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(54) COOLING SYSTEM FOR A DILUTION REFRIGERATOR SYSTEM

(57) This disclosure relates to a cooling system. The cooling system comprises one or more reservoirs for holding a cooling liquid. The cooling system also comprises a chiller system that is configured to cool the cooling liquid in the one or more reservoirs. Further, the cooling system comprises a first liquid transportation system, such as a first tube system, that is configured to accommodate a first flow of the cooling liquid from the one or more reservoirs to a helium pump configured to pump a He-3/He-4 mixture into a mixing chamber of a dilution refrigerator system so that the cooling liquid cools the helium pump. Additionally, the cooling system comprises a second liquid transportation system, such as a second tube system, that is configured to accommodate a second flow of the cooling liquid from the one or more reservoirs to a compressor of a cryocooler so that the cooling liquid cools the compressor. The cooling system further comprises a cooling liquid pump system that is configured to pump the cooling liquid from the one or more reservoirs to the to the helium pump herewith causing the first flow and configured to pump the cooling liquid from the one or more reservoirs to the compressor herewith causing the second flow.

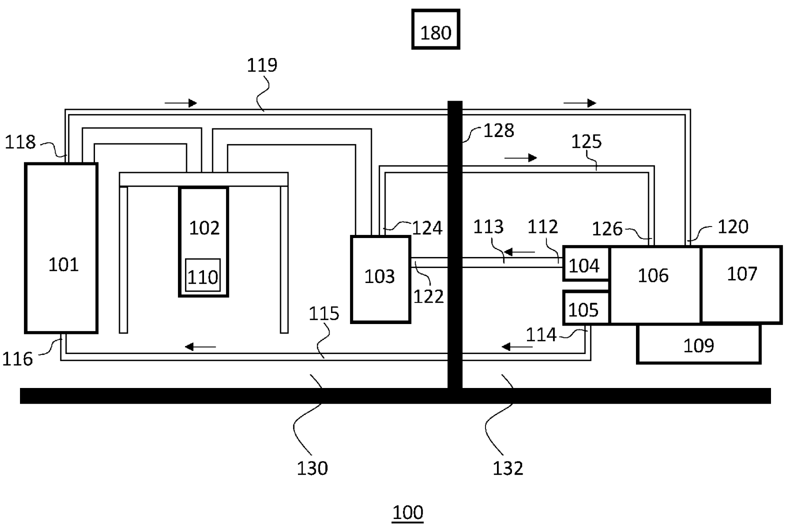

Fig. 1

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Description

Technical field

[0001] This disclosure generally relates to a cooling system for elements of a dilution refrigerator system, and in particular to a cooling system that comprises a cooling liquid pump system. This disclosure also relates to a dilution refrigerator system comprising such cooling system. Further, this disclosure relates to a computer-implemented method for controlling such cooling system, and to a computer-readable medium and computer program for such computer-implemented method.

Background

[0002] The operation of a modern quantum chip test system or quantum computer requires the processor to be cooled to ultra-low temperatures near absolute zero. Commercial dilution refrigerators cool the payload in two steps. In a first step, the payload is cooled to 4K using liquid He-4 or a He-4 close-cycle cryorefrigerator, which may be referred to more generically as a cryocooler. In a second step, the payload is cooled to the milliKelvin range by mixing He-3 and He-4 isotopes.

[0003] With dry dilution refrigerators, the first step is performed using a cryocooler. Typically, a pulse tube (PT) cooler is used as cryocooler. A cryocooler comprises a compressor that periodically compresses Helium gas. At one point in time, the gas is decompressed causing the gas to cool down allowing the cryocooler, at one heat exchanger, take on heat from the to-be-cooled surroundings. After decompression, the gas is displaced to the compressor after which it is compressed again causing the gas to heat up allowing the gas to, at another heat exchanger, transfer heat to the surroundings. The second step referred to above requires one or more pumps, typically turbopumps, that pump a He-3 / He-4 mixture to the mixing chamber of the dilution fridge.

[0004] The compressor of the cryocooler needs to be cooled using a flow of cooling liquid that can take on heat from said other heat exchanger. Further, the one or more helium pumps pumping the He-3 / He-4 mixture, also produce heat when they are in operation. Therefore, the one or more pumps are typically also cooled using a flow of cooling liquid.

[0005] In the state of the art, the cooling liquid for a dilution refrigerator system is typically provided by a rooftop water chiller system that can provide cold water to multiple rooms in the building, and thus to multiple dilution refrigerator systems in the building. Drawbacks of such a rooftop water chiller system are that installing such system is very cumbersome and that such system does not allow for energy efficient cooling of the typical components of a dilution refrigerator system, such as compressors of pulse tube coolers and turbopumps of gas handling systems.

[0006] Hence, there is a need in the art for an improved cooling system that alleviates at least some of these drawbacks.

Summary

[0007] To that end, a cooling system is disclosed. The cooling system comprises one or more reservoirs for holding a cooling liquid. The cooling system also comprises a chiller system that is configured to cool the cooling liquid in the one or more reservoirs. Further, the cooling system comprises a first liquid transportation system, such as a first tube system, that is configured to accommodate a first flow of the cooling liquid from the one or more reservoirs to a helium pump configured to pump a He-3/He-4 mixture into a mixing chamber of a dilution refrigerator system so that the cooling liquid cools the helium pump. Additionally, the cooling system comprises a second liquid transportation system, such as a second tube system, that is configured to accommodate a second flow of the cooling liquid from the one or more reservoirs to a compressor of a cryocooler so that the cooling liquid cools the compressor. The cooling system further comprises a cooling liquid pump system that is configured to pump the cooling liquid from the one or more reservoirs to the helium pump herewith causing the first flow and configured to pump the cooling liquid from the one or more reservoirs to the compressor herewith causing the second flow.

[0008] This cooling system is advantageous in that it can be embodied as a relatively small cooling system that can be placed locally at a dilution refrigerator system, also referred to as a dilution fridge. The one or more reservoirs and the cooling liquid pump system can for example be placed in a room next to the room where the dilution refrigerator stands. The cooling liquid pump system can simply pump the required cooling liquid to respectively the compressor and the helium pump. Hence, the need for a centralized water chiller system and reservoirs on top of rooftops is obviated. The cooling system opens up the possibility of installing dilution refrigerators in buildings without having to install a centralized cooling infrastructure in and on the building if such is lacking.

[0009] Due the cooling liquid pump system, the cooling system can be suitably implemented as a dedicated cooling system dedicated to a single dilution fridge. This eases the installation of a new dilution fridge. Connecting a new dilution fridge to a central water chiller system to which other dilution fridges are already connected, can be problematic. Installing the new dilution fridge can namely distort the cooling liquid flows to these other, already present, dilution fridges. Naturally, this problem does not occur when a dilution fridge is installed with its own, dedicated cooling system.

[0010] The cooling liquid is typically water, such as tap water, however, the cooling liquid may also be glycol-based coolants.

[0011] The chiller system may be configured to transfer heat from the cooling liquid sitting in the one or more reservoirs to the air surrounding the chiller system. In other words, the chiller system may be air-cooled. Further, if the one or more reservoirs comprise several reservoirs, then the chiller system may comprise a chiller subsystem, e.g. one, for each reservoir, wherein each chiller subsystem is configured to cool the cooling liquid in its associated reservoir.

[0012] A liquid transportation system referred to herein may simply consist of tubes and/or pipes through which the cooling liquid can flow to an intended position. The first liquid transportation system may be configured to, in particular, guide the first flow to a heat exchanger of the helium pump. Likewise, the second liquid transportation system may be configured to, in particular, guide the second flow to a heat exchanger of the cryocooler of compressor. The compressor itself may function as the heat exchanger.

[0013] The mixing chamber is a well-known part of a dilution refrigerator system and may be understood to refer to the space in which, during the so-called circulation stage, the phase boundary is present between the two phases of a helium-3 and helium-4 mixture. As known, during the circulation stage, helium-3 is pumped through this phase boundary which causes a cooling effect in the mixing chamber.

[0014] Of course, the cooling system may comprise more than one pump for pumping helium into the mixing chamber, e.g. two pumps. In such case, preferably, the first liquid transportation system guides the first flow to all these pumps. The helium pump that is configured to pump helium into the mixing chamber may be a turbopump. Further, it should be appreciated that the helium pumps referred to herein, may be part of a gas handling system (GHS) known in the art. The helium pump may be configured to pump approximately 400 litres of gaseous helium-3 per second.

[0015] As referred to herein, a cryocooler may be understood as a device that can cool an area to below 120 K. In an embodiment, the cryocooler is a pulse tube (PT) cryocooler.

[0016] In an embodiment, the one or more reservoirs contain between 50 and 200 litres of cooling liquid.

[0017] In an embodiment, the cooling system comprises a third liquid transportation system that is configured to accommodate a first return flow from the helium pump to the one or more reservoirs, and a fourth liquid transportation system that is configured to accommodate a second return flow from the compressor to the one or more reservoirs.

[0018] This embodiment is advantageous in that a closed-loop may be formed in which the cooling liquid circulates, from the one or more reservoirs to the compressor and/or pump, and then back to the one or more reservoirs again. This constitutes an efficient use of the cooling liquid.

[0019] Further, this embodiment for example enables that the temperature measurement of the cooling liquid in the one or more reservoirs can be used to prevent failure of the dilution refrigerator system. If the temperature of the cooling liquid in the one or more reservoirs becomes too high, then this may indicate that the chiller system cannot provide the cooling power that is required for keeping the temperature of the cooling liquid in the one or more reservoirs at a desired value. In such case, the required cooling power may be lowered by causing the helium pump to change its operating frequency and/or by causing the cryocooler to change its cooling power. Thus, the control system may be configured to perform steps of:

- determining that the temperature indicated by the first signal is higher than a threshold value temperature, and
- based on this determination, causing the helium pump to lower its operating frequency and/or causing the cryocooler to lower its cooling power.

[0020] In such embodiment, the temperature of the cooling liquid in the one or more reservoirs can serve as an indication how the dilution refrigerator system is functioning.

[0021] In an embodiment, the cooling liquid pump system is configured to separately control the first flow and second flow. In such embodiment, the cooling system may comprise a control system that is configured to control the cooling liquid pump system and to perform a step of:

- based on an indication that the helium pump is in operation or is going to be in operation, causing the cooling liquid pump system to pump the cooling liquid from the one or more reservoirs to the helium pump herewith causing the first flow, for example by causing the first cooling liquid pump referred to below to pump the cooling liquid from the one or more reservoirs to the helium pump herewith causing the first flow.

[0022] This embodiment is advantageous in that it provides for energy efficient cooling of the helium pump. The control system may ensure that the first flow is only present when the helium pump is (going to be) in operation. This prevents that energy is wasted for unnecessarily causing the first flow. For example, if the cooling liquid pump system comprises a first cooling liquid pump for causing the first flow and a second cooling liquid pump for causing the second flow, as described below, then the first cooling liquid pump may be controlled by the control system to only work in case the helium pump is in operation as well.

[0023] As referred to herein, a control system causing some device to perform one or more steps typically comprises the control system sending one or more control signals to the device.

[0024] The control system of the cooling system may for example receive a signal from the helium pump and/or from the gas handling system comprising the helium pump, in particular from a control system thereof, wherein this signal indicates that the helium pump is or is going to be in operation. In an example, the signal indicates an operational frequency of the helium pump. Then, based on the indicated operational frequency being higher than zero, the control system of the cooling system may cause the cooling liquid pump system to pump the cooling liquid from the one or more reservoirs to the helium pump.

[0025] Preferably, the control system, when it causes the cooling liquid pump system to pump the cooling liquid from the one or more reservoirs to the helium pump, the cooling liquid pump system is already pumping the cooling liquid from the one or more reservoirs to the cryocooler. After, all the helium pump are typically switched on only in the circulation stage, which follows the fast cooling stage and the condensation stage. In contrast, the cryocooler is typically in operation during all these stage.

[0026] In an embodiment in which the cooling system comprises a control system, which may be the control system referred to above, that is configured to control the first cooling liquid pump, the control system may be configured to perform a step of:

- based on an indication that the helium pump is not in operation or is going to operate at a lower operating frequency, e.g. is going to be switched off, causing the cooling liquid pump system to decrease a volumetric flow rate of the first flow, preferably to switch off, for example by causing the first cooling liquid pump referred to below to decrease the volumetric flow rate of the first flow, preferably to switch off.

[0027] This embodiment ensures that the first cooling liquid pump is only switched on if necessary.

[0028] The control system of the cooling system may for example receive a signal from the helium pump and/or from the gas handling system comprising the helium pump, in particular from a control system thereof, wherein this signal indicates that the helium pump is not in operation or is going to operate at a lower operating frequency. In an example, the signal indicates an operational frequency of the helium pump. Then, based on the indicated operational frequency being zero, the control system of the cooling system may cause the cooling liquid pump system to decrease the volumetric rate of the first flow.

[0029] In an embodiment, the cooling liquid pump system comprises a first cooling liquid pump that is configured to pump the cooling liquid from the one or more reservoirs to the helium pump herewith causing the first flow, and a second cooling liquid pump that is configured to pump the cooling liquid from the one or more reservoirs to the compressor herewith causing the second flow.

[0030] The separate cooling liquid pumps allow for separate and accurate control of the cooling liquid flows to the compressor and, respectively, the helium pump. To illustrate, if the helium pump is switched off, which is the case in the fast-cooling stage and the condensation stage, which will be explained in more detail below, the first cooling liquid pump can be switched off. After all, the helium pump does not produce heat so cooling it is not necessary. At the same time, the second cooling liquid pump can remain in operation, which is required for cooling the compressor of the cryocooler. The first cooling liquid pump can thus be switched on only when required, which constitutes an efficient use of resources, such as energy and cooling water.

[0031] Preferably, each of the first and second cooling liquid pump can be controlled, for example by the control system referred to below, in the sense that the volumetric flow rate of the flow caused by the cooling liquid pump can be controlled. Preferably, each cooling liquid pump can cause different flows having different volumetric flow rates. However, this is not per se required, because typically, for each of the compressor and the one or more pumps, a specific volumetric flow rate is defined at which the device in question is effectively cooled. To illustrate, a turbopump may require cooling with a flow having a volumetric flow rate of approximately 200 litres / hour, whereas the compressor of a pulse tube cryocooler may require a flow having a volumetric flow rate of approximately 700 litres / hour.

[0032] In an embodiment, the cooling system comprises a first temperature sensor for measuring a temperature of the cooling liquid in the one or more reservoirs. In such embodiment, the cooling system may comprise a control system, which may be any of the control systems referred to above, that is configured to control the chiller system and/or the helium pump and/or the cryocooler. The control system may then be configured to perform steps of:

- receiving a first signal from the first temperature sensor, the first signal being indicative of the temperature of the cooling liquid in the one or more reservoirs, and
- based on the temperature indicated by the first signal, causing the chiller system to change (decrease or increase) its cooling power and/or causing the helium pump to change (increase or decrease) its operating frequency and/or causing the cryocooler to change (increase or decrease) its cooling power.

[0033] The temperature of the cooling liquid in the one or more reservoirs is an important parameter. In an embodiment, the control system is configured to control the chiller system such that the cooling liquid in the one or more reservoirs has a predetermined temperature. To this end, the cooling system may comprise a feedback loop based on which the control system causes an increase of the cooling power of the chiller system if the temperature of the cooling liquid in the one or more reservoirs is higher than the predetermined temperature, and a decrease the cooling power of the chiller system if the temperature of the cooling liquid in the one or more reservoirs is lower than the predetermined temperature. Thus, the control system may be configured to perform steps of:

- comparing the temperature indicated by the first signal with a predetermined temperature, and
- based on the comparison, causing the chiller system to increase or decrease its cooling power.

[0034] In particular, the control system may be configured to perform steps of:

- determining that the temperature indicated by the first signal is higher or lower than the predetermined temperature, and
- based on this determination, causing the chiller system to increase or, respectively, decrease its cooling power.

[0035] This embodiment enables to keep the temperature of the cooling liquid in the one or more reservoirs, and thus the temperature of the cooling liquid that is pump into the first and second liquid transportation system constant, even when the temperature of the surroundings is varying and/or when the rate of heat generation by the system under test in the dilution fridge changes. The temperature of the surroundings may for example vary due to the day - night cycle.

[0036] The first temperature sensor may be positioned at the outlet of the reservoir, for example, or somewhere inside of the one or more reservoirs.

[0037] In an embodiment, the cooling system comprises a second temperature sensor that is configured to measure a temperature of the cooling liquid, in the second liquid transportation system, that is provided to the compressor. Additionally or alternatively, the cooling system comprises a third temperature sensor that is configured to measure a temperature of the cooling liquid, in the fourth liquid transportation system, that has been heated by the compressor. The second temperature sensor may be understood as configured to measure the temperature of the cooling liquid at a cooling liquid inlet of the compressor and the third temperature sensor may be understood as configured to measure the temperature of the cooling liquid at a cooling liquid outlet of the compressor. In such embodiment, the cooling system may comprise a control system, which may be any of the control systems referred to above, the control system being configured to control the cryocooler and to perform steps of:

- receiving a second signal from the second temperature sensor, the second signal being indicative of the temperature of the cooling liquid provided to the compressor, and/or
- receiving a third signal from the third temperature sensor, the third signal being indicative of the temperature of the cooling liquid that has been heated by the compressor, and
- based on the temperature indicated by the second signal and/or based on the temperature indicated by the third signal, causing the cryocooler to change, preferably lower, its cooling power.

[0038] This embodiment advantageously allows to prevent the cryocooler from overheating. Especially if the temperature as measured by the third temperature sensor exceeds some threshold temperature, then this may indicate that the compressor is heating up too much. If this happens, then the control system may cause the cryocooler to shut down.

[0039] In an embodiment, the cooling system comprises a fourth temperature sensor for measuring a temperature of the helium pump. In such embodiment, the cooling system may comprise a control system, which may be any of the control systems referred to above, the control system being configured to control the helium pump and to perform steps of:

- receiving, from the fourth temperature sensor, a fourth signal indicative of the temperature of the helium pump, and
- based on the indicated temperature of the helium pump, causing the helium pump to change, preferably lower, its operating frequency.

[0040] This embodiment advantageously allows to prevent the helium pump from overheating.

[0041] The fourth temperature sensor may be configured to measure the temperature of the helium pump by being configured to measure a temperature of cooling liquid that has been heated by the helium pump, in particular by a casing of the helium pump.

[0042] In an embodiment, the cooling system comprises a fifth temperature sensor that is configured to measure a temperature of air surrounding the chiller system. In such embodiment, the cooling system may comprise a control system, which may be any of the control systems referred to above, the control system being configured to control the helium pump and/or the cryocooler and/or the chiller system and to perform steps of:

- receiving a fifth signal from the fifth temperature sensor indicative of the temperature of the air surrounding the chiller system, and
- based on the temperature indicated by the fifth signal, causing the chiller system to change its cooling power and/or causing the helium pump to change its operating frequency and/or causing the cryocooler to change its cooling power.

[0043] This embodiment enables to prevent failures due to air surrounding the chiller system being too hot so that heat from the chiller system cannot be transferred effectively to the air. This embodiment may thus prevent the chiller system as well as the cooling liquid pump system, e.g. the first and second cooling liquid pumps, to overheat. This embodiment also enables to make the cooling system independent from seasonal temperature changes or changes in the heat generated by the quantum chip testing.

[0044] In such embodiment, the chiller system is preferably an air-cooled chiller system. The control system may compare the measured air temperature with a threshold temperature, such as 55 degrees Celsius, and cause the cryocooler to lower its cooling power if the measured air temperature is higher than this threshold temperature.

[0045] One aspect of this disclosure relates to a dilution refrigerator system comprising any of the cooling systems disclosed herein. Such dilution refrigerator system also comprises any of the helium pumps disclosed herein for pumping the helium mixture into the mixing chamber, and any of the cryocoolers disclosed herein.

[0046] Further aspects of this disclosure respectively relate to respective computer-implemented methods that comprise one or more of the steps that any of the control systems referred to herein can perform.

[0047] An aspect of this disclosure for example relates to a computer-implemented method for controlling any of the cooling systems disclosed herein. In this aspect, the method comprises causing, based on an indication that the helium pump is in operation or is going to be in operation, the cooling liquid pump system to pump the cooling liquid from the one or more reservoirs to the helium pump herewith causing the first flow. Such computer-implemented method provides for energy efficient cooling of the helium pump as explained above.

[0048] In an embodiment, this computer-implemented method comprises causing, based on an indication that the helium pump is not in operation or is going to operate at a lower operating frequency, e.g. is going to be switched off, the cooling liquid pump system to decrease a volumetric flow rate of the first flow, preferably to zero.

[0049] Thus, this embodiment may ensure that the cooling liquid pump system stops causing the first flow if the helium pump is (going to be) switched off.

[0050] In a further embodiment, this computer-implemented method comprises

- receiving a signal from the helium pump, the signal indicating that the helium pump is in operation or is going to be in operation, and/or
- receiving a further signal from the helium pump, the further signal indicating that the helium pump is not in operation or is going to operate at a lower operating frequency.

[0051] An aspect of this disclosure relates to a computer-implemented for controlling the chiller system and/or the helium pump and/or the cryocooler.

[0052] This computer-implemented method may comprise receiving a first signal from a first temperature sensor, the first signal being indicative of the temperature of the cooling liquid in the one or more reservoirs, and causing, based on the temperature indicated by the first signal, the chiller system to change its cooling power and/or causing the helium pump to change its operating frequency and/or causing the cryocooler to change its cooling power.

[0053] Additionally or alternatively, this computer-implemented method comprises receiving a second signal from a second temperature sensor, the second signal being indicative of the temperature of the cooling liquid provided to the compressor and/or receiving a third signal from a third temperature sensor, the third signal being indicative of the temperature of the cooling liquid that has been heated by the compressor, and causing, based on the temperature indicated by the second signal and/or based on the temperature indicated by the third signal, the cryocooler to change, preferably lower, its cooling power.

[0054] Additionally or alternatively, this computer implemented method comprises receiving, from a fourth temperature sensor, a fourth signal indicative of the temperature of the helium pump, and causing, based on the indicated temperature of the helium pump, the helium pump to change, preferably lower, its operating frequency.

[0055] Additionally or alternatively, this computer-implemented method comprises receiving a fifth signal from a fifth temperature sensor indicative of the temperature of the air surrounding the chiller system, and causing, based on the temperature indicated by the fifth signal, the chiller system to change its cooling power and/or causing the helium pump to change its operating frequency and/or causing the cryocooler to change its cooling power.

[0056] Any of the computer-implemented methods disclosed herein that comprise a step of controlling the chiller system, may comprise obtaining one or more measured parameter values of one or more respective parameters, the one or more parameters comprising

- the temperature of the cooling liquid in the one or more reservoirs, and/or
- the temperature of the cooling liquid, in the second liquid transportation system, that is provided to the compressor, and/or
- the temperature of the cooling liquid, in the fourth liquid transportation system, that has been heated by the compressor, and/or
- the temperature of the helium pump, and/or
- temperature of air surrounding the chiller system. Then, the method may comprise determining, based on the obtained parameter values, and based on a model associating sets of one or more parameter values to respective set values of the chiller system, a set value, preferably a temperature value, for the chiller system, and transmitting the determined set value to the chiller system so that the chiller system

will operate based on the set value, wherein

the model has been determined by

- obtaining training data, the training data respectively associating a plurality of previously measured parameter value sets with previous set values for the chiller system, each previously measured parameter value set comprising one or more previously measured parameter values of the respective one or more parameters, and
- constructing the model based on the training data using a machine learning method.

[0057] This embodiment is advantageous in that it allows for accurate, energy-efficient control of the chiller system. To illustrate, by determining the set value based on the model, it can be prevented that the temperature in the one or more reservoirs is cooled too fast resulting in lower temperatures than necessary.

[0058] The above disclosed computer-implemented methods may be suitably combined.

[0059] One aspect of this disclosure relates to a data processing system that is configured to perform any of the computer-implemented methods disclosed herein.

[0060] One aspect of this disclosure relates to a computer program or suite of computer programs comprising at least one software code portion the software code portion, when run on a computer, being configured for executing any of the computer-implemented methods disclosed herein.

[0061] The embodiments may also relate to a computer program or suite of computer programs comprising at least one software code portion the software code portion, when run on a computer, being configured for executing the method steps according any of claims.

[0062] As will be appreciated by one skilled in the art, aspects of the present invention may be embodied as a system, method or computer program product. Accordingly, aspects of the present invention may take the form of an entirely hardware embodiment, an entirely software embodiment (including firmware, resident software, micro-code, etc.) or an embodiment combining software and hardware aspects that may all generally be referred to herein as a "circuit," "module" or "system." Functions described in this disclosure may be implemented as an algorithm executed by a microprocessor of a computer. Furthermore, aspects of the present invention may take the form of a computer program product embodied in one or more computer readable medium(s) having computer readable program code embodied, e.g., stored, thereon.

[0063] Aspects of the present invention are described below with reference to flowchart illustrations and/or block diagrams of methods, apparatus (systems), and computer program products according to embodiments of the invention. It will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, can be implemented by computer program instructions. These computer program instructions may be provided to a processor, in particular a microprocessor or central processing unit (CPU), of a general purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer, other programmable data processing apparatus, or other devices create means for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks.

[0064] These computer program instructions may also be stored in a computer readable medium that can direct a computer, other programmable data processing apparatus, or other devices to function in a particular manner, such that the instructions stored in the computer readable medium produce an article of manufacture including instructions which implement the function/act specified in the flowchart and/or block diagram block or blocks.

[0065] The computer program instructions may also be loaded onto a computer, other programmable data processing apparatus, or other devices to cause a series of operational steps to be performed on the computer, other programmable apparatus or other devices to produce a computer implemented process such that the instructions which execute on the computer or other programmable apparatus provide processes for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks. Additionally, the Instructions may be executed by any type of processors, including but not limited to one or more digital signal processors (DSPs), general purpose microprocessors, application specific integrated circuits (ASICs), field programmable logic arrays (FPGAs), or other equivalent integrated or discrete logic circuitry.

[0066] The flowchart and block diagrams in the figures illustrate the architecture, functionality, and operation of possible implementations of systems, methods and computer program products according to various embodiments of the present invention. In this regard, each block in the flowchart or block diagrams may represent a module, segment, or portion of code, which comprises one or more executable instructions for implementing the specified logical function(s). It should also be noted that, in some alternative implementations, the functions noted in the blocks may occur out of the order noted in the figures. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that each block of the block diagrams and/or flowchart illustrations, and combinations of blocks in the block diagrams and/or flowchart illustrations, can be implemented by special purpose hardware-based systems that perform the specified functions or acts, or combinations of special purpose hardware and computer instructions.

Brief Description of the drawings

[0067]

Fig. 1 illustrates a dilution refrigerator system according to an embodiment comprising a cooling system according to an embodiment, wherein the cooling system comprises two cooling liquid pumps;
Fig. 2 illustrates a dilution refrigerator system according to an embodiment comprising a cooling system according to an embodiment, wherein the cooling system comprises a valve;
Fig. 3 shows three graphs indicating the time-course of parameters during different cooling stages;
Fig. 4 illustrates the data flow, according to an embodiment, between a control system and different devices and sensors;
Fig. 5 illustrates a method for determining a set value for the chiller system the method involving constructing a model;
Fig. 6 illustrates a data processing system according to an embodiment.

Description of the embodiments

[0068] In the figures, same reference numbers indicate the same or similar elements. Further, reference number that differ by 100 also indicate the same or similar elements.

[0069] Figure 1 schematically illustrates a dilution refrigerator system 100 according to an embodiment that may be used to test for example a quantum chip 110. As known, quantum chips should be tested at very low temperatures. Quantum chip test equipment to test superconducting quantum chips require a temperature of 20 mK or less. The depicted dilution refrigerator system 100 comprises a dilution refrigerator 102. Typically, such a dilution refrigerator is divided into several stages, wherein each stage is associated with a temperature range. The lowest temperature in the dilution fridge is in the so-called mixing chamber, where two phases of a He-3 / He-4 mixture are present. The dilution refrigerator system 100 comprises a gas handling system (GHS) 101 that comprises a plurality of, e.g. two, helium pumps (not shown). These helium pumps may be turbopumps. These helium pumps are configured to pump a He-3 / He-4 mixture to the mixing chamber of the dilution refrigerator 102. Such helium pumps may represent a heat load of approximately 0.4 kW per pump and, if water is used as cooling liquid, preferably a cooling liquid flow of 200 litres / hour is used, wherein the cooling liquid has a temperature between 15 - 35 degrees Celsius.

[0070] The dilution refrigerator system further comprises a cryocooler 103 that comprises a compressor (not shown). An important function of the cryocooler is to cool down the dilution refrigerator, in particular the mixing chamber, to a temperature of approximately 4 Kelvin.

[0071] As explained above, the helium pumps as well as the compressor of the cryocooler heat up when they are in operation. This heat should be dissipated and to this end the dilution refrigerator system 100 comprises a cooling system according to an embodiment. In figure 1, the cooling system comprises a reservoir 106 for holding cooling liquid, typically tap water. The cooling liquid in reservoir 106 is cooled by a chiller system 107, which may be air-cooled. The temperature of the cooling liquid in reservoir 106 is for example approximately between 1-27 degrees Celsius. A temperature sensor 109 is configured to measure the air surrounding the chiller system. The reservoir 106 may also function as a buffer in the sense that it can smooth out any peaks of heat loads.

[0072] Further, the cooling system comprises a first liquid transportation system and a second liquid transportation system. In figure 1, the first liquid transportation system is embodied as tubing 115 between an outlet 114 of the reservoir 106 and a cooling liquid inlet 116 of the gas handling system 101, and the second liquid transportation system is embodied as tubing 113 between a cooling liquid outlet 112 of the reservoir and a cooling liquid inlet 122 of the cryocooler 103. The tubing 115 is configured to accommodate a first flow of the cooling liquid from the reservoir 106 to the helium pumps of gas handling system 101. The arrows in the figure indicate the direction of flow of the cooling liquid. Tubing 113 is configured to accommodate a second flow from the reservoir 106 to the compressor of the cryocooler 103. These respective cooling liquid flows cool the helium pumps and, respectively, the compressor of the cryocooler.

[0073] In order to cause these flows, the cooling system also comprises a cooling liquid pump system that is configured to pump the cooling liquid out of reservoir 106 towards the helium pumps and the compressor. In other words, the cooling liquid pump system is configured to cause the first flow and the second flow. In particular, in figure 1, the cooling liquid pump system comprises a first cooling liquid pump 105 and a second cooling liquid pump 104. Herein, the first cooling liquid pump 105 is configured to pump cooling liquid from reservoir 106 to the helium pumps and the second cooling liquid pump is configured to pump cooling liquid from reservoir 106 to the compressor. In this example, the cooling liquid pump system can thus separately control the first flow and the second flow because the cooling liquid pump 104 and cooling liquid pump 105 can be separately controlled as well. The second flow of cooling liquid may be approximately five times larger than the first flow.

[0074] The cooling system of figure 1 also comprises a third liquid transportation system for accommodating a first return flow from the helium pumps to the reservoir 106. In figure 1, this third liquid transportation system is embodied as tubing 119 between an outlet of gas handling system 118 and the reservoir 106. Further, the depicted cooling system comprises a fourth liquid transportation system for accommodating a second return flow from the compressor of the cryocooler 103 to the reservoir 106. In figure 1, this fourth liquid transportation system is embodied as tubing 125 between the cryocooler 103 and the reservoir 106.

[0075] The depicted cooling system also comprises a control system 180. This control system, which may also be referred to as a data processing system, can control various devices of the dilution refrigerator system and of the cooling system in particular. The control system 180 is for example configured to control the cooling liquid pumps 104 and 105 by sending appropriate control signals to these pumps. Likewise, the control system 180 may be able to control the cryocooler 103 and/or the gas handling system 101, in particular the helium pumps thereof, and/or the chiller system 107 by sending appropriate control signals.

[0076] Figure 1 schematically shows two adjacent rooms within a building: a room 130 and a room 132 separated by a wall 128. Room 130 may be the room where the laboratory has been established for testing quantum chips. As shown, the reservoir 106 may be placed in room 132 next to it. Such a dilution refrigerator system 100 can thus be installed in any building, also in buildings that do not have an on-board water cooling system, for example.

[0077] Figure 2 schematically shows an embodiment of the cooling system. Herein, the cooling system does not comprise two cooling liquid pumps. Instead, in order to be able to separately control the first flow and the second flow, the cooling system comprises a single cooling liquid pump 204 and a valve 234. The cooling liquid pump 204 is configured to pump cooling liquid out of reservoir 206, out of the outlet 212. As can be seen, the flow that is created by cooling liquid pump 204 is divided into the first flow towards valve 234 and the second flow towards the cryocooler. By opening and closing of the valve 234, can the first flow be controlled separately from the first flow. Preferably, the valve 234 can be controlled by the control system 280. For example, the valve 234 may be an electromagnetic valve of which the state depends on control signals received from the control system 280.

[0078] Figure 3 shows the development of three parameters with respect to time (horizontal axis) during three subsequent stages of cooling a quantum chip to the mK regime. The graph on the top shows the cooling power of the chiller system, the middle graph indicates the total flow of cooling liquid out of the one or more reservoirs, and the bottom graph shows the temperature.

[0079] The horizontal axis is divided into three stages, namely the fast-cooling stage I, the condensation stage II, and the circulation stage III.

[0080] At the beginning of stage I, the entire system is at room temperature. In stage I, the cryocooler cools the dilution refrigerator system, in particular the mixing chamber of the dilution refrigerator system, down to approximately 4K. In this stage, the cryocooler is in operation, typically at maximum capacity, and the helium pumps of the gas handling system are not. The flow of cooling liquid in this stage, which is completely due to the second flow, is approximately 700 litres per hour. This is a typical volumetric flow rate for a cooling liquid flow cooling a compressor of a cryocooler. Further, the cooling power of the chiller system remains constant at 10 kW. The chiller system may operate based on a set temperature value. This may mean that the chiller system is trying to cool down the cooling liquid in the one or more reservoirs to this set temperature value. Of course, the warmer the return flow of the cooling liquid is, the more power the chiller system should consume to keep the cooling liquid in the reservoir at the set temperature value. Stage I typically takes approximately 62 hours.

[0081] At the end of stage I, the coldest part of the dilution refrigerator has reached a temperature of approximately 4K. As a result, an (already present) He-3 / He-4 mixture will start to condensate. This condensation marks the start of the stage II. In this stage, the mixing chamber fills with liquid helium and the temperature drops to 1 K. In this stage, the cooling power of the chiller system is lower than in stage I. However, the second flow remains the same (approximately 700 litres / hour).

[0082] Then, after approximately 8 hours, the gas handling system starts its helium pump(s) in order to start circulating He-3, which, as well-known in the art, cools down the mixing chamber and quantum chip even more, to the mK regime. In this stage, the helium pump(s) of the gas handling system also produce heat, which should be compensated in order to prevent distortions. Hence, in stage III, the cooling liquid pump system initiates the first flow (see the checkered part of the graph). The additional heat that is produced by the helium pump(s) also causes the cooling power of the chiller system to increase (see the hashed part of the graph). Note that the second flow is also used in stage III in order to cool the compressor of the cryocooler, which remains in operation throughout all three stages.

[0083] Figure 4 schematically illustrates, according to an embodiment, the data flow between the control system 480 and different sensors and devices.

[0084] In an embodiment, the cooling system comprises a temperature sensor for measuring the temperature of the cooling liquid that is provided to the compressor. In figure 1, such temperature sensor may be positioned at inlet 122, for example. Additionally or alternatively, the cooling system may comprise a temperature sensor for measuring the temperature of the cooling liquid that has been heated by the compressor or, in other words, that has cooled the compressor. Such temperature sensor may for example be positioned at cooling liquid outlet 124 (see figure 1). The control system 480 may then receive, as indicated in figure 4, from the cryocooler's cooling liquid inlet temperature sensor a signal "T_PT,!n" indicating the temperature it has measures and from the cryocooler's cooling liquid outlet temperature sensor a signal "T_PT, Out" indicating the temperature it has measured. The control system 480 may then, based on the temperature indicated by one or both of these signals, cause the cryocooler to change, preferably lower, its cooling power. This is indicate in figure 4 by the control system 480 sending a control signal "Set State" to the cryocooler 403. Figure 4 further shows that the cryocooler may send a signal "State" to the control system. This signal is indicative of a state of the cryocooler, e.g. indicating whether it is on or off and/or indicating its cooling power. Based on this signal, the control system 480 can send a control signal "Set_flow 2" to the second cooling liquid pump 404 in order to initiate the second flow.

[0085] Figure 4 also shows that the gas handling system may send a signal "F_pump" to the control system 480. This signal may indicate a current operational frequency of the helium pump(s) of the gas handling system 401. As such, this signal indicates whether the one or more helium pumps of the gas handling system are operation or not. Basedon this signal, the control system 480 may send a signal "Set_flow 1" to the first cooling liquid pump 405 in order to cause pump 405 to initiate or stop the first flow.

[0086] In an embodiment the cooling system comprises a temperature sensor for measuring a temperature of the one or more helium pumps. Figure 4 indicates that the temperature as measured by this sensor may be sent in a signal "T_turbopump" to the control system 480. Based on this temperature, the control system 480 can cause the helium pumps to change its operating frequency. If for example, the measured temperature is too high, then this may indicate that the pump is overheating and that a lower operating frequency is more appropriate.

[0087] In an embodiment, the cooling system comprises a temperature sensor for measuring a temperature of the cooling liquid in the one or more reservoirs 406. This measured temperature value may be sent to the control system 480 in a signal "T_Buffer". The control system 480 can then control any of the chiller system 407, the helium pump and the cryocooler based on the measured temperature of the cooling liquid in the one or more reservoirs 406.

[0088] The cooling system may also comprise a temperature sensor for measuring the temperature of the cooling liquid that the chiller system expels into the reservoir 406 (if the chiller system is indeed configured to do so). This temperature may be sent to the control system 480 in a signal "T_out".

[0089] In an embodiment, the cooling system comprises a temperature sensor for measuring a temperature of air surrounding the chiller system. This measured temperature may be sent to the control system 480 in signal "T_Air". The control system 480 can then control any of the chiller system 407, the helium pump and the cryocooler based on the measured temperature of the air surrounding the chiller system.

[0090] Figure 5 illustrates a sophisticated method for determining a set temperature value for the chiller system. This method involves constructing a model that associates sets of one or more parameter values to respective set values of the chiller system. When this model is used, input into this model are parameter values of parameters like

- the temperature of the cooling liquid in the one or more reservoirs, and/or
- the temperature of the cooling liquid, in the second liquid transportation system, that is provided to the compressor, and/or
- the temperature of the cooling liquid, in the fourth liquid transportation system, that has been heated by the compressor, and/or
- the temperature of the helium pump, and/or
- temperature of air surrounding the chiller system.

[0091] Output out of this model would then be a set value that can be transmitted to the chiller system so that the chiller system can operate based on the set value.

[0092] It should be appreciated that the parameter values that are input into the model may span, for each parameter, a certain time period, for example fifteen minutes. The behavior of the system may thus be monitored for some time before a set value is determined for the chiller system.

[0093] Figure 5 illustrates how such model can be determined and continuously improved. In step 542, training data is used to construct the model. The training data would typically comprise historical, actually measured data. To illustrate, the training data may comprise the parameter values for all above-mentioned parameters and the set value for the chiller system at any given point in time during many experiments. Machine learning methods known in the art, such as machine learning methods using regression techniques, may then be used to construct the model. The model then allows to, given a certain set of parameter values, predict how these parameter values will develop if the set value for the chiller system is changed in some way.

[0094] Indeed, in step 544, the model is used to, based on measured parameter values, determine an appropriate set value for the chiller system, which is transmitted to the chiller system in step 546. Preferably, the determined set value is such that the cooling system works efficiently, for example in the sense that the cooling liquid in the one or more reservoirs is not cooled too fast (no overshoot).

[0095] After, the set value has been communicated to the chiller system, the parameters are measured again. It should be appreciated that the parameters are preferably measured continuously. The measured values may then be used when step 544 is performed again.

[0096] As part of determining the set value in step 544, it was predicted how the values of the different parameters would develop. In fact, the set value that is selected in step 544 is selected because it is expected to cause the parameters to develop in a desired way. Hence, predicted parameter values are also output from step 544.

[0097] In step 550, the measured, actual parameter values of the parameters are compared with the predicted values in order to test the accuracy of the model. If the model turns out to be inaccurate, the error can be taken into account when step 542 is reperformed in order to improve the model.

[0098] Fig. 6 depicts a block diagram illustrating a data processing system according to an embodiment. This data processing system may represent any of the control systems referred to herein.

[0099] As shown in Fig. 6, the data processing system 680 may include at least one processor 682 coupled to memory elements 688 through a system bus 697. As such, the data processing system may store program code within memory elements 688.

[0100] Further, the processor 680 may execute the program code accessed from the memory elements 688 via a system bus 697. In one aspect, the data processing system may be implemented as a computer that is suitable for storing and/or executing program code. It should be appreciated, however, that the data processing system 680 may be implemented in the form of any system including a processor and a memory that is capable of performing the functions described within this specification.

[0101] The memory elements 688 may include one or more physical memory devices such as, for example, local memory 689 and one or more bulk storage devices 692. The local memory may refer to random access memory or other non-persistent memory device (s) generally used during actual execution of the program code. A bulk storage device may be implemented as a hard drive or other persistent data storage device. The processing system 680 may also include one or more cache memories (not shown) that provide temporary storage of at least some program code in order to reduce the number of times program code must be retrieved from the bulk storage device 692 during execution.

[0102] Input/output (I/O) devices depicted as an input device 694 and an output device 695 optionally can be coupled to the data processing system. Examples of input devices may include, but are not limited to, a keyboard, a pointing device such as a mouse, any of the sensors described herein, or the like. Examples of output devices may include, but are not limited to, a monitor or a display, speakers, cryocoolers, gas handling systems, helium pumps, chiller systems, cooling liquid pump system, cooling liquid pumps, or the like. Input and/or output devices may be coupled to the data processing system either directly or through intervening I/O controllers.

[0103] In an embodiment, the input and the output devices may be implemented as a combined input/output device (illustrated in Fig. 6 with a dashed line surrounding the input device 694 and the output device 695) . An example of such a combined device is a touch sensitive display, also sometimes referred to as a "touch screen display" or simply "touch screen". In such an embodiment, input to the device may be provided by a movement of a physical object, such as e.g. a stylus or a finger of a user, on or near the touch screen display.

[0104] A network adapter 696 may also be coupled to the data processing system to enable it to become coupled to other systems, computer systems, remote network devices, and/or remote storage devices through intervening private or public networks. The network adapter may comprise a data receiver for receiving data that is transmitted by said systems, devices and/or networks to the data processing system 680, and a data transmitter for transmitting data from the data processing system 680 to said systems, devices and/or networks. Modems, cable modems, and Ethernet cards are examples of different types of network adapter that may be used with the data processing system 680.

[0105] As pictured in Fig. 6, the memory elements 688 may store an application 690. In various embodiments, the application 690 may be stored in the local memory 689, the one or more bulk storage devices 692, or apart from the local memory and the bulk storage devices. It should be appreciated that the data processing system 680 may further execute an operating system (not shown in Fig. 6) that can facilitate execution of the application 690. The application 690, being implemented in the form of executable program code, can be executed by the data processing system 680, e.g., by the processor 680. Responsive to executing the application, the data processing system 680 may be configured to perform one or more operations or method steps described herein.

[0106] Various embodiments of the invention may be implemented as a program product for use with a computer system, where the program(s) of the program product define functions of the embodiments (including the methods described herein). In one embodiment, the program(s) can be contained on a variety of non-transitory computer-readable storage media, where, as used herein, the expression "non-transitory computer readable storage media" comprises all computer-readable media, with the sole exception being a transitory, propagating signal. In another embodiment, the program(s) can be contained on a variety of transitory computer-readable storage media.

[0107] Illustrative computer-readable storage media include, but are not limited to: (i) non-writable storage media (e.g., read only memory devices within a computer such as CD-ROM disks readable by a CD-ROM drive, ROM chips or any type of solid- state nonvolatile semiconductor memory) on which information is permanently stored; and (ii) writable storage media (e.g., flash memory, floppy disks within a diskette drive or hard disk drive or any type of solid-state random-access semiconductor memory) on which alterable information is stored. The computer program may be run on the processor 682 described herein.

[0108] The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting. As used herein, the singular forms "a," "an," and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises" and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[0109] The corresponding structures, materials, acts, and equivalents of all means or step plus function elements in the claims below are intended to include any structure, material, or act for performing the function in combination with other claimed elements as specifically claimed. The description of the present invention has been presented for purposes of illustration and description, but is not intended to be exhaustive or limited to the invention in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the invention. The embodiment was chosen and described in order to best explain the principles of the invention and the practical application, and to enable others of ordinary skill in the art to understand the invention for various embodiments.

Claims

1. A cooling system comprising

one or more reservoirs for holding a cooling liquid, and
a chiller system that is configured to cool the cooling liquid in the one or more reservoirs, and
a first liquid transportation system, such as a first tube system, that is configured to accommodate a first flow of the cooling liquid from the one or more reservoirs to a helium pump configured to pump a He-3/He-4 mixture into a mixing chamber of a dilution refrigerator system so that the cooling liquid cools the helium pump, and
a second liquid transportation system, such as a second tube system, that is configured to accommodate a second flow of the cooling liquid from the one or more reservoirs to a compressor of a cryocooler so that the cooling liquid cools the compressor, and
a cooling liquid pump system that is configured to pump the cooling liquid from the one or more reservoirs to the helium pump herewith causing the first flow and configured to pump the cooling liquid from the one or more reservoirs to the compressor herewith causing the second flow.

2. A dilution refrigerator system comprising

the helium pump defined in claim 1, and
the cryocooler comprising the compressor defined in claim 1, and
a cooling system according to claim 1.

3. The dilution refrigerator system according to claim 2, wherein the cooling system comprises

a third liquid transportation system that is configured to accommodate a first return flow from the helium pump to the one or more reservoirs, and
a fourth liquid transportation system that is configured to accommodate a second return flow from the compressor to the one or more reservoirs.

4. The dilution refrigerator system according to any of the preceding claims 2-3, wherein

wherein the cooling liquid pump system is configured to separately control the first flow and second flow, and wherein
the cooling system comprises a control system, the control system being configured to control the cooling liquid pump system and to perform a step of:

- based on an indication that the helium pump is in operation or is going to be in operation, causing the cooling liquid pump system to pump the cooling liquid from the one or more reservoirs to the helium pump herewith causing the first flow.

5. The dilution refrigerator system according to any of the preceding claims 2-4, comprising a or the control system, the control system being configured to perform a step of:

- based on an indication that the helium pump is not in operation or is going to operate at a lower operating frequency, e.g. is going to be switched off, causing the cooling liquid pump system to decrease a volumetric flow rate of the first flow, preferably to switch off.

6. The dilution refrigerator system according to any of the preceding claims 2-5, wherein the cooling liquid pump system comprises

a first cooling liquid pump that is configured to pump the cooling liquid from the one or more reservoirs to the helium pump herewith causing the first flow, and
a second cooling liquid pump that is configured to pump the cooling liquid from the one or more reservoirs to the compressor herewith causing the second flow.

7. The dilution refrigerator system according to any of the preceding claims 2-6, wherein the cooling system comprises

a first temperature sensor for measuring a temperature of the cooling liquid in the one or more reservoirs, and
a or the control system, the control system being configured to control the chiller system and/or the helium pump and/or the cryocooler, wherein the control system is configured to perform steps of:

- receiving a first signal from the first temperature sensor, the first signal being indicative of the temperature of the cooling liquid in the one or more reservoirs, and
- based on the temperature indicated by the first signal, causing the chiller system to change its cooling power and/or causing the helium pump to change its operating frequency and/or causing the cryocooler to change its cooling power.

8. The dilution refrigerator according to any of the preceding claims 2-7, wherein the cooling system comprises

a second temperature sensor that is configured to measure a temperature of the cooling liquid, in the second liquid transportation system, that is provided to the compressor, and/or
a third temperature sensor that is configured to measure a temperature of the cooling liquid, in the fourth liquid transportation system, that has been heated by the compressor, and
a or the control system, the control system being configured to control the cryocooler and to perform steps of:

- receiving a second signal from the second temperature sensor, the second signal being indicative of the temperature of the cooling liquid provided to the compressor, and/or
- receiving a third signal from the third temperature sensor, the third signal being indicative of the temperature of the cooling liquid that has been heated by the compressor, and
- based on the temperature indicated by the second signal and/or based on the temperature indicated by the third signal, causing the cryocooler to change, preferably lower, its cooling power.

9. The dilution refrigerator system according to any of the preceding claims 2-8, wherein the cooling system comprises

a fourth temperature sensor for measuring a temperature of the helium pump, and
a or the control system, the control system being configured to control the helium pump and to perform steps of:

- receiving, from the fourth temperature sensor, a fourth signal indicative of the temperature of the helium pump, and
- based on the indicated temperature of the helium pump, causing the helium pump to change, preferably lower, its operating frequency.

10. The dilution refrigerator system according to any of the preceding claims 2-9, wherein the cooling system comprises

a fifth temperature sensor that is configured to measure a temperature of air surrounding the chiller system, and
a or the control system, the control system being configured to control the helium pump and/or the cryocooler and/or the chiller system and to perform steps of:

- receiving a fifth signal from the fifth temperature sensor indicative of the temperature of the air surrounding the chiller system, and
- based on the temperature indicated by the fifth signal, causing the chiller system to change its cooling power and/or causing the helium pump to change its operating frequency and/or causing the cryocooler to change its cooling power.

11. A computer-implemented method for controlling a cooling system, wherein
the cooling system comprises one or more reservoirs for holding a cooling liquid, and a chiller system that is configured to cool the cooling liquid in the one or more reservoirs, and a first liquid transportation system, such as a first tube system, that is configured to accommodate a first flow of the cooling liquid from the one or more reservoirs to a helium pump configured to pump a He-3/He-4 mixture into a mixing chamber of a dilution refrigerator system so that the cooling liquid cools the helium pump, and comprises a second liquid transportation system, such as a second tube system, that is configured to accommodate a second flow of the cooling liquid from the one or more reservoirs to a compressor of a cryocooler so that the cooling liquid cools the compressor, and comprises a cooling liquid pump system that is configured to pump the cooling liquid from the one or more reservoirs to the helium pump herewith causing the first flow and configured to pump the cooling liquid from the one or more reservoirs to the compressor herewith causing the second flow, wherein the

cooling liquid pump system is configured to separately control the first flow and second flow, the computer-implemented method comprising

- based on an indication that the helium pump is in operation or is going to be in operation, causing the cooling liquid pump system to pump the cooling liquid from the one or more reservoirs to the helium pump herewith causing the first flow.

12. The computer-implemented method according to claim 11, further comprising

- based on an indication that the helium pump is not in operation or is going to operate at a lower operating frequency, e.g. is going to be switched off, causing the cooling liquid pump system to decrease a volumetric flow rate of the first flow, preferably to zero.

13. The computer-implemented method according to claim 11 or 12, further comprising

- receiving a signal from the helium pump, the signal indicating that the helium pump is in operation or is going to be in operation, and/or
- receiving a further signal from the helium pump, the further signal indicating that the helium pump is not in operation or is going to operate at a lower operating frequency.

14. The computer-implemented method according to any of the preceding claims 11-13, wherein

the cooling system comprises a first temperature sensor for measuring a temperature of the cooling liquid in the one or more reservoirs, and the computer-implemented method comprises receiving a first signal from the first temperature sensor, the first signal being indicative of the temperature of the cooling liquid in the one or more reservoirs, and causing, based on the temperature indicated by the first signal, the chiller system to change its cooling power and/or causing the helium pump to change its operating frequency and/or causing the cryocooler to change its cooling power,
and/or wherein
the cooling system comprises a second temperature sensor that is configured to measure a temperature of the cooling liquid, in the second liquid transportation system, that is provided to the compressor, and/or comprises a third temperature sensor that is configured to measure a temperature of the cooling liquid, in the fourth liquid transportation system, that has been heated by the compressor, and the computer-implemented method comprises receiving a second signal from the second temperature sensor, the second signal being indicative of the temperature of the cooling liquid provided to the compressor and/or receiving a third signal from the third temperature sensor, the third signal being indicative of the temperature of the cooling liquid that has been heated by the compressor, and causing, based on the temperature indicated by the second signal and/or based on the temperature indicated by the third signal, the cryocooler to change, preferably lower, its cooling power,
and/or wherein
the cooling system comprises a fourth temperature sensor for measuring a temperature of the helium pump, and the computer-implemented method comprises receiving, from the fourth temperature sensor, a fourth signal indicative of the temperature of the helium pump, and causing, based on the indicated temperature of the helium pump, the helium pump to change, preferably lower, its operating frequency,
and/or wherein
the cooling system comprises a fifth temperature sensor that is configured to measure a temperature of air surrounding the chiller system, and the computer-implemented method comprises receiving a fifth signal from the fifth temperature sensor indicative of the temperature of the air surrounding the chiller system, and causing, based on the temperature indicated by the fifth signal, the chiller system to change its cooling power and/or causing the helium pump to change its operating frequency and/or causing the cryocooler to change its cooling power.

15. The computer-implemented method according to any of the preceding claims 11-14, further comprising

obtaining one or more measured parameter values of one or more respective parameters, the one or more parameters comprising

- the temperature of the cooling liquid in the one or more reservoirs, and/or
- the temperature of the cooling liquid, in the second liquid transportation system, that is provided to the compressor, and/or
- the temperature of the cooling liquid, in the fourth liquid transportation system, that has been heated by the compressor, and/or
- the temperature of the helium pump, and/or
- temperature of air surrounding the chiller system, the method comprising

based on the obtained parameter values, and based on a model associating sets of one or more parameter values to respective set values of the chiller system, determining a set value, preferably a set temperature value, for the chiller system, and

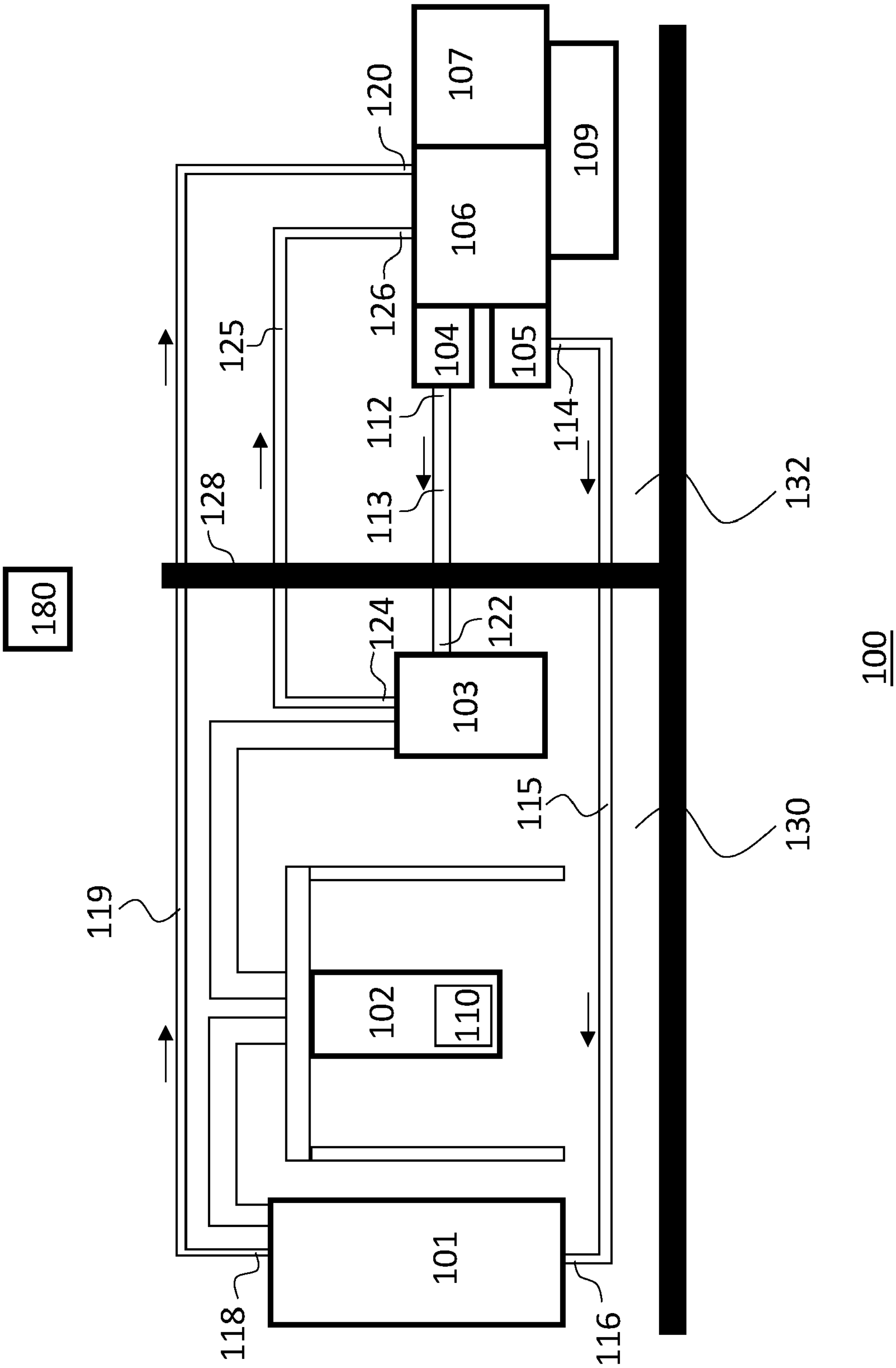
transmitting the determined set value to the chiller system so that the chiller system will operate based on the set value, wherein

the model has been determined by

- obtaining training data, the training data respectively associating a plurality of previously measured parameter value sets with previous set values for the chiller system, each previously measured parameter value set comprising one or more previously measured parameter values of the respective one or more parameters, and
- constructing the model based on the training data using a machine learning method.

16. A data processing system that is configured to perform the computer-implemented method according to any of the preceding claims 11-15.

17. A computer program or suite of computer programs comprising at least one software code portion the software code portion, when run on a computer, being configured for executing the computer-implemented method according any of claims 11 - 15.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126
125
104
105
112
114
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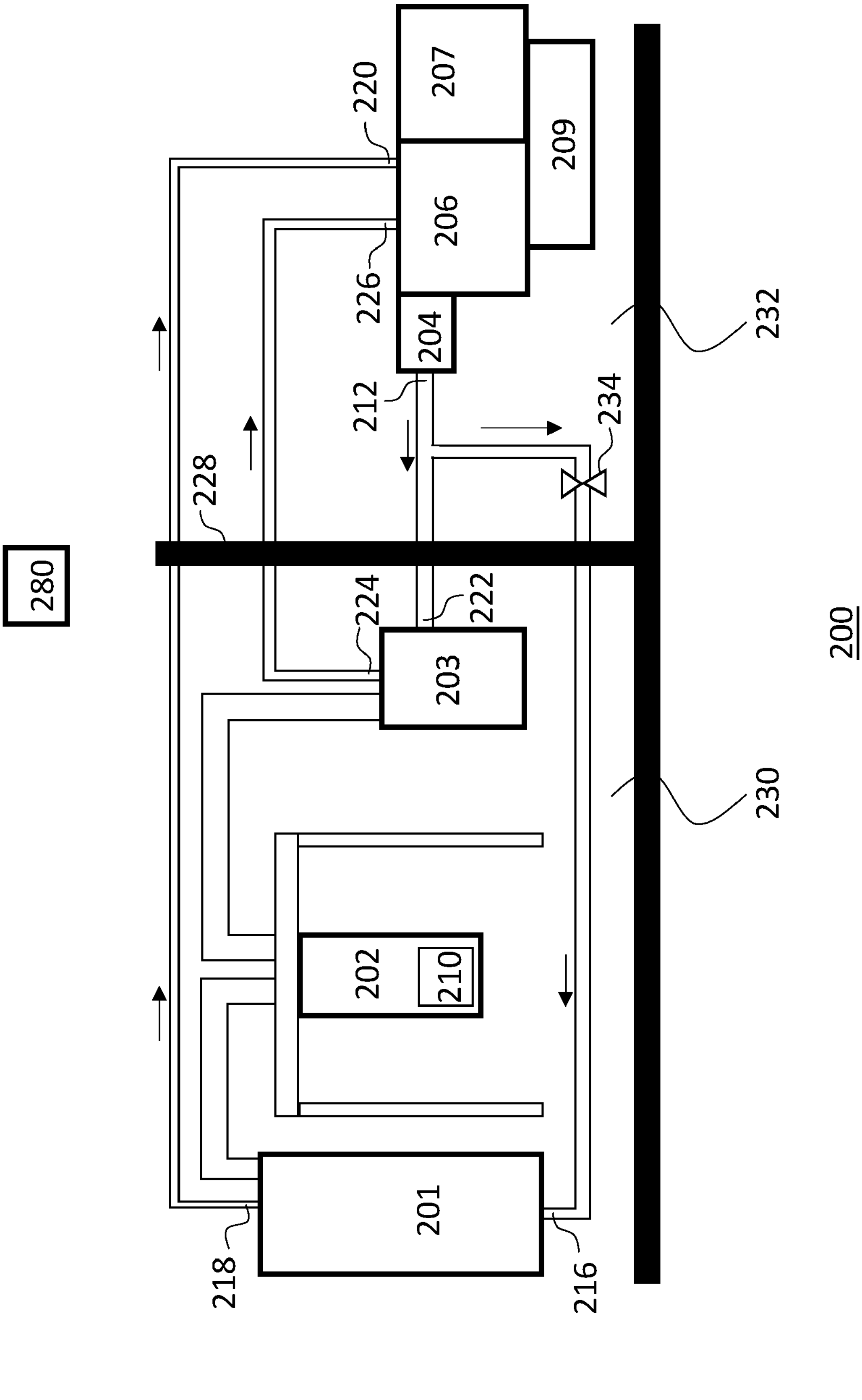
119
102
110
101
118
116

Fig. 1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200

Fig. 2

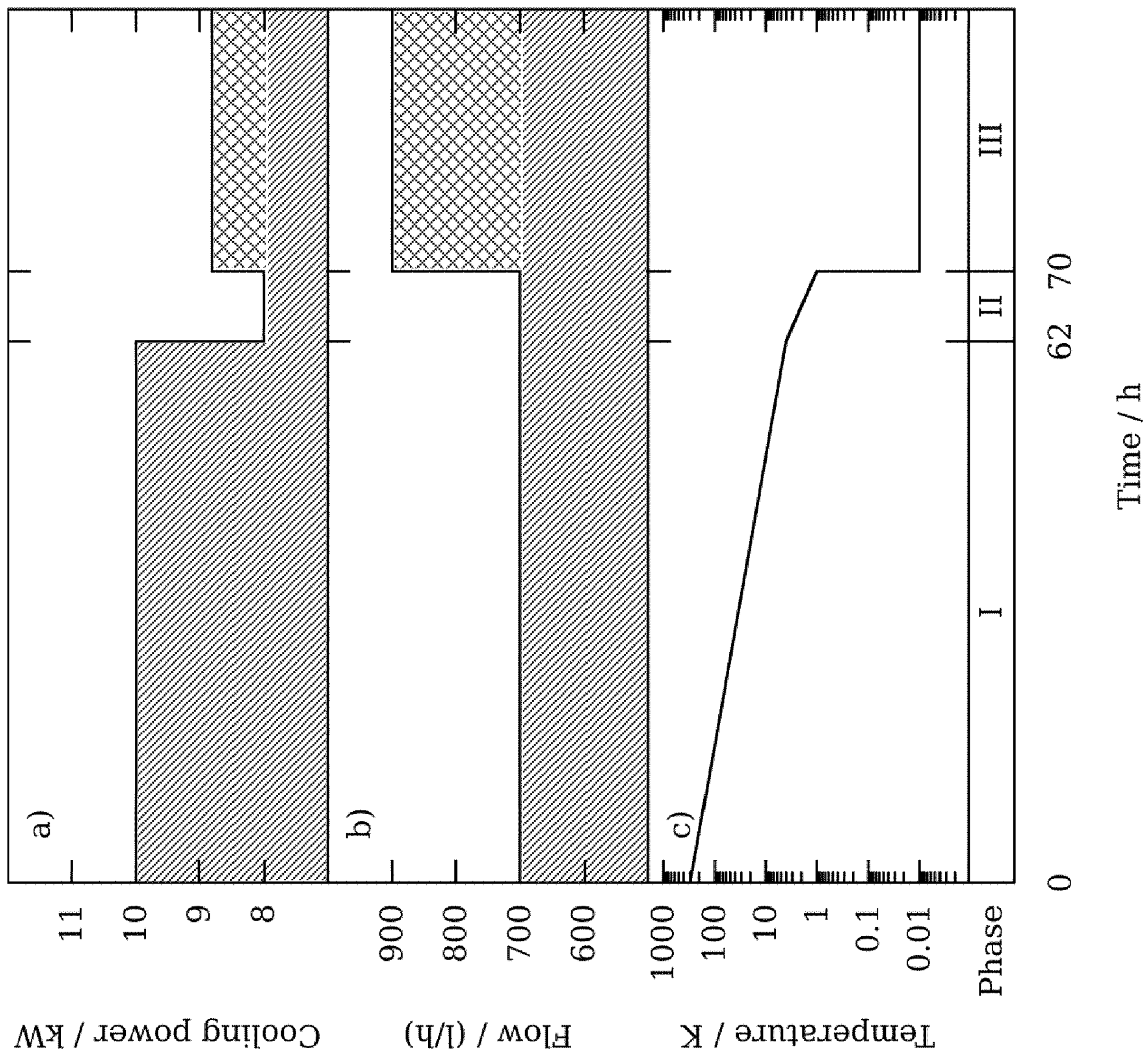
Cooling power / kW
11
10
9
8
Flow / (l/h)
900
800
700
600
Temperature / K
1000
100
10
1
0.1
0.01
Phase
a)
b)
c)
I
II
III
0
62
70
Time / h

Fig. 3

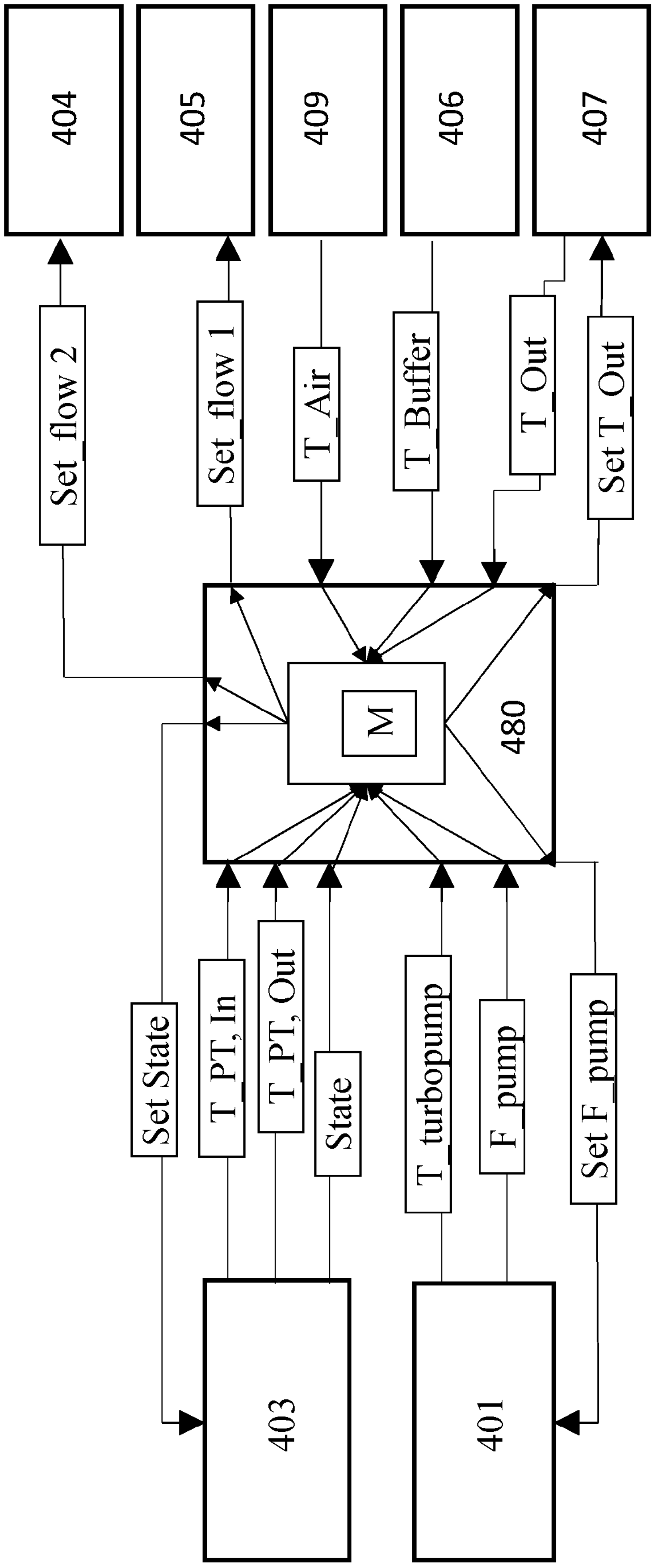
404
405
409
406
407
Set_flow 2
Set_flow 1
T_Air
T_Buffer
T_Out
Set T_Out
480
M
Set State
T_PT, In
T_PT, Out
State
T_turbopump
F_pump
Set F_pump
403
401

Fig. 4

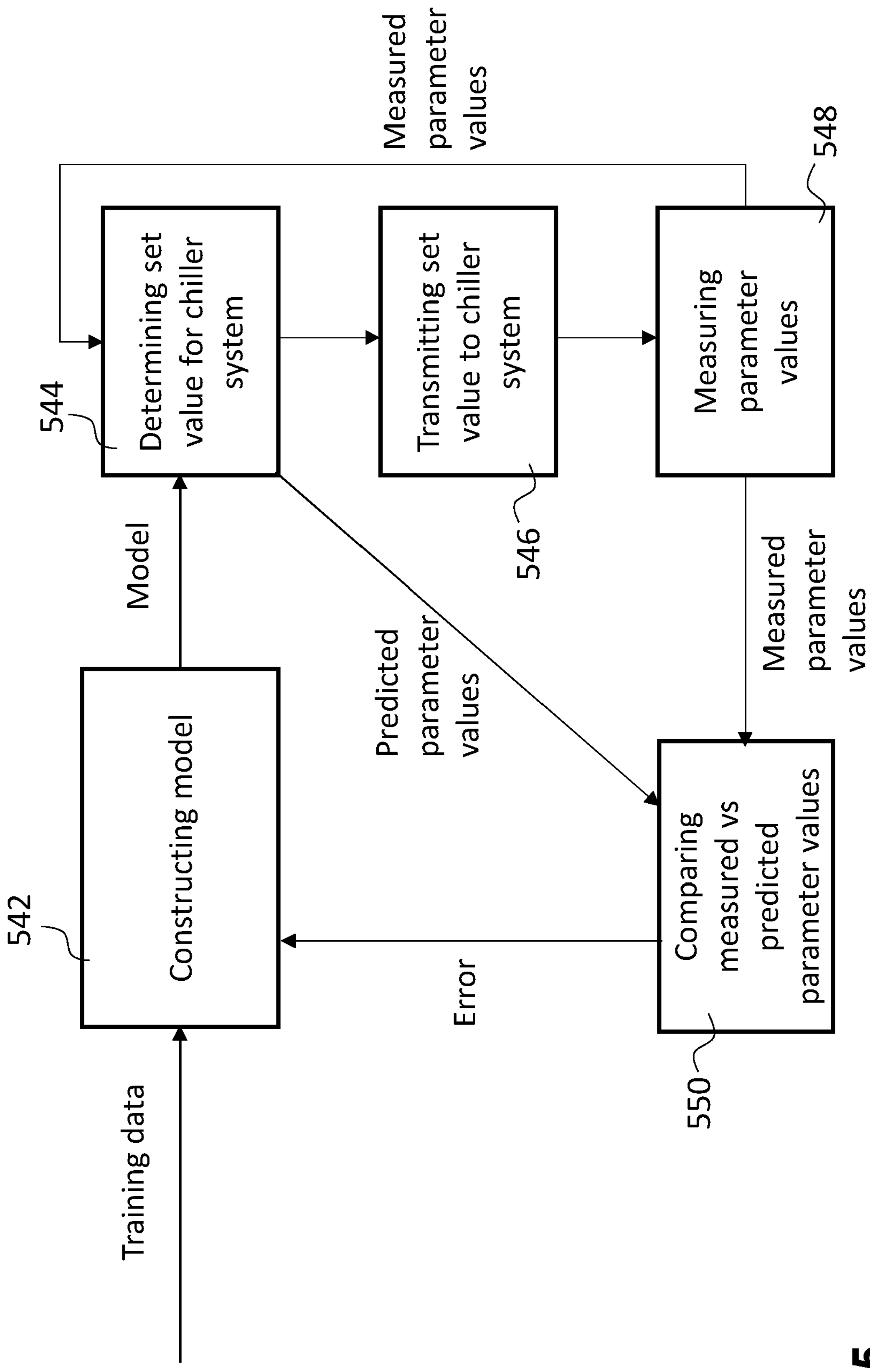
Training data
Constructing model
542
Model
Determining set value for chiller system
544
Predicted parameter values
Transmitting set value to chiller system
546
Measuring parameter values
548
Measured parameter values
Measured parameter values
Comparing measured vs predicted parameter values
550
Error

Fig. 5

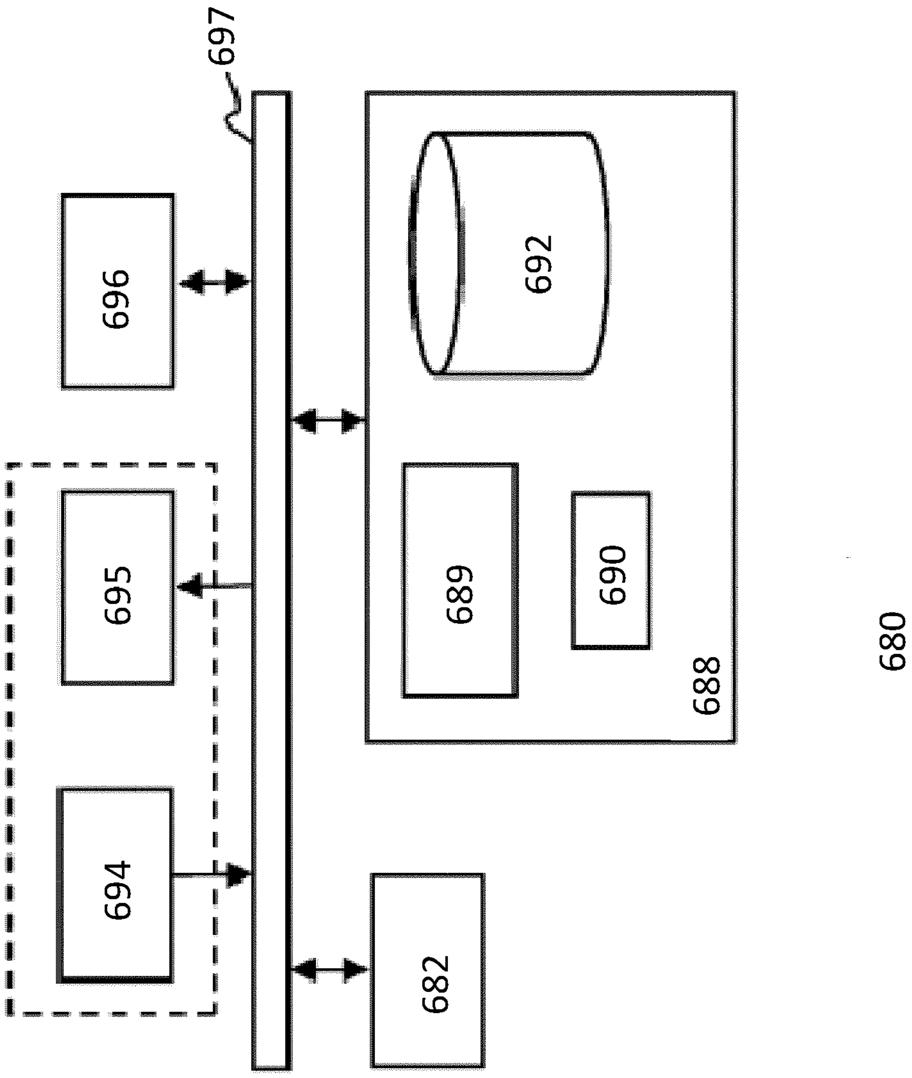

Fig. 6

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EUROPEAN SEARCH REPORT

Application Number
EP 23 21 6732

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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
The Hague	25 March 2024	de Graaf, Jan Douwe

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Place of search	Date of completion of the search	Examiner
The Hague	25 March 2024	de Graaf, Jan Douwe

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