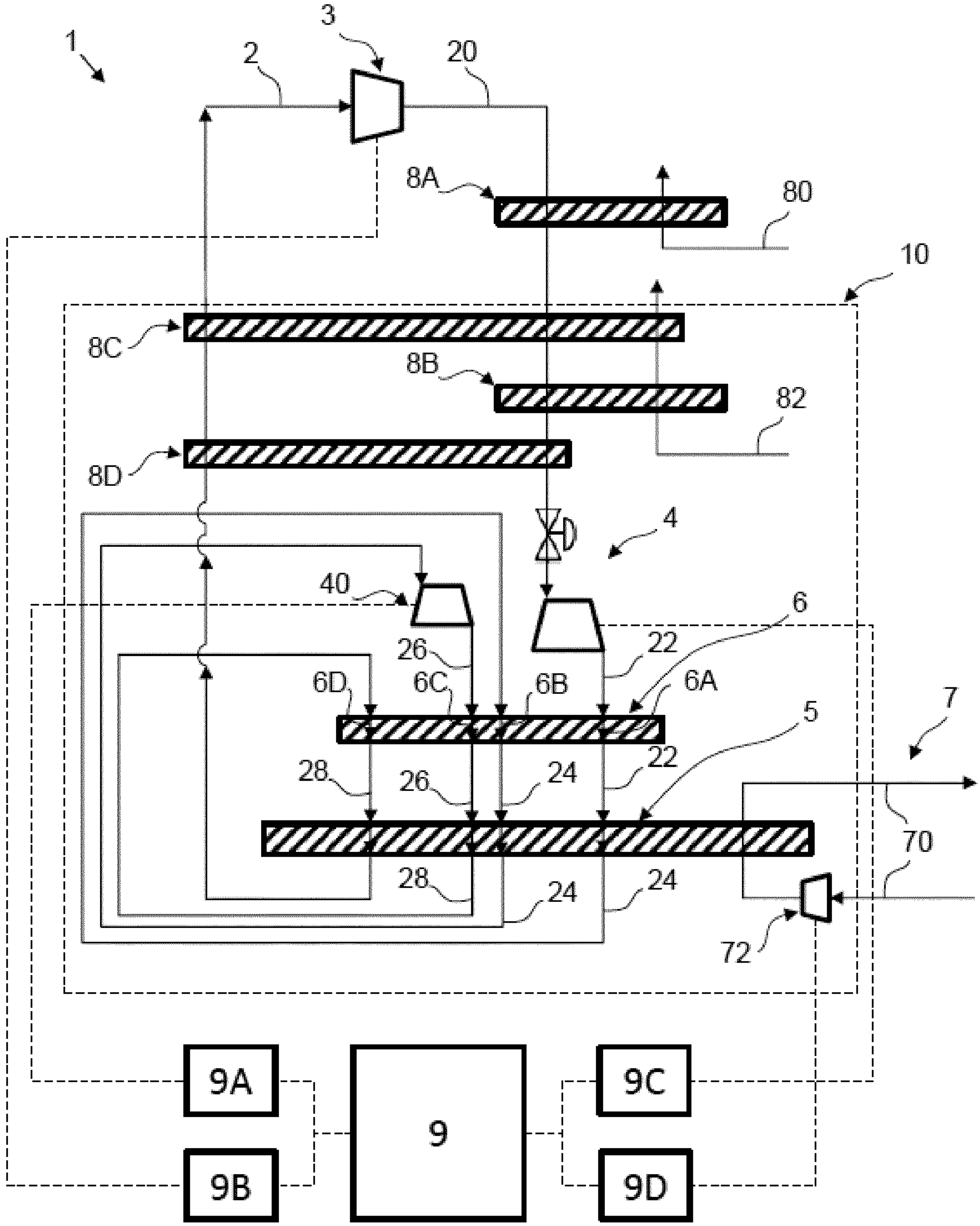


Fig. 3


1
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8A
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8C
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6D
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6A
5
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28
26
24
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70
28
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24
72
9A
9C
9
9B
9D

Fig. 4

HIGH TEMPERATURE SUPERCONDUCTOR REFRIGERATION SYSTEM

TECHNICAL FIELD

[0001] The invention relates to a system and a method for cryogenic refrigeration. In particular, the invention relates to a heat exchanger configuration to recycle a cryogenic refrigerant to improve the refrigeration efficiency, e.g. for a thermally coupled load such as a refrigeration circuit for high temperature superconductors.

TECHNOLOGICAL BACKGROUND

[0002] Superconductive cables are commonly cooled using a thermally coupled liquid nitrogen circuitry, wherein the liquid nitrogen absorbs excess heat produced in said cables during normal operation and is accordingly evaporated. The evaporated nitrogen often leaves the system without being recycled and is accordingly lost, e.g. in open configurations. Such solutions are generally only economically viable at low to medium cooling capacity requirements. At higher cooling capacities, e.g. above 10-20 kW, operating costs become predominant in such open systems. Here, closed loop refrigeration systems become favorable despite their high capital expenses.

[0003] Furthermore, to provide sufficient refrigeration for superconductive cables and similar loads it is required that the cooling is provided by recirculation of subcooled liquid nitrogen at supercritical pressure. However, the temperature range is generally limited as the capacity of high temperature superconductors, e.g. cables, is reduced with a dropping temperature while at the same time the triple point of nitrogen is at 63 K. Accordingly, the temperature range is generally predefined by the required temperature for superconductive properties of a used load and the lower temperature limit of the used refrigerant for avoiding said refrigerant to attain a solid phase.

[0004] Known systems to cool liquid nitrogen circuitries often comprise neon as a refrigerating agent. To further increase the cooling efficiency of the liquid nitrogen, refrigeration systems are known, which implement a compressor engine and turbo expander that are coupled. However, in terms of process control, this is difficult to implement and requires complicated control systems.

[0005] Due to the limited temperature range defined by the triple point of nitrogen and the high temperature superconductor's requirement for the lowest possible cooling temperature, larger cooling capacities can only be achieved by increasing the refrigerant mass flow. However, increasing the pressure ratio over the expansion stage would generate too big temperature differences that are not compatible with high temperature superconductor cooling provided by nitrogen recirculation. As a result the potential isentropic efficiency of 40 percent in such coupled Turbo-Brayton systems remains limited in such high temperature superconductor applications to below about 28 percent.

[0006] Other attempts to further increase the cooling efficiency include the implementation of a helium-based refrigerating line. However, helium is a very light gas, i.e. having a low molecular weight, and is therefore very difficult to compress at ambient temperature. Helium is therefore typically compressed in oil injected screw compressors, which generally results in a total system isentropic efficiency of below 20 percent.

[0007] Accordingly, a need exists to further increase the isentropic efficiency of cryogenic refrigeration systems without significantly increasing the complexity and/or the control of such systems.

SUMMARY OF THE INVENTION

[0008] It is an object of the present invention to provide an improved cryogenic refrigeration system and a corresponding method for providing a cryogenic refrigeration that reduces the above problems.

[0009] This object is achieved by the cryogenic refrigeration system comprising the features of claim **1** and the cryogenic refrigeration method comprising the features of claim **12**. Preferred embodiments are provided in the dependent claims and by the specification and the Figures.

[0010] Accordingly, in a first aspect, a cryogenic refrigeration system is suggested, which comprises a supply means for providing a supply flow of a cryogenic refrigerant, a compressor fluidly coupled to said supply means and configured to compress the supplied cryogenic refrigerant, and a cold box fluidly coupled to the compressor. The cold box comprises a first expansion device and a first heat exchanger, wherein the first expansion device is configured to receive the compressed cryogenic refrigerant from the compressor and expand it and provide the expanded refrigerant to the first heat exchanger, and wherein the first heat exchanger is configured to be thermally coupled to a load. According to the invention, the system comprises a second heat exchanger arranged in the cold box, which comprises at least a first and second heat exchanging section. The first heat exchanging section is configured to receive the expanded refrigerant from the expansion device and to subsequently provide the received expanded refrigerant to the first heat exchanger and the second heat exchanging section is configured to receive the expanded refrigerant from the first heat exchanger and to subsequently provide the expanded heated refrigerant to the first heat exchanger, wherein the first and second heat exchanger sections are thermally coupled. The first heat exchanger is configured to provide the received expanded refrigerant to the supply means and/or the compressor.

[0011] Such configuration has the advantage that instead of directly providing a cooling medium to the first heat exchanger after the expansion stage the expanded or cooled refrigerant is first warmed up by the received expanded refrigerant from the first heat exchanger, i.e. the expanded refrigerant is recycled after a first round of cooling provided in the first heat exchanger. This allows expanding the cryogenic refrigerant to a much colder temperature according to the required and allowable cryogenic refrigeration capacity of the first heat exchanger. At the same time, by providing both the received expanded refrigerant, which may hence be a warmed cooled refrigerant, from the first heat exchanging section, and the received expanded refrigerant, i.e. from the second heat exchanging section, to the first heat exchanger, this allows to transfer double the cooling capacity without increasing the mass flow.

[0012] Furthermore, by recycling the refrigerant and thereby doubling the cooling capacity, the isentropic efficiency of the first heat exchanger is increased without requiring a coupled compressor and expansion device and corresponding control system. In addition, the adversary effect of a loss of refrigerant in common compressors is not enhanced since the mass flow is not required to be increased.

[0013] The various features of the system may be connected to each other either directly or by means of at least one conduit or tube section. The cold box may furthermore be fluidly coupled with the compressor and/or supply means by means of valves, e.g. check valves, arranged outside or at the junction of the cold box. The compressor and/or the supply means may hence be connected to the cold box via said valves either directly or by means of a conduit, wherein an outlet of the compressor is connected to an inlet of a valve of the cold box, i.e. to provide a supply flow to the cold box, and an inlet of the compressor and/or supply means is connected to an outlet of a valve of the cold box, i.e. to provide a return supply flow from the first heat exchanger.

[0014] By the same token, the first and second heat exchanger may comprise inlets and outlets to provide a fluid coupling between each other and the expansion device, supply means, and/or compressor, where applicable. For example, the first expansion device may be configured to provide the expanded refrigerant to a first inlet of the first heat exchanger for providing an expanded and/or cooled refrigerant to the first heat exchanger, wherein the first heat exchanging section of the second heat exchanger is fluidly coupled with the first expansion device via a first inlet of the second heat exchanger to receive the expanded refrigerant and is fluidly coupled with the first inlet of the first heat exchanger via a first outlet of the second heat exchanger to provide the expanded refrigerant to the first heat exchanger. In addition, the second heat exchanging section may be fluidly coupled to the first outlet of the first heat exchanger via a second inlet of the second heat exchanger to receive the expanded refrigerant and is configured to provide the received expanded refrigerant to the first heat exchanger via a second outlet of the second heat exchanger and a second inlet of the first heat exchanger. The first heat exchanger may then be configured to provide the received expanded refrigerant to the supply means and/or the compressor via a second outlet of the first heat exchanger.

[0015] As outlined in the above, the system comprises a supply means and a compressor to provide a compressed cryogenic refrigerant to the cold box. The supply means may comprise e.g. a large vessel or any other means providing a sufficient supply flow of the cryogenic refrigerant, e.g. a coupling to a process medium flow of a refrigeration plant or refrigerant producing means. The supply means and the compressor may be fluidly coupled and arranged separately from each other, but may also be combined at an inlet of the system to provide a more compact arrangement.

[0016] The expansion device may be configured as an expansion valve, expansion vessel or expansion turbine, with or without an additional pressure regulator and/or pressure control valve. The expansion device comprises a constant pressure, which is lower than the pressure upstream of the expansion device. Accordingly, the expansion device is configured to reduce the pressure of the compressed cryogenic refrigerant to such an extent that due to a sudden volume increase in the expansion device, e.g. by correspondingly sizing and dimensioning, the compressed refrigerant is relaxed resulting in a rapid pressure reduction of the refrigerant, such that preferably a gas phase is generated. Although the temperature of the relaxed refrigerant may remain constant or be reduced, the latent heat of the refrigerant is reduced, such that an amount of heat may be absorbed. To increase the amount of heat that may be absorbed, all features of the system are preferably thermally isolated, such that the amount of heat entering and leaving the system is considered to be zero or negligible.

[0017] To further increase to isentropic efficiency of the system, the cold box may further comprise a second expansion device, wherein the second heat exchanger further may comprise a third and fourth heat exchanging section. In such configuration, the second expansion device may be fluidly coupled to the first heat exchanger and the second heat exchanger and be configured to receive the expanded refrigerant received by the first heat exchanger from the second heat exchanging section, provide an expansion of said refrigerant, and subsequently provide the secondary expanded refrigerant to the first heat exchanger via the third heat exchanging section. The fourth heat exchanging section may accordingly be configured to receive the secondary expanded refrigerant from the first heat exchanger and to subsequently provide the received secondary expanded refrigerant to the first heat exchanger. Furthermore, at least the third and fourth heat exchanging section may be thermally coupled.

[0018] Accordingly, heat may be exchanged between the third and fourth heat exchanger sections, such that the secondary expanded refrigerant may be warmed by the received secondary expanded refrigerant from the first heat exchanger before being provided to the first heat exchanger. In addition, the third and/or fourth heat exchanging sections may be thermally coupled to the first and/or second heat exchanging sections, such that an even further improved heat exchange may be provided and an even colder expanded refrigerant may be provided by the first expansion device. According to such configuration, the refrigerant exiting the first heat exchanger may hence be recycled twice, such that a quadruple cooling capacity is provided without increasing the mass flow. In other words, going through a second expansion machine and the second heat exchanger enables to transfer even four times the cooling capacity with the same mass flow at the same temperature range. Hence, the lower level heat of the cryogenic refrigerant can be used a second time resulting in a significantly more efficient cooling process.

[0019] Although this requires that the cryogenic refrigerant is compressed to a higher ratio by the compressor, this does not adversely affect the efficiency to a significant extent since the compression power increases only with natural logarithm of pressure ratio whereas it increases linearly with mass flow. Accordingly, such configuration allows achieving the same isentropic efficiency of about 28 percent compared with a neon-based Turbo-Brayton cycle.

[0020] Furthermore, compared to known Turbo-Brayton processes, the energetic efficiency of such configuration is significantly higher while at the same time the process control is much simpler, since the compressor performance is not linked to the mechanics of the expansion turbine, i.e. the expansion device is not used to also drive the compression of the refrigerant by the compressor.

[0021] Depending on the required system, the recycling of the refrigerant by means of an expansion device and the heat exchanger may be repeated by including further expansion devices and heat exchanging sections. For example, the recycling may be repeated a third or more time.

[0022] In addition, further heat exchangers may be provided. For example, the first and/or second heat exchanger may be configured as a series of heat exchangers. Furthermore, one or more additional heat exchangers may be provided that are arranged in the cold box and upstream of the expansion device. Such heat exchangers may hence receive both the compressed refrigerant from the compressor and the expanded refrigerant from the first heat exchanger, such that the compressed refrigerant is preheated before expansion and the expanded refrigerant that is returned to the supply means and/or compressor is pre-cooled before compression.

[0023] Preferably, the compressor of the cryogenic refrigeration system is a screw compressor or a turbo compressor. When implementing a turbo compressor, the compressor furthermore preferably comprises magnetic couplings and/or comprises or is configured as a serial compressor. Alternatively, or in addition, the compressor may be configured to compress the refrigerant at ambient temperature.

[0024] The implementation of a screw compressor provides a cost efficient compression while at the same time this increases the isentropic efficiency to about 31 percent. In particular, the implementation of a screw compressor is advantageous for refrigerants having a higher density, e.g. neon, which may hence be compressed at higher efficiencies.

[0025] Alternatively, the implementation of a turbo compressor may be advantageous for refrigerants having a lower density, e.g. helium, and further improves the isentropic efficiency to over 42 percent. This furthermore allows a configuration of the compressor with magnetic couplings to ensure that only a minimum of refrigerants is lost. Accordingly, one or more serial turbo compressors may be used, as known from e.g. climatization or buildings. The use of a turbo compressor furthermore has the advantage that a hermetic sealing is provided, which is free of oil lubrication. Accordingly, an oil removal system, which may be required in a helium-based cryogenic refrigeration system, may be omitted.

[0026] Furthermore, a compression at ambient temperature does not require any pre-cooling or temperature control and hence provides a cost efficient compression.

[0027] As outlined in the above, the compressor and the expansion device are controlled separately and operated independently, e.g. the expansion device does not drive the compressor and vice versa. Accordingly, a control system may be provided, which independently regulates the compression pressure by controlling the compressor and the constant pressure of the expansion device. Furthermore, such control system may be provided with a feedback mechanism, e.g. one or more sensors, in particular pressure sensors that are in fluid communication with the refrigerant and/or temperature sensors, to ensure that the system provides the cryogenic refrigeration according to predefined or set values and parameters.

[0028] Preferably, the first heat exchanger of the cryogenic refrigeration system is thermally coupled to a load. In particular, the load may comprise a refrigeration circuit for a high temperature superconductor, e.g. a cable system.

[0029] For example, the load may be a refrigeration circuit or circuitry, which enters a warm end of the first heat exchanger and exits the first heat exchanger at a cold end. The term “warm end” is to be understood as the end of the first heat exchanger, where the expanded or cooled refrigerant has been heated for at least a first cycle and exits the first heat exchanger as an expanded or heated refrigerant. By the same token, the term “cold end” is to be understood as the end of the first heat exchanger, where the expanded refrigerant provided via the second heat exchanger enters the first heat exchanger. By means of the thermal coupling, heat exchange occurs, such that the refrigerant absorbs heat from the refrigeration circuit and the refrigeration circuit is hence cooled to a predefined temperature.

[0030] Preferably, the load comprises a second cryogenic refrigerant, wherein said second cryogenic refrigerant preferably comprises liquid nitrogen. The use of liquid nitrogen may be advantageous for a variety of loads with superconductor characteristics at relatively high temperatures. However, other circulating liquids or gases at different temperatures may be efficiently refrigerated with the proposed configuration. By the same token, alternatively or in addition, other cooling circuits may be provided. For example, instead of traversing the first heat exchanger, the load may be thermally coupled by means of an adjacent arrangement. Also, the first heat exchanger, or a series of first heat exchangers, may be arranged to provide cryogenic refrigeration for a plurality of loads or refrigeration circuits.

[0031] To further increase the heat exchange in the first heat exchanger, the second refrigerant in the refrigeration circuit may be compressed before entering the first heat exchanger. A further or alternative compression of the second refrigerant may be provided downstream of the first heat exchanger and upstream of the load to be cooled.

[0032] To increase the stability and the predictability of the system, the load is preferably provided us as a constant load and/or the cryogenic refrigeration is preferably provided at a constant mass flow, temperature, and physical state of the cryogenic refrigerant. Accordingly, the system preferably comprises fixed process conditions, which hence may be compatible with refrigeration plants and/or supply flows of a process medium.

[0033] Depending on the required refrigeration capacity and the dimensioning of the second heat exchanger, at least the first and second heat exchanging sections and/or the third and fourth heat exchanging sections may be arranged to each other to provide counter flow, cross flow, or equal flow heat exchanging sections. This also applies to the first heat exchanger, such that heat exchanging sections of the first heat exchanger may be similarly arranged to each other and/or with respect to a thermally coupled load, such as a refrigeration circuit.

[0034] In order to facilitate the cryogenic refrigeration by the first heat exchanger, the compressor and/or the supply means may be configured to provide the refrigerant to the first expansion device as a gaseous refrigerant. Preferably, said configuration also ensures that a gaseous refrigerant is provided to the second expansion device.

[0035] This at least has the advantage that the first heat exchanger does not require e.g. a vessel or phase separator at the lower temperature range to collect a liquid phase of the refrigerant and at the same time an evaporated gas flow with low specific enthalpy may be provided. In addition, smaller equipment such as compressors and heat exchangers may be provided, such that the dimensions of the system may be reduced.

[0036] The first expansion device may also be configured to provide a two-phase or gas phase refrigerant, wherein the first heat exchanger is configured as a cold gas heat exchanger and to receive a gas phase from the cooled refrigerant. In such configuration, the expansion device may hence also provide a liquid and a gas phase, wherein preferably the first heat exchanger comprises a vessel, which collects the liquid phase and provides the gas phase as a cryogenic refrigerant. The use of a cold gas heat exchanger, in comparison to an evaporating gas exchanger, has the advantage that no recirculation of flash gas or evaporated helium on the atmospheric pressure occurs.

[0037] Preferably, the cryogenic refrigerant comprises helium and/or neon. As outlined in the above, the used cryogenic refrigerant may be chosen according to the required cooling. For example, the cooling may be dependent on the required temperature of a thermally coupled high temperature superconductor, which is known to reduce the capacity with decreasing temperature. At the same time, the cryogenic refrigerant needs to be maintained and a pressure and temperature above the respective triple point. For example, the triple point of nitrogen is at 63 K, such that for lower temperature ranges the use of nitrogen may not be applicable and hence other refrigerants, such as e.g. helium and/or neon may be used. Furthermore, the choice of cryogenic refrigerant may depend on the implemented compressor type, as outlined in the above. In addition, also other refrigerants such as hydrogen or mixtures or compositions may be used.

[0038] In order to pre-cool the compressed cryogenic refrigerant, the cryogenic refrigeration system may further comprise an evaporating heat exchanger arranged outside of the cold box and upstream of the first expansion device and which is thermally coupled to the provided compressed cryogenic refrigerant supply flow. The expanded refrigerant or cooled refrigerant may hence be provided at a lower temperature to the second heat exchanger, thereby further improving the cooling efficiency of the first heat exchanger. The evaporating heat exchanger preferably comprises a liquid water or hydrogen circuit as a refrigerant to be evaporated. However, as an alternative, also gaseous hydrogen may be provided as a cold gas heat exchanger. The implementation of water or hydrogen has the advantage that this forms a cost-effective cooling and the evaporated refrigerant may be simply released into the atmosphere after exiting the evaporating heat exchanger.

[0039] By the same token, the system may further comprise an evaporating heat exchanger arranged in the cold box and upstream of the first expansion device and which is thermally coupled to the provided compressed cryogenic refrigerant supply flow to pre-cool said refrigerant. Preferably, the evaporating heat exchanger comprises a liquid nitrogen circuit as a refrigerant to be evaporated. The arrangement within the cold box has the advantage that the pre-cooling efficiency is increased while simultaneously reducing the dimensions of the system. Furthermore, a part of or excess second refrigerant being used in a load, e.g. in a refrigeration circuit, such as liquid nitrogen, may be provided to pre-cool the compressed cryogenic refrigerant prior to expansion.

[0040] According to a further aspect of the invention, a method for providing a cryogenic refrigeration is suggested, comprising the steps of providing a supply flow of a cryogenic refrigerant by a supply means, compressing the supplied cryogenic refrigerant by a compressor, expanding the compressed cryogenic refrigerant by a first expansion device in a cold box, and providing the expanded refrigerant to a first heat exchanger in the cold box, wherein the first heat exchanger is configured to be thermally coupled to a load. According to the invention, the expanded refrigerant is received from the expansion device by a first heat exchanging section of a second heat exchanger in the cold box is subsequently provided to the first heat exchanger. Furthermore, the expanded refrigerant from the first heat exchanger is received by a second heat exchanging section of the second heat exchanger and is subsequently provided to the first heat exchanger, wherein heat is exchanged between the first and second heat exchanger section. The expanded refrigerant received by the first heat exchanger from the second heat exchanging section is furthermore provided to the supply means and/or the compressor.

[0041] As outlined in the above, providing the expanded refrigerant from the first heat exchanger to the second heat exchanger and allowing a heat exchange through a thermal coupling with the expanded refrigerant received from the expansion device has the advantage that the expanded refrigerant is first warmed up before being used as a cryogenic refrigerant for, which allows expanding the cryogenic refrigerant to a much colder temperature according to the required and allowable cryogenic refrigeration capacity of the first heat exchanger. At the same time, by providing both the received expanded refrigerant, which may hence be a pre-warmed cooled or expanded refrigerant, from the first heat exchanging section, and the received expanded refrigerant, i.e. from the second heat exchanging section, to the first heat exchanger, this allows to transfer double the cooling capacity without increasing the mass flow. Again, no complicated control system is required as opposed to systems with a coupled compressor and expansion device.

[0042] Preferably, the method also comprises that the expanded refrigerant received by the first heat exchanger from the second heat exchanging section is received and expanded by a second expansion device, wherein the secondary expanded refrigerant is provided to the first heat exchanger via a third heat exchanging section of the second heat exchanger. The secondary expanded refrigerant from the first heat exchanger is furthermore received by a fourth heat exchanging section of the second heat exchanger and subsequently provided via the fourth heat exchanging section to the first heat exchanger, wherein heat is exchanged between at least the third and fourth heat exchanger section.

[0043] Accordingly, the method may provide that the refrigerant exiting the first heat exchanger is hence recycled twice, such that a quadruple cooling capacity is provided without increasing the mass flow.

[0044] In other words, going through a second expansion device and the second heat exchanger enables to transfer even four times the cooling capacity with the same mass flow at the same temperature range.

[0045] The compression of the supplied first cryogenic refrigerant may furthermore be provided by a screw compressor, a turbo compressor, and/or at ambient temperature. The cryogenic refrigerant preferably comprises helium and/or neon.

[0046] To apply the cryogenic refrigeration, the method may furthermore comprise that the first heat exchanger provides a cryogenic refrigeration of a thermally coupled load, wherein said load preferably comprises a refrigeration circuit for a high temperature superconductor. Such load preferably comprises liquid nitrogen as a second cryogenic refrigerant. Accordingly, the first heat exchanger may provide cryogenic refrigeration to e.g. a liquid nitrogen-based refrigeration circuit, which provides refrigeration to a high temperature superconductor at a supercritical temperature and pressure, wherein the provided recycling of the cryogenic refrigerant provides an improved cooling efficiency compared with known systems without requiring a complex control system or increasing the mass flow.

BRIEF DESCRIPTION OF THE DRAWINGS

[0047] The present disclosure will be more readily appreciated by reference to the following detailed description when being considered in connection with the accompanying drawings in which:

[0048] FIG. **1** is a schematic view of a first and second heat exchanger in a cryogenic system with a single recycling of the first cryogenic refrigerant;

[0049] FIG. **2** is a schematic view of the embodiment according to FIG. **1** with a double recycling of the first cryogenic refrigerant;

[0050] FIG. **3** is a schematic view of a first and second heat exchanger in a cryogenic system with a double recycling of the first cryogenic refrigerant and additional evaporating heat exchangers; and

[0051] FIG. **4** is a schematic view of a first and second heat exchanger in a further cryogenic system with a double recycling of the first cryogenic refrigerant and additional evaporating heat exchangers.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0052] In the following, the invention will be explained in more detail with reference to the accompanying Figures. In the Figures, like elements are denoted by identical reference numerals and repeated description thereof may be omitted in order to avoid redundancies.

[0053] In FIG. **1** a cryogenic refrigeration system **1** is schematically shown in operation using liquid helium as a cryogenic refrigerant and thermally coupled to a load **7**. Accordingly, a supply flow of the liquid helium is provided by a supply means **2**, which is fluidly coupled to a compressor **3**. The supply means **2** according to the embodiment of FIG. **1** is configured as a coupling to a refrigeration plant, which provides a continuous supply flow of liquid helium. However, the supply means **2** may also comprise e.g. a larger vessel providing the required amount and flow of liquid helium to the system **1**.

[0054] The supply means **2** provides the supply flow of liquid helium as a cryogenic refrigerant to the fluidly coupled compressor **3**, which is arranged downstream thereof and is configured as a screw compressor. Accordingly, the liquid helium is pressurized and provided as a compressed cryogenic refrigerant **20**. The use of a screw compressor may require the implementation of a downstream oil removal system (not shown), depending on the used refrigerant and specifications of the compressor. The compressed cryogenic refrigerant **20**, i.e. the pressurized liquid helium, is then provided to the cold box **10** by means of a fluid coupling or valve at the junction of the cold box **10**. This configuration ensures that the cold box **10** is essentially thermally isolated and only connected to the outside components via a said fluid coupling.

[0055] Within the cold box **10**, the compressed cryogenic refrigerant **20** is received by a first expansion device **4**, which is depicted as a pressure regulator and an expansion valve. However, other configurations, including only an expansion valve, an expansion turbine, or a combined expansion valve and pressure regulator may be provided. Although the cryogenic refrigeration system **1** requires a normalization and stabilization of the temperatures in the system **1** during start up or an initial phase of operation, the temperature and pressure of the cryogenic refrigerant at various points or locations in the system **1** is considered to be constant and predictable during normal operation. In this regard, the expansion device **4** comprises a constant pressure, which is lower than the pressure upstream of the expansion device **4**, and is configured to provide a gas phase from the compressed cryogenic refrigerant **20**. Due to a sudden pressure drop in the expansion device **4**, the compressed cryogenic refrigerant **20** is hence expanded, such that a relaxation of the pressurized liquid helium occurs, thereby increasing the volume of the first cryogenic refrigerant. Accordingly, the latent heat of the compressed cryogenic refrigerant **20** is reduced, thereby allowing the liquid helium to further absorb heat. The expansion device **4** hence provides an expanded refrigerant **22**, which may have a lower temperature compared with the compressed cryogenic refrigerant **20** and which is received by a first heat exchanging section **6**A of a second heat exchanger **6**.

[0056] After traversing the first heat exchanger section **6**A, the expanded refrigerant **22** is then passed to a first heat exchanger **5** via a respective inlet. Although the expansion device **4** may be configured to provide the expanded refrigerant **22** as a liquid or two-phase refrigerant, the expansion device **4** according to FIG. **1** is configured to provide the expanded refrigerant **22** in a gaseous state, such that the first heat exchanger **5** is configured as a cold gas heat exchanger. Within the first heat exchanger **5**, the cooled helium absorbs heat from the thermally coupled load **7**, such that the cooled helium exits the first heat exchanger **5** via a respective outlet as an expanded refrigerant **24**, which may be a heated refrigerant compared with the expanded refrigerant **22** exiting the expansion device. Simultaneously, the load **7** is provided with cryogenic refrigeration, such that e.g. a high temperature superconductor may be accordingly cooled.

[0057] Instead of returning the expanded refrigerant **24** from the first heat exchanger **5** directly to the supply means **2**, the expanded refrigerant **24** from the first heat exchanger is provided to a second heat exchanger section **6**B of the second heat exchanger **6**, which is thermally coupled to the first heat exchanging section **6**A. The received expanded refrigerant **24** hence traverses the second heat exchanging section **6**B and is then passed to the first heat exchanger **5** via a respective inlet. Again, the expanded refrigerant **24** received from the second heat exchanging section **6**B absorbs heat within the first heat exchanger **5**. The received expanded refrigerant **24** then exits the first heat exchanger **5** via a respective outlet and returns the expanded refrigerant **24** to the supply means **2**, such that it can be re-used in the system **1**.

[0058] Accordingly, the cryogenic refrigerant is recycled once before being returned to the compressor **3**. Since the first and second heat exchanging sections **6**A, **6**B are thermally coupled, the expanded refrigerant **22** is provided to the first heat exchanger **5** in a relatively warmed state compared with the expanded refrigerant **22** exiting the expansion device **4** while at the same time the expanded refrigerant **24** from the first heat exchanger **5** exiting the second heat exchanger **6** is provided to the first heat exchanger **5**. Not only does this allow a further expansion and the provision of a corresponding lower temperature of the compressed first cryogenic refrigerant **20**, this also provides a doubling of the cooling capacity of the first heat exchanger **5** without increasing the mass flow.

[0059] Accordingly, the isentropic efficiency is improved by this configuration. Furthermore, the compressor **3** and the expansion device **4** may be controlled separately and independently without requiring complex control systems or a mechanical coupling, i.e. without having the output of the compressor linked to the expansion device and vice versa.

[0060] Although the embodiment according to FIG. **1** schematically depicts that he first heat exchanger **5** is configured to provide all of the expanded refrigerant **24** received from the first heat exchanging section **6**A to the second heat exchanging section **6**B, it may also be provided that only a branch of the expanded refrigerant **24** is provided to the second heat exchanging section **6**B, while the rest of the expanded refrigerant **24** is returned to the supply means **2**.

[0061] Furthermore, although the embodiment according to FIG. **1** is described with respect to liquid helium as a first cryogenic refrigerant, other refrigerants, such as e.g. neon, may be used. Furthermore, FIG. **1** schematically depicts the first and second heat exchanger **5**, **6** as equal flow heat exchangers. However, other configurations, such as a counter flow or cross flow heat exchanger may be provided instead of or in addition to an equal flow heat exchanger.

[0062] The embodiment according to FIG. **2** generally resembles the embodiment according to FIG. **1**. In addition, the embodiment according to FIG. **2** comprises a double recycling of the cryogenic refrigerant, as depicted by the additional return loop of the expanded refrigerant **24** from the first heat exchanger **5**. To provide the double recycling, the cryogenic refrigeration system **1** comprises a second expansion device **40** in the cold box **10** and the second heat exchanger **6** comprises an additional third and fourth heat exchanging section **6**C, **6**D. Accordingly, the second expansion device **40** is fluidly coupled to an outlet of the first heat exchanger **5** to accordingly receive the expanded refrigerant **24** received by the first heat exchanger **5** to expand said refrigerant **24** for providing a secondary expanded refrigerant **26** to the first heat exchanger **5** via the third heat exchanging section **6**C. Furthermore, the fourth heat exchanging section **6**D is configured to receive a secondary expanded refrigerant **28** from a respective outlet of the first heat exchanger **5** and to provide the received secondary expanded refrigerant **28** to the first heat exchanger **5**.

[0063] According to the embodiment, the third and fourth heat exchanger sections **6**C, **6**D are thermally coupled, such that heat is exchanged between said sections and the secondary expanded refrigerant **26** may hence be warmed by the secondary expanded refrigerant **28** before entering the first heat exchanger **5**. Therefore, the expanded refrigerant **22** may be provided at an even lower temperature. By the same token, the received secondary expanded refrigerant **28** from the first heat exchanger may be pre-cooled before entering the first heat exchanger **5**, such that the overall cooling capacity is quadrupled without increasing the mass flow.

[0064] In addition, the compressor **3** according to the embodiment is provided as a turbo compressor having magnetic couplings. Hence, no oil removal system is required and the energetic efficiency is even further increased. Alternatively, however, a screw compressor and, optionally, an oil removal system, may also be used. Furthermore, the first and second expansion devices **4**, **40** are configured to provide a gas phase of the liquid helium, such that the first and second heat exchangers **5**, **6** are configured as cold gas heat exchangers. However, the heat exchangers may also be configured to receive both a gas phase and a liquid phase, e.g. from a two-phase expanded refrigerant **22** and/or secondary expanded refrigerant **26**, for example, by means of a phase separator or a vessel.

[0065] As outlined in the above for FIG. **1**, it may also be provided that instead of providing all of the expanded refrigerant **24** received from the second heat exchanging section **6**B and/or the expanded refrigerant **28** received from the third heat exchanging section **6**C to the second expansion device **40** and the fourth heat exchanging section **6**D, respectively, it may also be provided that only a branch of said expanded refrigerants **24**, **28** is provided while the rest of the expanded refrigerant **24**, **28** is returned to the supply means **2**.

[0066] In FIG. **3** an embodiment of the system **1** is schematically depicted, which generally corresponds to the embodiment according to FIG. **2**. In addition to the second expansion device **40** and the third and fourth heat exchanging sections **6**C, **6**D, the thermally coupled load **7** is configured as a refrigeration circuit **70** for a high temperature superconductor, e.g. a cable. The refrigeration circuit **70** enters the cold box **10** and is configured in a counter flow arrangement with respect to the first heat exchanger **5**. Accordingly, the refrigeration circuit **70** is configured to enter the first heat exchanger **5** at a warm end and to exit the first heat exchanger **5** at a respective cold end, such that a second cryogenic refrigerant in the refrigeration circuit **70** may be efficiently cooled by the first heat exchanger **5**. The second cryogenic refrigerant, e.g. liquid nitrogen, then leaves the cold box **10** and is provided to e.g. a cable to provide the required cooling.

[0067] In addition, the cold box **10** comprises an evaporating heat exchanger **8**B, which is arranged upstream of the expansion device **4** and ensures that the compressed cryogenic refrigerant **20** is cooled down before being expanded by the expansion device **4**. The evaporating heat exchanger **8**B comprises a liquid nitrogen circuit **82**, which enters the evaporating heat exchanger at a warm end of the evaporating heat exchanger **8**B and is thermally coupled to the provided compressed cryogenic refrigerant **20**, such that heat from the compressed cryogenic refrigerant **20** may be absorbed by the liquid nitrogen. The liquid nitrogen thereby evaporates into a gas phase, which exits the evaporating heat exchanger **8**B and may be either released into the atmosphere or be received by e.g. a liquefaction plant. Although the liquid nitrogen circuit **82** is depicted in the embodiment to be provided within the cold box **10**, e.g. by a respective branch of the refrigeration circuit **70**, the liquid nitrogen circuit **82**, may also be partly provided outside of the cold box **10** via a respective coupling. By the same token, the evaporated liquid nitrogen may also be retained within the cold box **10** instead of being released outside of the cold box **10**, e.g. into the atmosphere.

[0068] To further pre-cool the compressed cryogenic refrigerant **20**, the system **1** furthermore comprises an evaporating heat exchanger **8**A, which is arranged outside of the cold box **10**, upstream of the evaporating heat exchanger **8**B, and downstream of the compressor **3**. The evaporating heat exchanger **8**A comprises a water circuit **80** and is thermally coupled to the supplied compressed cryogenic refrigerant **20**, such that heat may be exchanged between the compressed cryogenic refrigerant **20** and the water of the water circuit **80**. Accordingly, the water absorbs heat and is evaporated, such that the water exits the evaporating heat exchanger **8**A in a gas phase. The evaporated water may be released into the atmosphere or may be e.g. re-used after a corresponding condensation or be used for other purposes, such as gas or steam turbines.

[0069] Although the refrigeration circuit **70**, the water circuit **80**, and the liquid nitrogen circuit **82** are schematically depicted in a counter flow arrangement, other configurations, such as equal flow or cross flow arrangements may also be provided.

[0070] The embodiment according to FIG. **4** generally corresponds to the embodiment according to FIG. **3**, such that like features are denoted by identical reference numerals and repeated description thereof is omitted in order to avoid redundancies. In addition, the cold box **10** according to the embodiment of FIG. **4** comprises further cold gas heat exchangers **8**C, **8**D, which are arranged upstream of the expansion device **4**. The cold gas heat exchanger **8**C is arranged upstream of the evaporating heat exchanger **8**B, wherein the compressed cryogenic refrigerant **20** is thermally coupled both with the liquid nitrogen circuit **82** and the secondary expanded refrigerant **28** being returned to the supply means **2** from the first heat exchanger **5**. Hence, the compressed cryogenic refrigerant **20** is pre-cooled by the evaporating gas from the liquid nitrogen exiting the evaporating heat exchanger **8**B and the returning gas in the secondary expanded refrigerant **28**. By the same token, the returning gas in the secondary expanded refrigerant **28** may be pre-cooled due to the evaporating heat exchanger **8**A, depending on the system conditions.

[0071] The cold gas heat exchanger **8**D is arranged upstream of the first expansion device **4** and downstream of both the evaporating heat exchanger **8**B and the cold gas heat exchanger **8**C. Again, the compressed cryogenic refrigerant **20** is thermally coupled to the secondary expanded refrigerant **28** from the first heat exchanger **5**, such that the compressed cryogenic refrigerant **20** is further cooled due to heat exchange with the returning gas in the secondary expanded refrigerant **28**. Hence, the implementation of further evaporating heat exchangers **8**A, **8**B and cold gas heat exchangers **8**C, **8**D provides a system with an even further improved energetic efficiency.

[0072] In order to increase the cooling capacity of the first heat exchanger **5**, the refrigeration circuit **70** may comprise a compressor **72** upstream of the first heat exchanger **5**. Although the compressor **72** is schematically depicted in the cold box **10**, a compressor **72** may also be arranged outside of the cold box **10**, depending on the requirements of the system **1**. In any case, the liquid nitrogen being returned to the first heat exchanger **5** may be compressed before being cooled by the first heat exchanger **5** and before being returned to e.g. a cable. The refrigeration circuit **70** may furthermore comprise an expansion device arranged downstream of the first heat exchanger **5** (not shown) to further improve the cryogenic refrigeration capacity of the load **7**.

[0073] As outlined in the above, the compressor **3** and the first expansion device **4** are controlled separately and independently. Accordingly, the system **1** comprises control units **9**A, **9**C **2**, respectively control the compressor **3** and the first expansion device **4**. Both control units **9**A, **9**C are connected to a main controller **9**, which is generally configured to monitor the respective control units **9**A, **9**C. In order to provide a feedback mechanism, the system **1** may furthermore comprise one or more sensors, e.g., temperature and/or pressure sensors, which provide measurement signals to the respective control unit. In addition, the system **1** comprises further control units **9**B, **9**D to respectively control the second expansion device **40** and the compressor **72** of the refrigeration circuit **70**. Said control units **9**B, **9**D are furthermore in communication with the main controller **9**, such that these may also be monitored by the controller **9**. The provision of the independent control units **9**A, **9**B, **9**C, **9**D and the controller **9** generally improves the controllability, predictability, and stability of the system **1**. However, depending on the configuration of the system **1**, said one or more control units **9**A, **9**B, **9**C, **9**D may also be merely optional. For example, the second expansion device **40** and/or the compressor **72** may be e.g. not adjustable in a dynamic range and hence be configured to provide a constant pressure independently of a measured system parameter, which may be unproblematic with constant system conditions, e.g. a constant supply flow of the cryogenic refrigerant and a constant load **7**.

[0074] It will be obvious for a person skilled in the art that these embodiments and items only depict examples of a plurality of possibilities. Hence, the embodiments shown here should not be understood to form a limitation of these features and configurations. Any possible combination and configuration of the described features can be chosen according to the scope of the invention.

LIST OF REFERENCE NUMERALS

[0075] **1** Cryogenic refrigeration system
[0076] **10** Cold box
[0077] **2** Supply means
[0078] **20** Compressed cryogenic refrigerant
[0079] **22** Expanded refrigerant
[0080] **24** Expanded refrigerant from first heat exchanger
[0081] **26** Secondary expanded refrigerant
[0082] **28** Secondary expanded refrigerant from first heat exchanger
[0083] **3** Compressor
[0084] **4** First expansion device
[0085] **40** Second expansion device
[0086] **5** First heat exchanger
[0087] **6** Second heat exchanger
[0088] **6**A First heat exchanging section
[0089] **6**B Second heat exchanging section
[0090] **6**C Third heat exchanging section
[0091] **6**D Fourth heat exchanging section
[0092] **7** Load
[0093] **70** Refrigeration circuit
[0094] **72** Compressor
[0095] **8**A-**8**B Evaporating heat exchanger
[0096] **8**C-**8**D Cold gas heat exchanger
[0097] **80** Water circuit
[0098] **82** Liquid nitrogen circuit
[0099] **9** Controller
[0100] **9**A-**9**D Control unit

1. Cryogenic refrigeration system (**1**), comprising:

a supply means (**2**) for providing a supply flow of a cryogenic refrigerant;

a compressor (**3**) fluidly coupled to said supply means (**2**) and configured to compress the supplied cryogenic refrigerant; and a cold box (**10**) fluidly coupled to the compressor (**3**), said cold box (**10**) comprising a first expansion device (**4**) and a first heat exchanger (**5**),

wherein the first expansion device (**4**) is configured to receive the compressed cryogenic refrigerant (**20**) from the compressor (**3**) and expanded and provide the expanded refrigerant to the first heat exchanger (**5**), and

wherein the first heat exchanger (**5**) is configured to be thermally coupled to a load (**7**), wherein

the system (**1**) comprises a second heat exchanger (**6**) arranged in the cold box (**10**) comprising at least a first heat exchanging section (**6**A) and a second heat exchanging section (**6**B),

wherein the first heat exchanging section (**6**A) is configured to receive the expanded refrigerant (**22**) from the expansion device (**4**) and to subsequently provide the expanded refrigerant (**22**) to the first heat exchanger (**5**);

wherein the second heat exchanging section (**6**B) is configured to receive the expanded refrigerant (**24**) from the first heat exchanger (**5**) and to subsequently provide the received expanded refrigerant (**24**) to the first heat exchanger (**5**),

wherein the first and second heat exchanger sections (**6**A, **6**B) are thermally coupled, and wherein the first heat exchanger (**5**) is configured to provide the received expanded refrigerant (**24**) to the supply means (**2**) and/or the compressor (**3**).

2. Cryogenic refrigeration system (**1**) according to claim **1**, wherein the cold box (**10**) further comprises a second expansion device (**40**) and the second heat exchanger (**6**) comprises a third and a fourth heat exchanging section (**6**C, **6**D), wherein

the second expansion device (**40**) is fluidly coupled to the first heat exchanger (**5**) and the second heat exchanger (**6**) and is configured to receive the expanded refrigerant (**24**) received by the first heat exchanger (**5**) from the second heat exchanging section (**6**B), provide a secondary expansion of said refrigerant (**24**), and subsequently provide the secondary expanded refrigerant (**26**) to the first heat exchanger (**5**) via the third heat exchanging section (**6**C), and

the fourth heat exchanging section (**6**D) is configured to receive the secondary expanded refrigerant (**28**) from the first heat exchanger (**5**) and to subsequently provide the received secondary expanded refrigerant (**28**) to the first heat exchanger (**5**),

wherein at least the third and fourth heat exchanger sections (**6**C, **6**D) are thermally coupled.

3. Cryogenic refrigeration system (**1**) according to claim **1**, wherein the compressor (**3**) is a screw compressor or turbo compressor, said turbo compressor preferably comprising magnetic couplings and/or comprising a serial compressor, and/or wherein the compressor is configured to compress the refrigerant at ambient temperature.

4. Cryogenic refrigeration system (**1**) according to claim **1**, wherein the first heat exchanger (**5**) is thermally coupled to a load (**7**), said load (**7**) preferably comprising a refrigeration circuit (**70**) for a high temperature superconductor.

5. Cryogenic refrigeration system (**1**) according to claim **4**, said load (**7**) comprising a second cryogenic refrigerant, wherein said second cryogenic refrigerant preferably comprises liquid nitrogen.

6. Cryogenic refrigeration system (**1**) according to claim **1**, wherein at least the first and second heat exchanging sections (**6**A, **6**B) and/or the third and fourth heat exchanging sections (**6**C, **6**D) are arranged with respect to each other such that they provide counter flow, cross flow, or equal flow heat exchanging sections.

7. Cryogenic refrigeration system (**1**) according to claim **1**, wherein the compressor (**3**) and/or the supply means (**2**) are configured to provide the refrigerant to the first expansion device (**4**) is a liquid refrigerant, preferably also to the second expansion device (**40**).

8. Cryogenic refrigeration system (**1**) according to claim **1**, wherein the first expansion device (**4**) is configured to provide a two-phase or gas phase refrigerant; and wherein the first heat exchanger (**5**) is configured as a cold gas heat exchanger and wherein the first heat exchanger (**5**) is configured is to receive a gas phase from the cooled refrigerant (**22**).

9. Cryogenic refrigeration system (**1**) according to claim **1**, wherein the cryogenic refrigerant comprises helium and/or neon.

10. Cryogenic refrigeration system (**1**) according to claim **1**, wherein the system further comprises in evaporating heat exchanger (**8**A) arranged outside of the cold box (**10**) and upstream of the first expansion device (**4**), which is thermally coupled to the provided compressed cryogenic refrigerant supply flow to pre-cool said refrigerant, wherein the evaporating heat exchanger (**8**A) preferably comprises a liquid water circuit (**80**) as a refrigerant to be evaporated.

11. Cryogenic refrigeration system (**1**) according to claim **1**, wherein the system further comprises in evaporating heat exchanger (**8**B) arranged in the cold box (**10**) and upstream of the first expansion device (**4**), which is thermally coupled to the provided compressed cryogenic refrigerant supply flow to pre-cool said refrigerant, wherein the evaporating heat exchanger (**8**B) preferably comprises a liquid nitrogen circuit (**82**) as a refrigerant to be evaporated.

12. Method for providing a cryogenic refrigeration, comprising the steps of:

providing a supply flow of a cryogenic refrigerant with a supply means (**2**);

compressing the supplied cryogenic refrigerant with a compressor (**3**);

expanding the compressed cryogenic refrigerant (**20**) in a first expansion device (**4**) provided in a cold box (**10**), wherein the cold box is configured to be thermally coupled to a load (**7**); and

providing the expanded refrigerant (**22**) to a first heat exchanger (**5**) in the cold box (**10**)

wherein

the expanded refrigerant (**22**) is received from the expansion device (**4**) by a first heat exchanging section (**6**A) of a second heat exchanger (**6**) in the cold box (**10**) and is subsequently provided to the first heat exchanger (**5**);

the expanded refrigerant (**24**) from the first heat exchanger (**5**) is received by a second heat exchanging section (**6**B) of the second heat exchanger (**6**) and is subsequently provided to the first heat exchanger (**5**); and

wherein heat is exchanged between the first and second heat exchanger section (**6**A, **6**B) and wherein the expanded refrigerant (**24**) received by the first heat exchanger (**5**) from the second heat exchanging section (**6**B) is provided to the supply means (**2**) and/or the compressor (**3**).

13. Method according to claim **12**, wherein

the expanded refrigerant (**24**) received by the first heat exchanger (**5**) from the second heat exchanging section (**6**B) is received and expanded by a second expansion device (**40**), wherein the secondary expanded refrigerant (**26**) is provided to the first heat exchanger (**5**) via a third heat exchanging section (**6**C) of the second heat exchanger (**6**),

the secondary expanded refrigerant (**28**) from the first heat exchanger (**5**) is received by a fourth heat exchanging section (**6**D) of the second heat exchanger (**6**) and subsequently provided via the fourth heat exchanging section (**6**D) to the first heat exchanger (**5**), and

heat is exchanged between at least the third and fourth heat exchanger section (**6**C, **6**D).

14. Method according to claim **12**, wherein the supplied cryogenic refrigerant is compressed by a screw compressor, a turbo compressor, and/or at ambient temperature, wherein the cryogenic refrigerant preferably comprises helium and/or neon.

15. Method according to claim **12**, wherein the first heat exchanger (**5**) provides a cryogenic refrigeration of a thermally coupled load (**7**), said load (**7**) preferably comprising a refrigeration circuit (**70**) for a high-temperature superconductor, wherein preferably the load (**7**) comprises liquid nitrogen as a second cryogenic refrigerant.

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