



(51) International Patent Classification:
F25B 41/00 (2006.01)

(21) International Application Number:
PCT/EP2010/050161

(22) International Filing Date:
8 January 2010 (08.01.2010)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
0900268.4 8 January 2009 (08.01.2009) GB

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(81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,

AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ,
CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO,
DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,
HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP,
KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD,
ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI,
NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD,
SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR,
TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every
kind of regional protection available): ARIPO (BW, GH,
GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM,
ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ,
TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE,
ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV,
MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, SM,
TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW,
ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— of inventorship (Rule 4.17(iv))

Published:

— without international search report and to be republished
upon receipt of that report (Rule 48.2(g))

(54) Title: COOLING APPARATUS AND METHOD

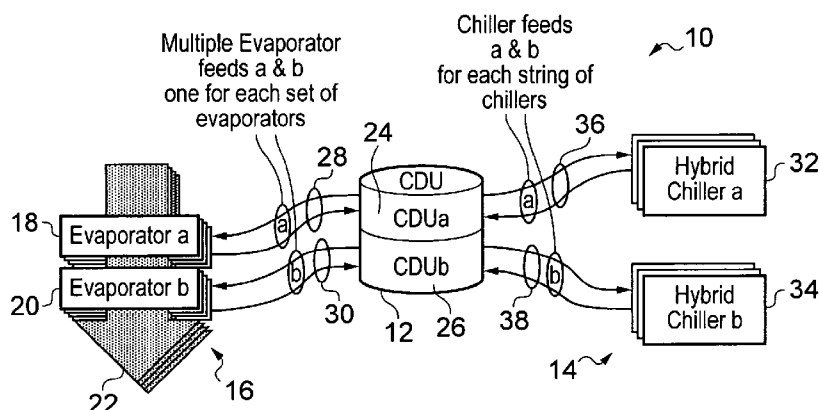


FIG. 1

(57) Abstract: Cooling apparatus providing two independent heat exchangers (18, 20) serially arranged with respect to a heat flow (42), each heat exchanger being connected to a respective independent chiller (32, 34). The apparatus incorporates an element of redundancy in order to effect an increase in operational efficiency, by being switchable between a first operation mode in which both chillers operate in a free cooling mode and a second operation mode in which a first chiller operates in a free cooling mode and a second chiller operates in a forced cooling mode.

COOLING APPARATUS AND METHOD**FIELD OF THE INVENTION**

5 This invention relates to cooling equipment, e.g. for air
conditioners, electrical appliances or the like, in which
fluid coolant is circulated between a absorbing region where
it absorbs energy from the surrounding environment and a
cooling region where it emits energy to the surrounding
10 environment.

BACKGROUND OF THE INVENTION

15 Electrical appliances, e.g. televisions, PCs, servers and
the like, emit heating during operation. In the case of
information technology (IT) equipment it is often necessary
for operation to be continuous. Problems, e.g. malfunction,
may occur if the equipment overheats, so it is important to
control the temperature of the surrounding environment.

20 Air conditioning may be used to control the temperature
of a space, e.g. room, warehouse or the like, that contained
heat generating equipment. Conventional air conditioning
apparatus operates to cool air, which is subsequently
circulated in the space to control the temperature.

SUMMARY OF THE INVENTION

25 At its most general, the invention provides cooling
apparatus which incorporates an element of redundancy in order
30 to effect an increase in operational efficiency. Put simply,
the invention involves providing two (or more) independent
heat exchangers which are serially arranged with respect to a
heat flow and operate to extract the full benefit of free
cooling.

35 The invention also proposes targeted cooling, i.e.
locating heat exchangers at heat sources to provide localised
cooling rather than global cooling seen in conventional air
conditioners.

40 In a development of the targeted cooling concept, the
invention may also provide a scalable cooling apparatus,
whereby the same principles may be used to build cooling

systems on widely varying scales.

According to one aspect of the invention there may be provided apparatus for cooling heat flow from a heat source, the apparatus comprising: a first heat exchanger and a second heat exchanger arranged serially to receive the heat flow, the first heat exchanger being closer to the heat source than the second heat exchanger, each heat exchanger being connected to a respective coolant distribution circuit arranged to transfer coolant through its heat exchanger; and a first chiller and a second chiller for cooling the coolant from the first and second heat exchangers respectively, wherein the apparatus is switchable between: a first operation mode in which both the first and second chiller operate in a free cooling mode; and a second operation mode in which the first chiller operates in a free cooling mode and the second chiller operates in a forced cooling mode.

The improved efficiency of the apparatus may be achieved by maintaining operation of the first chiller in the free cooling mode even when its coolant may be approaching its critical point. For example, if the heat flow causes the temperature of the coolant and/or system pressure in the first heat exchanger to rise above a threshold level, e.g. the boiling point of the coolant, the second heat exchanger may still operate to cool the heat flow to a desired temperature, e.g. a set room temperature. The apparatus may be arranged to switch into the second operation mode if the temperature of the coolant and or the system pressure in the second heat exchanger rises above a threshold level (which may be set slightly lower than the critical point of the coolant). Thus in both the first and second operation modes full use is made of the free cooling capability of the first chiller. The threshold level may be determined based on any one or more of the temperature of the heat flow, e.g. at the output from the second heat exchanger, the ambient temperature and the system pressure in each heat exchanger.

Having more than one heat exchanger at the heat source may also provide an element of redundancy. In the event that one of the cooling circuit becomes inoperative (e.g. due to malfunction or servicing) the other circuit may be operate alone. In that case, the single operating chiller may be arranged to operate in the forced cooling mode immediately if

the temperature of the coolant and/or pressure in the heat exchanger exceeds the threshold level.

The first and second chiller may both be selectively operable in a free cooling mode or a forced cooling mode. The apparatus may also be switchable to a third operation mode in which both the first and second chiller operate in the forced cooling mode. To operate efficiently, the apparatus may be arranged to switch into the third operation mode if the temperature of the coolant in the second heat exchanger when operating in the forced cooling mode rises above a threshold level (which may be set slightly lower than the critical point of the coolant).

The heat source may be any appliance that produces heat during operation. For example, the heat source may be a computer, e.g. PC or server.

The heat flow may be forced, e.g. on an air current directed away from the heat source. For example, the heat source or one or more of the heat exchangers may have a fan associated therewith for blowing the surrounding air in the direction of the heat flow. The first and second heat exchangers may be arranged in series in the path of the heat flow, with the first heat exchanger arranged to receive the heat flow first, i.e. at the hotter end of the temperature gradient across the exchangers. The heat exchangers may incorporate passageways to permit a medium carrying the heat flow, e.g. air, therethrough. The heat flow may be convective.

The heat source may be contained in a space having a internal temperature separated from an external environment having an ambient temperature that is lower than the internal temperature. The heat exchangers may be located in the space with the heat source to absorb the heat energy therein. The chillers may be arranged in the external environment. Free cooling may mean release of energy from the coolant with substantially no (i.e. very low) energy cost. For example, free cooling may be release of heat energy from the coolant to the external environment. Free cooling may be achieved by passing the coolant through a heat exchanger located in the external environment. If the ambient temperature is low enough the heat exchanger will operate to emit heat from the coolant to the external environment. Forced cooling may mean

release of heat energy with an energy cost, e.g. an energy input. For example, forced cooling may be achieved using conventional compressor based cooling, i.e. in which the pressure of the coolant is increased to increase its temperature to increase a temperature gradient and hence cooling efficiency.

Each coolant distribution circuit may operate convectively or may have a pump for circulating the coolant. Each coolant distribution circuit may comprise a cool input for receiving coolant from a chiller, a cool output for directing coolant to a heat exchanger, a hot input for receiving coolant from the heat exchanger and a hot output for directing coolant to the chiller.

The apparatus may include a detector arranged to measure temperature or pressure of the coolant transferred out of the second heat exchanger (i.e. temperature or pressure at the hot input of the relevant coolant distribution circuit), wherein the apparatus is arranged to switch to the second operation mode based on measurement made by the detector. As mentioned above, to achieve efficient operation, the apparatus may switch to the second operation mode only when the temperature or pressure of coolant from the second heat exchanger exceeds a threshold. Even then the first chiller continues to operate in the free cooling mode. No detector may be needed for the first heat exchanger.

The first and second chillers may each include a compressor connected to the respective coolant distribution circuit. Each chiller may include a bypass circuit for diverting coolant past the compressor when operating in the free cooling mode. The first chiller may be arranged only to operate in the free cooling mode, so may comprise a passive coolant distribution circuit.

The second chiller may include an auxiliary cooling circuit that is independent of the coolant distribution circuit connected to the second heat exchanger. The auxiliary cooling circuit may convey auxiliary coolant that is in thermal communication with the coolant distribution circuit connected to the second heat exchanger to cool the coolant in the coolant distribution circuit connected to the second heat exchanger. The coolant in the coolant distribution circuit may thus be isolated, which may prevent contamination.

Indeed, the coolant distribution circuit may in itself be a passive circuit; a compressor may be connected into the auxiliary cooling circuit when the second chiller operates in a forced cooling mode. The auxiliary cooling circuit may be part of a conventional, e.g. off the shelf, cooling device.

Thermal communication between the auxiliary coolant and the coolant in the coolant distribution circuit connected to the second heat exchanger may be achieved by providing an auxiliary heat exchanger, e.g. a plate heat exchanger, at an interface between the auxiliary cooling circuit and the coolant distribution circuit connected to the second heat exchanger.

The auxiliary coolant may be the same or different from the coolant flowing through the first and second heat exchangers. The auxiliary coolant may be CO₂, water, NH₃ or the like.

The first chiller may be configured in the same way as the second chiller, i.e. with its own auxiliary cooling circuit.

To provide localised cooling, the heat exchangers may be mounted on the heat source, e.g. on the door of a server rack. The heat exchangers may be evaporators, e.g. conduits arranged to carry liquid coolant which evaporates when energy is absorbed. The coolant may be CO₂.

In another aspect, the invention may provide a server rack comprising: one or more servers mounted therein; an air circulation unit arranged to direct a flow of air through the rack to draw heat away from the servers; and apparatus as described above arranged to cool the flow of air, wherein the heat source is the server(s) and the first and second heat exchangers are arranged serially to receive the flow of air, the first heat exchanger being closer to the servers than the second heat exchanger. In this aspect the cooling occurs at the rack itself, whereby the heat flow does not substantially affect the surrounding air temperature. Such targeted cooling may be more efficient.

In another aspect, the invention may provide a data centre comprising an enclosed space housing a plurality of server racks as described above. The chillers may include heat exchangers located outside the enclosed space, e.g. in a low temperature external environment, for use when operating

in the free cooling mode.

In yet another aspect, the invention may provide apparatus for cooling heat flow from a heat source, the apparatus comprising: a plurality of first heat exchangers and a plurality of second heat exchangers arranged as a plurality of first and second heat exchanger pairs serially mounted relative to respect to the heat flow, the first heat exchanger in each pair being closer to the heat source than the second heat exchanger; a first common coolant distribution circuit connected to the plurality of first heat exchangers to transfer coolant therethrough; a second common coolant distribution circuit connected to the plurality of second heat exchangers to transfer coolant therethrough; and a first chiller arrangement and a second chiller arrangement for cooling the coolant output from the plurality of first heat exchangers and the plurality of second heat exchangers respectively, wherein the apparatus is switchable between: a first operation mode in which both the first and second chiller arrangements operate in the free cooling mode; and a second operation mode in which the first chiller arrangement operates in the free cooling mode and the second chiller arrangement operates in the forced cooling mode. This aspect is similar to the first aspect mentioned above, but may further provide scalability and/or additional redundancy.

As above, both the first and second chiller arrangements may be selectively operable in a free cooling mode or a forced cooling mode, and which is switchable to a third operation mode in which both the first and second chiller arrangements operate in the forced cooling mode.

Each common coolant distribution circuit may comprise a plurality of parallel cool outputs, each cool output being connected to deliver coolant to a respective heat exchanger on the circuit. A coolant distribution circuit may be arranged to support a predetermined number of heat exchangers, which may be provide as connectable modules.

Each common coolant distribution circuit comprises a common hot input connected to receive coolant from a plurality of heat exchangers on the circuit. The heat exchangers may thus be provided as parallel connected modules.

Similarly, either or both of the first and second chiller arrangements may comprise a plurality of chillers connected in

parallel to the respective coolant distribution circuit, each chiller being selectively operable in a free cooling mode or a forced cooling mode. Each chiller may be provided in a selectively connectable module to facilitate disconnection and reconnection during servicing, load redistribution or the like.

In yet another aspect, the invention may provide a method of cooling heat flow from a heat source, the method comprising: delivering coolant independently to a first heat exchanger and a second heat exchanger from a first coolant transfer circuit and a second coolant transfer circuit respectively, the first and second heat exchangers being arranged serially to receive the heat flow, the first heat exchanger being closer to the heat source than the second heat exchanger; measuring temperature or pressure of the coolant transferred out of the first heat exchanger; and controlling the operation modes of a first chiller connected to the first coolant transfer circuit and a second chiller attached to the second coolant transfer circuit based on the measuring temperature or pressure, wherein the method includes operating the first chiller in a free cooling mode and operating the second chiller in a forced cooling mode if the temperature or pressure of the coolant transferred out of the first heat exchanger exceeds a threshold. In the method the first chiller may thus be held in the free cooling mode even if the cooling achieved in that mode is not enough to reduce the temperature of the heat flow to the desired level.

The invention may be implemented using sustainable refrigerants as the coolant. In the situation where the coolant from the first heat exchanger is gaseous, it may be desirable to have a blow out valve to prevent overpressure in the distribution circuit. This is undesirable or impractical with non-sustainable or toxic refrigerants.

The invention incorporates redundancy in a modular architecture by cooling each heat source with a passive or forced heat flow redundant evaporator. This redundancy also acts to improve operational efficiency.

BRIEF DESCRIPTION OF THE DRAWINGS

Examples of the concepts outlined above are discussed in

detail with reference to the accompanying drawings, in which:

Fig. 1 is a schematic block diagram of cooling apparatus that is an embodiment of the invention;

5 Fig. 2 is a schematic block diagram showing components of a cooling apparatus that is an embodiment of the invention;

Fig. 3 is a schematic block diagram showing a plurality of evaporators arranged serially with respect to a heat flow;

Fig. 4 is a schematic block diagram of a data centre that is an embodiment of the invention;

10 Fig. 5 is a schematic block diagram of modular cooling apparatus that is another embodiment of the invention;

Fig. 6 is a graph showing power consumption against ambient temperature for a chiller assembly suitable for use in the invention; and

15 Fig. 7 is a schematic block diagram showing components of a cooling apparatus that is another embodiment of the invention.

DETAILED DESCRIPTION; FURTHER OPTIONS AND PREFERENCES

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The present invention may provide a flexible solution to the problem of cooling a data centre efficiently. The invention may utilize natural and non-water-based refrigerants. The invention may provide scalable apparatus, e.g. to enable tailored control of cooling system, e.g. in accordance with a business plan or proposed development. The scalability may also enable increases in the overall power density of a rack to be catered for, thus supporting the development of high power density blade servers and network equipment.

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By providing heat exchangers associated with particular heat sources, the invention may limit or remove the need for forced airflow, which is standard in conventional cooling solutions. Similarly, the invention may remove the need for computational fluid dynamics (CFD) analysis of air flow patterns within a space to be cooled, and particularly the change of such patterns during operation, service and maintenance. This may be advantageous, in that predicting whether or not a certain airflow in data centre provides the right cooling capacity for a given operation pattern can be one of the most complex tasks in data centre management. The

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present invention may obviate this task.

Fig. 1 illustrated an architecture for a cooling apparatus 10 that is an embodiment of the invention. In this embodiment, the apparatus 10 comprises three main parts: an evaporator assembly 16, a coolant distribution unit (CDU) 12, and a hybrid chiller assembly 14.

The evaporator assembly 16 comprises two sets 18, 20 of multiple parallel heat exchangers (which in this embodiment are evaporators, e.g. HVAC coils or the like). The sets 18, 20 are coupled in series with respect to the direction of heat flow 22 from a heat source (indicated by an arrow in the drawing). For example, the sets 18, 20 may be arranged to formed multiple parallel pairs of serially arranged evaporators. Heat from the heat source thus first enters a first set 18 of evaporators (indicated as Evaporator a in the drawing). After the heat flow 22 passes through the first set 18 of evaporators, i.e. after the cooling effect of the first set 18 of evaporators is imparted to the heat flow, the heat flow 22 passes through a second set 20 of evaporators first (indicated as Evaporator b in the drawing). Thus heat flow entering the second set 20 of evaporators has already been exposed to the first set 18 of evaporators. This embodiment illustrates two serial sets of evaporators. There may be three or more sets arranged in series with respect to the heat flow. Furthermore, although this embodiment illustrates a plurality of evaporators in each set, each set may have only one evaporator. Other types of heat exchanger may be used instead of evaporators.

The CDU 12 is a system which distributes coolant (e.g. natural refrigerant such as liquid CO₂) to the evaporator assembly 16. The CDU 12 is a modular arrangement comprising a plurality similar or identical modules 24, 26. There is at least one module per set of evaporators. In this embodiment, a first distribution module 24 (CDUa) is connected via first input and output conduits 28 to the first set 18 of evaporators and a second distribution module 26 (CDUb) is connected via second input and output conduits 30 to the second set 20 of evaporators. The sets 18, 20 of evaporators thus have independent coolant circuits; there is no mixing of coolant circulating in the first and second evaporators.

The heat source may be contained in an enclosed space,

e.g. a room or warehouse. The evaporators are located with the heat source in the enclosed space (which may be referred to herein as the interior). The CDU 12 need not be contained in the interior. For example, if the enclosed space is defined within a building, the CDU 12 may be located outside the building, e.g. exposed to the outside environment.

The CDU 12 may also handle coolant flow control based on real time measurements of performance parameters of coolant in the first and second input and/or output conduits. The performance parameters may include any one or more of pressure, flow temperatures, evaporator assembly input and output temperatures, ambient temperature (i.e. temperature of the outside environment), and actual or predicted power usage of the heat source (which may be an electrical appliance such as a server or communication equipment, e.g. networking apparatus etc.).

In this embodiment, the hybrid chiller assembly 14 comprises two sets 32, 34 of multiple hybrid chillers. The purpose of each chiller is to condense (i.e. cool) evaporated (i.e. heated) coolant received from the CDU 12 and return it to the CDU 12 for recirculation to the evaporator assembly 16. Each set 18, 20 of evaporators has a corresponding set 32, 34 of hybrid chillers to maintain isolation of the coolant between the first and second sets of evaporators. Each set 32, 34 of hybrid chillers is therefore connected to the relevant distribution module by an independent input and output conduit. Thus, in the illustrated embodiment a first set 32 of hybrid chillers (indicated as Hybrid Chiller a in the drawing) is connected to first distribution module 24 by first input and output conduits 36 to receive, cool and output coolant from the first set 18 of evaporators. Similarly a second set 34 of hybrid chillers (indicated as Hybrid Chiller b in the drawing) is connected to second distribution module 26 by second input and output conduits 38 to receive, cool and output coolant from the second set 20 of evaporators. Each set of hybrid chiller may include only one hybrid chiller.

A hybrid chiller is a cooling system having two operating modes. One mode is a free cooling mode, in which the hybrid chiller works substantially passively as a so-called free cooler, gas condenser, or dry cooler. In this mode cooling occurs directly on the evaporated refrigerant without

increasing its working pressure. In practice operating in this mode may include transferring the coolant through a heat exchanger in a low temperature environment outside the enclosed space containing the heat source. The low
5 temperature environment may be in the open air. Night and/or cold season temperatures in some areas of the world (e.g. northern Europe, northern states of the US, etc.) may be low enough to enable operation in the mode for a coolant such as CO₂ or the like. The other operating mode is a forced cooling
10 mode in which an energy input is required to achieve cooling. An example of the forced cooling mode is compressor-based cooling, in which the coolant pressure is temporarily increased, which makes it possible to cool even at high ambient temperatures.

15 Whilst the embodiment illustrates hybrid chillers, i.e. chillers that can switch between the two operating modes described above, this need not be essential. Each set of chillers may be made up of one or more free coolers and one or more forced coolers. However, having hybrid chillers may be
20 advantageous in terms of providing increased energy efficiency and coping with redundancy demands.

Fig. 2 shows components of each of the main parts of one of the cooling circuits of the cooling apparatus 10 shown in Fig. 1. In this embodiment, the heat source is an IT rack 40
25 (e.g. a server rack containing one or more servers). The IT rack 40 may have a inbuilt fan for circulating air flow through the rack. The air flow may carry heat away from the IT rack 40 and hence may represent the heat flow 42 away from the heat source. Two heat exchangers 44, 46 are arranged
30 serially in the direction of the heat flow 42. The heat exchangers 44, 46 may be attached to the IT rack 40, e.g. mounted on its back door.

The cooling circuit connected to the second heat exchanger 46 is illustrated in more detail. The circuit
35 connected to the first heat exchanger is independent of the illustrated circuit.

The second heat exchanger 46 is connected to a CDU module 48 by feed conduits 50, 52. A first conduit 50 is a cool
40 output from the CDU module 48 which feeds coolant into the heat exchanger 46. A second conduit 52 is a hot input to the CDU module 48 which transfers heated coolant away from the

heat exchanger 46. The CDU module 48 consists of valves 54, 56 which may be arranged to operate as hot plugs, leakage protection and flow controllers for coolant flowing in the first and second conduits 50, 52 respectively. The CDU module 48 may include a pump 58 for driving the coolant. The pump is optional (i.e. the circuit may operate by convection), but has the advantage of extending the distance between the hybrid chiller(s) and the evaporator assembly.

The CDU module 48 is connected to the hybrid chiller 60 by a pair of conduits 62, 64. A first conduit 62 is a hot output from the CDU module 48 which transfers heated coolant to a reservoir 66 in the hybrid chiller 60. A second conduit 64 is a cool input to the CDU module 48 which transfers cooled, e.g. liquid, coolant from the reservoir 66 to be sent to the heat exchanger 46. A pump 68 to drive the circuit may be provided on the second conduit 64.

The reservoir 66 acts as a coolant receiver/buffer. The reservoir 66 retains liquid coolant (which can be transferred out via the second conduit 64) but has a gas outlet 70 that delivers heated coolant to a condenser 72 for cooling. Cooled, e.g. liquid, coolant from the condenser 72 is delivered back to the reservoir 66 via liquid inlet 74. A pressure relief valve 76 may be provided after the condenser 72 as a safety blow out mechanism.

In the embodiment there are two paths from the gas outlet 70 to the condenser 72. A first path 78 passes through a compressor 80, which acts to increase temporarily the pressure (and hence temperature) of the gas to facilitate cooling in the condenser 72. The second path 82 bypasses the condenser. A bypass valve 84 is provided on the second path 82 to enable the system to select which path the gas may take.

When the bypass valve 84 is open the hybrid chiller operates in a free cooling mode. When the bypass valve 84 is closed the hybrid chiller operates in a forced cooling mode.

The condenser 72 is exposed to an ambient temperature, e.g. an external temperature outside the enclosed space containing the IT rack. A fan 86 may blow air at the ambient temperature over the condenser 72 to facilitate cooling of coolant therein.

The circuit may also include a auto fill storage unit 88 connected to deliver extra coolant to either the CDU module 48

or hybrid chiller 66. In this embodiment the auto fill storage unit 88 has a first delivery conduit 90 for transferring coolant to the hot output 62 of the CDU module 48 and a second delivery conduit 92 for transferring coolant to the gas outlet 70 of the reservoir 66. Each delivery conduit 90, 92 has a respective control valve 94, 96 arranged to control flow rate therethrough.

Fig. 3 illustrates the series connection of multiple evaporators 100, 102, 104, 106 with respect to a heat flow 108. Each evaporator is connected to an independent circuit C1, C2, C..., Ci, e.g. as described above with respect to Fig. 2. In this way the cooling apparatus may be seen as a modular cooling system constructed around a redundant set of serially arranged evaporators. The (2 or more) evaporators may each be air to refrigerant micro tube heat exchangers. Each evaporator is coupled in a dedicated cooling circuit, in such a way that each evaporator in an assembly has a dedicated cooling circuit connecting it to an outdoor chiller, condenser or the like.

By using a set of paralleled or a single outdoor hybrid chiller for each cooling circuit, which hybrid chiller either operates as a free cooling condenser, or as a transcritical compressor based chiller, increased efficiency and multilevel redundancy may be achieved when compared with conventional cooling systems.

In a further development of the embodiments discussed herein, the CDU may allow several evaporators to be connected to share a common coolant circuits and redundant coolant feed to and from outdoor chillers. This may facilitate scalability, i.e. the ability to increase the number of paralleled hybrid chillers or evaporator sets. The CDU also provides integrated safety and service mechanisms such as limp home on faults, leakage detection, plug and play addition of evaporators, and filling of refrigerant.

Fig. 4 shows a cooling apparatus which makes use of the modular concept discussed herein. This drawing illustrates a data centre 110 having a wall 112 which separates an enclosed indoor space 114 from outside 116. A plurality of server racks 118 are arranged in the enclosed inside space 114. Each rack 118 has an evaporator assembly 120 mounted on its rear door. In the illustrated embodiment the data centre 110 has

four rows of eight racks. Each row of racks has its own CDU 122. Each evaporator assembly 120 has a plurality of serially arranged heat exchangers. The CDU 122 comprises a plurality of CDU modules (not shown) each of which connects to a plurality of parallel heat exchangers, one heat exchanger per rack in the row. Thus, although each rack has a plurality of heat exchangers with independent coolant circuit, the coolant circuits are shared between the racks, i.e. all of the first heat exchangers may be connected (e.g. in parallel) to a common coolant circuit.

Each CDU 122 may be connected to a main CDU (MCDU) 124, e.g. by two or more forward and return flow path pairs to provide redundancy. Thus there may be at least four connections from each CDU 122 to a MCDU 124. The MCDU 124 may be optional; it may be possible to couple a CDU 122 directly to a hybrid chiller assembly 126. In Fig. 4 the CDUs in the two rows on the left are shown as paralleled on to a common pipe installation; this may be beneficial, e.g. to reduce installation costs.

The hybrid chiller assembly is arranged outside 116. The assembly comprises a plurality of hybrid chiller independently connected to the MCDU 124. Details of the connection are discussed below with reference to Fig. 5.

Each evaporator 120 in Fig. 4 could be implemented as any one of a rear door assembly, a dedicated cooling rack, a hot aisle roof, a rack side panel, a blade chassis, or a embedded rack cooler unit. Alternatively, the heat exchangers may include a heat sink or heat pipe.

In operation, a control system (not shown) may handle system operation, fault detection and coolant handling. The evaporator assemblies may include thermal monitoring systems (which may be wireless or hardwired) and fire extinguishing valves controlled by the CDU evaporation/exhaust of the natural refrigerant. The CDU may be arranged to stabilise the average indoor temperature, e.g. to a reference value which may be selectable. The CDU may includes a controller arranged to operate based on measured values or any one or more of ambient (e.g. outdoor) temperature, chiller operating modes, indoor temperatures, evaporator performance measurements heat source measurements, and coolant pressure and temperature. The CDU may also be arranged to measure indoor temperatures,

either through a wireless sensor array or hardwired thermal sensors distributed in the data centre.

5 The CDU may also detect and isolate any leakage, hose or pipe bursts, blockages, or other abnormal behaviour. After isolating any leakage the CDU may control the auto fill storage to re-establish the lost amount of coolant within the affected circuits. The CDU can therefore handle any issues with availability, if such incidences should occur.

10 Where each CDU may connect to a plurality of heat exchangers, each connection may have a hot plug mechanism to handle unplugging and plugging of additional CDUs or evaporator assemblies.

15 In emergencies, e.g. a fire in cooled equipment such as a complete rack where the measured temperature indicates the a given burst is due to a fire, the cooling apparatus in the affected area can be shutdown without affecting other systems. The fire may thus be extinguished while all remaining systems are kept up and running.

20 The hybrid chiller assembly may control the working pressure of the coolant within each circuit. Each hybrid chiller may operate as a free cooler, which is a condenser unit without compressor, thus not changing the pressure of the evaporated coolant, or as a forced cooler, e.g. as a energy consuming compressor-based condenser, where the pressure of the coolant is increased above its critical point. Selecting the operation mode may be controlled by the hybrid chiller itself, based on ambient temperature, working pressure, and a maximum allowed room temperature (interior temperature). Hybrid chillers located outside may have a safety blow out valve, in case of over pressure in the system. Thus making
30 sure that a blow out would occur outside rather than inside.

Turning again to Fig. 1, operation of the system is as follows. A basic mode of operation is where both sets of hybrid chillers 32, 34 operate in free cooling mode. This
35 mode works when the ambient temperature is such that the coolant can be condensed without compression. As the ambient temperature and/or the heat energy of the heat flow increases, the coolant in the first set 18 of evaporators (i.e. the evaporators which see the heat flow at its hottest) may approach its critical point. Above this temperature and
40 pressure the remaining cooling capacity of the first set of

evaporators falls away. However, the second set 20 of evaporators receives the heat flow after cooling by the first set, and so the system may still operate to maintain the inside temperature at a set reference value.

5 If changes in the temperature and/or pressure of the coolant in the second circuit causes it to approach its critical point, the second set 34 of hybrid chillers may be switched to the forced cooling mode, in which they actively cool the coolant by increasing its pressure (e.g. by
10 transcritical CO₂ cooling), thus increasing the coolant temperature above ambient temperature to facilitate cooling it down before lowering the pressure again. This is a standard approach in compressor-based cooling.

 However, the first set 32 of hybrid chillers stays in the
15 free cooling mode at this time. Thus even though some forced cooling is taking place, this is only after the free cooling benefit of the first set 18 of evaporators has occurred. This may reduce the amount of forced cooling that is necessary, which may improve overall efficiency.

20 Thus, the main difference between the first and second sets 32, 34 of hybrid chillers is that the second set 34 may change to compressor mode before the first set 32, to extend to the highest possible degree the operation in free cooling mode of the first cooling circuit.

25 A further operational mode may be both cooling circuits operating in forced cooling mode. This may occur e.g. if the ambient temperature is too high for free cooling to be effective (e.g. when the ambient temperature approaches the critical temperature of the coolant).

30 By controlling each system like described above it is possible to maintain a reliable and cost effective system, which increases the year of year power usage efficiency of a data centre in for instance Denmark to 96% from below 50%, while also minimising the wear and thus increasing the
35 lifetime of the cooling apparatus. The possible power saving is discussed below with reference to Fig. 6.

 Fig. 5 shows in more detail the redundancy feature of cooling apparatus that is an embodiment of the invention. In Fig. 5 the heat source 130 (e.g. a plurality of server racks) emits a heat flow 132. An evaporator assembly 134 is arranged
40 in the path of the heat flow 132. The evaporator assembly

comprises two sets of heat exchangers arranged such that the heat flow passes through them. A first set of heat exchangers is located closer to the heat source 130 than a second set. The sets of heat exchangers are fed coolant from coolant distribution unit (CDU) 140 via respective input conduits 136. The heat exchangers in each set may be connected in parallel to their respective input conduit 136. The sets of heat exchangers transfer heated coolant to the CDU 140 via respective output conduits 138. The heat exchangers in each set may be connected in parallel to their respective output conduit 138. As in earlier embodiments, the coolant for the first heat exchangers is isolated from the coolant for the second heat exchangers throughout the circuit. Accordingly the apparatus provides a first hybrid condenser 142 for coolant from the first heat exchangers and a second hybrid condenser 144 for coolant from the second heat exchangers. To provide redundancy, each hybrid condenser 142, 144 may comprise a plurality of modules. The modules in each hybrid condenser 142, 144 are connected to the CDU 140 via a respective modular interface 146, 148. The purpose of the modular interface is to direct the coolant to certain modules in the hybrid condenser. The modular interface may provide user control over how many and which particular modules are used, e.g. to promote efficiency and enable servicing and maintenance to take place without shutdown of the apparatus.

Each modular interface 146, 148 is also connected to a service unit, which may perform the auto fill storage function described above.

The cooling apparatus described herein may be redundant in its construction, e.g. through the provision of multiple evaporators, each having its own cooling circuit, CDU module and dedicated hybrid chiller. With two evaporators per heat flow, the apparatus may easily achieve 2N redundancy (i.e. where no single point of failure will interrupt overall operation).

However, the benefits of such redundancy are greatly extended when the system is scaled up. For example, if the system is designed to cope with a maximum power of 30 kW from a server rack, the more racks there are the more free capacity that may be available because loads vary between racks. Since all non-cooled heat sources will contribute to a shared

increase in room temperature, this free capacity may operate as a global redundancy for the other racks.

For example, consider a data centre with 300 kW IT power usage creating approximate 300 kW heat. If this is divided up
5 in 40 racks at 7.5 kW per rack, and the cooling capacity of the evaporator assembly on each rack is 30 kW, the redundancy on its cooling capacity may be $2N + 39$.

If the rear door of a rack is opened, the heat flow from that rack may escape the local evaporator assembly. This heat
10 will dissipate in the enclosed space and hence effectively be divided among other racks. Whilst in this circumstance the local evaporator may cause a loss in efficiency, this is far outweighed by the ability of the apparatus to use existing air flow from the servers, i.e. there may be no need to circulate
15 air within the enclosed space.

Fig. 6 is a graph that schematically illustrates the potential power saving achievable by using the invention. A bold line on the graph shows the power consumed by the hybrid chiller assembly of the invention as the ambient temperature varies. A dotted line shows the power consumed by a chiller
20 assembly connected to a circuit in which there is only one heat exchanger. Clearly, as ambient temperature increases the efficiency of free cooling decreases. In a system with only one heat exchanger (evaporator), the switch to forced cooling
25 must occur as soon as the temperature of the coolant in the heat exchanger approaches the boiling point of the coolant. This is indicated at ambient temperature T_1 in Fig. 6. Where there are two or more evaporators, both evaporators may be able to continue to operate in a free cooling mode beyond
30 ambient temperature T_1 .

In the apparatus according to the invention, the compressor in the second cooling circuit is switched on first (when the temperature of the coolant in its heat exchanger approaches boiling point). This occurs at temperature T_2 in
35 Fig. 6. Eventually the ambient temperature may reach a point where the compressor in the first cooling circuit is switched on (e.g. when the temperature of the coolant in the heat exchanger of the second cooling circuit approaches boiling point despite operating in the forced cooling mode). This
40 occurs at temperature T_3 in Fig. 6.

Fig. 6 shows that if the ambient temperature is between

T_1 and T_3 the system of the invention consumes less power than the single evaporator option. Thus, if the range of typical outdoor temperatures of a location fall within the range T_1 and T_3 the cooling apparatus of the invention may enable significant power savings.

The switch from free cooling to forced cooling in each circuit may be based on measurements of any one or more of ambient temperature, pressure and/or temperature of the coolant, room (inside) temperature. The coolant pressure may be measured in either the inlet, or exhaust from the chiller, or the receiver of the particular cooling circuit. The coolant temperature may be measured in either the inlet, or exhaust from the chiller, or the receiver of the particular cooling circuit.

It may be possible to match the cooling apparatus of the invention to a given rack power density spread through out a complete data centre. The modular nature of the apparatus may facilitate changing the capacity and availability of cooling to follow changes in the data centre through its lifetime.

A configuration device may be provided to calculate the exact need for evaporator panel placement and quantity based on power usage profiles for each rack in a given data centre configuration. This should be based on varying power usages over time, due to changing power usage of it equipment caused by virtualization, load shedding etc.

The apparatus may be implemented using a combination of room air conditioning (when panels are shared among several racks) and dedicated rack cooling (when a panel cools a single rack). All evaporators will have a positive effect on the entire room cooling, extending the efficiency benefits of individual rack cooling. This arrangement may both focus on removing hot spots in the data centre, by direct cooling of high density racks, and using the remaining evaporators as standard room air conditioning as a redundant fall back solution.

Fig. 7 shows components of each of the main parts of one of the cooling circuits of a cooling apparatus that is another embodiment of the invention. Components in Fig. 7 which perform the same function as those described above with respect to Fig. 2 are given the same reference numbers and description thereof is not repeated.

In this embodiment, the heat exchanger 46 is connected to receive coolant (in this case CO₂) from a free cooling loop 160, i.e. a coolant distribution circuit without a compressor. Similarly to the arrangement in Fig. 2, the reservoir 66 has a gas outlet 170 that delivers heated coolant via conduit 178 to a condenser 72. In this embodiment there is no compressor on the path between the reservoir 66 and condenser 72. Liquid coolant from the condenser 72 is delivered back to the reservoir 66 via liquid inlet 180. In this embodiment there is an auxiliary heat exchanger 182 (a plate heat exchanger in this embodiment) on the path between the condenser 72 and the reservoir 66.

During operation in the forced cooling mode, the coolant from the condenser 72 is cooled by being brought into thermal communication with auxiliary coolant in the auxiliary heat exchanger 182. The auxiliary coolant is cooled in a chiller 184, e.g. a conventional compressor or the like, where heat extracted from the auxiliary coolant is transferred to an external environment. The chiller may comprise a plurality of cascading cooling loops. The chiller 184 receives heated auxiliary coolant from the auxiliary heat exchanger 182 via a hot input conduit 186 and conveys cooled auxiliary coolant to the auxiliary heat exchanger 182 via a cool output conduit 186. The auxiliary coolant is independent from the coolant in the free cooling loop 160 and may be different therefrom. For example, the auxiliary coolant may be water under vacuum, NH₃ or other similar refrigerants, or heat transferring medias such as oils, glycol etc.

The embodiment shown in Fig. 7 may be beneficial because it reduces the risk that CO₂ is contaminated with oil from the compressor, which may occur in the hybrid chiller arrangement shown in Fig. 2. Such contamination will over time reduce the efficiency and cooling capacity of the system.

The arrangement shown in Fig. 7 also provides advantages in terms of availability and serviceability, since the system may be more configurable and maintenance of the compressor and/or chillers may take place without affecting the closed CO₂ loop. It may even be possible to shutdown and perform maintenance work on the chiller while still running the free cooling CO₂ circuit. In arrangement where there are a plurality of second heat evaporators connected to the same

CDU, there may be a plurality of parallel auxiliary cooling circuit (i.e. paralleled chillers) in thermal communication with the cooling distribution circuit.

5 The condenser 72 in the Fig. 7 arrangement is also able to free cool while the chiller 184 is active. The on/off control of the condenser 72 may be based on the ambient temperature and temperature of the coolant. Other factors may also be taken into account, e.g. the time of the day if noise level is to be controlled.

10 As mentioned above, the CDU for the first heat exchanger may not be operational in a forced cooling mode, i.e. it may not have a compressor or auxiliary cooling circuit associated therewith.

15 The condenser 66 may consist of multiple paralleled or series coupled condensers with bypass valves for maintenance. A water spraying system (not shown) may be arranged to spray water on the condenser(s) to facilitate operation thereof, e.g. to maintain temperature and/or pressure conditions therein at a configurable level below the critical point of
20 the coolant. Spraying may occur before and/or during activation of the chiller. Operation of the water spraying system may be based on the ambient temperature, temperature and pressure of the coolant (e.g. as measured by the detector).

CLAIMS

1. Apparatus for cooling heat flow from a heat source, the apparatus comprising:

5 a first heat exchanger and a second heat exchanger arranged serially to receive the heat flow, the first heat exchanger being closer to the heat source than the second heat exchanger, each heat exchanger being connected to a respective coolant distribution circuit arranged to transfer coolant
10 through its heat exchanger; and

a first chiller and a second chiller for cooling the coolant from the first and second heat exchangers respectively,

wherein the apparatus is switchable between:

15 a first operation mode in which both the first and second chiller operate in a free cooling mode; and

a second operation mode in which the first chiller operates in a free cooling mode and the second chiller operates in a forced cooling mode.

20 2. Apparatus according to claim 1, in which the first and second chiller are both selectively operable in a free cooling mode or a forced cooling mode, and which is switchable to a third operation mode in which both the first and second
25 chiller operate in the forced cooling mode.

3. Apparatus according to claim 2, wherein the first and second chillers each include a compressor selectively connectable into the respective coolant distribution circuit.

30 4. Apparatus according to claim 3, wherein each chiller includes a bypass circuit for diverting coolant past the compressor when operating in the free cooling mode.

35 5. Apparatus according to claim 1, wherein the second chiller includes an auxiliary cooling circuit that is independent of the coolant distribution circuit connected to the second heat exchanger, the auxiliary cooling circuit conveying auxiliary coolant that is in thermal communication
40 with the coolant distribution circuit connected to the second heat exchanger to cool the coolant in the coolant distribution

circuit connected to the second heat exchanger.

5 6. Apparatus according to claim 5, wherein a compressor is connected into the auxiliary cooling circuit when the second chiller operates in a forced cooling mode.

10 7. Apparatus according to any preceding claim including a detector arranged to measure temperature or pressure of the coolant transferred out of the first heat exchanger, wherein the apparatus is arranged to switch to the second operation mode based on measurement made by the detector.

15 8. Apparatus according to any preceding claim, wherein the heat exchangers are mounted on the door of a server rack.

 9. Apparatus according to any preceding claim, wherein the heat exchangers are evaporators.

20 10. Apparatus according to any preceding claim, wherein the coolant is liquid CO₂.

 11. A server rack comprising:
 one or more servers mounted therein;
25 an air circulation unit arranged to direct a flow of air through the rack to draw heat away from the servers; and
 apparatus according to claim 1 arranged to cool the flow of air, wherein the heat source is the server(s) and the first and second heat exchangers are arranged serially to receive
30 the flow of air, the first heat exchanger being closer to the servers than the second heat exchanger.

 12. A data centre comprising an enclosed space housing a plurality of server racks according to claim 11.

35 13. Apparatus for cooling heat flow from a heat source, the apparatus comprising:

 a plurality of first heat exchangers and a plurality of second heat exchangers arranged as a plurality of first and second heat exchanger pairs serially mounted relative to
40 respect to the heat flow, the first heat exchanger in each

pair being closer to the heat source than the second heat exchanger;

5 a first common coolant distribution circuit connected to the plurality of first heat exchangers to transfer coolant therethrough;

a second common coolant distribution circuit connected to the plurality of second heat exchangers to transfer coolant therethrough; and

10 a first chiller arrangement and a second chiller arrangement for cooling the coolant output from the plurality of first heat exchangers and the plurality of second heat exchangers respectively,

wherein the apparatus is switchable between:

15 a first operation mode in which both the first and second chiller arrangements operate in the free cooling mode; and

20 a second operation mode in which the first chiller arrangement operates in the free cooling mode and the second chiller arrangement operates in the forced cooling mode.

25 14. Apparatus according to claim 13, in which both the first and second chiller arrangements are selectively operable in a free cooling mode or a forced cooling mode, and which is switchable to a third operation mode in which both the first and second chiller arrangements operate in the forced cooling mode.

30 15. Apparatus according to claim 13 or 14, wherein each common coolant distribution circuit comprises a plurality of parallel cool outputs, each cool output being connected to deliver coolant to a respective heat exchanger on the circuit.

35 16. Apparatus according to any one of claims 13 to 15, wherein each common coolant distribution circuit comprises a common hot input connected to receive coolant from a plurality of heat exchangers on the circuit.

40 17. Apparatus according to claim 14, wherein either or both of the first and second chiller arrangements comprise a plurality of chillers connected in parallel to the respective coolant distribution circuit, each chiller being selectively

operable in a free cooling mode or a forced cooling mode.

18. Apparatus according to any one of claims 13 to 17,
wherein the heat flow is a forced air current flowing from the
5 heat source.

19. A method of cooling heat flow from a heat source,
the method comprising:

10 delivering coolant independently to a first heat
exchanger and a second heat exchanger from a first coolant
transfer circuit and a second coolant transfer circuit
respectively, the first and second heat exchangers being
arranged serially to receive the heat flow, the first heat
exchanger being closer to the heat source than the second heat
15 exchanger;

measuring temperature or pressure of the coolant
transferred out of the first heat exchanger; and

20 controlling the operation modes of a first chiller
connected to the first coolant transfer circuit and a second
chiller attached to the second coolant transfer circuit based
on the measuring temperature or pressure,

wherein the method includes operating the first chiller
in a free cooling mode and operating the second chiller in a
forced cooling mode if the temperature or pressure of the
25 coolant transferred out of the first heat exchanger exceeds a
threshold.

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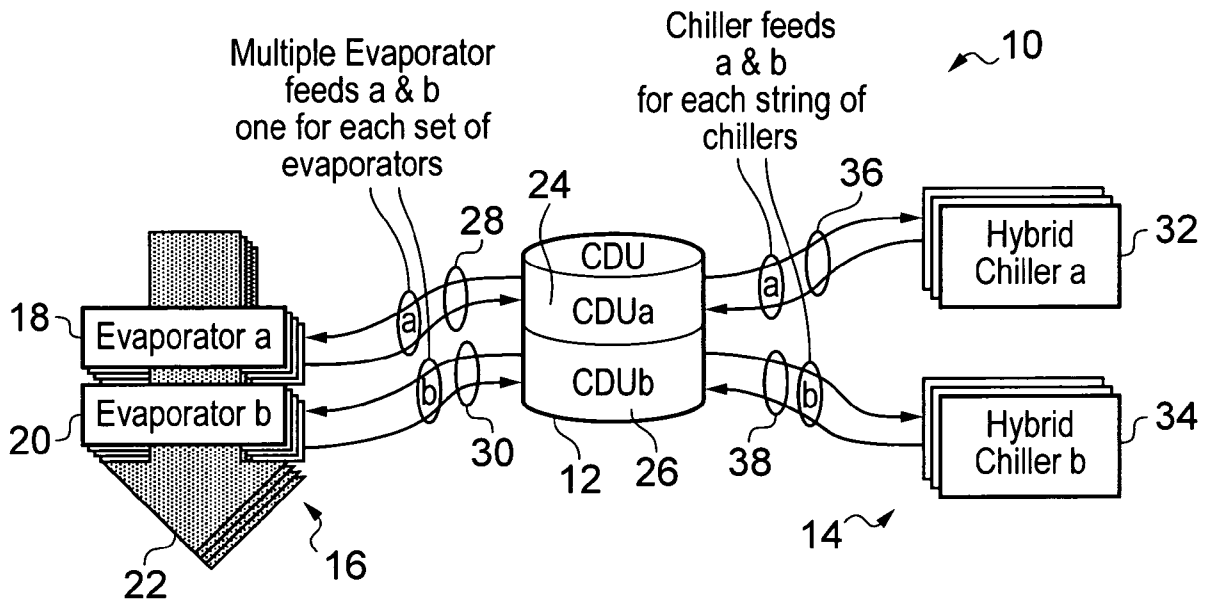


FIG. 1

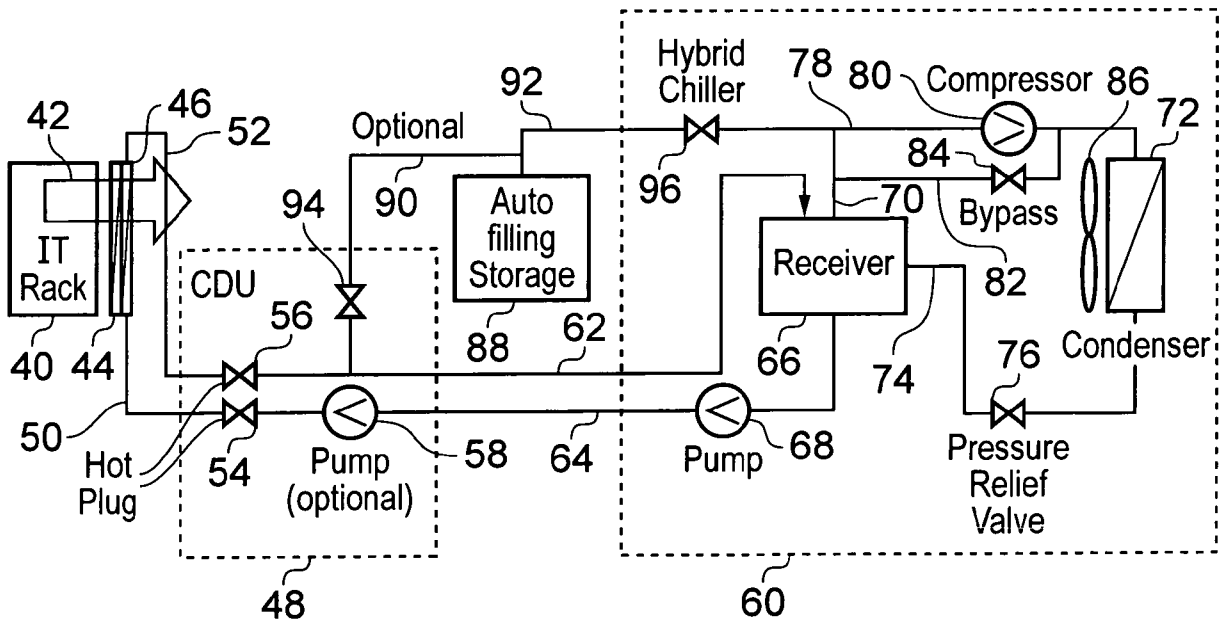


FIG. 2

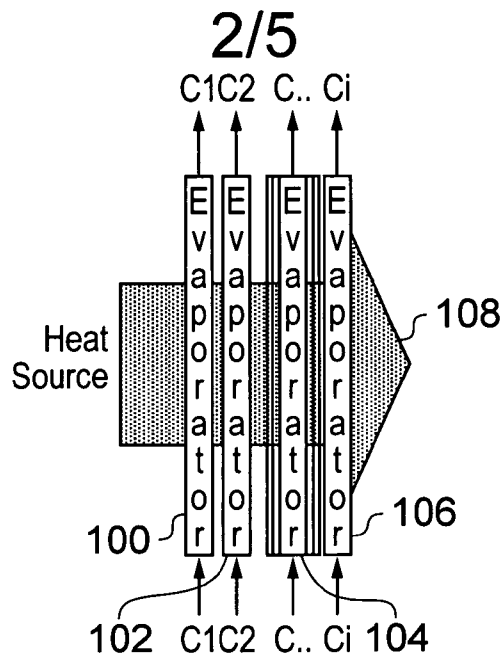


FIG. 3

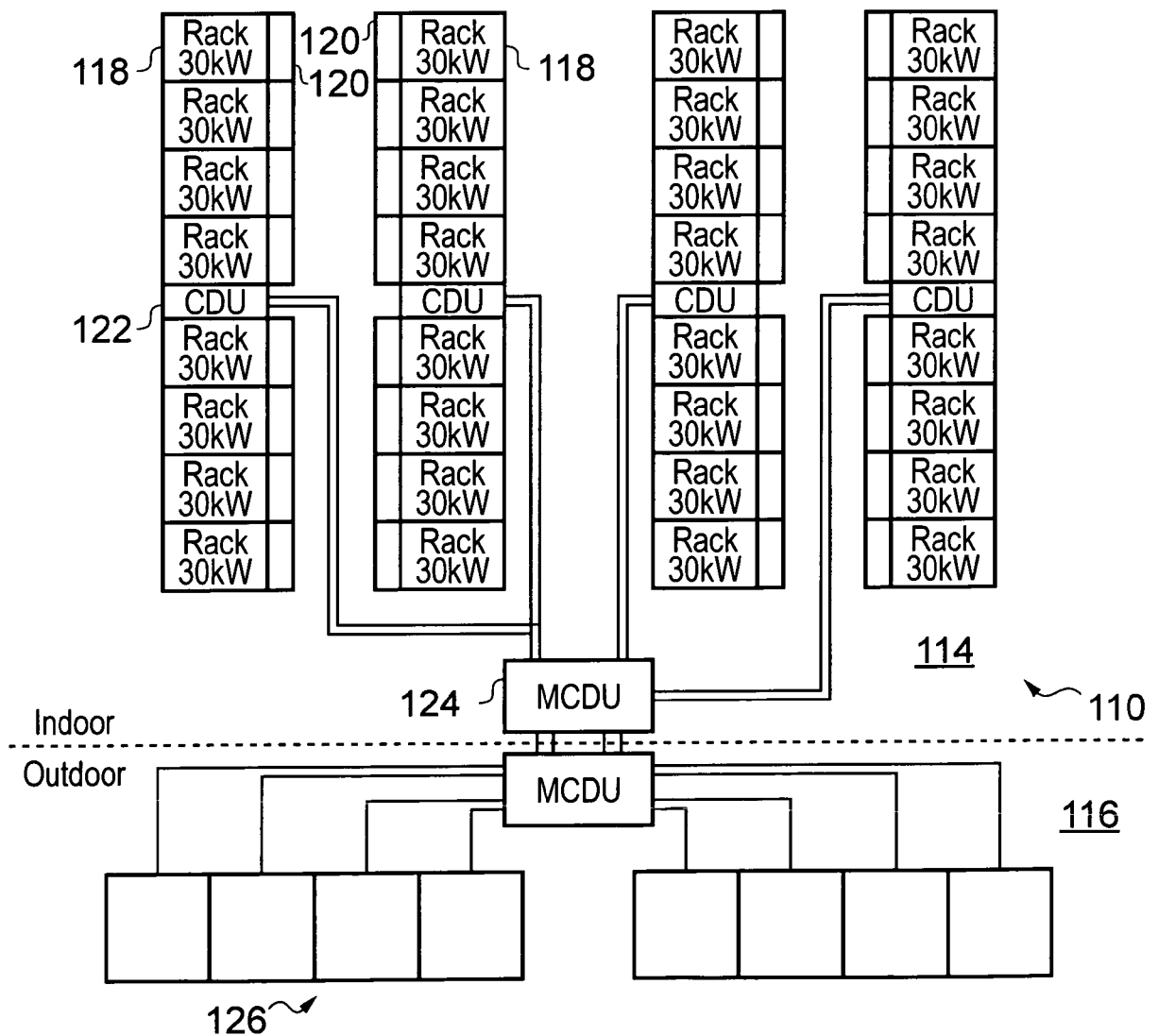


FIG. 4

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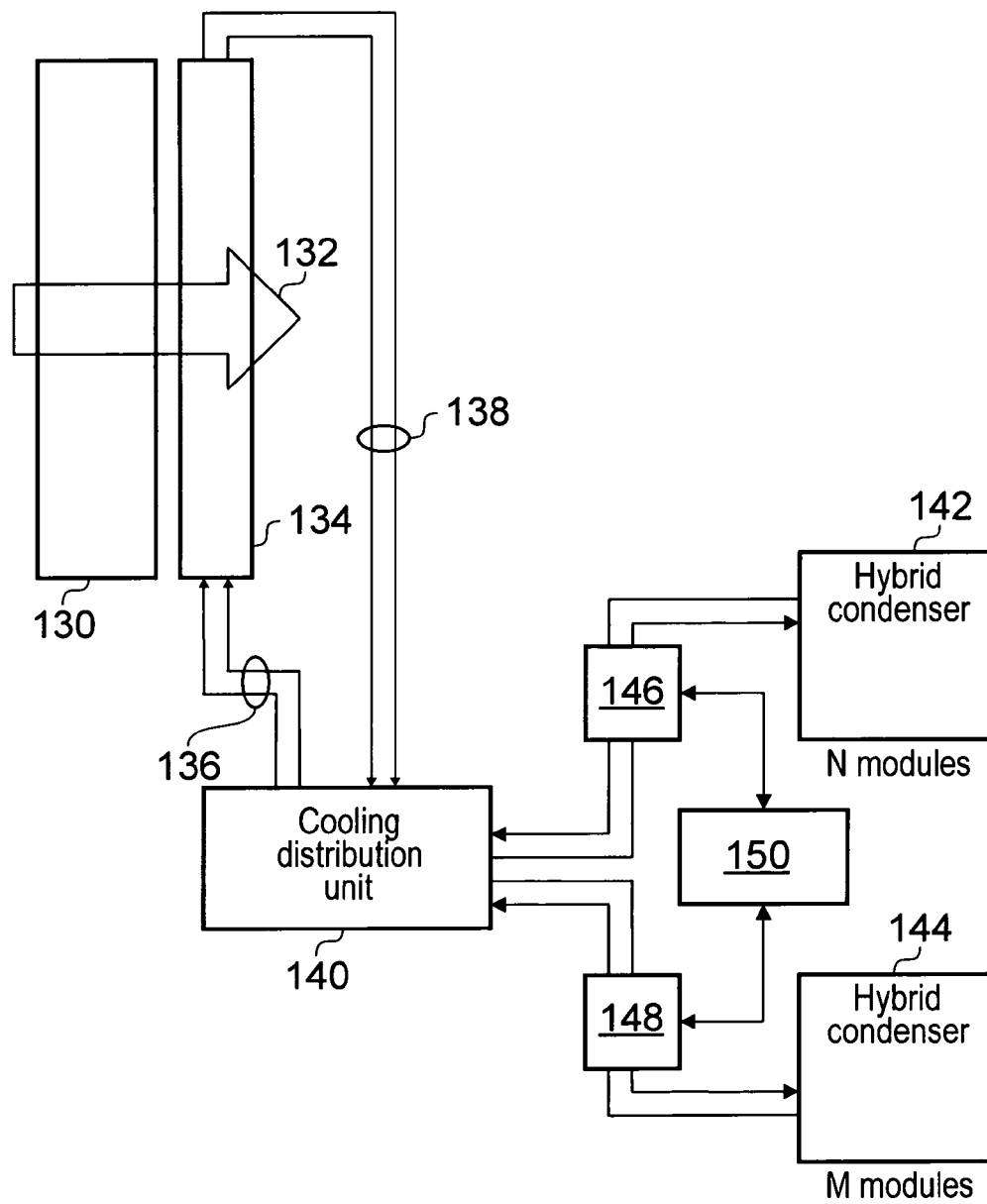


FIG. 5

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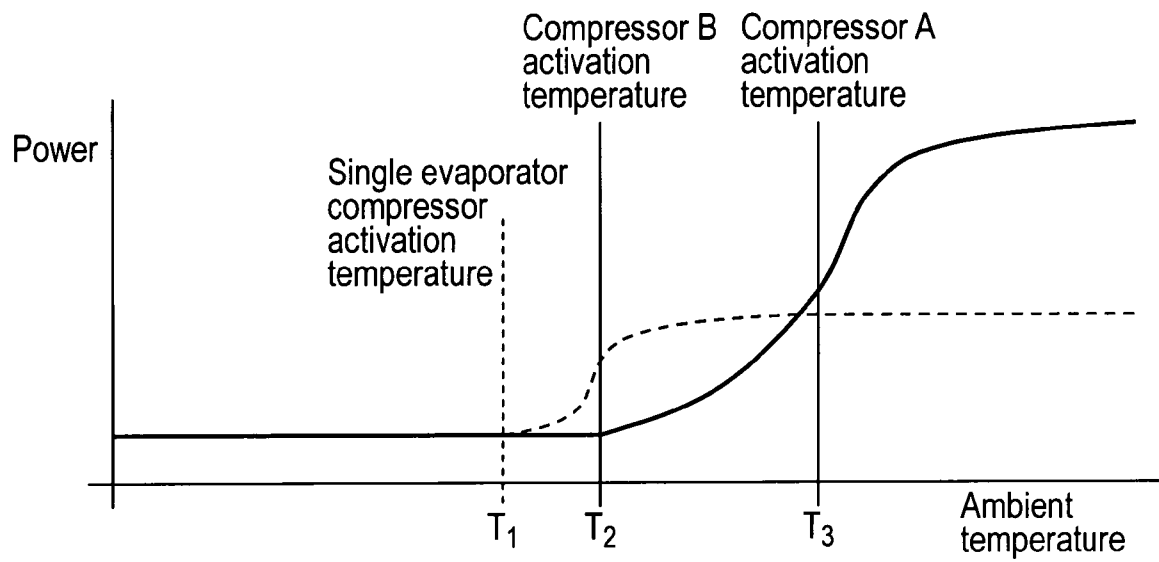


Fig. 6

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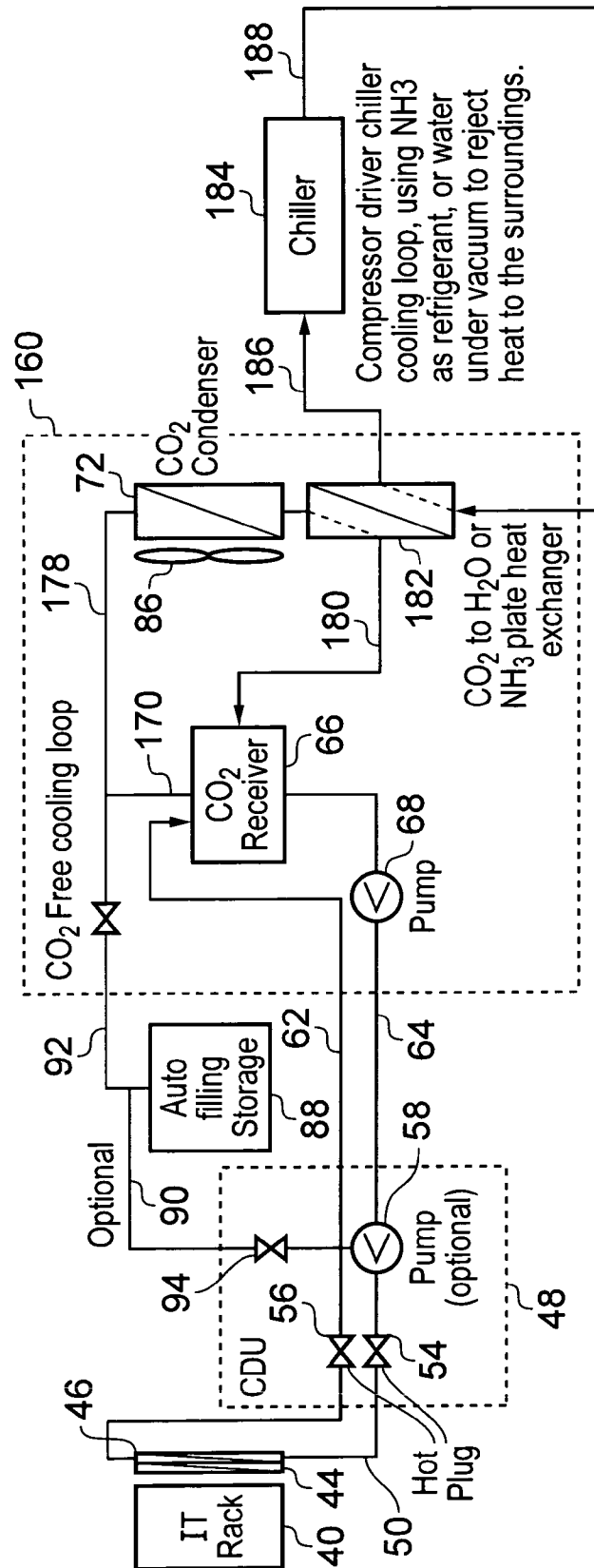


FIG. 7