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(54) **REAL-TIME INDIVIDUAL ELECTRONIC
ENCLOSURE COOLING SYSTEM**

(71) Applicant: **R4 Ventures LLC**, Phoenix, AZ (US)

(72) Inventors: **Mikhail Pavlovich Reytblat**, Chandler,
AZ (US); **Darrell Richardson**,
Phoenix, AZ (US)

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filed on Jan. 23, 2013, now Pat. No. 8,857,204, and a
continuation-in-part of application No. 13/624,912,
filed on Sep. 22, 2012, now Pat. No. 8,899,061.

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23, 2011.

(51) **Int. Cl.**

F25D 23/12 (2006.01)

F28D 5/00 (2006.01)

H05K 7/20 (2006.01)

(52) **U.S. Cl.**

CPC **F28D 5/00** (2013.01); **H05K 7/2079**
(2013.01); **H05K 7/20827** (2013.01); **H05K**
7/20836 (2013.01)

(58) **Field of Classification Search**

CPC F28C 2001/006; F28C 2001/00;
F28B 9/06; H05K 7/20827; H05K 7/2079;
H05K 7/20836; H05K 7/20718; H05K
7/20763; F28D 5/00

See application file for complete search history.

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Primary Examiner — Tho V Duong

Assistant Examiner — Raheena Rehman

(74) *Attorney, Agent, or Firm* — Charles E. Runyan

(57) **ABSTRACT**

This discloses apparatuses for cooling individual server racks or electrical enclosures. These devices maintain target enclosure temperatures within plus or minus 1 or 2 degrees F. The devices employ industrial cooling using staged cooling towers to evaporatively reach temperatures below the wet bulb temperature of the ambient air. Methods for using such apparatuses are disclosed as well.

20 Claims, 24 Drawing Sheets

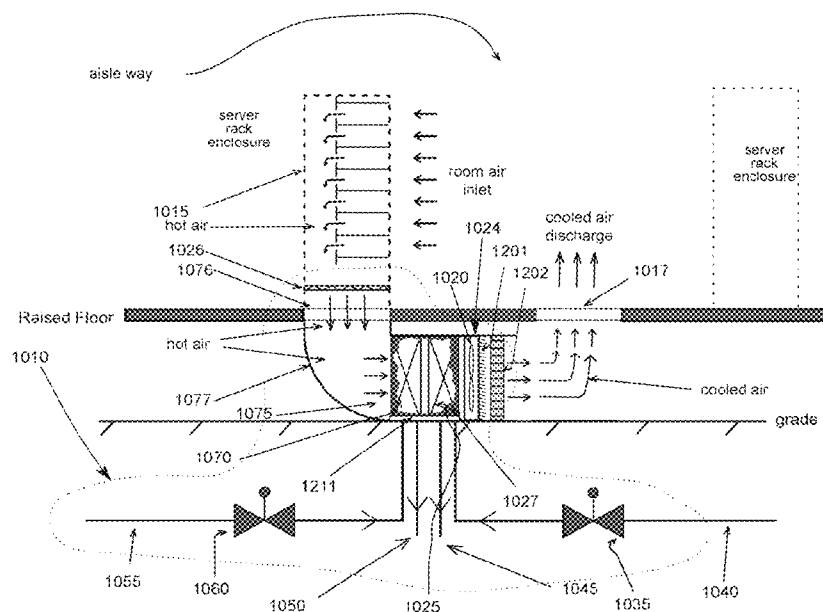


Figure 2

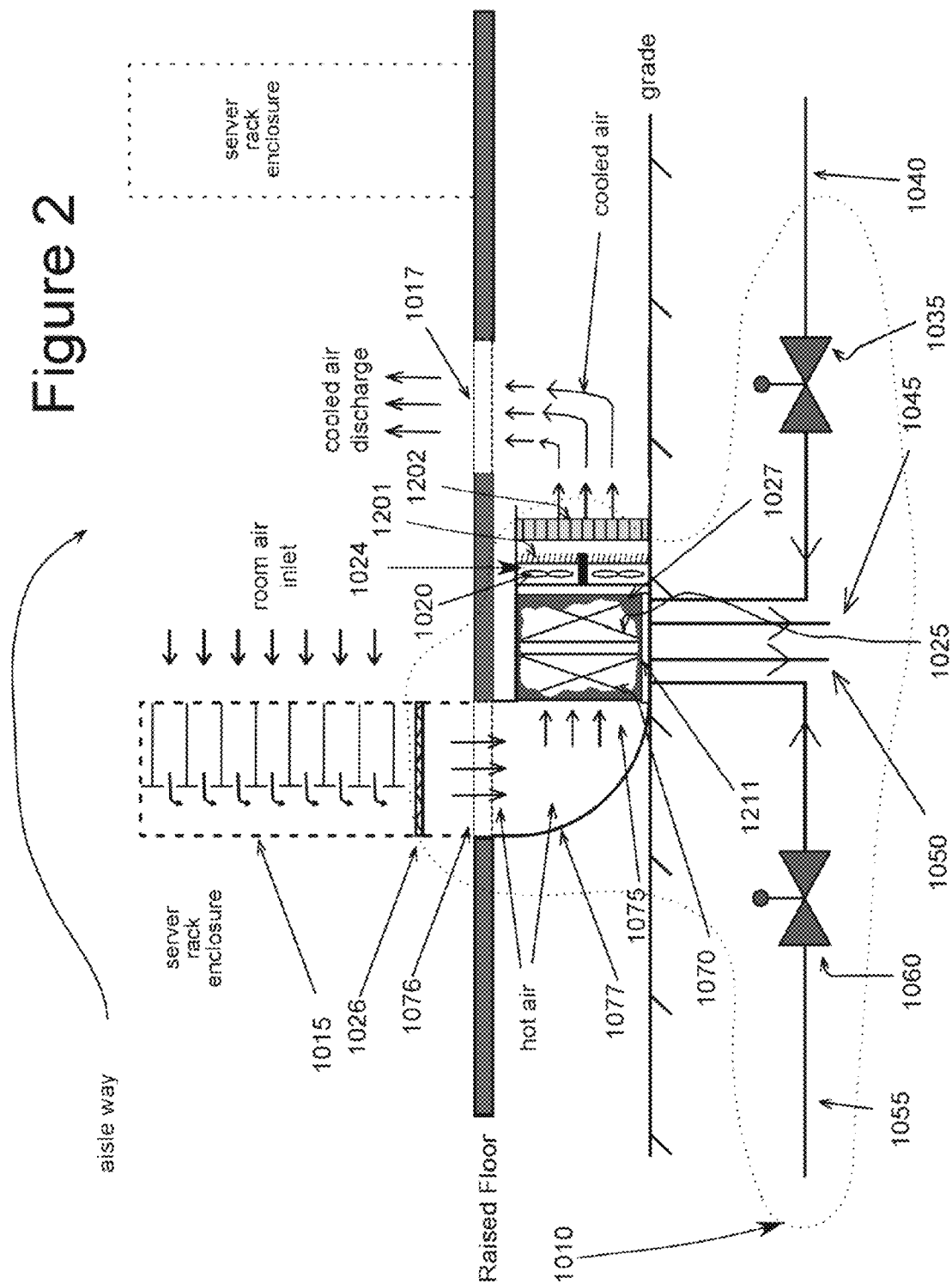
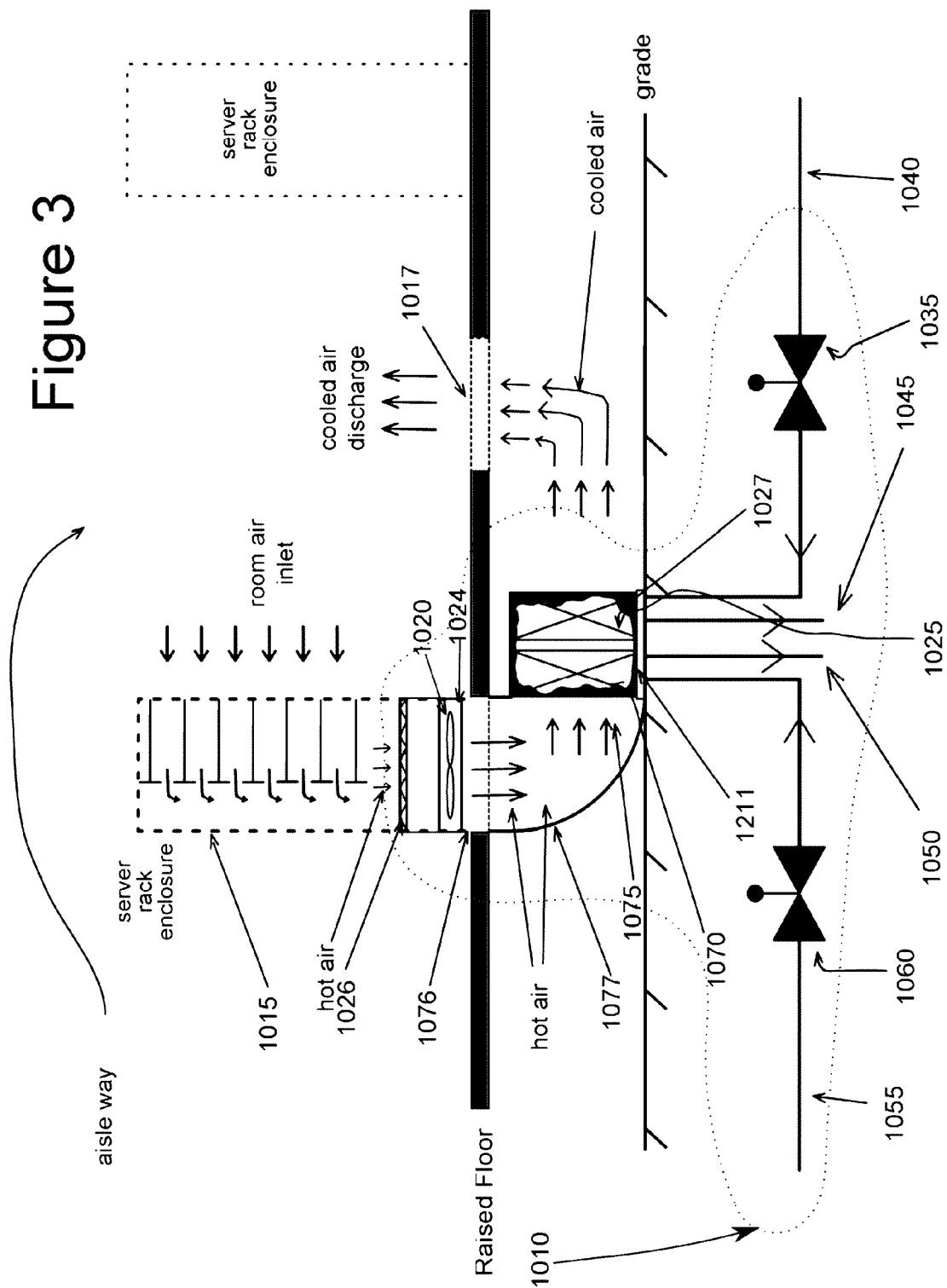
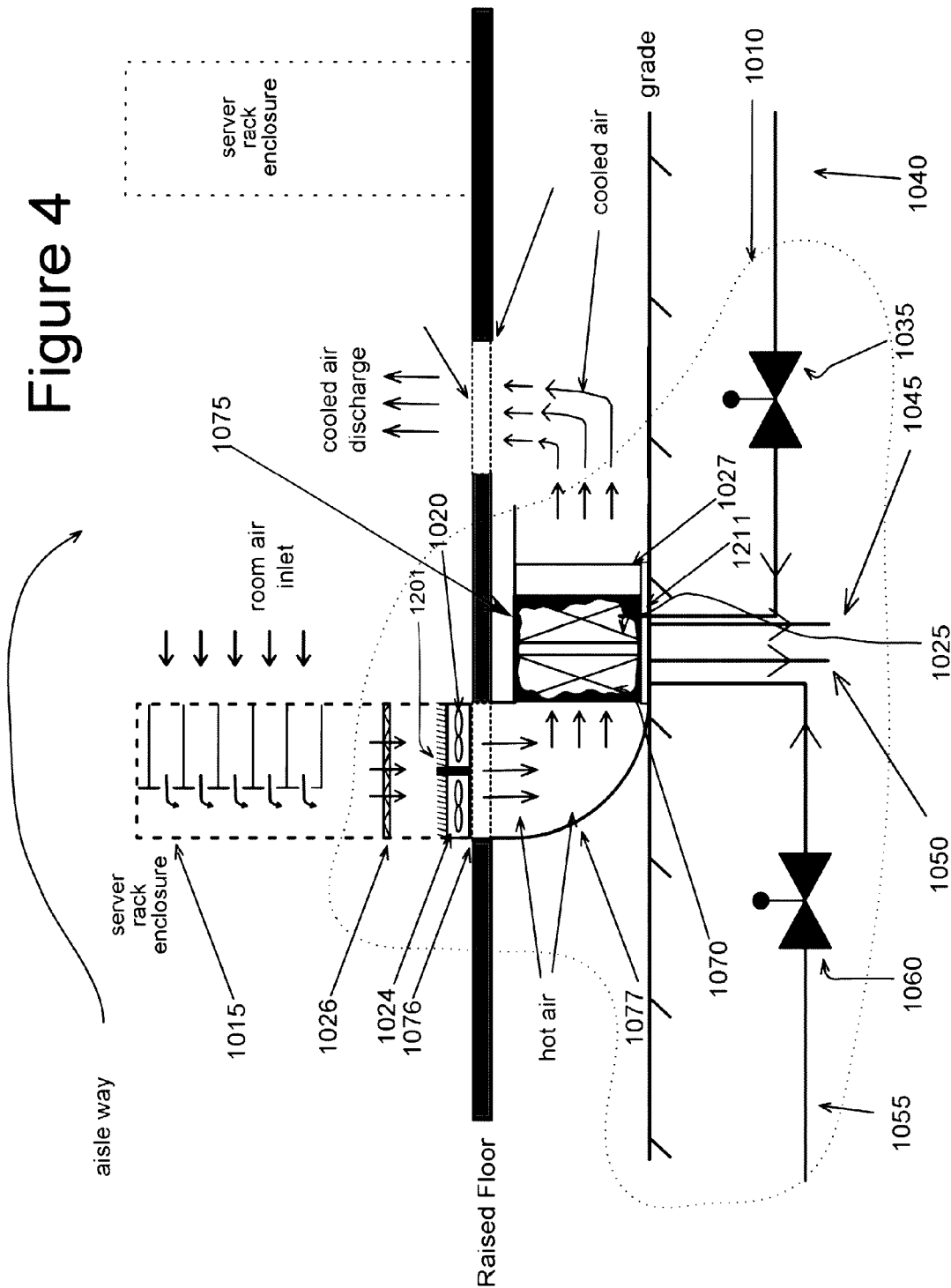


Figure 3





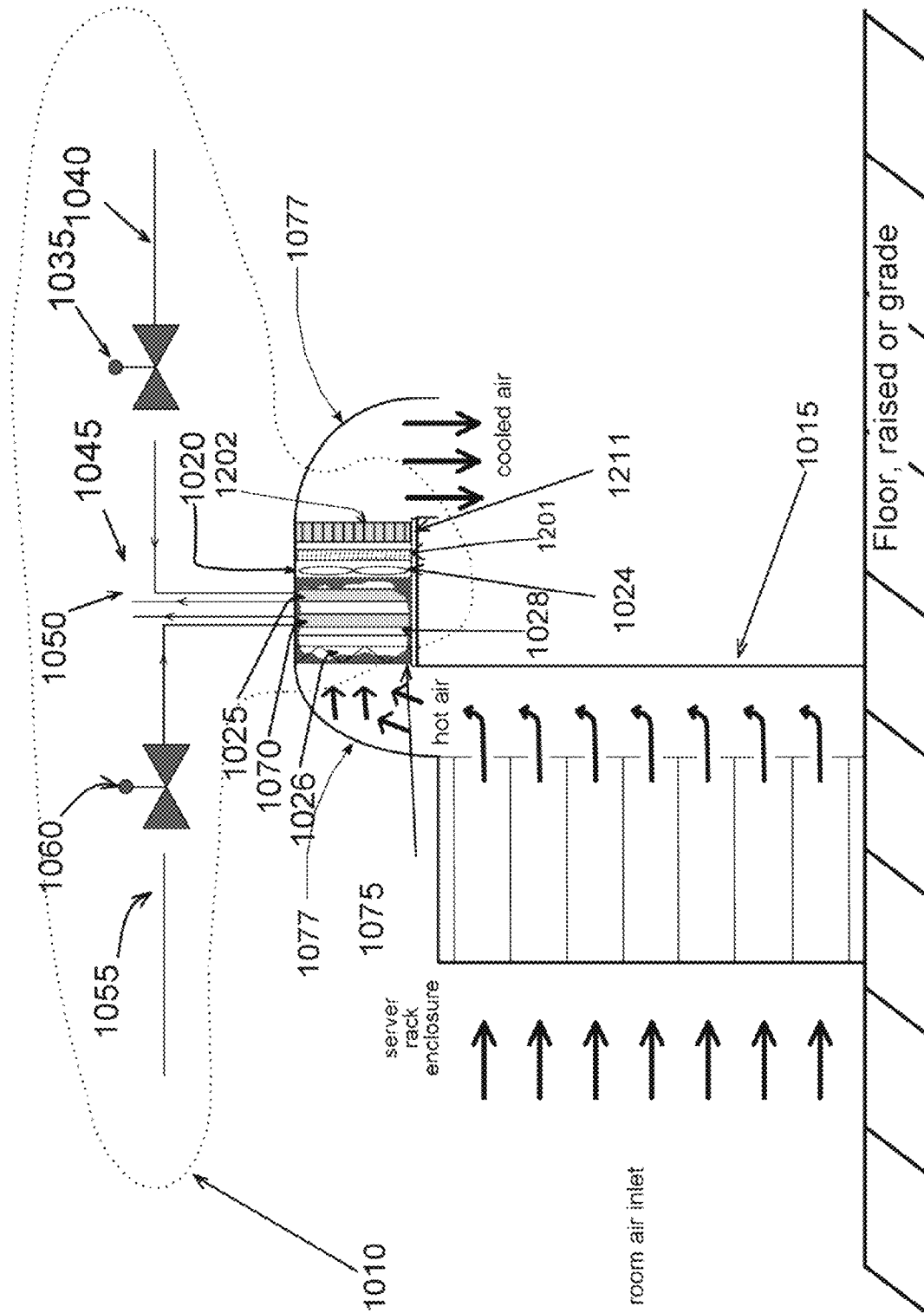


Figure 5

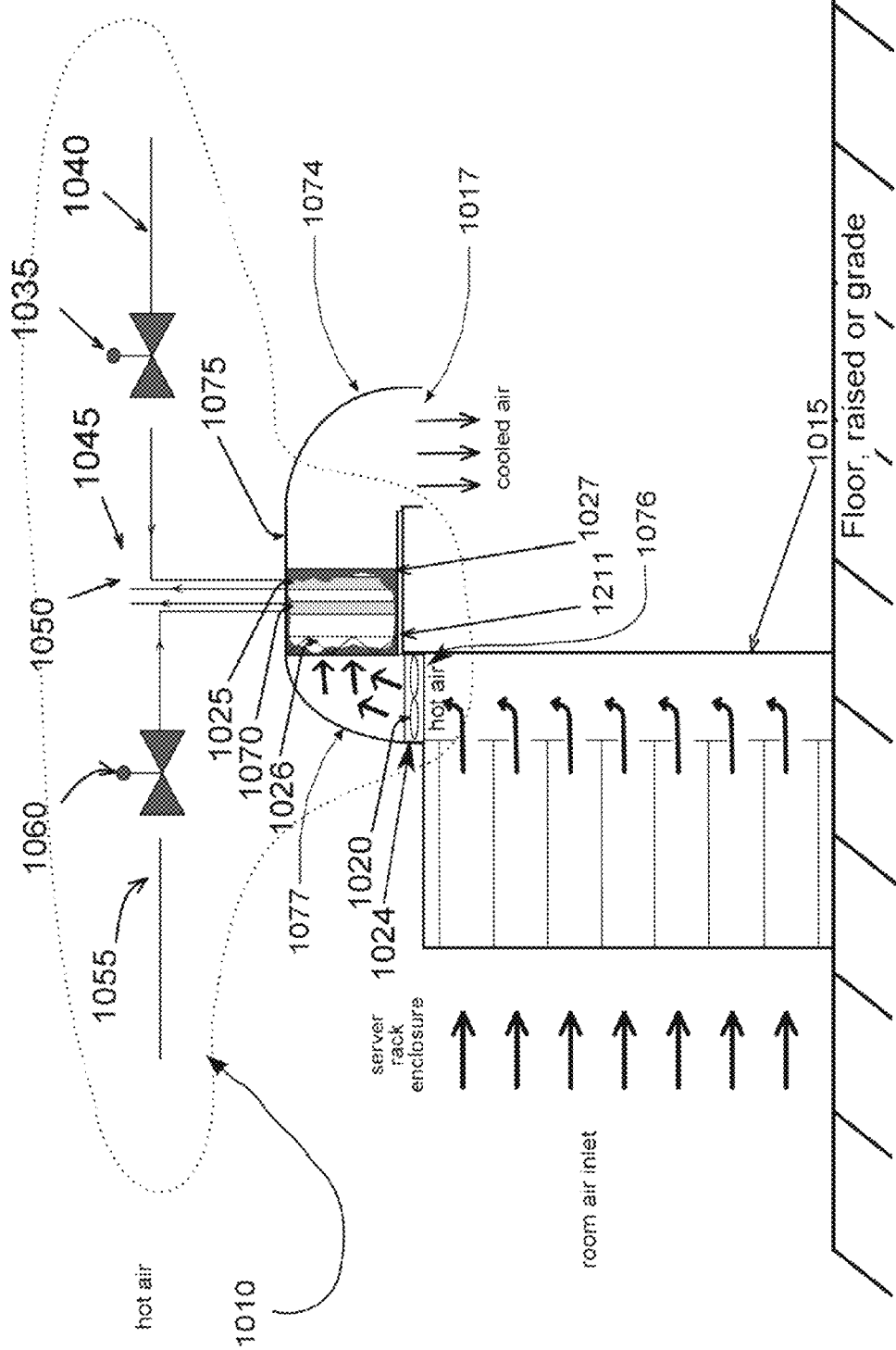


Figure 6

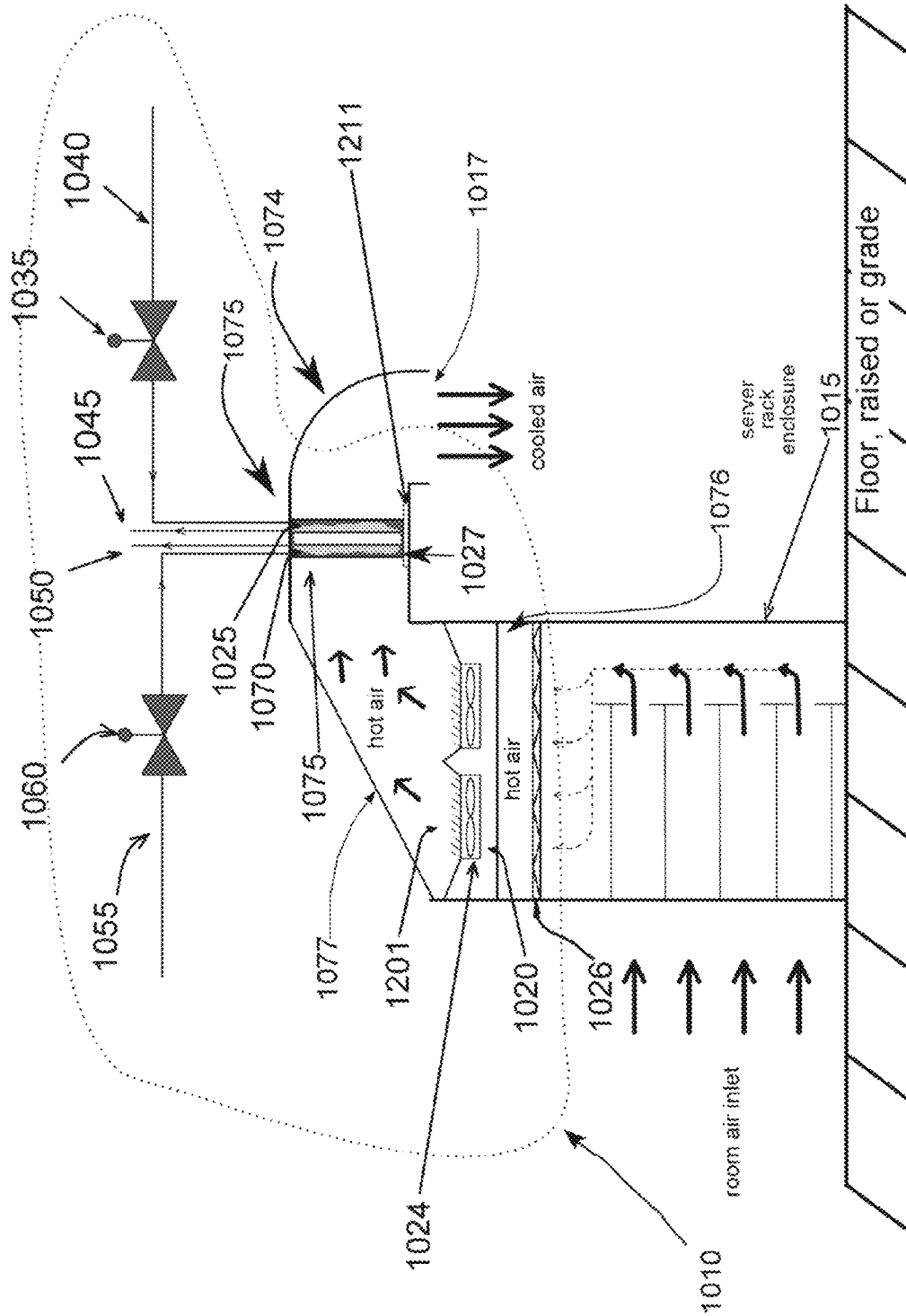
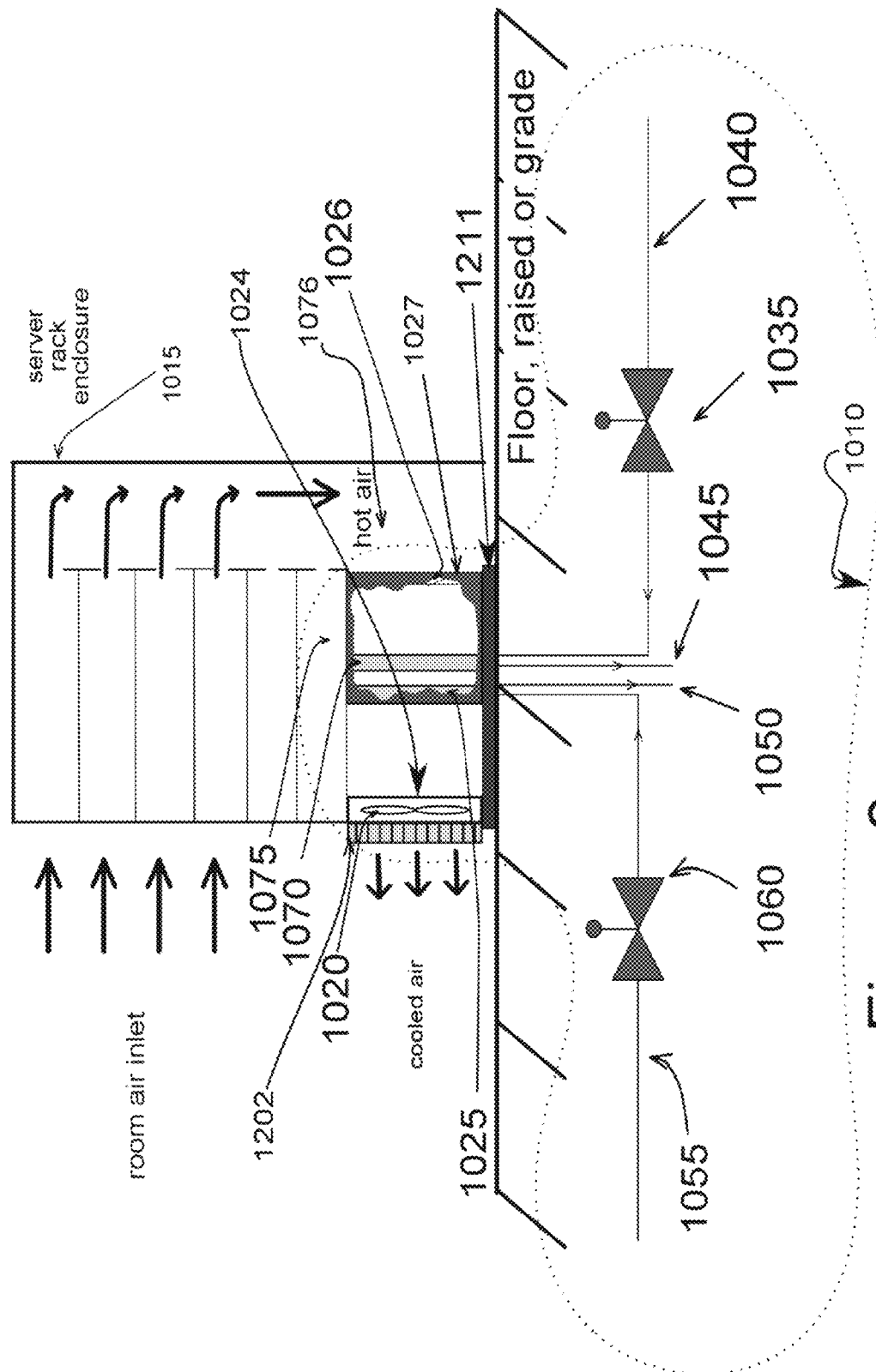
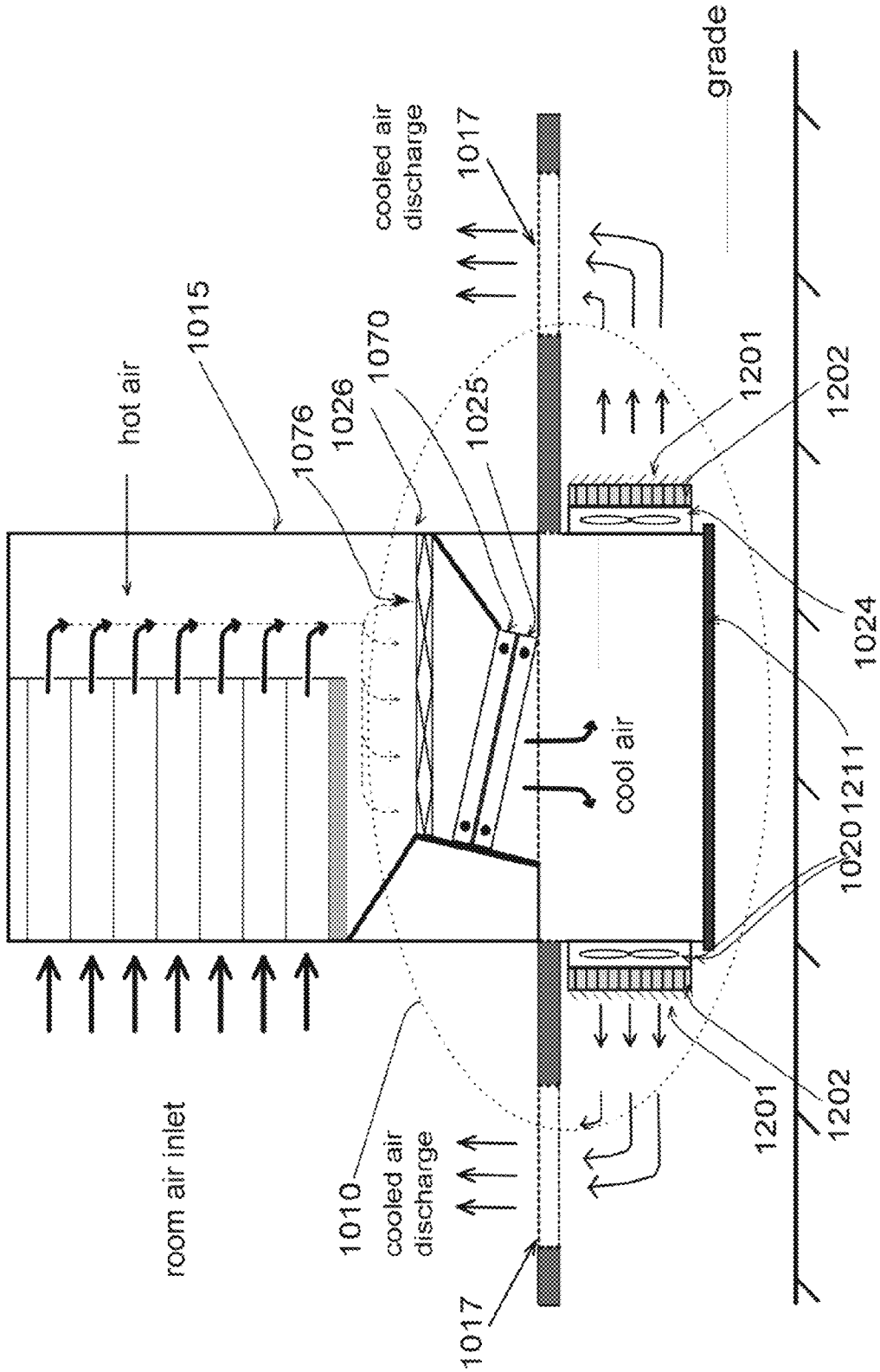


Figure 7



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Figure 9



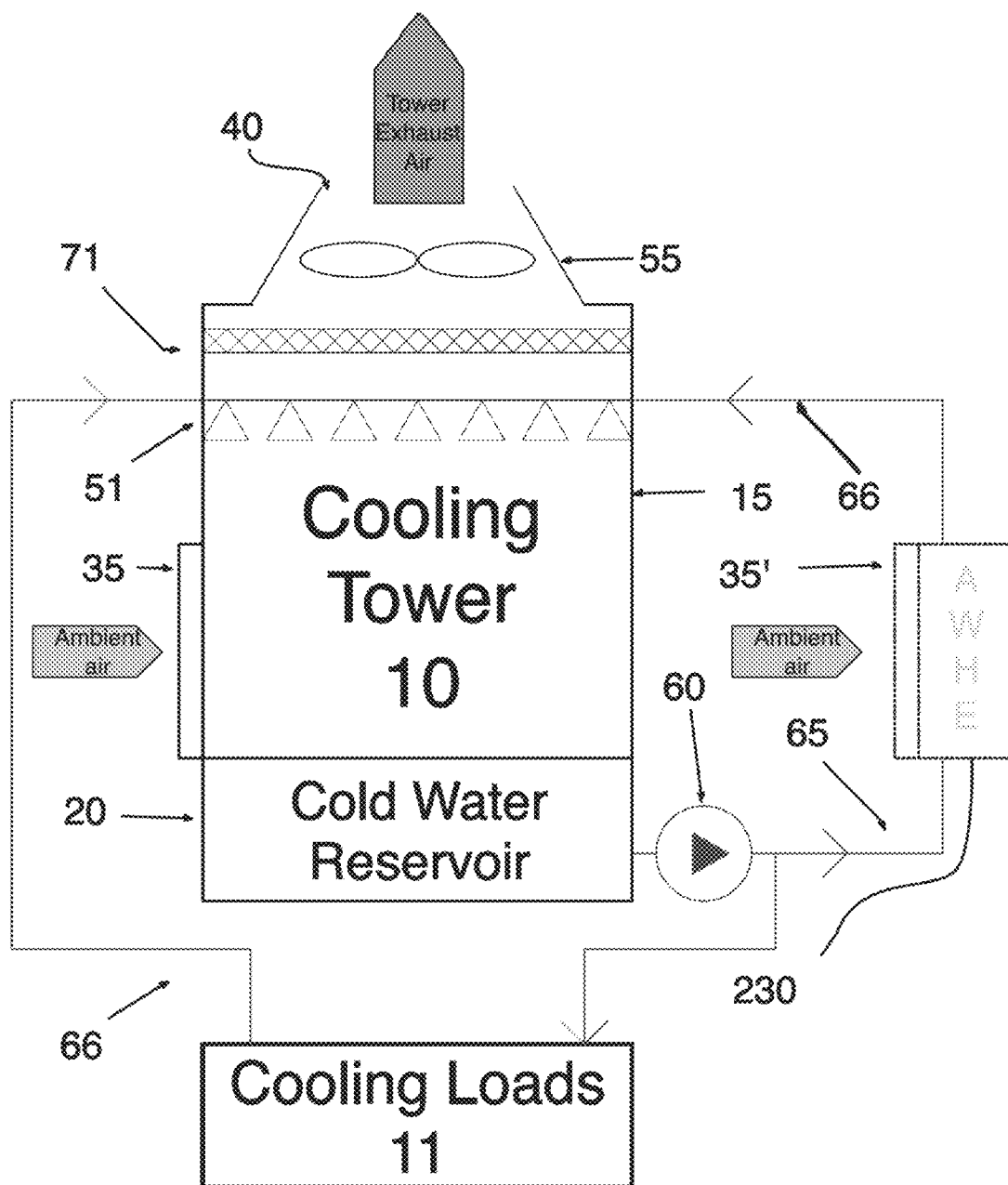


Fig. 10

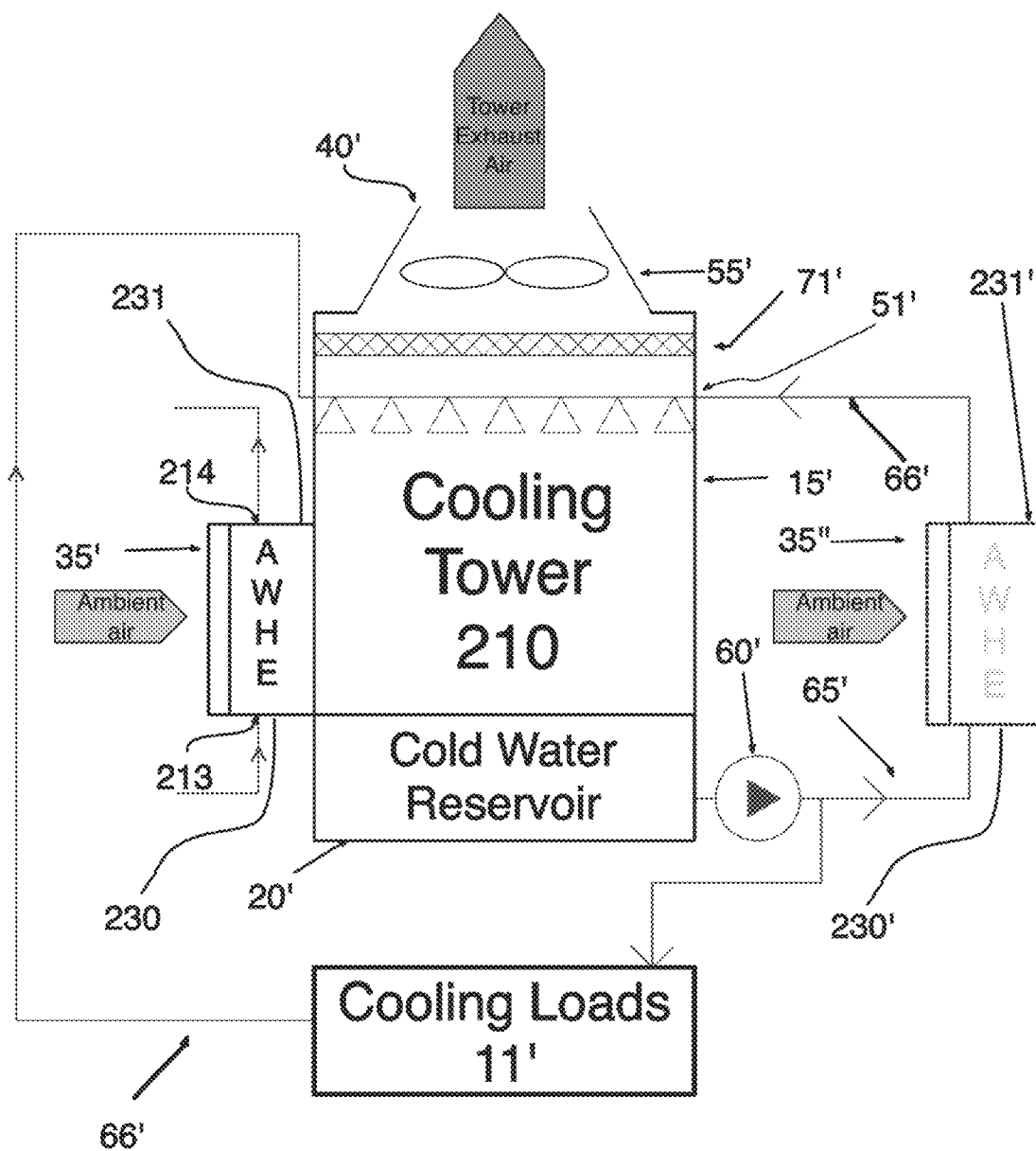


Fig. 11

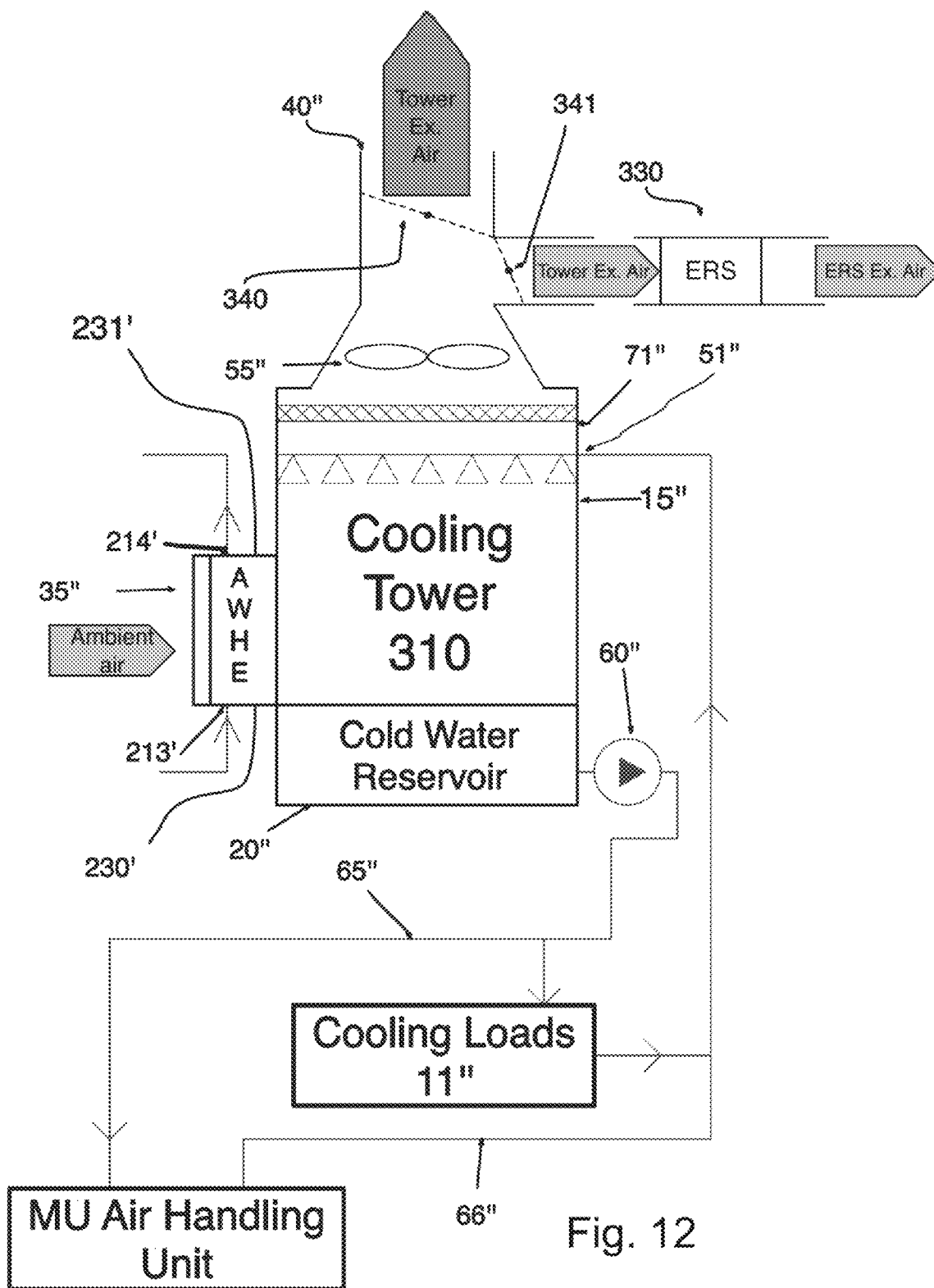
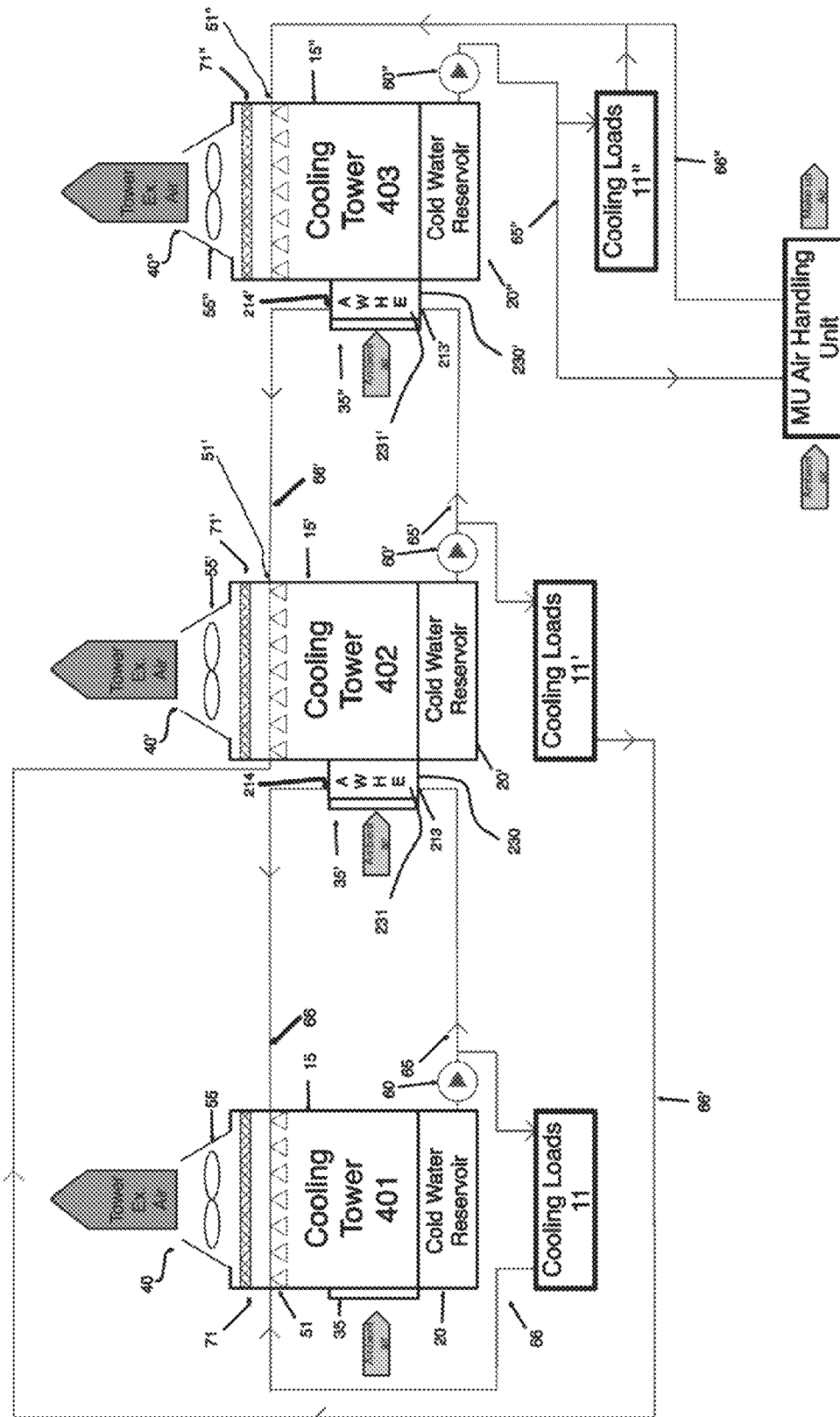
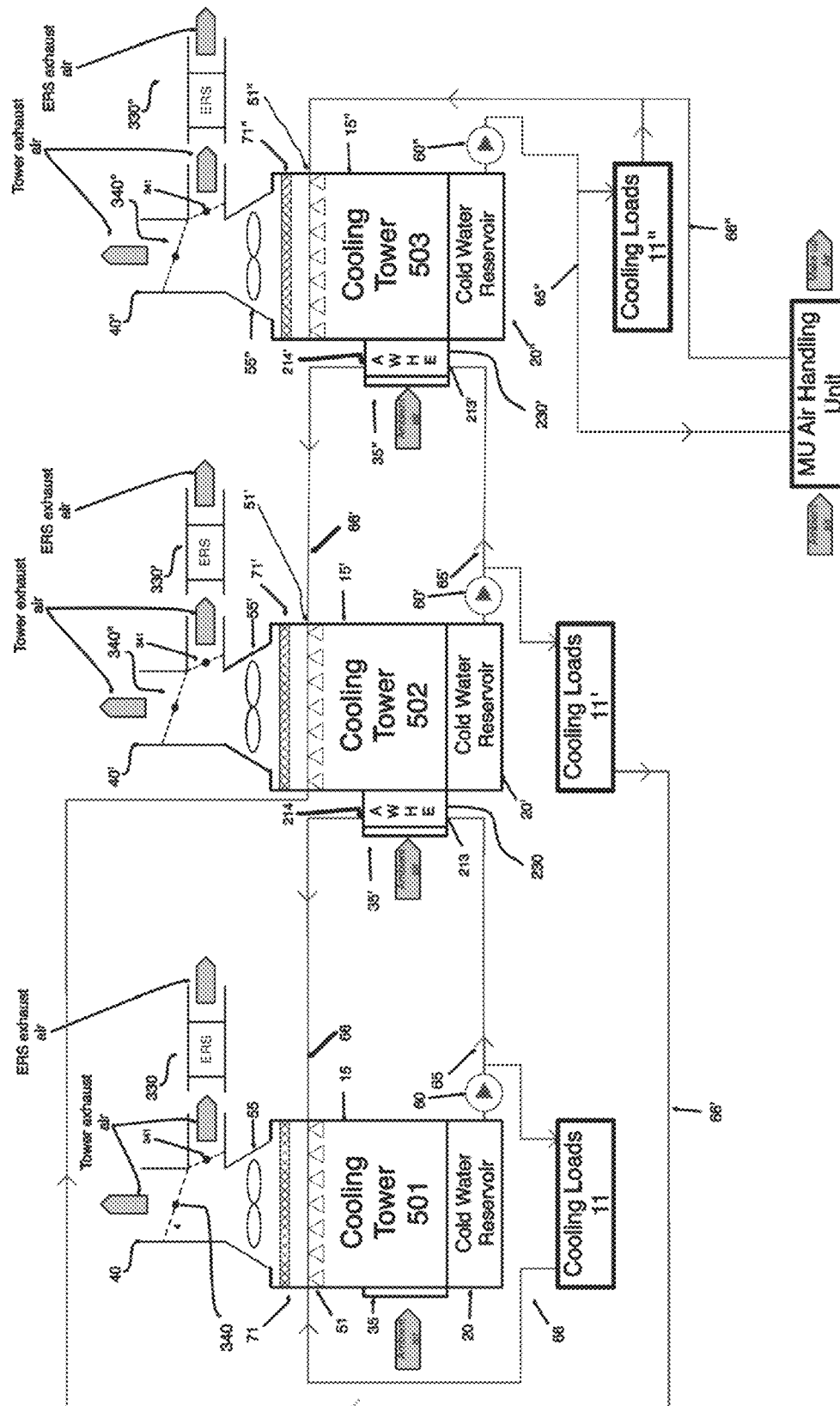


Fig. 12



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445



405

35

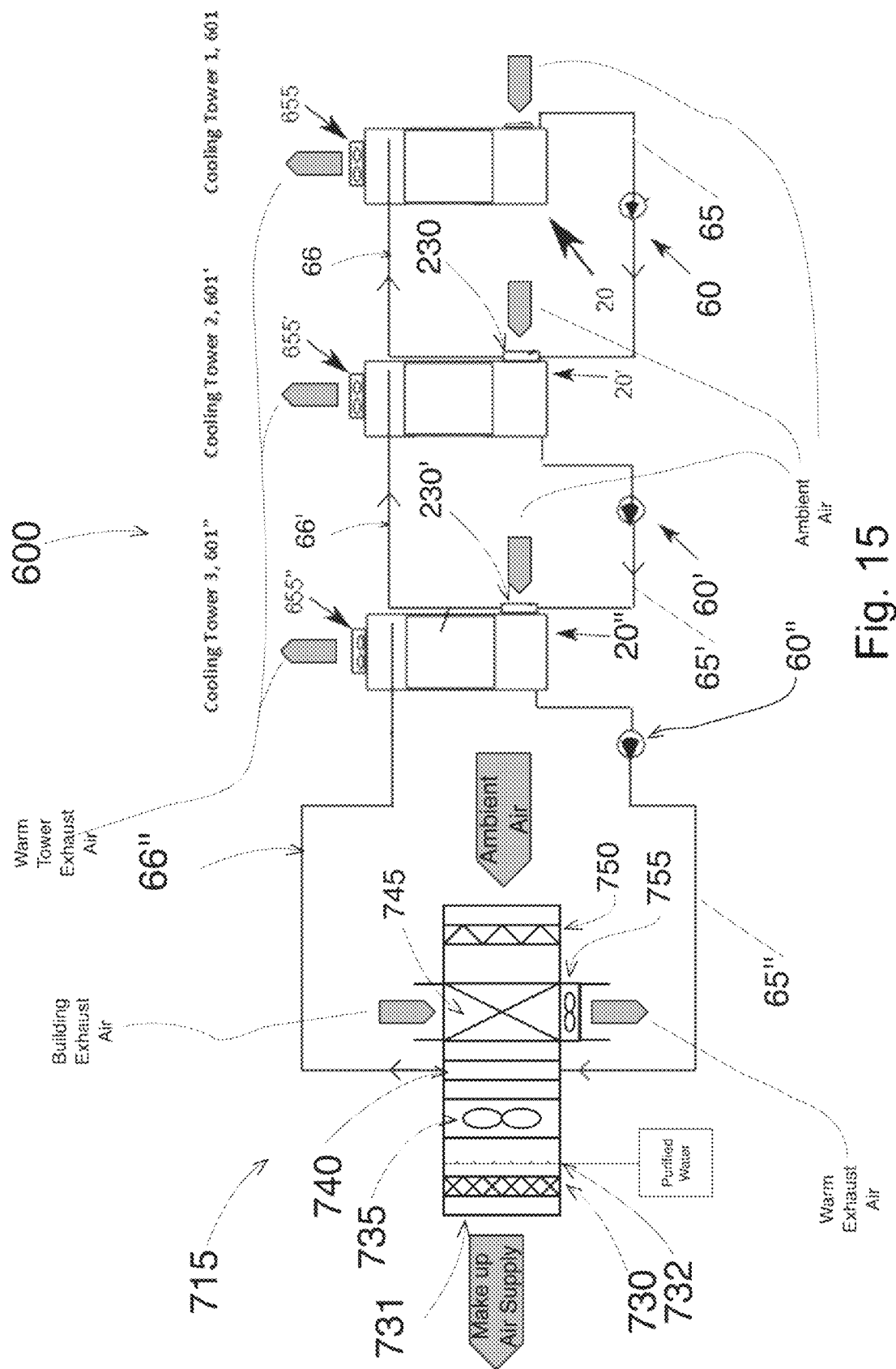
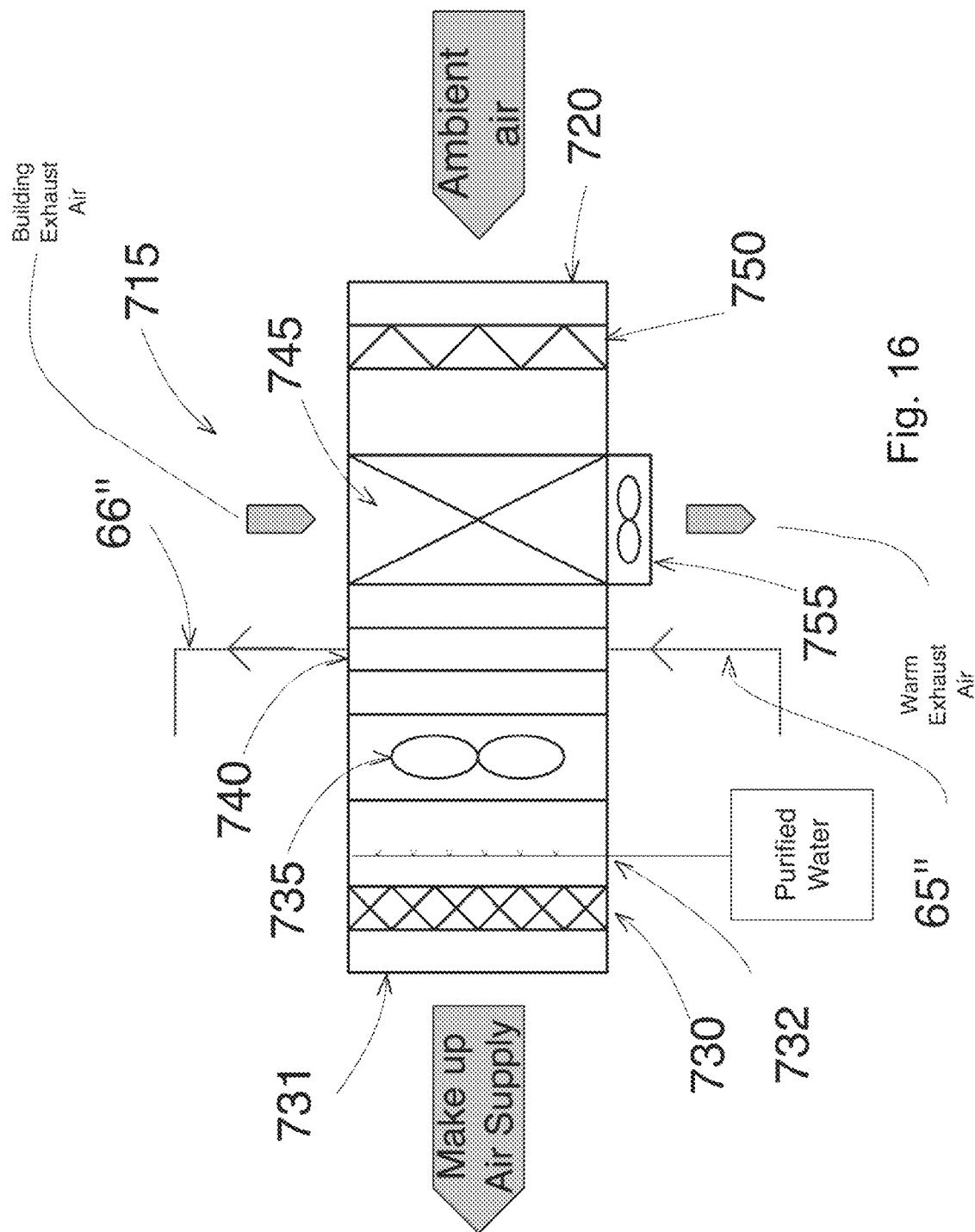


Fig. 15



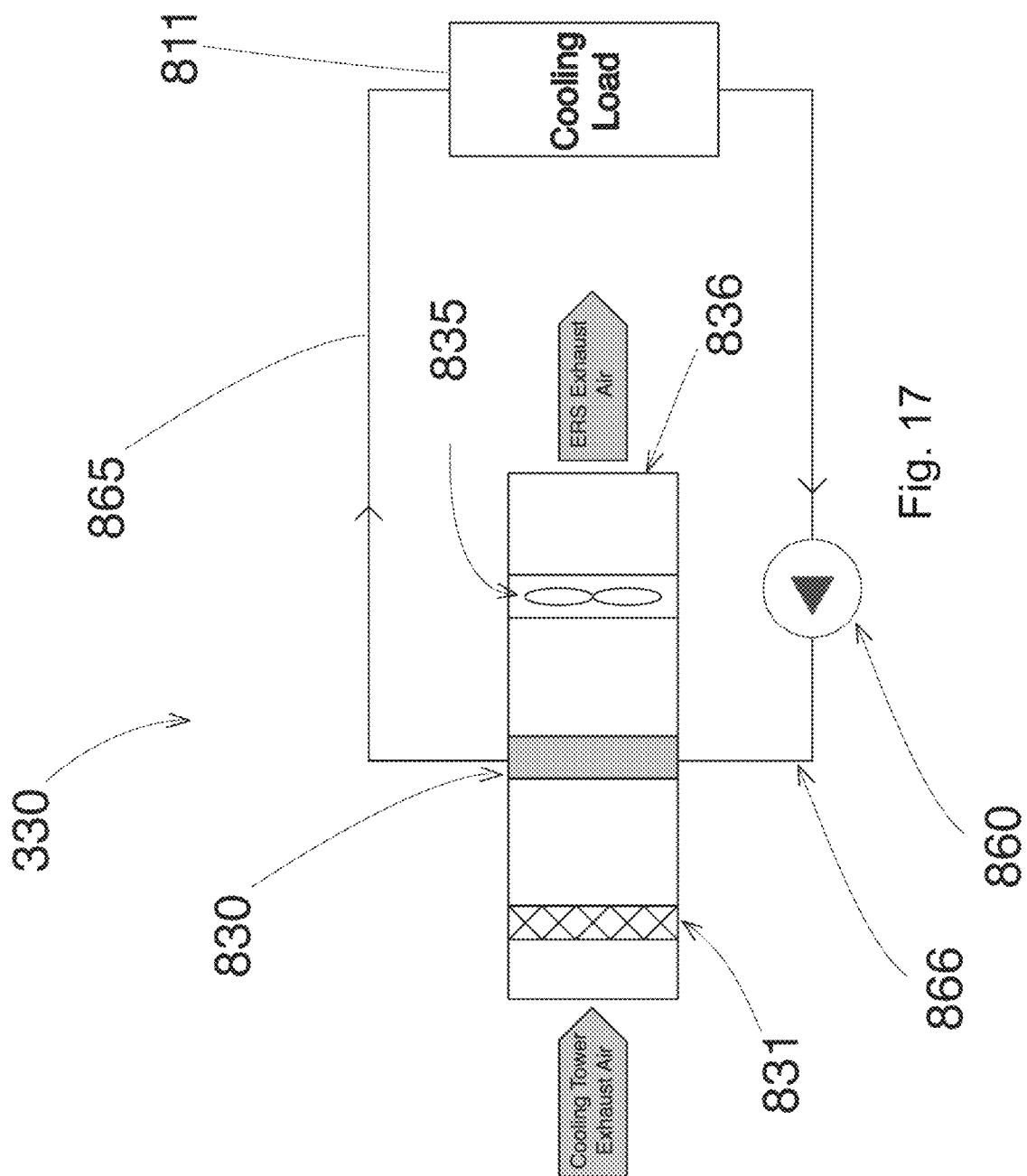


Fig. 17

8
1
5
1

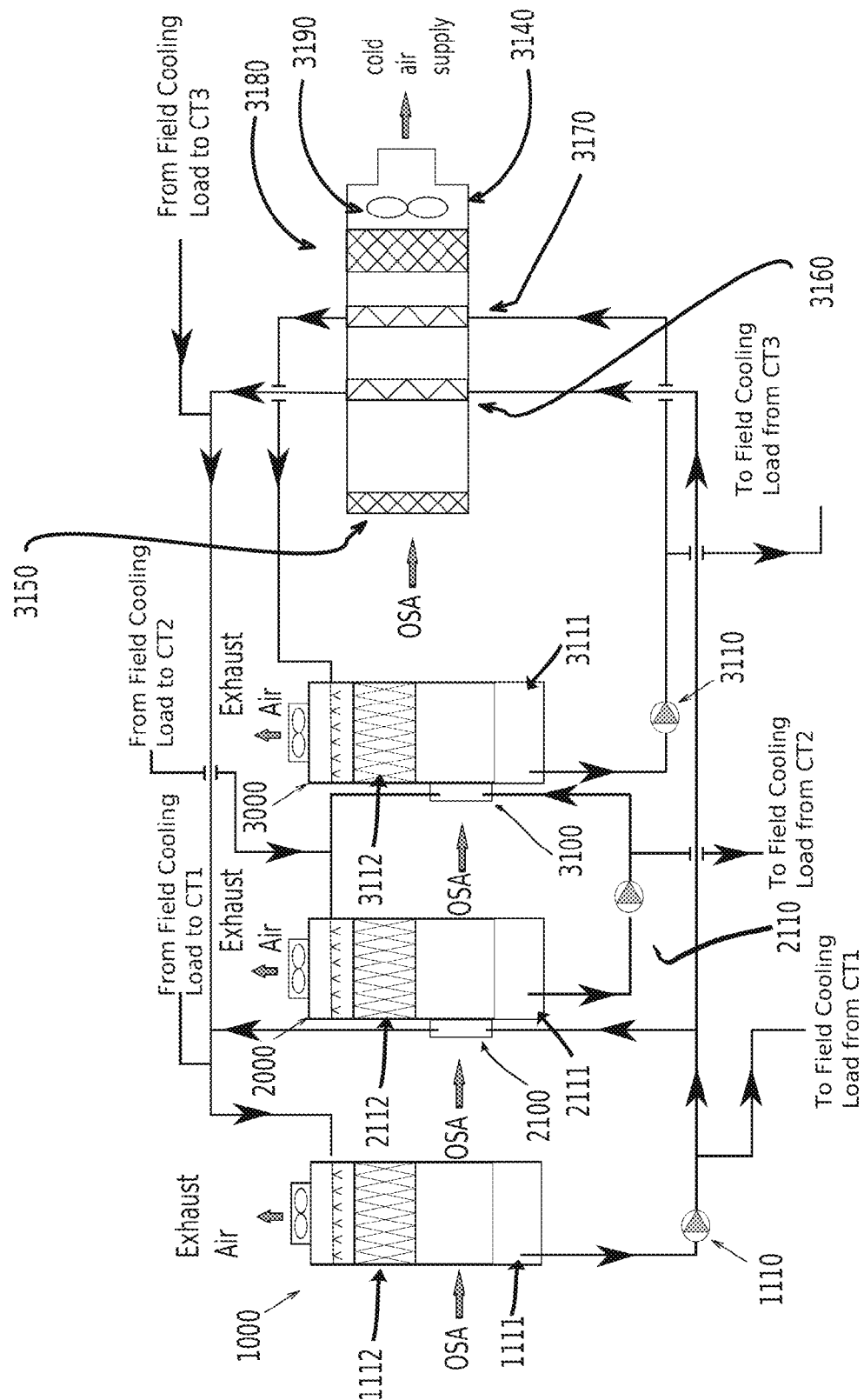


Fig. 19

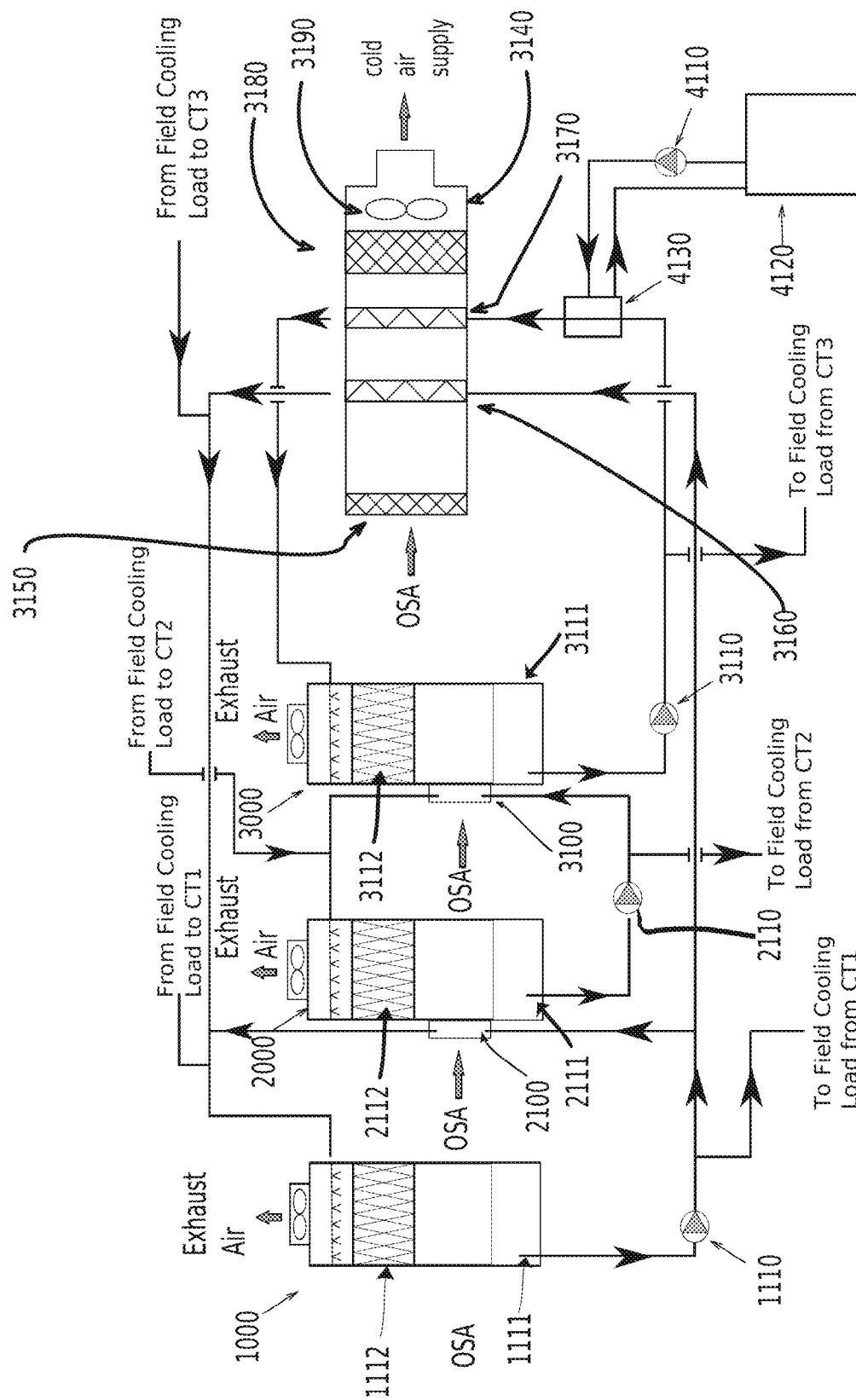


Fig. 20

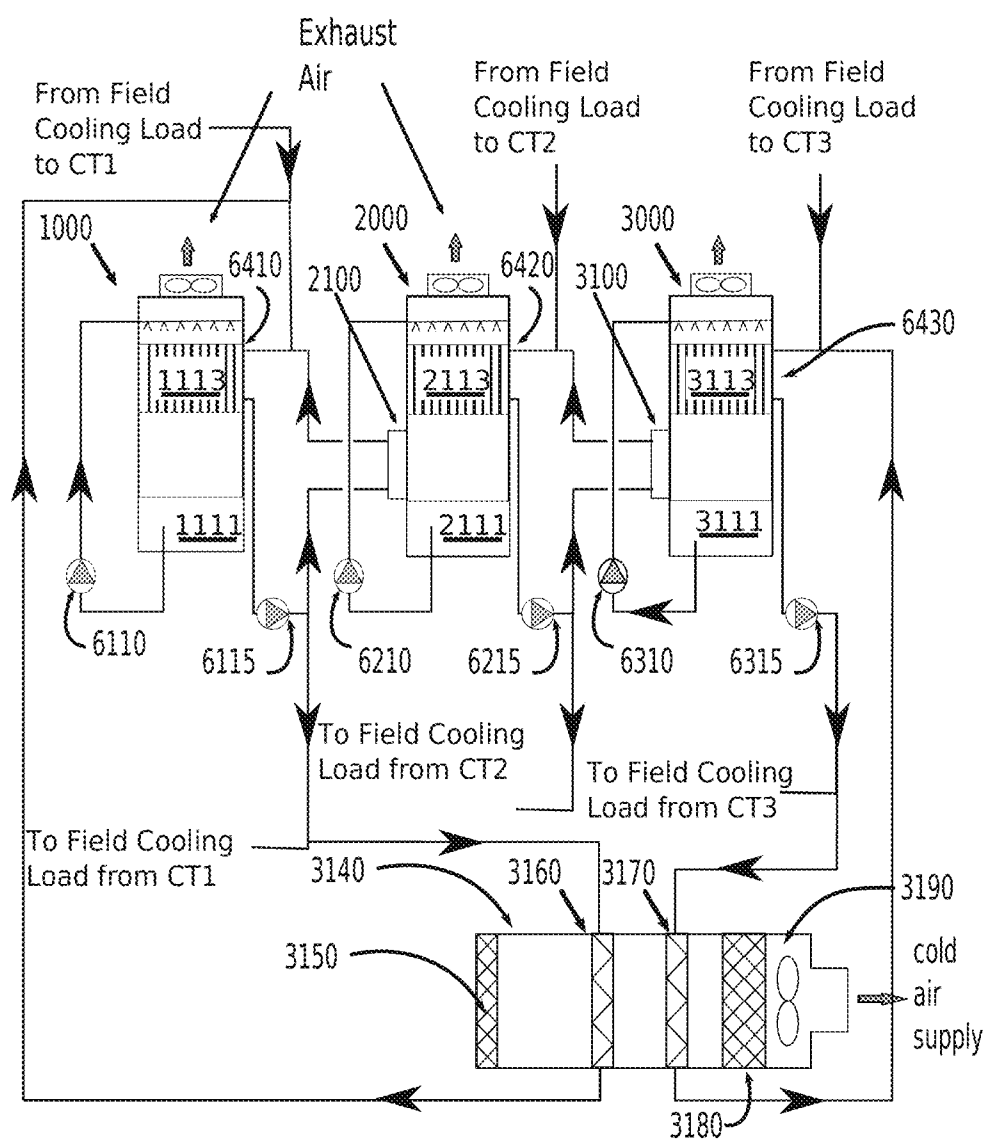


Fig. 21

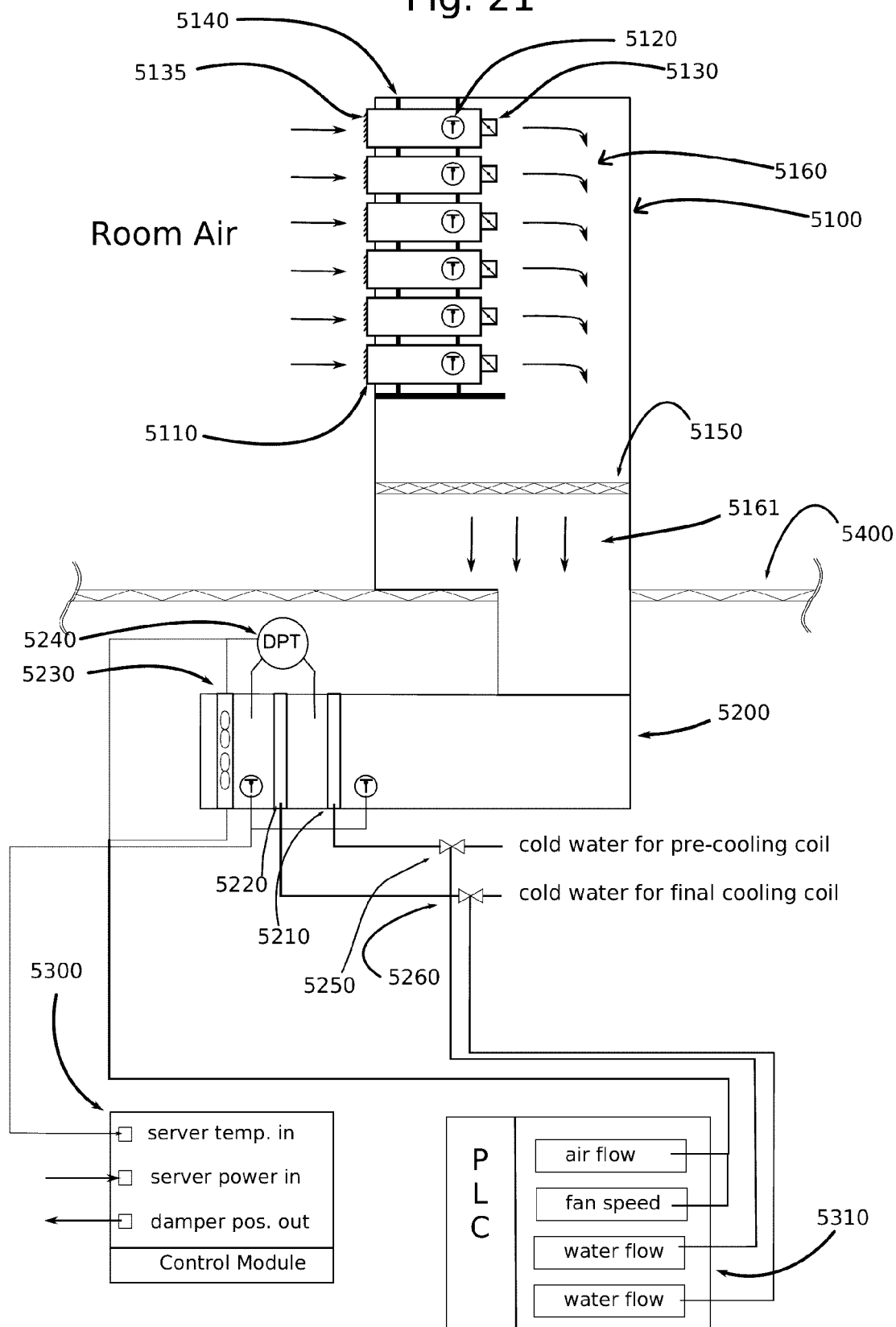


Fig. 22

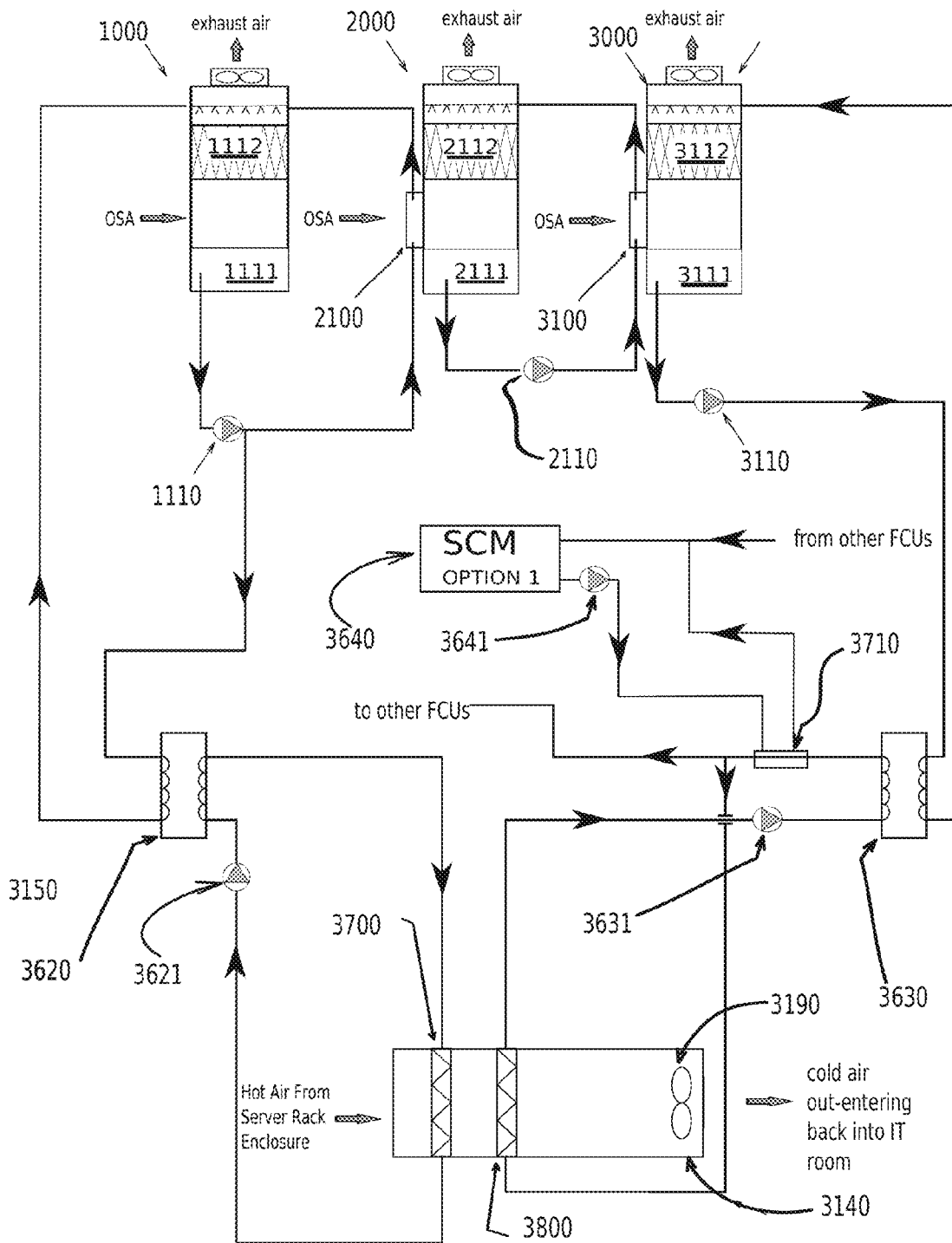


Fig. 23

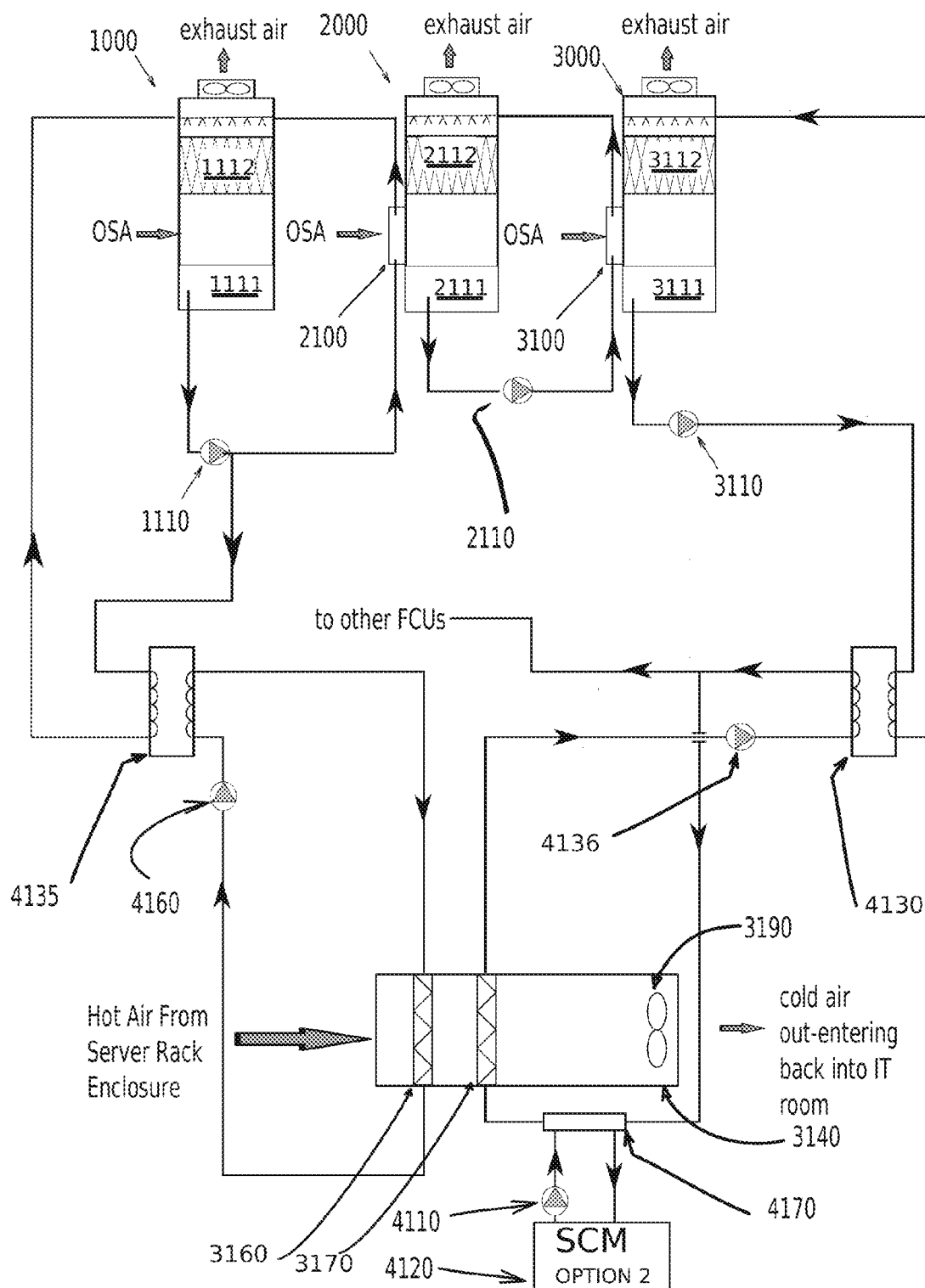
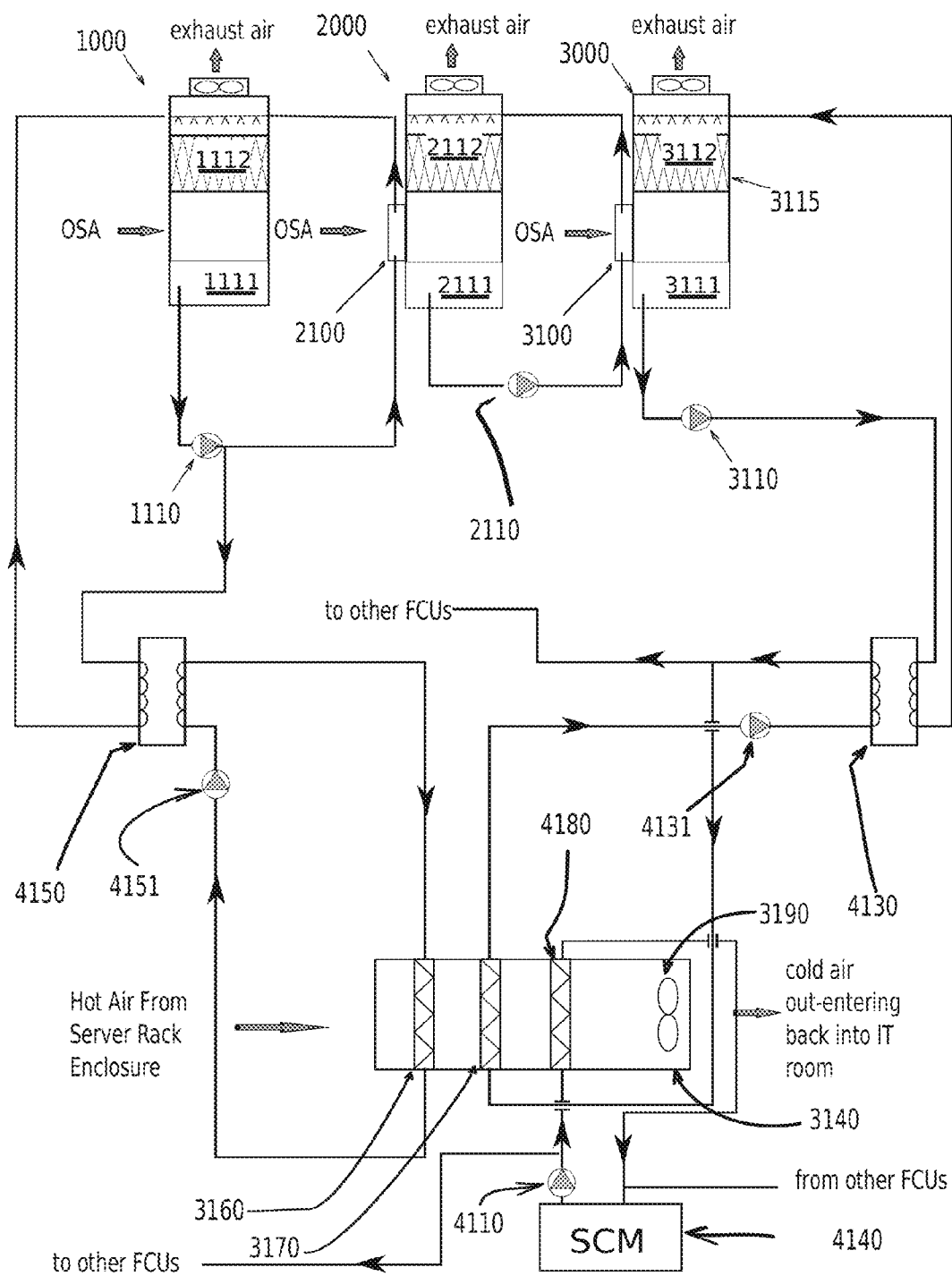


Fig. 24



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REAL-TIME INDIVIDUAL ELECTRONIC ENCLOSURE COOLING SYSTEM

BACKGROUND

“Data center energy usage has risen dramatically over the past decade and will continue to grow in-step with the processor intensive applications that support business and day-to-day life in the modern world. The growth of technology has driven the data center into a new phase of expansion, and while data centers themselves may vary over different industry segments, there are common factors influ-

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below lists some methods commonly used in the industry. These products are available from various manufacturers—some have been available for quite some time and others have just recently been introduced. The table is not a complete list of vendors, but is intended as a reference for some of the most commonly deployed systems.

Table 1 illustrates energy usage by evaluating the energy required to operate the system in kilowatts (kW) versus the cooling capacity provided in tons of cooling/refrigeration (12,000 BTU/hr is equivalent to 1 ton of refrigeration)—a kW/ton rating.

TABLE 1

	Availability	Manufacturers	Commonality in the Industry
CRAC Cooled System	30+ Years	Liebert, DataAire,	Very Common
CRAH Cooled System	30+ Years	Liebert, DataAire,	Very Common
CRAC Cooled System W/Containment	5-10 Years	The above for Cooling units; containment from Rittal, CPI, Polargy, APC, Knurr	Gaining Widespread Acceptance
CRAH Cooled System W/Containment	5-10 Years	The above for Cooling units; containment from Rittal, CPI, Polargy, APC, Knurr	Gaining Widespread Acceptance
Liquid Cooled Rack Unoptimized	8 Years	Rittal, APC, Knurr, Liebert, HP	Common
Liquid Cooled Racks Chilled Water Temperature Optimized	8 Years	Rittal, HP, Knurr	Less Common
Liquid Cooled Racks Chilled Water Temperature Optimized and Free Cooling Systems	8 Years	Rittal, HP, Knurr	Less Common
Liquid Cooled Racks Chilled Water Temperature Optimized and Evaporative Free Cooling Systems	8 Years	Rittal, HP, Knurr	Less Common
Active Liquid Cooled Doors, Chilled Water Temperature Optimized and Evaporative Free Cooling Systems	5 Years	Rittal	Less Common
Passive Liquid Cooled Doors Chilled Water Temperature Optimized and Evaporative Free Cooling Systems	8 Years	Rittal, IBM, Vette	Less Common
Pumped Refrigerant Systems Air Side Economizing	5 Years 30+ Years	Liebert Custom Engineered Solutions with components from various providers	Less Common Common
Liquid Cooled Servers	30+ Years	Originally used in mainframes, but proposed 100% heat removal very rare, closest manufacturer would be SprayCool	Rare

encing all of them including a need to do more with the same resources, or in some cases, even less. To this end, much has been done to increase server efficiency and IT space utilization, but the actual space and cooling infrastructure supporting these intensified loads has often not been properly addressed to keep pace with these developments—an important oversight since cooling can represent up to 42% of a data center’s energy usage.”

Daniel Kennedy, Rittal White Paper 507: Understanding Data Center Cooling Energy Usage & Reduction.

Available Cooling Systems

Over the years, many methods have been used to cool IT loads in the Data Center environment. The master table

Typical Data Center cooling is accomplished using standard HVAC techniques. That is, the whole building is cooled just as any other building is cooled using supply and return air ductwork, under-floor air distribution space, air inlets, air outlets, etc. Primarily, the air is conditioned at a small number of locations and then moved through ductwork and/or via under-floor air distribution space to a desired outlet location. Once expelled from the outlet, the cooled air mixes with room air. Eventually, the room air enters a server rack where it picks up heat from the servers and the hot air is expelled back into the room where it again mixes with room air. In some slightly more sophisticated systems, the

server racks are arranged into aisles, which do a better job of segregating warmed air from cooled air. But in most cases, heat is generated far from the location of the room temperature controllers and far from where heat is removed. This distance causes a big thermal lag or inertia in the system and requires that some areas be over cooled to insure sufficient cooling building wide. This wastes energy. The following table provides data about the capacity, operation; CAPital Expenditures (CAPEX) and OPERating cost Expenditures (OPEX) of typical Data Centers where even the oversized cooling systems are unable to provide the required cooling to the all IT Room server rack enclosures.

Data Center LOST capacity is the inability to convert the intended design loading capacity into operational reality, or in other words, resources are not fully utilized. Changes to the Data Center capacity roadmap, i.e. increased Rack load densities, which fail to conform to initial design and design assumptions results in lost capacity. Data Center capacity is LOST when changes from the original design causes space, power, COOLING, or network to become unavailable to the IT equipment. For example, if Rack densities increase from 4 KW per Rack to 8 KW per Rack, the IT load in the average enterprise Data Center is increased from IX KW to 2X KW, but the COOLING system was initially design for IX KW plus, in some cases, 50% accounting for unexpected additional COOLING requirements or 1.5X KW. At an increased density to 2X KW per Rack, the Data Center will have to decommission 25% of its Racks reducing its Data Center Capacity by 25% due to lack of COOLING resources. Analysis shows an Annual Cost of Deployed Capital of \$8,308 per KW related to Data Center CAPEX and OPEX resulting in substantial costs to the Data Center for loosing capacity due to lack of COOLING.

TABLE 2

Lost Capacity and its Capital Cost to a Data Center Based on Future Facilities White Paper "The Elephant in the Room is Lost Capacity" and the Uptime Institute Analysis of 3 MW Data Center		
MWs	1.3	
KWs	1300	
Annualized CAPEX	\$6,300,000	
Annualized OPEX	\$3,100,000	
Load Dependent OPEX	\$1,400,000	
Total Annual Capital Deployed	\$10,800,000	
Total Annual Capital Deployed per KW	\$8,308	
Lost Capacity - 20% for 1 year and for 5 years	\$2,160,000	\$10,800,000
Lost Capacity - 30% for 1 year and for 5 years	\$3,240,000	\$16,200,000
Lost Capacity - 40% for 1 year and for 5 years	\$4,320,000	\$21,600,000

What is needed is a system of cooling server racks or electronics enclosures that more closely places cooling means near the heat load of the server and which is capable to provide real time cooling for an individual server rack or electronics enclosure based on its load demand.

SUMMARY

Invention embodiments comprise a system comprising a multistage evaporative cooling system and an individual server enclosure cooling system. In various embodiments, the ISECS comprises a housing, a cooling coil unit including a cooling coil mounted in the housing wherein the cooling coil is adapted to circulate a volume of cold water; a fan rack including at least one fan wherein the fan rack is located within or services the housing; and a computer-based com-

mand-and-control system in signal communication with one or more sensors configured to sense a cooling parameter wherein the individual server enclosure cooling system is adapted to connect to or sit within a server rack or electronics enclosure and wherein the individual server enclosure cooling system is in fluid communication with a multistage evaporative cooler.

In some embodiments the fan rack and the cooling coil unit sit within the housing at an air inlet to the server rack enclosure; the fan rack and the cooling coil unit sit within the housing at an air outlet from the server rack enclosure; the fan rack sits at an air outlet from the server rack enclosure and the cooling coil units sits at an air inlet to the server rack enclosure; or the fan rack sits at an air inlet to the server rack enclosure and the cooling coil unit sits at an air outlet from the server rack enclosure. Some embodiments use one, two, three, four, or more fans. Similarly, some embodiments use one, two, three, four, or more cooling coils.

Various embodiments draws electrical power at a rate of less than 0.93, 0.9, 0.85, 0.82, 0.80, 0.78, 0.75, 0.73, 0.70, 0.69, 0.65, or 0.60 kilowatts per ton of cooling.

In some embodiments, the system uses a computer-based command-and-control system that monitors a cooling parameter. Some embodiments monitor the cooling parameter and run algorithms that facilitate drawing electrical power at a rate of less than 0.93, 0.9, 0.85, 0.82, 0.80, 0.78, 0.75, 0.73, 0.70, 0.69, 0.65, or 0.60 kilowatts per ton of cooling. In some of these embodiments, the rate of electrical power use is less than 0.60 kilowatts per ton of cooling under appropriate ambient and operating conditions. Sometimes monitoring a cooling parameter encompasses evaluating the instantaneous value, a time-differentiated value, or a time-integrated value of the cooling parameter. In these or in these or other embodiments, the cooling parameter is at least one of air and water temperature; air and water flows, differential air and water pressures, air humidity; electric power consumption (loads) of racks, servers, power distribution units, uninterruptable power supplies, lighting, transformers and switchgear, pumps, fans, motors or combinations of these. In these or other embodiments, the cooling parameters are measured throughout the system such as measured through the individual server enclosure cooling system, in the individual server enclosure cooling system, or at some point within the server rack enclosure or within some other part of the building.

In some embodiments, the computer-based command-and-control system adjusts at least one cooling control that manipulates a control parameter. In these or other embodiments, a control parameter is any one or any combination of fan speed for one or more fans; cooling fluid pump speed for one or more cooling coils; cooling fluid flow rate for one or more cooling coils; cooling fluid temperature for one or more cooling coils; or cooling air flow rate. Invention computer-based command-and-control system may monitor one or more cooling parameters or adjusts one or more cooling controls such that the average temperature of air moving through the server rack enclosure remains within 5, 4, 3, 2, 1, 0.75, or 0.5 degrees of a set point temperature.

In some system embodiments, the cooling coil unit sits near the air outlet of the server rack enclosure and comprises at least two cooling coils and wherein the fan rack sits disposed cooling coil unit, wherein the cooling coil unit and the fan rack are disposed within the housing; and wherein the individual server enclosure cooling system sits under a floor supporting the server rack enclosure or sits within the server rack enclosure.

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In some embodiments, an invention system comprises a multistage evaporative cooling system and an individual server enclosure cooling system adapted to connect to a server rack enclosure or located within a server rack enclosure, wherein the individual server enclosure cooling system comprises a housing; a cooling coil unit including a cooling coil mounted in the housing wherein the cooling coil is adapted to circulate a volume of cold water; a fan rack including at least one fan wherein the fan rack is located within or services the housing; and a computer-based command-and-control system in signal communication with one or more sensors configured to sense a cooling parameter and that monitors at least one cooling parameter by evaluating an instantaneous value, a time-differentiated value, or a time-integrated value of the cooling parameter wherein the cooling parameter is at least one of air and water temperature; air and water flow; differential air and water pressures; air humidity; or electric power consumption of racks, servers, power distribution units, uninterruptible power supplies, lighting, transformers, switchgear, pumps, fans, or motors and the cooling parameter is measured through the individual server enclosure cooling system, in the individual server enclosure cooling system, or at some point within the server rack enclosure or within some other part of the building and wherein the computer-based command-and-control system is capable of adjusting at least one cooling control that manipulates a control parameter comprising fan speed for one or more fans; cooling fluid pump speed for one or more cooling coils; cooling fluid flow rate for one or more cooling coils; cooling fluid temperature for one or more cooling coils; or cooling air flow rate such that the average temperature of air moving through the server rack remains within 5, 4, 3, 2, 1, 0.75, or 0.5 degrees of a set point temperature and wherein the fan rack and the cooling coil unit sit within the housing at an air inlet to the server rack enclosure; the fan rack and the cooling coil unit sit within the housing at an air outlet from the server rack enclosure; the fan rack sits at an air outlet from the server rack enclosure and the cooling coil units sits at an air inlet to the server rack enclosure; or the fan rack sits at an air inlet to the server rack enclosure and the cooling coil unit sits at an air outlet from the server rack enclosure and wherein the system draws electrical power at a rate of less than 0.93, 0.9, 0.85, 0.82, 0.80, 0.78, 0.75, 0.73, 0.70, 0.69, 0.65, or 0.60 kilowatts per ton of cooling. In some of these embodiments, the rate of electrical power use is less than 0.60 kilowatts per ton of cooling under appropriate ambient and operating conditions.

FIGURES

FIG. 1 depicts a variation of an ISECS with an under-floor outlet.

FIG. 2 depicts another variation of an ISECS with an under-floor outlet and two fans.

FIG. 3 depicts another variation of an ISECS with an under-floor outlet and a rack-mounted fan.

FIG. 4 depicts another variation of an ISECS with an under-floor outlet and dual rack-mounted fans.

FIG. 5 depicts another variation of an ISECS with an overhead outlet and an overhead fan.

FIG. 6 depicts another variation of an ISECS with an overhead outlet and a rack-mounted fan.

FIG. 7 depicts another variation of an ISECS with an overhead outlet and dual rack-mounted fans.

FIG. 8 depicts another variation of an ISECS mounted within a server rack enclosure.

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FIG. 9 depicts another variation of an ISECS mounted within a server rack enclosure.

FIG. 10 depicts a cooling tower useful in cooling system embodiments.

FIG. 11 depicts another useful cooling tower further comprising an air-to-water heat exchanger or an air pre-cooling heat exchanger.

FIG. 12 depicts another useful cooling tower further comprising an energy recovery system.

FIG. 13 depicts a cooling system embodiment.

FIG. 14 depicts another cooling system embodiment.

FIG. 15 depicts another cooling system embodiment.

FIG. 16 depicts a makeup air-handling unit.

FIG. 17 depicts an energy recovery system.

FIG. 18 is a diagram of another MECS embodiment.

FIG. 19 is a diagram of another MECS embodiment with supplemental cooling module.

FIG. 20 is a diagram of another MECS embodiment with a closed-loop cooling tower.

FIG. 21 is a diagram of an ISECS embodiment.

FIG. 22 is a diagram of an ISECS embodiment with a supplemental cooling module.

FIG. 23 is a diagram of another ISECS embodiment with a supplemental cooling module.

FIG. 24 is a diagram of an ISECS with a third cooling coil.

DETAILED DESCRIPTION

The following description of several embodiments describes non-limiting examples that further illustrate the invention. No titles of sections contained herein, including those appearing above, are limitations on the invention, but rather they are provided to structure the illustrative description of the invention that is provided by the specification.

Unless defined otherwise, all technical and scientific terms used in this document have the same meanings that one skilled in the art to which the disclosed invention pertains would ascribe to them. The singular forms “a”, “an”, and “the” include plural referents unless the context clearly indicates otherwise. Thus, for example, reference to “fluid” refers to one or more fluids, such as two or more fluids, three or more fluids, etc. Any mention of an element includes that element’s equivalents as known to those skilled in the art.

Any methods and materials similar or equivalent to those described in this document can be used in the practice or testing of the present invention. This disclosure incorporates by reference all publications mentioned in this disclosure and all of the information disclosed in the publications.

This disclosure discusses publications only to facilitate describing the current invention. Their inclusion in this document is not an admission that they are effective prior art to this invention, nor does it indicate that their dates of publication or effectiveness are as printed on the document.

The features, aspects, and advantages of the invention will become more apparent from the following detailed description, appended claims, and accompanying drawings. Individual Server Enclosure Cooling System (ISECS)

In various embodiments, an invention individual server enclosure cooling system or a rack cooling system or electronics enclosure cooling system (collectively ISECS) uses a process cooling model to cool the equipment inside of the rack or enclosure with real time monitoring and control over the cooling needs of the IT and other Data Center support equipment. In some embodiments, the cooling needs of a rack or electronics enclosure range from 500 watts to ± 50 kW, 1 kW to ± 40 kW, or 3 kW to ± 35 kW. In some

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embodiments, an invention ISECS connects with a real time monitoring and control system, as described below. In some embodiments, an invention ISECS connects to a Multistage Evaporative Cooling System (MECS), as described below. In some embodiments, an invention ISECS connects to a Multistage Evaporative Cooling System and a real time monitoring and control system. In some invention embodiments, when connected to the MECS, the invention ISECS receives cold water at temperatures of $61\pm 4^{\circ}\text{F}$., $61\pm 5^{\circ}\text{F}$., $61\pm 10^{\circ}\text{F}$., $61\pm 15^{\circ}\text{F}$., or $61\pm 20^{\circ}\text{F}$.

This invention among other things applies semiconductor clean room process cooling methods to Data Center or mission critical environments providing real-time, load-based process cooling at the server rack or electronics enclosure and eliminating hot and cold aisles by combining the Multistage Evaporative Cooling System (MECS—the cold water generating source), ISECS (ISECS), and Real Time Monitoring and Control System (RTMCS).

Invention embodiments comprise cooling systems that are coupled with the server rack or electronics enclosure containing the heat load. In some embodiments, ISECS attaches to server racks or electronics enclosures. ISECS or a local cooling system comprises a housing within which sits a cooling coil or multiple cooling coils and a fan or multiple fans. The housing may additionally comprise air filters, dampers, condensate pan, condensate removal means, etc. ISECS also contains sensors and controllers attached to control system that enable the control system to supply cooling capacity matched to the real-time needs of an individual server rack or electronics enclosure.

FIG. 1, FIG. 2, FIG. 3, and FIG. 4 depict invention ISECS 1010 for placement beneath a raised floor of one or more server rack enclosures 1015 or electronics enclosures 1015. (Sometimes throughout this document server racks and electronics enclosures are referred to collectively as server rack enclosure(s).) Alternatively, ISECS 1010 may sit in a crawl space or basement beneath server rack enclosure 1015. ISECS 1010 comprises hot air inlets 1076 into housing 1075 through hot air duct elbow 1077. One or more fan racks 1024 and one or more cooling coil units 1027 are disposed within housing 1075. Fan rack 1024 comprises one or more fans 1020. Cooling coil unit 1027 comprises one or more final cooling coils 1025, and optionally one or more pre-cooling coils 1070 are disposed within housing 1075. In some embodiments, at least one pre-cooling coil 1070 is disposed upstream of final cooling coil 1025 within cooling coil unit 1027. FIG. 1 shows fan rack 1024 located downstream of cooling coil unit 1027, but other embodiments exist in which fan rack 1024 is located anywhere along the air path through housing 1075. Thus, some embodiments locate fan rack 1024 without respect to the location of cooling coil unit 1027, final cooling coil 1025, or pre-cooling coil 1070.

Hot air inlet 1076 into ISECS 1010 may attach to a standard server rack enclosure 1015 though hot air duct elbow 1077. ISECS 1010 in the embodiment depicted in FIG. 1, FIG. 2, FIG. 3, and FIG. 4 vents to the region below the raised floor. Cool air exits ISECS 1010 into the region underneath the raised floor and in some embodiments air returns to the server room through cold air discharge grill 1017 located within the aisle way between rows of server rack enclosures 1015. Some embodiments employ a condensate pan 1211 that captures water that condenses on the pre-cooling coil 1070 or the final cooling coil 1025, or both.

FIG. 2 depicts an invention embodiment substantially like that of FIG. 1. The difference in this embodiment from that of the FIG. 1 embodiment is that FIG. 2 depicts fan rack 1024 comprising two fans 1020.

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FIG. 3 depicts an invention embodiment substantially like that of FIG. 1. The difference in this embodiment from that of the FIG. 1 embodiment is that fan rack 1024 is located in server rack enclosure 1015.

FIG. 4 depicts fan rack 1024 located similarly to FIG. 3, except fan rack 1024 comprises two fans 1020.

FIG. 5 depicts ISECS 1010 similar to the embodiments of this invention discussed above, but in which ISECS 1010 is adapted to mount to the top of server rack enclosure 1015. In this embodiment, ISECS 1010 comprises housing 1075 connected to the top of server rack enclosure 1015. Housing 1075 contains, in order, an insulated hot air duct 1077 (in some embodiments an elbow), air filter 1026; followed by cooling coil unit 1027, comprising precooling coil 1070 and final cooling coil 1025; fan rack 1024, comprising at least one fan 1020; and automatic air damper 1201 and a louver door 1202 that provides access to fan rack 1024. In some embodiments similar to FIG. 5, louver door 1202 comprises safety features that prevent fan 1020 from operating when louver door 1202 is open. In these or other embodiments, an air duct 1074 (in some embodiments, an elbow) sits at the end of housing 1075 providing duct work for air to exit ISECS 1010 from.

FIG. 6 depicts a cooling system embodiment that is similar to the embodiment shown in FIG. 5. FIG. 6 shows ISECS 1010 in which fan rack 1024 sits at the outlet to server rack enclosure 1015.

FIG. 7 depicts a cooling system embodiment similar to that of FIG. 6 but in which fan rack 1024 comprises two or more fans 1020.

FIG. 8 depicts a cooling system embodiment in which ISECS 1010 is housed within server rack enclosure 1015. In this specific embodiment, ISECS 1010 sits beneath the servers of server rack enclosure 1015. In other embodiments, ISECS 1010 sits above the servers. This embodiment of ISECS 1010 comprises air filter 1026; followed by cooling coil unit 1027, comprising pre-cooling coil 1070 and final cooling coil 1025; fan rack 1024, comprising at least one fan 1020; and louver door 1202.

In some embodiments, housing 1075 is constructed of standard HVAC sheet metal using standard HVAC construction methods. But in other embodiments, housing 1075 is constructed using different methods or materials as is known to those of ordinary skill in the art.

In some embodiments, fan 1020 sits after a final cooling coil 1025 or pre-cooling coil 1070. In these or other embodiments, two, three, or more fans compose fan rack 1024, which sits within housing 1075 of ISECS 1010. In some embodiments, each fan 1020 has the same air-handling capacity as the others. In some embodiments, fans 1020 have different air-handling capacities. Moreover, separate fans 1020 may service pre-cooling coils 1070 and final cooling coils 1025, in some embodiments. Some of these embodiments divide the air path into two or more paths. To prevent air back flow into ISECS 1010, some invention ISECS 1010 comprise one or more automatic air dampers 1201.

Similarly, in some embodiments ISECS may comprise two or more cooling coils. Some embodiments comprise two or more cooling coils. Some embodiments comprise coils with substantially the same capacity and some embodiments comprise coils with differing capacities.

Final cooling coil 1025 attaches to a final cooling coil cold-water inlet pipe 1040. As shown in FIG. 1 through FIG. 7, a final cooling water flow control valve 1035 also attaches to final cooling coil cold-water inlet pipe 1040, as well. Final cooling coil 1025 also connects to final cooling coil water

outlet pipe **1045**. ISECS **1010** serving dedicated individual server rack enclosures **1015** connect to secondary cooling loops fed by a MECS or by traditional water chillers that provide cold water to one or more ISECS **1010**. One pump provides cold water to the pre-cooling coils **1070** of one or more ISECS **1010**, while another one provides cold water to the final cooling coils **1025** of at least one ISECS **1010**. Together with various sensors, controllers, and command-and-control hardware or software, final cooling water flow control valve **1035** allows control over cold-water flow through final cooling coil **1025**. Together with various sensors, controllers, and command-and-control hardware and/or software, precooling coil water flow control valve **1060** allows control over cold-water flow through precooling coil **1070** to meet the cooling demand in real time. Cooling water enters pre-cooling coil **1070** through pre-cooling coil cold water supply pipe and leaves through pre-cooling coil water outlet pipe **1050**.

The hot air inlet **1076** to ISECS **1010** may attach to a standard server rack enclosure **1015** through hot air duct elbow **1077**. The air exits through a standard, perforated, cold air discharge grill **1017** supplying cooled air back into the IT Room in the embodiment depicted in FIG. 1-FIG. 5, for example.

In some embodiments the transition from the bottom of server rack enclosure **1015** into housing **1075** up to at least a final cooling coil **1025** is thermally insulated to keep heat from the server from escaping into the region beneath the raised floor or in the basement or crawl space beneath server rack enclosure **1015**. In some embodiments, a thermally insulated hot air duct elbow **1077** extends from the housing **1075** up into server rack enclosure **1015** to help direct hot air from the servers or other equipment into ISECS **1010**.

Fans suitable for use in ISECS **1010** include any type of fan useful in the HVAC arts. Some embodiments use variable speed fans in one or more positions within ISECS **1010**. The fans can be powered by any type of motor used in HVAC arts such as hydraulic, pneumatic, or later developed motors adapted for use in that industry. Some invention fans are powered with energy-efficient motors. Invention fans can be fixed or variable speed. For purposes of this invention, "fan" encompasses any device designed to move air, such as air within an HVAC system. In addition to other air-moving devices, "fan" includes fans, blowers, etc.

Cooling coils useful in invention embodiments include any type of air-to-water heat exchanger useful in the HVAC arts. The coils are supplied with cold water using a system that comprises a water cooling system, comprising at least one shutoff valve. In some embodiments, the shutoff valve is combined with variable flow control. The water cooling system can be any cooling system as used in HVAC arts or other arts encompassing chilled water. Variable flow, shutoff valves can be remotely controlled in some embodiments. In some embodiments, at least some cooling load is serviced by a MECS as described below. In some embodiments greater than 25 percent, 50 percent, 75 percent, or 99 percent of the cooling is supplied by a MECS, as described below.

Real Time Monitoring and Control System

Command-and-control systems, units, or devices such as a real time Data Center cooling systems employing real time monitoring and control systems comprise programmable logic controllers (PLC), field programmable gate arrays, or programmable controllers that are or that function as digital computers. In some invention embodiments, the digital computer is configured for use in the automation of electromechanical processes. In addition to programmable controllers or alternatively to programmable controllers, some

command-and-control devices comprise computer-, micro-processor-, microcontroller-, programmable-logic-device-, or analog-based control systems. Generally, these are all referred to as computers or as computer-based.

A digital computer configured for use in the automation of electromechanical processes comprises at least one sensor. These or other embodiments comprise at least one controller. One or more sensors monitor a cooling parameter. A cooling parameter is any of the following: air and water temperature; air and water flows, differential air and water pressures, air humidity; electric power consumption (loads) of racks, servers, power distribution units, uninterruptable power supplies, lighting, transformers and switchgear, pumps, fans, motors or combinations of these. The controllers control at least one of air and water flow in real time to automatically adjust water temperature and flow, air temperature and flow, and motor and fan speeds to meet the immediate electric power consumption (loads) of each individual server rack enclosure or the immediate cooling needs of the space or both.

Real Time Data Center Cooling System

Real Time Data Center Cooling Systems employing MECS generate cold water to cool individual server rack enclosures for a Data Center have capital expenditure first costs and startup costs within about $\pm 50\%$ of the costs of traditional mechanical refrigeration systems. In some embodiments, the overall system uses no HVAC-type refrigeration compressors and no halogenated refrigerant chemicals, such as freons.

Operation

For embodiments similar to those of FIG. 1, FIG. 2, FIG. 5, and FIG. 7, in which cooling fan **1020** sits downstream of final cooling coil **1025** and/or pre-cooling coil **1070**, the operation is as follows. In the operation of local cooling systems ISECS **1010**, one or more fans **1020** composing fan rack **1024** move hot air from server rack enclosure **1015** across one or more final cooling coil **1025** and/or pre-cooling coil **1070**, dropping the temperature of the hot air to a target exhaust temperature before returning the cooled air to the room. This air movement facilitates room air to enter server rack enclosure **1015**. Once inside server rack enclosure **1015**, the entering room air stream cools the servers in server rack enclosure **1015** becoming hot in the process. Operation of cooling system fans **1020** causes air to move through server rack enclosure **1015** and pick up heat from the servers. This air continues through housing **1075** where it passes over final cooling coil **1025** and/or pre-cooling coil **1070** and transfers heat to the cooling water. Finally, the cooled air passes fan **1020** and exits cooling unit housing **1075**, returning to the room. The air coming out of ISECS **1010** pressurizes the total underfloor space. The pressure causes the return air to be discharged through perforated tiles or cold air discharge grill **1017**.

In embodiments similar to FIG. 3, FIG. 4, and FIG. 6, since fan **1020** pushes air through ISECS **1010**, cooled air exits cooling unit housing **1075** without passing fan **1020**.

Any number of sensors as described above sense the power usage of the servers, power supplies, or other equipment within server rack enclosure **1015**, as discussed above. Sensors can also monitor air temperature and other conditions and parameters of the air. The command-and-control system receives signals from one or more sensors and applies special algorithms to adjust one or more controllers so that an appropriate amount of cooling is accomplished. The amount of cooling is commensurate with the cooling needs of the individual server rack enclosures **1015**.

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In some embodiments, the command-and-control system adjusts airflow through ISECS **1010** to adjust the amount of cooling. Airflow adjustments come from adjusting fan **1020** speed. In these or other embodiments, the command-and-control system adjusts the flow rate of cooling water through final cooling coil **1025** and/or pre-cooling coil **1070** to adjust the amount of cooling. Cooling water flow rate can be adjusted by adjusting water flow control valves, either **1035** and/or **1060**, for each individual local cooling system and adjusting speeds of the main pumps serving the secondary cooling water loops as well as in some embodiments adjusting accordingly cooling capacity of cooling water loops. In some embodiments, environmental air conditioning for the data center is provided by cooling coils serviced with cold water from a MECS, as defined in this document.

In some embodiments, ISECS use less than 0.93, 0.9, 0.85, 0.82, 0.80, 0.78, 0.75, 0.73, 0.70, 0.69, or 0.69 kilowatts of energy to provide one ton of cooling.

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lation location because of the variances in ambient outdoor temperatures in different parts of the world. The average annual hourly energy usage analysis figures for six major cities (New York, Chicago, San Francisco, Phoenix, Miami, and Atlanta) were used in developing this analysis and KW/Ton calculations. Overall, these cities average approximately 2,856 hours of free cooling, or 33% of the year. The summer design cooling criteria for each city was not used, only the annual averages.

Note 2: Natural Cycle Energy, Inc. data and analysis for determining energy usage of the Real Time Data Center Cooling System (RTDCCS), which incorporates the Multi-stage Evaporative Cooling System (MECS) and the Individual Server Enclosure Cooling System (ISECS), is based on ASHRAE summer design conditions for cooling applications in Phoenix Ariz. at 0.4% Occurrence i.e. 110.2° F. DB and 70° F. WB. Therefore, it can be assumed the

TABLE 3

Real Time Data Center Cooling System Energy and GHG (Carbon Footprint) Savings Comparing Various Data Center Cooling System Energy Usage in KW/Ton. KW/Ton data from Rittal White Paper 507: Understanding Data Center Cooling Energy Usage & Reduction Methods by Daniel Kennedy. White Paper 507 uses the annual average temperature of six major U.S. cities, whereas, the Real Time Data Center Cooling System uses a Worst Case Scenario - Phoenix Summer Design Conditions for Average Data Center										
	Condenser Fan/Cooling Tower	Compressor	Evaporated Fan	Chilled Water Pump	Refrigerant Pump	Pumped Refrig Fan	Humidification	Liquid Cooled Svr Pump	Server Fans	Total KW/ Ton
CRAC Cooled System	0.24	1.29	0.51				0.58		0.26	2.88
CRAH Cooled Systems - Chilled Water Based	0.16	1.12	0.51	0.10			0.58		0.26	2.73
CRAC Cooled System w Containment	0.21	1.25	0.45				0.50		0.26	2.67
CRAH Cooled System w Containment	0.15	1.08	0.45	0.10			0.50		0.26	2.54
Liquid Cooled Racks	0.15	1.08	0.28	0.10			0.50		0.26	2.37
Unoptimized Liquid Cooled Racks Chilled Water	0.13	0.96	0.28	0.09					0.26	1.72
Optimized Liquid Cooled Racks Chilled Water	0.13	0.63	0.28	0.09					0.26	1.39
Optimized and Free Cooling Systems										
Liquid Cooled Racks Chilled Water	0.22	0.36	0.28	0.09					0.26	1.21
Active Liquid Cooled Doors, Chilled Water	0.22	0.36	0.24	0.09					0.26	1.17
Passive Liquid Cooled Doors Chilled Water	0.22	0.36		0.09					0.26	0.93
Pumped Refrigerant Systems	0.16	1.12		0.10	0.04	0.06		0.26	1.74	
Air Side Economizing	0.05	0.37	0.51	0.03			0.19		0.26	1.41

Natural Cycle Energy Inc.

Note 1: Rittal Corporation White Paper Data—The impact of these energy savings is dependent on the instal-

65 KW/Ton for the RTDCCS is higher than it would be if using the same six city averages used in the Rittal White.

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TABLE 4

KW per Ton Analysis Comparing Various Data Center Cooling Methods vs. Real Time Data Center Cooling System		
Total kW/Ton		
Multistage Evaporative Cooling System (MECS)		
Cooling towers all with fans, pumps, etc.	0.29	See Note 2, above.
Individual Server Enclosure Cooling System (ISECS)		
Rack Fan Coil Unit	0.14	See Note 2, above.
Server Fans	0.26	
KW per Ton		
Total Real Time Data Center Cooling System	0.69	

TABLE 5

Natural Cycle Energy, Inc. Energy Usage Comparison of Traditional Data Center Cooling Systems to the Natural Cycle Energy, Inc. RTDCCS				
	Traditional Mechanical Cooling KW/Ton	RTDCCS	KW/Ton Savings	% Energy Savings
CRAC Cooled System	2.88	0.69	2.19	76.0%
CRAH Cooled Systems - Chilled Water Based	2.73	0.69	2.04	74.7%
CRAC Cooled System w Containment	2.67	0.69	1.98	74.2%
CRAH Cooled System w Containment	2.54	0.69	1.85	72.8%

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TABLE 5-continued

Natural Cycle Energy, Inc. Energy Usage Comparison of Traditional Data Center Cooling Systems to the Natural Cycle Energy, Inc. RTDCCS					
		Traditional Mechanical Cooling KW/Ton	RTDCCS	KW/Ton Savings	% Energy Savings
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10	Liquid Cooled Racks Unopti- mized	2.37	0.69	1.68	70.9%
	Liquid Cooled Racks Chilled Wa- ter Temperatures Optimized	1.72	0.69	1.03	59.9%
15	Liquid Cooled Racks Chilled Wa- ter Temperatures Optimized and Free Cooling Sys- tems	1.39	0.69	0.70	50.4%
20	Liquid Cooled Racks Chilled Wa- ter Temperatures Optimized and Evaporative Free Cooling Systems	1.21	0.69	0.52	43.0%
25	Active Liquid Cooled Doors, Chilled Water Temp Optimized, & Evaporative Free Cooling Sys- tems	1.17	0.69	0.48	41.0%
30	Passive Liquid Cooled Doors Chilled Water Temp Optimized & Evaporative Free Cooling Systems	0.93	0.69	0.24	25.8%
35	Pumped Refriger- ant Systems	1.74	0.69	1.05	60.3%
	Air Side Econo- mizing	1.41	0.69	0.72	51.1%

TABLE 6

Energy Usage and Savings Comparison of Traditional Data Center Cooling Systems to the RTDCCS							
Annual Cooling Energy Cost Calculation							
Electric Energy Unit Cost USD kW/IT Load					0.10		
Tons of Cooling Required					2000		
					569		
	Energy Usage KW/ton				Annual Energy Cost		
	Traditional Mech. Cooling KW/Ton	RTDCCS KW/Ton	KW/Ton Savings	% Energy Savings	Trad'l Mech. Cooling \$/Year	RTDCCS Cooling \$/Year	\$ Savings
CRAC Cooled System	2.88	0.69	2.19	76.0%	\$1,434,101	\$343,926	(\$1,090,175)
RAH Cooled System - Chilled Water Based	2.73	0.69	2.04	74.7%	\$1,350,885	\$343,926	(\$1,006,959)
CRAC Cooled System w/ Containment	2.67	0.69	1.98	74.2%	\$1,331,452	\$343,926	(\$987,525)
CRAH Cooled System w/ Containment	2.54	0.69	1.85	72.8%	\$1,262,413	\$343,926	(\$918,486)
Liquid Cooled Racks Unoptimized	2.37	0.69	1.68	70.9%	\$1,179,695	\$343,926	(\$835,769)
Liquid Cooled Racks Chilled Water Temperature Optimized	1.72	0.69	1.03	59.9%	\$857,072	\$343,926	(\$513,146)
Liquid Cooled Racks Chilled Water Temperature Optimized and Evaporative Free cooling Systems	1.21	0.69	0.52	43.0%	\$600,548	\$343,926	(\$256,622)
Active Liquid Cooled Doors, Chilled Water Temperature Optimized and Evaporative Free cooling Systems	1.17	0.69	0.48	41.0%	\$583,008	\$343,926	(\$239,082)

TABLE 6-continued

Energy Usage and Savings Comparison of Traditional Data Center Cooling Systems to the RTDCCS							
Passive Liquid Cooled Doors, Chilled Water Temperature Optimized and Evaporative Free cooling Systems	0.93	0.69	0.24	25.8%	\$463,417	\$343,926	(\$119,490)
Liquid Cooled Racks Chilled Water Temperature optimized and Free Cooling Systems	1.39	0.69	0.70	50.4%	\$694,428	\$343,926	(\$350,501)
Pumped Refrigerant Systems	1.74	0.69	1.05	60.3%	\$865,543	\$343,926	(\$521,617)
Air Side Economizing	1.41	0.69	0.72	51.1%	\$705,988	\$343,926	(\$362,062)

Multistage Evaporative Cooling System (MECS)

The MECS's new methods and systems allows the generation of cold makeup or process and/or comfort cooling supply air or cold cooling fluid, such as water, at a low temperature, meeting the conditioned space's temperature control requirements without adding moisture to the supply air in most cases.

Main Features of the MECS are:

Design Simplicity (MECS does not need to rely on any high-energy-using refrigeration compressors).

Ecologically sound design (MECS uses only water and atmospheric air-no need to use Freon-type refrigerants such as hydrochlorofluorocarbons (HCFCs)).

Scalability (MECS can be scaled to provide as little as 5 tons to well over 500 tons of equivalent Conventional Mechanical Refrigeration Cooling).

Economical Energy Use (MECS has significantly lower power consumption compared to Conventional Mechanical Refrigeration Systems).

Green Electrical Energy Use (MECS can use green electrical energy sources (solar, wind, etc.)).

FIG. 10 shows cooling tower 10, a Type-I cooling tower. Cooling tower 10 comprises tower casing 15, cold-water reservoir 20, air inlet 35, air outlet 40, water distribution system with nozzles 51, fan 55, pump 60, cold-water outlet 65, warm or spent water inlet 66, and mist eliminator 71. Fan 55 is not present in some examples. Air inlet 35 sits near the bottom of cooling tower 10 in the embodiment depicted FIG. 10. Other examples can be envisioned in which air inlet 35 sits remotely from cooling tower 10, but in those examples, ambient air should enter cooling tower 10 below air outlet 40. Cold-water reservoir 20 sits near the bottom of cooling tower 10. But other examples exist in which cold-water reservoir 20 sits remotely from cooling tower 10. In those types of examples, one of ordinary skill in the art would recognize that additional piping and plumbing would be useful in such examples.

In some examples, airflow through cooling tower 10 is assisted by fan 55. Fan 55 sits near the uppermost part of cooling tower 10 near air outlet 40. Fan 55 may either be located downstream of mist eliminator 71 or upstream of mist eliminator 71. Alternatively, a fan may mount at the inlet of cooling tower 10, pushing ambient air through cooling tower 10. Of course, a cooling tower could use two or more fans.

In some examples, water is distributed by the water distribution system with nozzles 51 over a mass heat transfer media (fill). In these types of examples, one of ordinary skill in the art would recognize that mass heat transfer occurs through the interaction between the water and air on the surface of the fill.

As stated previously, FIG. 10 depicts fan 55 on the top of cooling tower 10. Mist eliminator 71 sits near the top of cooling tower 10 in the embodiment depicted in FIG. 10, as

will be the case in most examples that employ a counter flow design. Some examples may use a cross flow cooling tower design, which would lead to a different arrangement of air inlets, water distribution systems, fans, etc. Water distribution system with nozzles 51 attaches to warm or spent water inlet 66, which connects between cooling load 11 and the warm outlet of air-to-water heat exchanger 230 and water distribution system with nozzles 51. Pump 60 connects to cold-water reservoir 20 and connects to cooling loads 11 and an external air-to-water heat exchanger, such as air-to-water heat exchanger 230, through cold-water outlet 65. Cold-water outlet 65 also connects to the cold-water inlet of air-to-water heat exchanger 230.

Invention cooling systems use a variety of cooling towers in addition to cooling tower 10.

FIG. 11 shows another type of cooling tower used in invention cooling systems—cooling tower 210, a Type-II cooling tower. Cooling tower 210 comprises tower casing 15', cold-water reservoir 20', air inlet 35', air outlet 40', water distribution system with nozzles 51', fan 55', pump 60', cold water outlet 65', warm water inlet 66', mist eliminator 71', and air-to-water heat exchanger 230.

Air-to-water heat exchanger 230 comprises a housing 231, heat exchanger cold-water inlet 213, and heat exchanger warm water outlet 214. In some examples, cold-water inlet 213 connects to cold-water outlet 65 and heat exchanger warm water outlet 214 connects to warm water inlet 66 of a Type-I cooling tower. In other examples, cold-water inlet 213 connects to cold-water outlet 65' and heat exchanger warm water outlet 214 connects to warm water inlet 66' of a Type-II cooling tower.

Air inlet 35' sits near the bottom of cooling tower 210, in the embodiment depicted by FIG. 11. Other examples exist in which air inlet 35' sits remotely from cooling tower 210 as long as ambient air enters cooling tower 210 below air outlet 40'. Air-to-water heat exchanger 230 sits between air inlet 35' and cooling tower 210. Cold-water reservoir 20' sits near the bottom of cooling tower 210. But other examples exist in which cold-water reservoir 20' sits remotely from cooling tower 210. In those types of examples, one of ordinary skill in the art would recognize that additional piping and plumbing would be useful.

In some examples, fan 55' assists air in flowing through cooling tower 210. Fan 55' sits on the top of cooling tower 210 near air outlet 40'. Fan 55' may sit either downstream of mist eliminator 71' or upstream of mist eliminator 71'. Alternatively, a fan mounts at the inlet of cooling tower 210, designed to push ambient air through cooling tower 210. Of course, this cooling tower may use two or more fans.

In some examples, water is distributed by the water distribution system with nozzles 51 over a mass heat transfer media (fill). In these types of examples, one of ordinary skill in the art would recognize the mass heat transfer interaction between the water and air on the surface of the fill.

Pump 60' is in fluid communication with cold-water reservoir 20' and in fluid communication with water distribution system with nozzles 51', which is located near the uppermost part of cooling tower 210. In some examples, "fluid communication" encompasses a cold-water outlet 65' connected to pump 60'. Cold-water outlet 65' connects through an external device, comprising a pipe, heat exchanger, or other external device (such as cooling load 11'), to warm water inlet 66'. In these or other examples, pump 60' connects to cold-water reservoir 20' and connects to cooling loads 11' and an external air-to-water heat exchanger, such as air-to-water heat exchanger 230', through cold-water outlet 65'. Warm water inlet 66' connects to water distribution system with nozzles 51'. In some examples, cold-water outlet 65' connects to an external device such as an air-to-water heat exchanger mounted upon another or an adjacent cooling tower or a cooling tower of another cooling stage, and then continues on to water distribution system with nozzles 51' through warm water inlet 66'.

In some examples, pump 60' services water distribution system with nozzles 51'. In these or other examples, pump 60' or another pump pumps cold water from cold-water reservoir 20' to the cold-water inlet on an air-to-water heat exchanger mounted on another cooling tower and another pump pumps water-to-water distribution system with nozzles 51'.

FIG. 12 shows another type of cooling tower for use in invention cooling systems—Cooling tower 310, a Type-III cooling tower. Cooling tower 310 comprises tower casing 15", cold-water reservoir 20", air inlet 35", air outlet 40", water distribution system with nozzles 51", fan 55", pump 60", pipe 65", mist eliminator 71", air-to-water heat exchanger 230', and energy recovery system 330.

Air-to-water heat exchanger 230' comprises a housing 231', cold-water inlet 213', and heat exchanger warm water outlet 214'.

Air inlet 35" sits near the bottom of cooling tower 310 in the embodiment depicted by FIG. 12. Other examples exist in which air inlet 35" sits remotely from cooling tower 310 as long as ambient air enters cooling tower 310 below air outlet 40". Air-to-water heat exchanger 230' sits between air inlet 35" and cooling tower 310. Cold-water reservoir 20" sits near the bottom of cooling tower 310. But other examples exist in which cold-water reservoir 20" sits remotely from cooling tower 310. In those types of examples, one of ordinary skill in the art would recognize that additional piping and plumbing would be useful in such examples. As in cooling tower 210, various examples exist in which cold-water reservoir 20 and cold-water reservoir 20' are located remotely from cooling tower 10 and cooling tower 210, respectively.

In some examples, fan 55" assists air in flowing through cooling tower 310. Fan 55" sits on the top of cooling tower 310 near air outlet 40". Fan 55" may sit downstream of mist eliminator 71" or upstream of mist eliminator 71". Alternatively, a fan mounts at the inlet of cooling tower 310, designed to push ambient air through cooling tower 310. Of course, a cooling tower may use two or more fans.

In some examples, water is distributed by the water distribution system with nozzles 51" over a mass heat transfer media (fill). In these types of examples, one of ordinary skill in the art would recognize that the mass heat transfer interaction between the water and air on the surface of the fill.

Pump 60" is in fluid communication with cold-water reservoir 20" and in fluid communication with water distribution system with nozzles 51" located near the uppermost

part of cooling tower 310. In some examples, fluid communication encompasses a pipe 65", connected between pump 60" and water distribution system with nozzles 51".

In some examples, pump 60" services water distribution system with nozzles 51". In these or other examples, pump 60" or another pump pumps cold water from cold-water reservoir 20" to a cooling load (such as cooling loads 11" or a makeup air handling unit 715). Invention examples may cool any suitable cooling load (cooling loads 11"). Suitable cooling loads can be virtually any cooling load and include the following cool loads: environmental cooling (HVAC), building comfort cooling, process cooling, individual server enclosure/rack cooling, or any electronics enclosure generating a heat load. In some examples, the cooling load is a make-up air-handling unit (MU Air Handling Unit or MUAHU). In some examples, any cooling load that can be cooled with one or more cooling coils is suitable for this invention.

In some examples, such as the embodiment depicted in FIG. 17, energy recovery systems, such as energy recovery systems (ERS) 330 comprise a water circulation system comprising a pump 860 and an air-to-water heat exchanger 830. A particulate filter 831 sits upstream of air-to-water heat exchanger 830, between an associated cooling tower and air-to-water heat exchanger 830. After air-to-water heat exchanger 830 comes fan 835 and finally outlet 836 to ambient air. ERS 330 connects to any suitable cooling load 811 through a closed-loop water circulation system. The water circulation system comprises air-to-water heat exchanger 830, warm water inlet pipe 866, pump 860, cooling load 811, and cold-water outlet pipe 865. Beginning with air-to-water heat exchanger 830, cold-water outlet pipe 865 connects to the output of air-to-water heat exchanger 830 and connects to the cold-water inlet of cooling load 811. The warm water outlet of cooling load 811 connects to pump 860. Pump 860 connects to warm water inlet pipe 866, which in turn connects to the warm water inlet of air-to-water heat exchanger 830. ERS 330 recovers "coolness" from the exhaust stream of an associated cooling tower. Since this is a closed loop system, the water can be any suitable heat transfer fluid including a water and glycol mixture.

In some examples, energy recovery system 330 operates in conjunction with dampers 340, 341 in an associated cooling tower. Damper 340 sits in the air outlet pathway and damper 341 sits in the ERS air pathway. Both are disposed to allow the airflow to be adjusted from 100% through air outlet 40" and 0% through ERS 330, 0% air outlet 40" to 100% through ERS 330, or any air mixture or combination of mixtures. Any of the cooling tower examples described in this document may additionally comprise an energy recovery system located at the air outlet of the cooling tower.

In any of the cooling tower types, one or more pumps may be variable speed pumps or fixed speed pumps. In any of the cooling tower types, one or more fans may be fixed speed fans or variable speed fans.

In addition to the components discussed above, the cooling towers comprise monitoring and command-and-control hardware and optionally software, to monitor and control the operation of the cooling towers. Various types of monitoring and command-and-control hardware and software are familiar to those of ordinary skill in the art. For instance, variable speed fans have command-and-control hardware and software that operate to vary the speed of fans to control airflow through the cooling towers. Variable speed pumps have command-and-control hardware and software to control the flow rate of cold water from cold-water reservoir through the

various other components of the cooling tower and to cooling loads. Control over such components is based on the cooling needs of the cooling load, outside temperatures, etc. Control is exercised in some examples to run only necessary fans, pumps, etc. to meet the necessary cooling load without wasting energy. One category of energy that is saved because of the intervening command and control systems, is energy normally wasted by operating fans, pumps, etc. faster or at a higher capacity than necessary to satisfy the cooling load demands on the cooling system. In some examples, components of the MECS are operated by a dedicated control system communicating with a building energy management system. The control software of the control system optimizes the operation of the cooling system components to meet variable or constant conditioned space cooling loads, process-cooling loads, or other cooling loads at the absolute lowest or minimum amount of energy consumption.

FIG. 13 depicts an embodiment of an invention cooling system. Cooling system 400 comprises three cooling towers: a Type-I cooling tower, cooling tower 401; a Type-II cooling tower, cooling tower 402; and a Type-III cooling tower, cooling tower 403. Cold-water reservoir 20 of cooling tower 401 connects through cold-water outlet 65 to cold-water inlet 213, which connects to air-to-water heat exchanger 230 of cooling tower 402. Air-to-water heat exchanger 230 of cooling tower 402 connects through heat exchanger warm water outlet 214 to warm water inlet 66, which returns warm water to cooling tower 401, as shown in the figure. In some examples, warm water returns to the water distribution system with nozzles 51 of cooling tower 401.

Cold-water reservoir 20' of cooling tower 402 connects through cold-water outlet 65' to cold-water inlet 213' of air-to-water heat exchanger 230' of cooling tower 403. Air-to-water heat exchanger 230' connects through heat exchanger warm water outlet 214', to warm water inlet 66', which returns warm water to cooling tower 402, as shown in FIG. 13. In some examples, warm water returns to the water distribution system with nozzles 51' of cooling tower 402.

Cold-water reservoir 20" of cooling tower 403 has cold-water outlet 65" that connects to the cold-water inlet of any suitable cooling load 11". Likewise, warm-water returns through warm water inlet 66" that connects to the warm water outlet of cooling load 11" to the water distribution system with nozzles 51" of cooling tower 403.

Cold-water reservoir 20 of cooling tower 401 and cold-water reservoir 20' of cooling tower 402 may connect to optional cold-water supply and warm-water return lines connecting to various different cooling loads 11, 11'. One of ordinary skill in the art would choose which cold-water reservoir (which cooling stage) to use based on the nature of the cooling load. In some examples, the cooling system comprises four or more cooling towers.

FIG. 14 depicts cooling system 500, which is similar to cooling system 400 of FIG. 13, discussed above. In addition to the components and connectivity discussed for the cooling system above, this cooling system contains at least one energy recovery system 330 wherein the energy recovery system 330 attaches to one or more cooling towers such as cooling towers 501, 502, 503 to recapture the "coolness" of cold air exiting from the cooling tower. In some examples, cooling system 500 comprises a second or third energy recovery system 330, 330' on the second or third cooling towers, such as cooling tower 502 or cooling tower 503. And in some examples, the cooling system comprises four or more cooling stages with an energy recovery system on one or more cooling towers.

One typical, suitable cooling load for a cooling system such as cooling system 400 or 500 is a Make Up Air Handling Unit (MUAHU).

Makeup Air Handling Unit 715 comprises one or more air particulate Filters 750 at or near air inlet 720 of MUAHU 715. Following the air path through MUAHU 715 air-to-air heat exchanger 745 is downstream of air inlet 720 and air particulate Filters 750. Air-to-air heat exchanger 745 comprises two air paths that do not mix with each other. One of those air paths relates to the makeup air and the other relates to the building exhaust air. Fan 755 pulls building exhaust air through air-to-air heat exchanger 745, and fan 735 pulls make up air through air-to-air heat exchanger 745. An air-to-water heat exchanger 740 comes after air-to-air heat exchanger 745 in MUAHU 715. A variable or fixed speed supply fan 735 is disposed in MUAHU 715 downstream of air-to-air heat exchanger 740. In some examples, a direct evaporative or adiabatic water humidifier (with mist eliminator) 730 sits near air outlet 731 of MUAHU 715, just upstream of nozzles 732. Cold-water outlet 65" transports cold water from a cooling system to the cold-water inlet of air-to-water heat exchanger 740. Warm water inlet 66" transports warm water from the warm water outlet of air-to-water heat exchanger 740 to the cooling system.

In some examples, components of the MECS are operated by a dedicated control system communicating with a building energy management system. The control software of the control system optimizes the operation of the cooling system components to meet variable or constant conditioned space cooling loads, process-cooling loads, or other cooling loads at the absolute lowest or minimum amount of energy consumption. Executing this software, the control system, depending on the conditioned space load, the process cooling load, or some other cooling load and indoor and outdoor air dry bulb and wet bulb temperatures, automatically provides the necessary speed control over cooling towers fans, supply air fans of makeup air-handling units, return and supply air fan, return and supply air humidifiers, etc., and the necessary flow control over the cooling fluids by controlling pumps, which are typical components of commercial, industrial, or other cooling systems. The control system also automatically adjusts all operational components of the MECS to achieve the amount of cooling needed for the load in real time to maximum cooling efficiency.

In some examples, determined by the cooling application and the environmental conditions of the specific geographical area, components of the MECS are rearranged in an order and sequence and properly sized to maximize the generation of cold water for given environments. These cooling applications or any kind of cooling application in commercial real estate buildings, industrial real estate buildings, and government real estate buildings; manufacturing plants; industrial processing plants; food/beverage processing plants and agricultural buildings.

In some examples, an individual electronics enclosure cooling system uses cold water generated by the different stages of the MECS to apply process cooling method to each cooling load in each individual electronics enclosure. In some examples, invention-cooling systems are optimized for providing cold water to individual electronics enclosures or racks, such as server racks to cool the loads. The electronics enclosure is designed to allow space air to be drawn in to cool the electronics equipment inside the enclosure through an air inlet and further pulled through the enclosure to an air outlet exit point. The warm air, which was heated by the electronics within the enclosure, exits the air outlet of the enclosure and enters into an air inlet of one or more fan coils

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units. There the warm air is cooled by circulating cooling water such as from an invention cooling system, i.e. cold water from different stages of the MECS, before the cooled air is returned to the space from the air outlet of the fan coil unit.

Cooling system examples exist comprising 2-10 2-5, 5, 4, 3, or 2 types of cooling towers or cooling tower cells. Each of these examples comprises 0, 1, or 2 energy recovery system per cooling tower.

Operation of MECS System

Operationally, any cooling tower suitable for use with the cooling systems of the current invention operates as described below. A cooling tower cools incoming ambient air and water from the cold-water reservoir 20. Fan 55 assists in moving air through the cooling tower. Ambient air enters the cooling tower through air inlet 35 and exits the cooling tower at the top through air outlet 40. As the fan pulls air into the cooling tower, water distribution system with nozzles 51 introduces water on top of the fill through water distribution system nozzles 51 causing or allowing contact between the moving ambient air and the falling liquid water within the fill. The cooled falling liquid water is collected in the cold-water reservoir 20 and the saturated cold air exits the cooling tower through air outlet 40.

Pump 60 pumps water from cold-water reservoir 20 through cold-water outlet 65 to a cooling load, such as air-to-water heat exchanger 230. After moving through the cooling load, the now warmer, cold water travels through warm water inlet 66 into water distribution system with nozzles 51 located above the fill of cooling tower 10. Water falling from the top of cooling tower 10 passes by ambient air moving from air inlet 35 at the bottom of cooling tower 10 to air outlet 40 at the top of cooling tower 10. Fan 55 moves air through cooling tower 10.

This air-water interaction causes some water to evaporate. Water evaporation requires energy, in this case, the energy is extracted from the water flowing through the fill, leaving the water at a lower temperature and the air exiting air outlet 40 at DB temperature lower than ambient air temperature. That is, the air-water interaction lowers the temperature of the air as the air passes through the cooling tower. Cold water falls to the bottom of cooling tower 10 and collects in cold-water reservoir 20.

All psychometric parameters of the given air have direct correlation with each other in any kind of cooling apparatus. Knowing the dry bulb temperature, the wet bulb temperature, and the barometric pressure of the air allows the determination of all other parameters of the air such as enthalpy, relative humidity, dew point temperature, absolute moisture content, specific volume, etc. For a particular sample of air, the maximum wet bulb temperature is equal to the dry bulb temperature. Larger differences between the dry bulb temperature and the wet bulb temperature indicate drier air.

One of ordinary skill in the art knows that adiabatic cooling of a particular sample of ambient air equal to or below its wet bulb temperature is not possible. During the adiabatic air cooling process, the air's dry bulb temperature is lowered and its moisture content is increased, however, its wet bulb temperature and enthalpy do not change. This has ramifications in using evaporative cooling towers.

Cold-water reservoir 20 located near the bottom of cooling tower 401 feeds cooling loads 11. The warm water from cooling load 11 connects to warm water inlet 66, and to water distribution system with nozzles 51 of cooling tower 401 completing the cycle. Gravity causes the water to fall through the cooling tower fill back into the cold-water

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reservoir. During this trip, the water again interacts with the air flowing up through the cooling tower and is in direct contact with the air flowing through the cooling tower. The main result from this air-water contact is that, as before, some amount of the water evaporates in the air flowing up through the cooling tower. And the cycle continues. The difference between the dry bulb temperature and the wet bulb temperature is smaller after passing through the cooling tower. Therefore, one of ordinary skill in the art recognizes that the trip through the cooling tower lowers the temperature of the water.

Each of the multiplicity of invention cooling towers operates in this manner. The temperature of the cold water generated by any cooling tower is dependent on the wet bulb temperature of the air entering the cooling tower. The cooling towers use ambient air during operation. Therefore, the only way of attaining cold water temperatures lower than the wet bulb temperature of the ambient air, is to lower the wet bulb and dry bulb temperatures of the ambient air entering the cooling tower. In other words, sensible pre-cooling of the ambient air entering the cooling tower reduces its wet bulb and dry bulb temperature thereby allowing colder water temperatures to be achieved at each cooling stage.

The Type-II cooling towers and Type-III cooling towers add sensible pre-cooling of the ambient air entering the cooling towers through an air-to-water heat exchanger at their air inlets. These air-to-water heat exchangers, also called pre-cooling heat exchangers sit between their respective air inlet and respective cooling tower. A cold-water reservoir of another stage of the cooling system or of a previous stage of the cooling system provides cold water for the air-to-water heat exchanger. As ambient air passes through the heat exchanger, it cools and water from the cold-water reservoir warms. The water returns to the source cooling tower water distribution system with nozzles 51 continuing the cycle. The source cooling tower ultimately removes the heat gained by the cold water as it passed through the air-to-water heat exchanger.

The ambient air passes through the air-to-water heat exchangers which lowers the wet bulb and dry bulb temperatures of the air entering the Type-II or Type-III cooling towers. Since the wet bulb temperature serves as the lower limit for the temperature of the cold-water in this cooling towers and since the wet bulb temperature of the pre-cooled air is lower than that of the incoming ambient air in a previous cooling stage, the Type-II or Type-III cooling tower produces cold water with a temperature lower than cold water produced by an earlier cooling stage. This ability of a later cooling stage to produce colder water than an earlier cooling stage stems directly from the fact that the sensible pre-cooling of ambient air without exposing it to added moisture simultaneously drops the air's dry bulb and wet bulb temperatures. Dropping the wet bulb temperature of each stage's air entering the cooling towers lowers the temperature of the cold water produced by these stages. Thus, cascading cooling towers allows the cooling system to produce lower temperature cold water in each of the successive stages.

Returning to FIG. 13, the cooling system functions to produce cold water to service cooling loads 11, 11', 11'', and the cooling load resulting from MU Air Handling Unit 715. In cooling tower 401, fan 55 operates to pull air ambient air through air inlet 35, through air-to-water heat exchanger 230, through the wet fill, past the water distribution system with nozzles 51, through the mist eliminator 71, up through the fan 55, and finally out air outlet 40. Simultaneously with

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air moving up through the cooling tower 401, pump 60 pumps cold water from cold-water reservoir 20, through cold water outlet 65, connected to inlet water pipe 213, through air-to-water heat exchanger 230 on cooling tower 402, out air-to-water heat exchanger 230, through outlet water pipe 214 connected to warm water inlet 66, and, completing the cycle, to water distribution system with nozzles 51 of cooling tower 401. Water distribution system with nozzles 51 distributes water evenly across the top of the fill of cooling tower 401. The water falls by gravity through the fill of cooling tower 401 to cold-water reservoir 20. As cold water from cold-water reservoir 20 moves through the system, it provides a source of indirect sensible precooling for air entering cooling tower 402 through air-to-water heat exchanger 230. The warmed water is returned to cooling tower 401 via the water distribution system with nozzles 51.

Fan 55' of cooling tower 402 operates to pull ambient air into cooling tower 402 through air inlet 35', through air-to-water heat exchanger 230, through the wet fill, past the water distribution system with nozzles 51, through the mist eliminator 71, up through fan 55', and finally out air outlet 40' of cooling tower 402. Water from water distribution system with nozzles 51' distributes water evenly across the top of the fill of cooling tower 402. As the water falls by gravity through the fill of cooling tower 402, it interacts with the moving pre-cooled air stream that has been pre-cooled by air-to-water heat exchanger 230. The air-water interaction within cooling tower 402 causes some water to evaporate. This evaporation extracts (heat) energy out of the circulating water stream and transfers this energy to the interacting air stream of cooling tower 402. The cold water obtained by the result of the above air-water interaction is collected in cold-water reservoir 20'. The journey of the cold water begins again as pump 60' pumps water from cold-water reservoir 20' through cold-water outlet 65', to pipe 213' into air-to-water heat exchanger 230', out pipe 214', through warm water inlet 66', into water distribution system with nozzles 51'. Since cooling tower 402 operates with an air stream comprising air with a lower wet bulb temperature and dry bulb temperature (because of the air's trip through air-to-water heat exchanger 230), the achievable temperature of the cold water in cold water reservoir 20' is substantially lower than the temperature that the cold water of cold water reservoir 20 can achieve.

As described above for tower 402, fan 55" of cooling tower 403 operates to pull ambient air into air inlet 35", through air-to-water heat exchanger 230', through the wet fill, past the water distribution system with nozzles 51", through the mist eliminator 71", up through fan 55" and finally out air outlet 40" of cooling tower 403. Pump 60" pumps water from cold-water reservoir 20", through pipe 65", to cooling loads 11" and MU Air Handling Unit 715. The warm water from the above loads is returned back to cooling tower 403 through pipe 66". Pipe 66" connects to the water distribution system with nozzles 51" of cooling tower 403, which evenly distributes water across the top of the fill. As the water falls by gravity through the fill of cooling tower 403, it interacts with the moving pre-cooled air stream that has been pre-cooled by air-to-water heat exchanger 230. The air-water interaction within cooling tower 403 causes some water to evaporate. This evaporation extracts (heat) energy out of the circulating water stream and transfers this energy to the interacting air stream of cooling tower 403. The cold water obtained by the result of the above air-water interaction is collected in cold-water reservoir 20". The

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journey of the cold water begins again as pump 60" pumps water from cold-water reservoir 20" to cooling loads 11" and MU Air Handling Unit.

The first cooling state, comprising cooling tower 401, produces cold water that approaches the wet bulb temperature of the ambient air. This cold-water services air-to-water heat exchanger 230, a pre-cooling heat exchanger, located at air inlet 35' of cooling tower 402. Cooling tower 402 composes part of cooling stage 2. Since the cooling system operates to provide pre-cooled air ultimately to cooling tower 402, when cooling stage 2 comprising cooling tower 402 operates, it produces water that is colder than the cold water produced by cooling stage 1. This colder water ultimately provides cooling tower 403 with air that has an even lower wet bulb and dry bulb temperature than previous stages allowing cooling tower 403 to produce cold water that is even colder than the cold water produced in the second cooling stage.

Each of cooling towers 402 and 403 uses pre-cooled air that has a lower wet bulb temperature than ambient air. Using the pre-cooled air allows these cooling towers to reach significantly lower cold-water temperatures and exhaust air temperatures than cooling towers without air pre-cooling. In some examples, the cold exhaust air exiting the cooling towers is utilized as a source of energy by the Energy Recovery Systems to produce further useable cold water or cold air and to produce additional energy savings as compared to traditional cooling methods. Such an embodiment is depicted in FIG. 14.

The cooling system depicted in FIG. 14 functions substantially similarly to that of the cooling system of FIG. 13.

In addition to the cold water generated by the cooling towers, such as cooling towers 501, 502, 503, the cooling towers generate exhaust air that is colder than ambient air and can be utilized as a significant energy source for additional cooling loads. The exhaust air exits the cooling towers through air outlets 40, 40', 40". In some examples, dampers 340, 340', 340" control exhaust air flow out of the respective cooling towers. These dampers divert the exhaust airflow from cooling tower air outlets 40, 40', 40". Dampers 340, 340', 340" can direct exhaust air streams in the following optional ways. Option A—the dampers direct 100% of the exhaust air through energy recovery systems 330, 330', and 330". Option B—the dampers direct 100% of the exhaust air through air outlet 40, 40', 40" to the outside atmosphere bypassing the energy recovery systems. Option C—based on cooling load demands, the dampers split the exhaust air stream in any desired ratio between energy recovery systems 330, 330', 330" and exhaust air outlets 40, 40', 40".

As seen in FIG. 17, energy recover system 330 functions to reclaim some of the "coldness" from the cooling tower exhaust air by using internal fan 835 to move cool exhaust air past air-to-water heat exchangers 830 in ERS 330. This cold source can be used to service any appropriate cooling load that one of ordinary skill in the art would consider suitable. Warm water enters air-to-water heat exchangers 830 through warm water inlet pipe 866 and travels through air-to-water heat exchangers 830 where the water gives off heat to the air stream flowing out of the cooling tower. Next cold water flows from the cold-water outlet of air-to-water heat exchangers 830 into cold-water outlet pipe 865. Cold-water outlet pipe 865 carries the cold water to the cold-water inlet of cooling load 811 where the cold water picks up heat from cooling load 811 and flows through the warm water outlet of cooling load 811, through pump 860 into warm

water inlet pipe **866** to begin the cycle again. Pump **860** drives the flow through the closed loop system.

Primary Cooling Load Having Pre-Cooling Coil and Final Cooling Coil

In some embodiments the temperature of the generated cold air, for example, in a MUAHU, is lowered in two or more steps. One way of accomplishing two or more steps of air cooling is to use two cooling coils in the MUAHU. Such embodiments are described below. The first cooling step doesn't need cooling fluid as cold as the second or final step needs. Either the cooling fluid of the first or second cooling tower can supply the necessary cooling for the first stage. Sometimes this disclosure refers to cooling fluid reservoir and cooling fluid. For purposes of this disclosure, water is sometimes used as a shorthand description of any appropriate cooling fluid such as water, water solutions, or other neat or pure liquids. Cooling fluid is used interchangeably with water.

Inspection of FIG. **18** reveals the cooling towers: CT-1 (**1000**), CT-2 (**2000**), and CT-3 (**3000**). CT-1 has an air inlet and outlet powered by a fan. At the bottom of CT-1 sits cooling fluid reservoir **1111**. Cooling fluid reservoir **1111** is in fluid or liquid communication with at least heat exchanger (HX) **2100**. HX **2100** is attached to or mounted in front of the air inlet to CT-2. Essentially all of the air flowing into CT-2 passes through HX **2100**. Fluid communication from reservoir **1111** is facilitated by pump **1110**. In some embodiments, reservoir **1111** is in fluid communication with other cooling loads, indicated in FIG. **18** as "to field cooling load from CT-1". (For purposes of this disclosure, "liquid communication" is synonymous with "fluid communication" unless the context of the use of "fluid communication" clearly indicates that the term is meant to include "gaseous communication".) Warmed cooling fluid returns from the field cooling load as indicated by "from field cooling load to CT-1". HX **2100** connects to piping that returns warmed cooling fluid to CT-1, as well.

CT-2 is similar. At the bottom of CT-2 sits cooling fluid reservoir **2111**. Cooling fluid reservoir **2111** is in fluid or liquid communication with at least HX **3100**. HX **3100** is attached to or mounted in front of the air inlet to CT-3. Essentially all of the air flowing into CT-3 passes through HX **3100**. Fluid communication from reservoir **2111** is facilitated by pump **2110**. In some embodiments, reservoir **2111** is in fluid communication with other cooling loads, indicated in FIG. **18** as "to field cooling load from CT-2". Warmed cooling fluid returns from the field cooling load as indicated by "from field cooling load to CT-2". HX **3100** connects to piping that returns warmed cooling fluid to CT-2, as well.

CT-3 is similar to CT-1 and CT-2. At the bottom of CT-3 sits cooling fluid reservoir **3111**. Cooling fluid reservoir **3111** is in fluid or liquid communication with at least the primary cooling load. Fluid communication from reservoir **3111** is facilitated by pump **3110**. In some embodiments, reservoir **3111** is in fluid communication with other cooling loads, indicated in FIG. **18** as "to field cooling load from CT-3". Warmed cooling fluid returns from the field cooling load as indicated by "from field cooling load to CT-3". Primary cooling load connects to piping that returns warmed cooling fluid to CT-3, as well.

The primary cooling load depicted in FIG. **18** is an MUAHU, but those of ordinary skill in the art will recognize that the system described for this embodiment can provide the cooling load for a number of cooling loads. In fact, simply replacing the cooling coils of the MUAHU with a

liquid-to-liquid heat exchanger converts the system from cooling air to cooling a fluid.

In this embodiment one of the field cooling loads associated with CT-1 is precooling coil **3160** of MUAHU **3140**. The primary cooling load, served by CT-3, is final cooling coil **3170** of MUAHU **3140**, in this embodiment.

As can be seen, the MUAHU **3140** comprises the two cooling coils discussed above: pre-cooling coil **3160** and final cooling coil **3170**. These coils are mounted inside of MUAHU **3140** downstream of air filter **3150**. This embodiment also depicts an adiabatic humidifier **3180**.

This embodiment operates similarly to those discussed above. Operation of CT-1 begins by circulating cooling fluid using pump **1110** from cooling fluid reservoir **1111** through HX **2100**, through pre-cooling coil **3160**, and perhaps additional field cooling loads. This warmed cooling fluid returns to wet media **1112** in CT-1 and finally back to cooling fluid reservoir **1111**. At the same time, a fan moves air into the air inlet of CT-1 up through the tower counter to the downward flow of cooling fluid in wet media **1112**. This process evaporatively cools the warmed cooling fluid flowing over the wet media **1112** and humidifies the exhaust air. The now-chilled cooling fluid returns to cooling fluid reservoir **1111**.

The same thing happens in CT-2 as the air moving through the tower counter to the flow of cooling fluid through wet media **2112** couples the fluid in cooling fluid reservoir **2111**. For CT-2, the ambient air coming in has been sensibly cooled by passing through HX **2100**. The Dry Bulb and Wet Bulb of the ambient air are being reduced without changing moisture content of the air. This lower Wet Bulb temperature of the air allows for colder cooling fluid to be produced by CT-2.

Likewise, CT-3 passes even cooler air at lower Wet Bulb temperature through wet media **3111**. For CT-3, the ambient air coming in has been sensibly cooled by passing through HX **3100**. The Dry Bulb and Wet Bulb of the ambient air are being reduced without changing moisture content of the air. This lower Wet Bulb temperature of the air allows for colder cooling fluid to be produced by CT-3. Thus, the temperature of the cooling fluid in cooling fluid reservoir **3111** becomes low enough to adequately service the final cooling load of final cooling coil **3170**. Using pre-cooling coil **3160** can greatly reduce the cooling load on the final cooling coil **3170** being served by CT-3.

MECS Plus Supplemental Cooling Means (SCM)

In the embodiments discussed above, each of the cooling towers is size optimized to provide the cooling capacity that the cooling load requires. For instance, if the cooling load includes process cooling loads and a comfort cooling load for a building, the MECS must be configured, designed and sized to meet that load every day of the year. Since weather or atmospheric conditions influence the ultimate efficiency of the MECS, some days will have a combination of temperatures, relative humidity, and other parameters that make the day's cooling fluid generation easier than on other days that have less favorable weather conditions. To meet the cooling load, the MECS must be configured, designed and sized to provide the needed amount(s) of cooling fluid at the appropriate temperature(s) even on days with the least favorable conditions (typically days with high enthalpy, at corresponding Dry Bulb and Wet Bulb temperatures, which usually occurs at a high moisture content of ambient air or high dew point).

This alternative embodiment essentially works by properly configuring, designing and sizing the MECS to meet the cooling load for all but some number of the most difficult

days. Therefore, for some days, it will not provide the adequate cooling fluid flow at the appropriate temperature. To make up that shortfall in cooling fluid flow at the appropriate temperature to meet the cooling load application requirements, this embodiment places a means for supplementally cooling referred to throughout as a supplemental cooling module (SCM) in line with the MECS cooling fluid delivery system to provide a boost in cooling fluid flow and temperature on the difficult days. I discuss this embodiment below. In some embodiments, the SCM attaches into the cooling lines going into or coming out of the MECS using a fluid-to-fluid heat exchanger. An advantage to this arrangement is that the cooling fluid of the MECS and the cooling fluid of the SCM remain segregated

Inspection of FIG. 19 reveals three cooling towers: CT-1 1000, CT-2 2000, and CT-3 3000. CT-1 has an air inlet and outlet powered by a fan. At the bottom of CT-1 sits cooling fluid reservoir 1111. Cooling fluid reservoir 1111 is in fluid or liquid communication with at least heat exchanger (HX) 2100. HX 2100 is attached to or mounted in front of the air inlet to CT-2. Essentially all of the air flowing into CT-2 passes through HX 2100. Fluid communication from reservoir 1111 is facilitated by pump 1110. In some embodiments, reservoir 1111 is in fluid communication with other cooling loads, indicated in FIG. 19 as "to field cooling load from CT-1". Warmed cooling fluid returns from the field cooling load as indicated by "from field cooling load to CT-1". HX 2100 connects to piping that returns warmed cooling fluid to CT-1, as well.

CT-2 is similar. At the bottom of CT-2 sits cooling fluid reservoir 2111. Cooling fluid reservoir 2111 is in fluid or liquid communication with at least HX 3100. HX 3100 is attached to or mounted in front of the air inlet to CT-3. Essentially all of the air flowing into CT-3 passes through HX 3100. Fluid communication from reservoir 2111 is facilitated by pump 2110. In some embodiments, reservoir 2111 is in fluid communication with other cooling loads, indicated in FIG. 19 as "to field cooling load from CT-2". Warmed cooling fluid returns from the field cooling load as indicated by "from field cooling load to CT-2". HX 3100 connects to piping that returns warmed cooling fluid to CT-2, as well.

CT-3 is similar to CT-1 and CT-2. At the bottom of CT-3 sits cooling fluid reservoir 3111. Cooling fluid reservoir 3111 is in fluid or liquid communication with at least the primary cooling load. Fluid communication from reservoir 3111 is facilitated by pump 3110. In some embodiments, reservoir 3111 is in fluid communication with other cooling loads, indicated in FIG. 19 as "to field cooling load from CT-3". Warmed cooling fluid returns from the field cooling load as indicated by "from field cooling load to CT-3". Primary cooling load connects to piping that returns warmed cooling fluid to CT-3, as well.

This embodiment shows the use of three cooling towers. But the number of cooling towers depends on the load and the expected atmospheric design conditions. Embodiments using more than three cooling towers can be envisioned. Moreover, the cooling towers in a particular MECS need not have the same capacity.

SCM 4120 used any known cold or cold producing source. SCM 4120 generates chilled cooling media that is pumped through supply piping by pump 4110 to a fluid-to-fluid heat exchanger 4130. The cooling media returns to SCM 4120 through return piping. Cooling media in CT-3 flows through the other side of HX 4130 where it transfers heat to the SCM circuit dropping the temperature of the cooling media in the CT-3 circuit.

The SCM or alternatively a means for providing supplemental cooling may use a means for cooling selected from any number of now known or later invented cooling systems or cold water sources including natural sources. In some 5 embodiments, the cooling means is selected from different cooling fluid generating equipment or from natural cooling fluid sources listed below: thermally driven adsorption chillers supplying cold water or cold water-glycol solution; thermally driven absorption chillers supplying cold water or cold water-glycol solution; conventional mechanical water chillers; natural cooling fluid sources; river water, sea water, lake water, geothermal water, or other cooling sources. The adsorption/absorption chillers could be fired as is typically done in the art or by variations of art-known methods, such as low pressure water steam, hot water (solar heat, waste heat, hydrocarbon generated heat, etc.) or by direct contact with heaters fired by natural gas, or liquid propane, etc. The condensers of the chillers could be either water or air-cooled.

The MECS functions effectively for a majority of time during the year in regions with low and moderate ambient humidity. The addition of the SCM to the MECS allows it to operate year round within all global regions even those with adverse climate.

The SCM supplies cold fluid (water) at a temperature to meet the requirements of the cooling application. In some 25 embodiments, the SCM comes on line as needed with the MECS only during peak cooling conditions (such as high ambient humidity).

MECS with Closed-Loop Cooling Towers

In addition to the open-loop cooling towers used in some of the above embodiments, closed-loop cooling towers are useful, as well. FIG. 20 illustrates a MECS with closed-loop cooling towers. Of course, embodiments exist where some 35 of the cooling towers are closed-loop towers and some are open-loop towers.

ISECS with Control Over Individual Server Air Flow

In some embodiments, the MECS cooling system is used to service the cooling load of one or more heat-generating electrical or electronic devices in a process cooling manner. One set of such embodiments uses the ISECS to cool standard electronic enclosure server racks. These were discussed above. Other sets are discussed below.

Approximately 20% or more of the energy used in an individual server or individual server rack and consequently approximately 20% of the heat generated comes from the cooling fans in the servers.

Some embodiments of the ISECS partially or completely transfer this air-flow function of the server fans to the ISECS fans. In some embodiments, this allows the server fan speeds to be slowed or deactivated. Such an embodiment is depicted in FIG. 21. Similar to the ISECS discussed above, the 50 embodiments have fan coil unit (FCU) 5200 comprising housing 5201 that positions pre-cooling coil 5210 (PCC) upstream of final cooling coil (FCC) 5220, which is, in turn, upstream of FCU fans 5230.

While FIG. 21 shows two FCU fans 5230 and two cooling coils 5210 and 5220, various other embodiments exist that comprise one FCU fan 5230, one cooling coil 5220, three or more FCU fans 5230, or three or more cooling coils 5210 and 5220. Cooling coils 5210 and 5220 receive cold cooling fluid from any type of fluid cooling system. Cooling coils 5210 and 5220 circulate cooling fluid inside of FCU 5200.

Various embodiments exist where the fluid cooling system for both coils is the same, the system for the coils is different, the temperatures of the cooling fluid are the same, the temperatures of the cooling fluids are different, the

temperature of the cooling fluid into FCC 5220 is lower than that of PCC 5210, or the temperature of the cooling fluid into FCC 5220 is higher than that of PCC 5210. Some embodiments use a MECS to supply the cold cooling fluid. Some embodiments use CT-1, CT-2 or the Energy Recovery Unit of the MECS to supply cold cooling fluid to PCC 5210 and CT-1, CT-2, CT-3 or the Energy Recovery Unit to supply cold cooling fluid to FCC 5220. And some embodiments use an SCM together with CT-1, CT-2, CT-3 or Energy Recovery Unit or independently to supply cold cooling fluid to FCC 5220.

FCU 5200 additionally comprises one or more differential pressure transmitters (DPT) to provide pressure-drop information throughout FCU 5200, which is used by a command-and-control unit (in this embodiment programmable logic controller 5310 (PLC)) to determine air-flow through FCU 5200. In some other embodiments, other sensor means of measuring air flow velocity can be used. FCU 5200 also comprises FCU temperature sensors 5231 within housing 5201 to provide temperature data to the command-and-control unit. In some embodiments, sensors are air temperature sensors, but temperature sensors could be configured to provide the temperature of any relevant or desired item inside of FCU 5200.

FIG. 21 depicts an embodiment that uses PLC 5310 as the command-and-control unit. PLC 5310 connects to the sensors inside of FCU 5200, specifically in this embodiment FCU 5231 air temperature sensor and DPT 5240. DPT 5240 is shown in this embodiment as sensing the pressure difference across FCC 5220. In other embodiments, DPT 5240 measures other pressure drops, such as between the entrance to FCU 5200 and the exit from FCU 5200. In yet other embodiments, more than one DPT 5240 is used depending upon what air-velocity and air-flow-rate measurements are needed or desired.

In the embodiment of FIG. 21, PLC 5310 receives air-flow, fan speed, cooling fluid flow or other data from sensors such as DPT 5240 for air-flow through the system, fan speed (sensors not shown), cooling fluid temperature or flow rate (sensors not shown) or both, among other sensor input. Using the input data, PLC 5310 controls at least fan speed or cooling fluid flow rate through one or more of cooling coil units 5210 or 5220. In some embodiments, such as those with two or more FCU fans 5230, individual fan speeds can be controlled to be the same or can be individually controlled. The FIG. 21 embodiments show two FCU fans 5230 located at the exit of FCU 5200. But FCU fans 5230 can be located at the entrance to FCU 5200 or placed somewhere between the entrance and the exit. Multi-fan embodiments exist in which the fans are located away from each other.

As can be seen in the figure, FCU 5200 is located below floor 5400 in the embodiment of FIG. 21. But embodiments exist in which FCU 5200 is located above server rack enclosure 5100 (SRE).

PLC 5310 connects to the various sensors and controllers through individual wires, wired local area networks or buses (such as Ethernet, CAN, i2c, 1-wire, or any other known bus), or wireless local area networks (using any of the widely known protocols).

In addition to FCU 5200, the ISECS embodied in FIG. 21 also comprises components that allow PLC 5310 or an associated control module 5300 (CM) to monitor the internal temperature of individual servers 5110 with temperature sensor 5120 and adjust that temperature by adjusting air flow through the individual servers 5110 individually or by individually controlling the server's cooling-fan speed.

Additional components included baffles or gap seals 5140 to direct air flow within enclosure 5100 and server air-flow control dampers 5130. Air temperature within each server 5110 is measured using server temperature sensor 5120.

In operation, servers or other electronic equipment mounted in rack enclosures generate heat as they use electric power to facilitate their desired functions. This raises their temperature. Optimal operation and longevity of the server or other electronic equipment mounted in rack enclosures calls for maintaining their temperature below values set by their manufacturers. Each server or other electronic equipment mounted in rack enclosures has different loads moment to moment. This difference in loads causes a moment-to-moment difference in temperature between the server or other electronic equipment mounted in rack enclosures and therefore a moment-to moment difference in cooling requirements. The efficiency of the cooling system suffers when the cooling supplied doesn't match with the needed cooling.

FCU fans 5230 pull air through enclosure 5100, past air filter 5150, and into FCU 5200. Server air intakes 5135 are located upstream of the server or other electronic equipment mounted in rack enclosure 5100. This is typically on the front or room-facing side of individual servers 5110. Intake 5135 is dedicated to an individual server. Gap seals 5140 are strategically located in enclosure 5100, for instance between servers or other electronic equipment, so that when FCU fans 5230 pull air through enclosure 5100, a majority (>60%, >70%, >80%, >90%, or >95%) of the incoming air must come through intakes 5135 on each individual server 5110. This arrangement directs room air through the front of servers 5110, across server 5110's heat-generating components and out through vents (not shown) on the back of each individual server 5110. This directional flow heats the air moving through the enclosure 5100 as indicated by arrows 5160 and arrows 5161 downstream of filter 5150.

The heated air passes into FCU 5200, across PCC 5210 and FCC 5220, through FCU fans 5230, and out of FCU 5200, cooled to a desired temperature. The cooled air eventually returns into the room and begins another cycle through enclosure 5100 (or enclosure of other server racks or other electronic equipment mounted in rack enclosures in the facility).

As air moves through FCU 5200, the air pressure drops. DPT 5240 communicates the pressure drop to PLC 5310, which uses the data to determine the air flow velocity and air-flow rate. FCU temperature sensors 5231 communicate air temperature data to PLC 5310.

From various data, such as cooling fluid temperature in one or more cooling coils 5210 and 5220, air flow rate, cooling fluid flow rate, server power usage, etc. PLC 5310 controls the speed of FCU fan 5230 (associated with air velocity and air-flow rate through FCU 5200) and cooling fluid flow rate through one or more cooling coils 5210 and 5220 to maintain the room air temperature with a range around a temperature set point. PLC 5310 controls coil-coil flow rates by controlling valves 5250 and 5260. PLC 5310 connects to valves 5250 and 5260 through individual wires or through the wired or wireless LANs or buses discussed above.

As this process continues CM 5300 either alone or under PLC 5310's control monitors server 5110 power usage and the internal temperature of servers 5110. Server temperature sensors 5120 supply the internal temperature data to CM 5300. CM 5300 controls the temperatures by further opening or closing server air-flow dampers 5130 (each one associated with an individual server 5110). Further opening or

closing a damper **5130** causes the associated server to receive more or less cooling air. CM **5300** controls the temperature of each server **5110** within a range of a set-point temperature, which may be the same as or different from the set-point of FCU **5200**. The server **5110** temperatures could be controlled in a group if desired instead of individually.

MECS Plus ISECS Plus SCM Inline with HX

In FIG. **22**, an embodiment of the ISECS has a MECS cooling system paired with an SCM, as described above. In this embodiment, the MECS services one or more ISECS.

Pump **1110** circulates cooling fluid from cooling fluid reservoir **1111**, associated with CT-1, to HX **3620** in addition to circulating it to HX **2100** associated with CT-2. After the cooling fluid passes through HX **3620**, it returns warmed cooling fluid to wet media **1112**. This embodiment shows only two cooling loads on CT-1, but embodiments exist in which CT-1 services additional cooling loads.

Returning to FIG. **22**, pump **3621** pumps cooling fluid in a closed loop through HX **3620**, a liquid-liquid heat exchanger, to PCC **3700** and back. Similarly, pump **3110** pumps cooling fluid from cooling fluid reservoir **3111** to HX **3630** and returns warmed cooling fluid to wet media **3112**. This embodiment shows only a single cooling load on CT-3, but embodiments exist in which CT-3 services additional cooling loads.

Returning to FIG. **22**, pump **3631** pumps cooling fluid in a closed loop through HX **3630**, a liquid-liquid heat exchanger, to FCC **3800** and back. In some embodiments, pump **3631** pumps cold cooling fluid to and from other FCUs. The embodiment depicted in FIG. **22** further comprises HX **3710**, a liquid-liquid HX, which has one side connected into the cooling circuit serviced by pump **3631**. SCM **3640** is connected to the other side of HX **3710**. The circuit connecting SCM **3640** to HX **3710** is serviced by pump **3641**. SCM **3640** is similar to the SCMs discussed above. This arrangement allows SCM **3640** to service or boost the cooling of several FCUs simultaneously.

The MECS portion of this embodiment operates as discussed above, wherein sometime after starting, the MECS reaches a state where each of the cooling reservoirs, **1111**, **2111**, and **3111** are cold (although each has a different temperature). This state services the cooling load presented by the ISECS. Servicing the cooling load includes supplying cold cooling fluid to PCC **3700** and FCC **3800** located in enclosure **3141** of FCU **3140**. Pump **1110** circulates cold cooling fluid through the CT-1 circuit. One side of HX **3620** is part of the CT-1 circuit. Pump **3621** circulates cooling fluid through the PCC circuit. The other side of HX **3620** is part of the PCC circuit. As cooling fluid circulates through the PCC circuit, the cooling fluid is chilled as it passes through HX **3620**. The PCC circuit circulates this chilled fluid to PCC **3700**. CT-1 through HX **3620** cools one side of HX **3620** allowing the other side of HX **3620** to cool the fluid in the PCC loop. Likewise, pump **3110** circulates cold cooling fluid through the CT-3 circuit. One side of HX **3630** is part of the CT-3 circuit. Pump **3631** circulates cooling fluid through the FCC circuit. The other side of HX **3630** is part of the FCC circuit. As cooling fluid circulates through the FCC circuit, the cooling fluid is chilled as it passes through HX **3630**. The FCC circuit circulates this chilled fluid to FCC **3800**. CT-3 through HX **3630** cools one side of HX **3630** allowing the other side of HX **3630** to cool the fluid in the FCC loop.

At a second state, the PCC **3700** and FCC **3800** combine to cool hot air that comes from the SRE (not shown). The hot air enters and passes by PCC **3700** and FCC **3800** pulled by

FCU fan **3190**. During this movement, the air is chilled. Finally, the cold air returns to the IT room.

When the atmospheric conditions are favorable, operating the MECS provides enough cooling capacity to maintain the temperature of the air returning to the IT room at or below a set-point temperature. In other words, the servers in the server rack enclosure are adequately cooled. The circuit containing SCM **3640** is present, but powered down. When the atmospheric conditions are unfavorable, operating the MECS may not adequately service the load. At that point, perhaps detected by the temperature of the cooling fluid in the CT-3 cooling circuit, the command-and-control device (not shown) starts SCM **3640**, which provides additional cooling to the HX **3800** cooling circuit, which allows the MECS to meet the cooling load.

ISECS Plus MECS Plus SCM Inline with FCC

In FIG. **23**, an embodiment of the ISECS has a MECS cooling system paired with an SCM, as described above. In this embodiment, the MECS services one or more ISECS.

Pump **1110** circulates cooling fluid from cooling fluid reservoir **1111**, associated with CT-1, to HX **4135**, a liquid-liquid heat exchanger, in addition to circulating it to HX **2100** associated with CT-2. After the cooling fluid passes through HX **4135**, it returns warmed cooling fluid to wet media **1112**. This embodiment shows only two cooling loads on CT-1, but embodiments exist in which CT-1 services additional cooling loads.

Returning to FIG. **23**, pump **4160** pumps cooling fluid in a closed loop through the other side of HX **4135** to PCC **3160** and back. Similarly, pump **3110** pumps cooling fluid from cooling fluid reservoir **3111** to HX **4130**, a liquid-liquid heat exchanger, and returns warmed cooling fluid to wet media **3112**. This embodiment shows only a single cooling load on CT-3, but embodiments exist in which CT-3 services additional cooling loads.

Returning to FIG. **23**, pump **4136** pumps cooling fluid in a closed loop through the other side of HX **4130** to FCC **3170** and back. In some embodiments, pump **4136** pumps cold cooling fluid to and from other FCUs. The embodiment depicted in FIG. **23** further comprises HX **4170**, a liquid-liquid HX, which has one side connected into the cooling circuit serviced by pump **4136**. SCM **4120** is connected to the other side of HX **4170**. The circuit connecting SCM **4120** to HX **4170** is serviced by pump **4110**. SCM **4120** is similar to the SCMs discussed above. This arrangement restricts SCM **4120** to servicing or boosting the cooling of a single FCC (in this embodiment FCC **3170**).

The MECS portion of this embodiment operates as discussed above; sometime after starting, the MECS reaches a state where each of the cooling reservoirs, **1111**, **2111**, and **3111** are cold (although each has a different temperature). This state services the cooling load presented by the ISECS. Servicing the cooling load includes supplying cold cooling fluid to PCC **3160** and FCC **3170** located in enclosure **3141** of FCU **3140**. Pump **1110** circulates cold cooling fluid through the CT-1 circuit. One side of HX **4135** is part of the CT-3 circuit. Pump **4160** circulates cooling fluid through the PCC circuit. The other side of HX **4135** is part of the PCC circuit. As cooling fluid circulates through the PCC circuit, the cooling fluid is chilled as it passes through HX **4135**. The PCC circuit circulates this chilled fluid to PCC **3160**. CT-1 through HX **4135** cools one side of HX **4135** allowing the other side of HX **4135** to cool the fluid in the PCC loop. Likewise, pump **3110** circulates cold cooling fluid through the CT-3 circuit. One side of HX **4130** is part of the CT-3 circuit. Pump **4136** circulates cooling fluid through the FCC circuit. The other side of HX **4130** is part of the FCC circuit.

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As cooling fluid circulates through the FCC circuit, the cooling fluid is chilled as it passes through HX 4130. The FCC circuit circulates this chilled fluid to FCC 3170. CT-3 through HX 4130 cools one side of HX 4130 allowing the other side of HX 4130 to cool the fluid in the FCC loop.

At a second state, PCC 3160 and FCC 3170 combine to cool the hot air coming from the SRE (not shown). This hot air enters and passes by PCC 3160 and FCC 3170 pulled through FCU 3140 by FCU fan 3190. As the hot air passes over PCC 3160 and FCC 3170, the air is cooled. Finally, the cold air returns to the IT room.

When the atmospheric conditions are favorable, operating the MECS provides enough cooling capacity to maintain the temperature of the air returning to the IT room at or below a set-point temperature. In other words, the servers in the server rack enclosure are adequately cooled. The circuit containing SCM 4120 is present, but powered down. When the atmospheric conditions are unfavorable, operating the MECS may not adequately service the load. At that point, perhaps detected by the temperature of the cooling fluid in the cooling circuit of FCC 3170, the command-and-control device (not shown) starts SCM 4120, which provides additional cooling to FCC 3170.

In FIG. 24, an embodiment of the ISECS has a MECS cooling system paired with an SCM, as described above. In this embodiment, the MECS services one or more ISECS.

Pump 1110 circulates cooling fluid from cooling fluid reservoir 1111, associated with CT-1, to HX 4150, a liquid-liquid heat exchanger, in addition to circulating it to HX 2100 associated with CT-2. After the cooling fluid passes through HX 4150, the warmed cooling fluid returns to wet media 1112. This embodiment shows only two cooling loads on CT-1, but embodiments exist in which CT-1 services additional cooling loads.

Returning to FIG. 24, pump 4151 pumps cooling fluid in a closed loop through the other side of HX 4150 to PCC 3160 and back. Similarly, pump 3110 pumps cooling fluid from cooling fluid reservoir 3111 to HX 4130, a liquid-liquid heat exchanger, and returns warmed cooling fluid to wet media 3112. This embodiment shows only a single cooling load on CT-3, but embodiments exist in which CT-3 services additional cooling loads.

Returning to FIG. 24, pump 4131 pumps cooling fluid in a closed loop through the other side of HX 4130 to FCC 3170 and back. In some embodiments, pump 4131 pumps cold cooling fluid to and from other FCUs.

In this embodiment, FCU 3140 comprises an additional cooling coil serviced by SCM 4120. This coiling coil is sometimes called SCC 4180. The circuit connecting SCM 4140 to SCC 4180 is serviced by pump 4110. SCM 4140 is similar to the SCMs discussed above. SCM 4120 provides a boost to the cooling directly to the air stream through SCC 4180. In some embodiments, SCM 4140 services SCCs located in more than one FCU.

The MECS portion of this embodiment operates as discussed above; sometime after starting, the MECS reaches a state where each of the cooling reservoirs, 1111, 2111, and 3111 are cold (although each has a different temperature). This state services the cooling load presented by the ISECS. Servicing the cooling load includes supplying cold cooling fluid to PCC 3160 and FCC 3170 located in enclosure 3141 of FCU 3140. Cold cooling fluid gets to PCC 3160 through the action of pump 4151. As cooling fluid circulates through the CT-1 circuit, it cools the cooling fluid of the PCC circuit as the respective cooling fluids pass through opposing sides

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of HX 4150. The action of pump 1110 cools one side of HX 4150 allowing the other side of HX 4150 to cool the fluid in the PCC loop.

At a second state, PCC 3160 and FCC 3170 combine to cool the hot air coming from the SRE (not shown). This hot air enters and passes by PCC 3160 and FCC 3170 pulled through FCU 3140 by FCU fan 3190. As the hot air passes over PCC 3160, FCC 3170, and SCC 4180, the air is cooled. Finally, the cold air returns to the IT room.

When the atmospheric conditions are favorable, operating the MECS provides enough cooling capacity to maintain the temperature of the air returning to the IT room at or below a set-point temperature. In other words, the servers in the server rack enclosure are adequately cooled. The circuit containing SCM 4120 is present, but powered down. SCM 4120 doesn't provide any cooling in this state. When the atmospheric conditions are unfavorable, operating the MECS may not adequately service the load. At that point, perhaps detected by the temperature of the air in FCU 3140, the command-and-control device (not shown) starts SCM 4120, which provides additional cooling by circulating cold cooling fluid to SCC 4180.

To present a better understanding of the design and operational specifics of the MECS, demonstration of its cooling capability and performance, and for eventual comparison with a Conventional Mechanical Refrigeration System, the following design conditions are used to provide a comparable engineering analysis for both systems performing equal tasks:

EXAMPLES

Example 1

Cooling Application

Cool a conditioned space with the summer design sensible cooling load of approximately 92 tons of equivalent refrigeration.

Project Location—Phoenix, Ariz.

The ASHRAE specified design ambient air parameters for Phoenix Ariz. for cooling applications are 110.2° F. DB and 70° F. WB.

The ASHRAE specified design ambient air parameters for Phoenix Ariz. for evaporation applications for 0.4% are 76.1° F. WB and 96.4° F. MCDDB (Mean Coincident dry bulb temperature). (For reference only)

The indoor design air temperature is approximately 80° F. DB at a comfortable 40 to 65% relative humidity range.

The preliminary estimate of required volume of makeup/supply cooled air into the conditioned space is approximately 35,000 CFM.

These calculations are provided as illustrative example only for the exemplary system described herein. They do not limit the invention in any way and are only provided to guide the user in implementing other equivalent implementations of the invention.

Typical MECS engineering design and component list selected for performing the above-mentioned cooling.

The MECS is configured for this particular application, and it consists of the following main components:

Three induced draft counter flow cooling towers or comparable Air Washers; variable speed exhaust air fans; and variable flow circulating water pumps; and.

Pre-cooling coils located at the ambient air inlets of the cooling towers.

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The components of makeup air-handling unit **715** sit in the following sequence and following the airflow direction. Powered by a fixed or variable speed supply fan **735**, ambient air passes through the air inlet **720** of makeup air-handling unit **715**. Then it passes through air particulate filter(s) **750** and air-to-air heater exchanger **745**. Airflow through air-to-air heat exchanger **745** is assisted by fan **755**. This airflow is building exhaust air, which pre-cools ambient air destined for introduction into the building. Next, it reaches cooling coil **740**. Cold water is pumped from a cooling stage of a cooling system, through pipe **65'** through the cold-water inlet **213** to cooling coil **740** of makeup air-handling unit **715** and then through the heat exchanger warm water outlet **214** to pipe **66'** back to the cooling system. As air passes over cooling coil **740**, it gives off heat to the cold water causing the temperature of the air to fall providing sensible cooling.

In applications where the space does not required 100% ambient air but still has the same space cooling load, the air-to-air heat exchanger **745** could be replaced with an air-mixing module (not shown). The air-mixing module mixes large volumes of lower temperature return air from the conditioned space with the minimal required volume of ambient air (ventilation air). This mixed air application will significantly reduce the total energy consumption of the MECS. (Note: If this air-mixing application is implemented, the need for humidification is greatly reduced or eliminated in most cases.)

Return Air Sub-System (RA Sub-System)—the RA Sub-System contains ductwork, an adiabatic humidification chamber, and return air exhaust fan. The RA Sub-System controls temperature, humidity, and air volume of the return air stream being fed to one side of the air-to-air heat exchanger **745** or to the air-mixing module.

The integrated MECS contains the following sequential process cooling stages:

Cooling Stage-1 (Water Cooling)

From FIG. **15**, this cooling stage comprises cooling tower **601** and a water pump **60**. Cooling tower **601** generates cold water that collects in its cold-water reservoir **20**. Cooling stage-1 generates cold water for pre-cooling ambient air entering into the next stage cooling towers. The cooling coil (air-to-water heat exchanger **230**) pre-cools ambient air entering into the next stage cooling tower **601'** using some of the cold water from cooling tower **601**.

Cooling Stage-2 (Water Cooling)

This cooling stage comprises a second cooling tower **601'**, a water pump **60'**, and a cooling coil (air-to-water heat exchanger **230'**). Cooling tower **601'** generates cold water that collects in its cold-water reservoir **20'** and supplies cold water to the air-to-water heat exchanger **230'** of the third cooling tower **601''**.

Cooling Stage-3 (Water Cooling)

This cooling stage comprises third cooling tower **601''**, a water pump **60''**, and a cooling coil (air-to-water heat exchanger **230''**). Cooling tower **601''** generates cold water that collects in its cold-water reservoir **20''**, and supplies cold water to a cooling coil (air-to-water heat exchanger **740**) installed in the housing of makeup air-handling unit **715** or some other cooling load or process cooling load.

Cooling Stage-3 (Water Cooling)

This cooling stage comprises a cooling coil (air-to-water heat exchanger **740**) installed in the makeup air-handling unit. The cooling coil (air-to-water heat exchanger **740**) receives cold water from third cooling tower **601''**. The cooling coil (air-to-water heat exchanger **740**) sits in the housing of makeup air-handling unit **715** downstream of an

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air-to-air heat exchanger **745** and can either cool air leaving the air-to-air heat exchanger **745** or, if the air-to-air heat exchanger is not included, pre-cools warm ambient air as it enters into the makeup air-handling unit **715**.

Cooling Stage-5 (Makeup Air Cooling)

This stage is the final cooling stage inside of the makeup air-handling unit **715**. It provides adiabatic cooling of the supply air using any suitable direct evaporative cooling system **732**, such as using high pressure fogging nozzles.

Cooling Stage-6 (Return Air Cooling)

This cooling stage is a part of the return air RA Sub-System, combining the return air (RA) ductwork, evaporative air humidification chamber, and the RA exhaust fan. The humidification chamber comprises a humidifier that could be either a high-pressure water dispersion type, or any other evaporative humidifier type appropriate for the application. The purpose of cooling stage-6 is to provide high-efficiency adiabatic cooling of the RA stream before its heat exchange interaction with the warm ambient air stream in the air-to-air heat exchanger **745**, or before mixing with ambient air (ventilation air) in the air-mixing module, if the cooling system is configured to use an air-mixing module.

Cooling Stage-7 (Makeup Air Cooling)

This cooling stage is an air-to-air heat exchanger and its function is to pre-cool outside warm air using the lower temperature return air stream from the conditioned space and thereby reduce the MECS total energy use.

Different cooling applications call for varying MECS configurations.

Each MECS is configured to produce the required amount of cooling for a defined application, such as conditioned space or process cooling for industry. Each design factors in the peak cooling demand at summer conditions for the local environment.

The MECS has a dedicated control and monitoring system with appropriate software to provide optimum, moment-to-moment control over operating parameters that yield the required amount of cooling at minimal power consumption based on constantly changing building cooling loads, process cooling loads, and ambient air conditions.

MECS Cooling Stages—Divided into Water and Air Cooling Stages

Described in a different way, in general, all cooling stages of MECS fall into two states: a water-cooling stage and an air-cooling stage.

A. Water Cooling Stages

The three water-cooling stages of the MECS use three cooling towers **601,601',601''** with each stage having a cooling tower, a cooling coil (optional in the first cooling tower), and a pump arranged in series to provide a cascade of cooling stages. That is, the cooling tower of a preceding stage generates cold water similarly to prior art cooling towers. This cold water is used to pre-cool the incoming air of a succeeding stage, allowing the cooling tower of the succeeding stage to produce cooler water than was possible in the preceding stage. In some examples, this cascading of one cooling tower after another with a lower stage bolstering the cooling ability of a higher stage continues, giving cooling systems with 3, 4, 5, or more successive stages, each stage capable of producing cold water at successively colder temperatures.

MECS operation begins with a command from the central computer of the energy management system and from the local programmable logic controller. The operation of the MECS takes place in the following sequential steps:

Step-1

The fan **655** of the first cooling tower **601** starts, using a slow start method. Water circulating pump **60** starts, using a slow start method. The pump **60** takes cold water from the cold-water reservoir **20** and directs the water to pre-cooling coils (air-to-water heat exchanger **230'**) installed at the ambient air intakes of another cooling tower(s), respectively. Water, warmed by pre-cooling coils, returns to the source cooling tower and distributes the water evenly over the top of cooling tower fill, positioning it for continuing the evaporative cooling cycle.

Step-2

The fan **655'** in the second cooling tower **601'** starts, using a slow start method. The water-circulating pump **60'** starts, using a slow start method. The pump **60'** takes cold water from cold-water reservoir **20'** and directs the water to pre-cooling coil (air-to-water heat exchanger **230'**) installed at the ambient air intakes of the next stage cooling tower **601''**. Warmed water from the pre-cooling coil returns to the source cooling tower **601'** and distributes the water evenly over the top of the fill of the cooling tower for continuing the evaporative cooling cycle.

Step-3

The fan **655'** of the third cooling tower **601''** starts, using a slow start method. The water circulating pump **60''** starts, using a slow start method. The pump **60''** takes cold water from the cold-water reservoir **20''** and directs the water to pre-cooling coil (air-to-water heat exchanger **740'**) installed in the makeup air-handling unit **715**. The warm water from the pre-cooling coil returns to the source cooling tower **601'** and distributes the water evenly over the top of the fill for continuing the evaporative cooling cycle.

Due to the heat-mass transfer process taking place in the fill of all cooling towers, part of the water falling over the cooling tower fill evaporates and this evaporation process lowers the temperature of the remaining water that is falling through the cooling tower and collected in the cold-water reservoirs. The dry bulb temperature of ambient air entering into the pre-cooling coils is higher than the temperature of the cooling coil cooling water. The precooling coils extract some amount of heat from the ambient air and, as a result, the dry bulb and wet bulb temperatures of the ambient air falls (is lowered). The calculations for the embodiment assume approach temperatures for cooling towers 2° F., and approach temperatures for pre-cooling coils 3° F.

These approach temperatures have been selected as illustrative examples only for the exemplary system described herein. Other approach temperatures may be applied that will provide a varying degree of results. The cooling towers may have approach temperatures that are different from one another or that are the same. Pre-cooling coils may have approach temperatures that are different from one another or that are the same.

Step-4

Supply fan **735** of makeup air-handling unit **715** starts, using a slow start method.

Step-5

The RA exhaust fan of the RA Sub System starts, using the slow start method.

Step-6

After the cooling system achieves the desired cold air supply from the makeup air-handling unit and achieves the desired temperature for the air leaving the pre-cooling coil, the control system, based on established parameters, activates the humidifier **730** at its minimum capacity and gradually adjusts its humidification capacity to humidify air

as set out in the specific design specifications of the application for the conditioned space.

Step-7

After the cooling system achieves the desired cold air supply from the makeup air-handling unit **715**, the control system adjusts and regulates the return air fan to meet the desired volume of return air.

Step-8

After the supply and return airflows are balanced as desired, the control system activates the humidifier in the RA Sub System at its minimum capacity and gradually adjusts its humidification capacity until it optimizes the humidification level to provide the lowest possible temperature of the return air stream. Lower air stream temperatures at this point provide maximum pre-cooling of ambient air in the air-to-air heat exchanger.

Example 2

The following estimates show cold water temperatures leaving the cooling towers for a cooling system design based on summer ambient air conditions for Phoenix, Ariz., and according to the MECS (cooling system) design. Since ASHRAE-specified design ambient air parameters for Phoenix, Ariz., for evaporation applications for 0.4% are 76.1° F. WB and 96.4° F. MCDB (evaporative application) exist at peak conditions for only a very short cooling time, these analysis and calculations focus on the ASHRAE Cooling Application corresponding to ambient air parameters for Phoenix, Ariz., of 110.2° F. DB and 70.0° F. WB temperatures. These parameters approximate some of the least favorable conditions for using evaporative cooling systems in Phoenix.

The estimated theoretical temperatures of cold water exiting any cooling tower with a design approach temperature of 2° F. operating at the design ambient air conditions of 76.1° F. WB and 96.4° F. MCDB (evaporative application) without using pre-cooling coils is approximately 78.1° F.

The estimated theoretical temperatures of cold water exiting a similarly designed cooling tower operating while not using a pre-cooling coil and cooling towers operating while using pre-cooling coils at the design ambient air conditions of 76.1° F. WB and 96.4° F. MCDB (evaporative application) are approximately 78.1° F., 73.6° F. and 72.6° F., respectively.

The estimated theoretical temperatures of cold water exiting any cooling tower with a design approach temperature of 2° F. (operating without pre-cooling coils) at the design ambient air conditions of 110° F. DB and 70° F. WB (cooling application) is approximately 72° F.

The estimated theoretical temperatures of cold water exiting a similarly designed cooling tower operating while not using a pre-cooling coil and second and third stage cooling towers operating while using pre-cooling coils at the design ambient air conditions of 110° F. DB and 70° F. WB (cooling application) are approximately 72° F., 60.2° F. and 55.5° F., respectively.

The design approach temperature for all the cooling towers is 2° F. The design approach temperature for all cooling coils in this calculation is 3° F. But approach temperatures may change to meet specific cooling design applications for specific locations and design parameters and will result in varying cooling results.

It should be noted that the estimated temperature values of cold water shown above for the cooling and evaporative applications does not include the pre-cooling of ambient air

in the cooling coil located at the air intake of the first cooling tower. If the MECS design includes the cooling effect of the cooling coil, the water temperatures leaving the next stage cooling towers would be lower.

Sequential Cold Water Temperature Chain of the MECS Water Cooling Stages

The temperature of cold water exiting the third cooling tower is approximately 55.5° F., lower than the temperature of cold water exiting the second cooling tower, and the temperature of cold water exiting the second cooling tower is approximately 60.2° F., lower than the temperature of cold water exiting the first cooling tower, which is approximately 72° F. Another means of stating the above is that the temperature of cold water exiting cooling towers is that the third cooling tower is approximately 55.5° F., which is less than the second cooling tower of approximately 60.2° F., which is less than the first cooling tower of approximately 72° F. In this design example, the initial ambient air wet bulb temperature is 70° F. Therefore, in this example, an invention cooling system provides evaporatively cooled cold water exiting the final cooling tower at approximately 55.5° F., which is lower than the 70° F. initial wet bulb temperature of the ambient air.

Some invention cooling systems achieve these effects using various methods and systems consisting of the following:

Pre-cooling the ambient air entering into the cooling tower(s) with cooling coil(s) to provide sensible cooling of the entering air for lowering the ambient air's dry bulb and wet bulb temperatures.

If more than one cooling tower is arranged in series (cascaded) to meet a specific application, cold water from a first stage cooling tower is supplied to the cooling coil of the second cooling tower and to other optional cooling loads. Cold water from a second-stage cooling tower is supplied to the cooling coil to a third or subsequent stage cooling towers and to other optional cooling loads. Cold water from a second, third, or greater stage is supplied to the cooling coil in the makeup air-handling unit and may be supplied to other optional cooling loads.

For the specific local design conditions and specific cooling application, the piping system configuration supplying cold water or cold air to the air or water cooling loads can be modified to provide flexibility in operating any combination of cooling towers.

In all cases, invention methods of arranging the cooling towers in a series/cascade providing for the operation of the cooling tower combinations using special direct/indirect evaporation techniques is able to generate cold water with a final temperature lower than the initial wet bulb temperature of ambient air. The temperature of cold water generated by MECS can be used to satisfy a majority of HVAC and process cooling applications while using significantly lower energy as compared to conventional mechanical refrigeration systems.

Air Cooling Stages

The makeup air-handling unit cools the makeup air for this particular application. The makeup air-handling unit comprises a pre-cooling coil providing sensible cooling (cooling stage-4) of the ambient air, an evaporative humidifier providing additional (if necessary) adiabatic cooling of the makeup air (cooling stage-5), and either an air-to-air heat exchanger (cooling stage-7) or air-mixing section or both use the return air from the conditioned space.

The makeup air-handling unit fan pulls the required amount of the makeup (ambient) air into the makeup air-handling unit housing through the air intake louver. The air then passes through the air filter section, the air-to-air heat exchanger section, and enters into the pre-cooling coil, which cools makeup air using cold water supplied from

cooling tower. (Note: At this point, it is not assumed that an air-to-air heat exchanger is incorporated thereby facilitating the next statement.) Air enters pre-cooling coil at conditions of 110.2° F. DB and 70° F. WB temperature and leaves pre-cooling coil at approximately 58.5° F. DB and 51.5° F. WB temperature. The sensible cooling load for pre-cooling coil for a cooling application described herein is approximately 168.0 tons of equivalent refrigeration.

Note: For demonstration of the available cooling capacity of the MECS, we do not take into consideration the heat rejected from the ambient air stream by pre-cooling the return air stream in the air-to-air heat exchanger.

Cooling Stage-5 (Makeup Air Cooling)

Cooling Stage-5 further increases cooling capacity of the cooled supply air, reducing its dry bulb temperature by means of adiabatic cooling of ambient air coming through the pre-cooling coil. Cooling Stage-5 comprises an evaporative air humidifier installed in the makeup air-handling unit housing downstream of the supply air fan. The adiabatic cooling capacity of cooling stage-5 is approximately 96,485 BTU/hr or 8 tons of equivalent refrigeration. The humidifier could be either a high-pressure water dispersion type or any other type of evaporative humidifier appropriate for the application. The integrated part of the cooling stage-5 is a mist eliminator situated downstream of the humidifier. The parameters of the supply air leaving cooling stage 5 and entering into the conditioned space are approximately 51.8° F. DB and 51.3° F. WB at the total supply airflow rate of approximately 35,000 CFM (air mass flow is equivalent to 160,809 lbs/hr). Assuming a condition space temperature of 80° F. DB, the assimilating sensible cooling capacity of the supply air is approximately 92 tons of equivalent refrigeration.

Cooling Stage-6 (Return Air Cooling)

The air cooling stage-6 provides the high-efficiency adiabatic cooling of the RA stream to reduce its temperature as low as possible before its heat exchange interaction with the warm ambient air stream in the air-to-air heat exchanger which is part of cooling stage-7. This air cooling stage-6 is a part of the RA Sub-System, combining the RA ductwork, evaporative air humidification chamber, and the air-to-air heat exchanger physically located in the makeup air-handling unit housing. The humidification chamber comprises the humidifier, which could be either a high-pressure water dispersion type or any other appropriate type of evaporative humidifier matching the application. The integrated part of cooling stage-6 is a mist eliminator situated downstream of the humidifier in the humidification chamber.

Cooling Stage-7 (Makeup Air Cooling)

Cooling Stage-7 allows significant reduction in the total energy usage by the MECS, especially at peak conditions, by pre-cooling ambient air using the lower temperature return air from the conditioned space. In our case, the estimated temperature of the adiabatically cooled RA entering the air-to-air heat exchanger could be within approximately 75-76° F. DB range while the temperature of ambient air entering the air-to-air heat exchanger is 110.2° F. DB. The anticipated heat transfer efficiency of the heat exchanger with the above interacting air-streams is approximately 70%.

Cooling Stage-7 consists of an air-to-air heat exchanger situated at ambient air intake of the makeup air-handling unit, RA exhaust fan, and RA ductwork. The RA exhaust fan is installed at the strategic location-downstream of the air-to-air heat exchanger. This location of the RA exhaust fan makes the following positive energy impacts:

It increases the total amount of heat extracted from the warm ambient air stream by eliminating the fan heat going to the RA stream resulting in the production of cooler

makeup air entering into pre-cooling coil and reducing the cooling load on the pre-cooling coil.

It decreases the required amount of cold water used by pre-cooling coil, and reduces the energy consumption of all the operating cooling towers and their respective water circulating pump(s).

The makeup air-handling unit of the MECS supplies into the conditioned space approximately 35,000 CFM of cooled air at the estimated parameters of 51.8° F. DB and 51.3° F. WB. The initial design parameters of ambient air entering

temperatures can provide specified indoor air conditions of 80° F. DB and relative humidity of 62.3% in the conditioned space. The corresponding net sensible cooling capacity of the cold supply air is approximately 92 tons of equivalent refrigeration.

Note: The design parameters of the return air exiting the conditioned space and entering into RA Sub-System are approximately 80° F. DB and 62.3° F. WB temperatures.

TABLE 7

Carbon Footprint Comparison of Traditional Data Center Cooling Systems to the Natural Cycle Energy, Inc. RTDCCS (From example above: 2000 KW and 569 tons of cooling). The carbon output per kWh assumed is 0.524 pounds per kWh based on Pacific Gas and Electric published numbers.										
	Traditional DC Cooling	RTDCCS	Reduction in Carbon	%			# of Trees	Environmental Impact per kW of Energy Savings		
	LBs of Carbon Released	LBs of Carbon Released	Footprint LBs Released	Reduction in Carbon Footprint	Tons of CO2 Reduced	Equivalent Mid-Sized Cars*	to Offset/ YR	Tons of CO2 Reduced	Equivalent Mid Sized Cars	# of Trees to Off-set/YR
CRAC Cooled System	7,541,693	1,806,864	(5,734,829)	76.0%	2867	434	14,337	1.43	0.22	7.17
CRAH Cooled System - Chilled Water Based	7,078,642	1,806,864	(5,271,778)	74.5%	2636	399	13,179	1.32	0.20	6.59
CRAC Cooled System w/ Containment	6,976,810	1,806,864	(5,169,946)	74.1%	2585	392	12,925	1.29	0.20	6.46
CRAH Cooled System w/ Containment	6,615,044	1,806,864	(4,808,180)	72.7%	2404	364	12,020	1.20	0.18	6.01
Liquid Cooled Racks Unoptimized	6,181,605	1,806,864	(4,374,741)	70.8%	2187	331	10,937	1.09	0.17	5.47
Liquid Cooled Racks Chilled Water Temperature Optimized	4,491,060	1,806,864	(2,684,196)	59.8%	1342	203	6,710	0.67	0.10	3.36
Liquid Cooled Racks Chilled Water Temperature Optimized and Free Cooling Systems	3,638,803	1,806,864	(1,831,939)	50.3%	916	139	4,580	0.46	0.07	2.29
Liquid Cooled Racks Chilled Water Temperature Optimized and Evaporative Free Cooling Systems	3,146,875	1,806,864	(1,340,011)	42.6%	670	102	3,350	0.34	0.05	1.68
Active Liquid Cooled Doors, Chilled Water Temperature Optimized and Evaporative Free Cooling Systems	3,054,965	1,806,864	(1,248,101)	40.9%	624	95	3,120	0.31	0.05	1.56
Passive Liquid Cooled Doors, Chilled Water Temperature Optimized and Evaporative Free Cooling Systems	2,428,306	1,806,864	(621,442)	25.6%	311	47	1,554	0.16	0.02	0.78
Pumped Refrigerant Systems	4,535,449	1,806,864	(2,728,585)	60.2%	1364	207	6,821	0.68	0.10	3.41
Air Side Economizing	3,699,380	1,806,864	(1,892,516)	51.2%	946	143	4,731	0.47	0.07	2.37

*Carbon Calculator (1000 miles driven per month) Environmental Impact per KW of Energy Savings

into the makeup air-handling unit are 110.2° F. DB and 70° F. WB temperatures. The indoor air design parameters for the conditioned space are approximately 80° F. DB and 62.3° F. WB temperatures. The cooling capacities of the air cooling stages of the makeup air-handling unit are:

Air Cooling Stage-4 168 tons of equivalent refrigeration.

Air Cooling Stage-5 (sensible equivalent adiabatic cooling) 8 tons of equivalent refrigeration.

The total gross air cooling capacity of the makeup air-handling unit in this example is approximately 176 tons of equivalent refrigeration. The total sensible cooling load for cooling 160,809 lbs/hr of ambient air mass at initial temperatures of 110.2° F. DB and 70° F. WB to supply air temperatures of 51.8° F. DB and 51.3° F. WB is approximately 170 tons of equivalent refrigeration. Therefore, to cool specified amounts of ambient air from the initial design parameters to the specified parameters of the supply requires a net of approximately 170 tons of equivalent refrigeration.

35,000 CFM (mass flow rate 160,809 lbs/hr) of supply air at approximate conditions of 51.8° F. DB and 51.3° F. WB

While particular embodiments of the present invention have been shown and described, it will be obvious to those skilled in the art that changes and modifications can be made without departing from the embodiments of this invention in its broader aspects and, therefore, the appended claims are to encompass within their scope all such changes and modifications as fall within the true, intended, explained, disclose, and understood scope and spirit of this invention's multitudinous embodiments and alternative descriptions.

Additionally, various embodiments have been described above. For convenience's sake, combinations of aspects composing invention embodiments have been listed in such a way that one of ordinary skill in the art may read them exclusive of each other when they are not necessarily intended to be exclusive. But a recitation of an aspect for one embodiment is meant to disclose its use in all embodiments in which that aspect can be incorporated without undue experimentation. In like manner, a recitation of an aspect as composing part of an embodiment is a tacit recognition that a supplementary embodiment exists that specifically excludes that aspect. All patents, test procedures, and other

documents cited in this specification are fully incorporated by reference to the extent that this material is consistent with this specification and for all jurisdictions in which such incorporation is permitted.

Moreover, some embodiments recite ranges. When this is done, it is meant to disclose the ranges as a range, and to disclose each and every point within the range, including end points. For those embodiments that disclose a specific value or condition for an aspect, supplementary embodiments exist that are otherwise identical, but that specifically exclude the value or the conditions for the aspect.

The invention claimed is:

1. A system comprising:

an individual server enclosure cooling system (ISECS) comprising:

a fan coil unit (FCU) comprising:

a housing;

a pre-cooling coil (PCC) mounted in the housing;

a final cooling coil (FCC) downstream of the PCC;

a fan that services the housing;

and

a computer-based command-and-control system in signal communication with one or more sensors configured to sense at least one cooling parameter;

wherein the housing of the FCU connects to a single server enclosure rack;

and

a multi-stage evaporative cooling system (MECS) comprising:

an initial-stage (IS) cooling assembly that comprises an IS cooling tower having:

an ambient air inlet without an associated heat exchanger,

an air outlet,

an IS cooling fluid reservoir disposed proximate a bottom of the IS cooling tower;

and

a fan dedicated to the IS cooling tower, and configured to move air through the IS cooling tower;

a final-stage (FS) cooling assembly that comprises a cooling tower having:

an air inlet,

an air outlet,

a cooling fluid reservoir disposed proximate a bottom of the FS cooling tower,

a fan dedicated to the FS cooling tower and configured to move air first through an FS air-inlet heat exchanger then the FS cooling tower,

and a variable-flow pump that is adapted to pump cooling fluid through FS supply piping;

wherein the IS cooling fluid reservoir at least directly or indirectly connects to the PCC and one or more of the following heat exchangers:

the FS air-inlet heat exchanger;

and

mid-stage (MS) air-inlet heat exchanger for an MS cooling assembly;

wherein warmed cooling fluid returns directly to wet media of the IS cooling tower and to the IS cooling fluid reservoir for reuse, and the FS cooling fluid reservoir directly or indirectly connects to:

the FCC;

and

one or more additional cooling loads,

wherein warmed cooling fluid returns directly to wet media of the FS cooling tower and returns to the FS cooling fluid reservoir for reuse.

2. The system of claim **1** further comprising a means for supplemental cooling (SCM).

3. The system of claim **2** wherein a cooling circuit directly or indirectly connects the FS cooling fluid reservoir, the FCC, and the SCM.

4. The system of claim **3** wherein the SCM comprises:

thermally driven adsorption chillers supplying water or water-glycol solution;

thermally driven absorption supplying water or water-glycol solution;

conventional mechanical water chillers;

natural cooling fluid sources;

river water;

sea or ocean water;

lake water;

or

geothermal water.

5. The system of claim **4** wherein the computer-based command-and-control system is configured to control the SCM.

6. The system of claim **5** wherein the SCM comprises a heat exchanger (SCM-HX) and the SCM-HX connects between the FS cooling fluid reservoir and the FCC.

7. The system of claim **6** wherein the MECS further comprises a heat exchanger B (HXB) connected between the FS cooling fluid reservoir and FCC such that HXB maintains separation between the cooling fluid of an HXB-FS cooling circuit connecting the FS cooling fluid reservoir to HXB and the cooling fluid of an HXB-FCC cooling circuit connecting HXB to the FCC.

8. The system of claim **7** wherein the HXB-FS cooling circuit comprises the SCM.

9. The system of claim **7** wherein the HXB-FCC cooling circuit comprises the SCM.

10. The system of claim **5** wherein the MECS further comprises a heat exchanger B (HXB) connected between the FS cooling fluid reservoir and the FCC such that HXB maintains separation between the cooling fluid of an HXB-FS cooling circuit connecting the FS cooling fluid reservoir to HXB and the cooling fluid of an HXB-FCC cooling circuit connecting HXB to the FCC.

11. The system of claim **10** wherein the ISECS further comprises an SCM cooling coil (SCM-CC) mounted in the housing between the FCC and the fan wherein a cooling circuit connects the SCM to the SCM-CC.

12. The system of claim **11** wherein the computer-based command-and-control system is configured to control the SCM.

13. The system of claim **1** additionally comprising:

an MS cooling assembly that comprises a cooling tower having:

an air inlet,

an air outlet,

a cooling fluid reservoir disposed proximate a bottom of the MS cooling tower,

a fan dedicated to the MS cooling tower, and configured to move air first through the MS air-inlet heat exchanger then the MS cooling tower,

a heat exchanger at the air inlet of the MS cooling tower,

and

a pump that is adapted to pump cooling fluid through MS supply piping;

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wherein the MS cooling fluid reservoir connects at least to one or more of the following heat exchangers:
 the FS air-inlet heat exchanger;
 and
 an MS air inlet heat exchanger serving the air inlet of another MS cooling tower;
 and

wherein warmed cooling fluid returns directly to wet media of the MS cooling tower and to the MS cooling fluid reservoir for reuse.

14. The system of claim **13** further comprising a means for supplemental cooling (SCM).

15. The system of claim **14** wherein the SCM comprises a heat exchanger (SCM-HX) and the SCM-HX connects between the FS cooling fluid reservoir and the FCC.

16. The system of claim **15** wherein the MECS further comprises a heat exchanger B (HXB) connected between the FS cooling fluid reservoir and the FCC such that HXB maintains separation between the cooling fluid of an HXB-

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FS cooling circuit connecting the FS cooling fluid reservoir to HXB and the cooling fluid of an HXB-FCC cooling circuit connecting HXB to the FCC.

17. The system of claim **16** wherein the HXB-FS cooling circuit comprises the SCM.

18. The system of claim **16** wherein the HXB-FCC cooling circuit comprises the SCM.

19. The system of claim **14** wherein the MECS further comprises a heat exchanger B (HXB) connected between the FS cooling fluid reservoir and the FCC such that HXB maintains separation between the cooling fluid of an HXB-FS cooling circuit connecting the FS cooling fluid reservoir to HXB and the cooling fluid of an HXB-FCC cooling circuit connecting HXB to the FCC.

20. The system of claim **19** wherein the ISECS further comprises an SCM cooling coil (SCM-CC) mounted in the housing between the FCC and the fan wherein a cooling circuit connects the SCM to the SCM-CC.

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