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(54) **TERMINAL UNIT FOR CONDITIONING OF INDOOR AIR**

(57) A system and terminal unit are provided for efficiently and effectively conditioning indoor air. Some embodiments address temperature control, humidity control, air quality control, while also introducing conditioned outdoor air. One aspect relates to a terminal unit that monitors and controls sensible and latent cooling rates to simultaneously meet temperature and humidity set-points for the conditioned space. A sensor suite provides measurements for monitoring cooling rates and a control system controls actuators to meet the sensible and latent cooling requirements. The terminal unit may have a secondary recirculation air intake that bypasses the cooling coil to warm supply air prior to exiting the terminal unit. The terminal unit may be part of an air conditioning system where it is connected to a main branch of a hybrid branch controller which avoids having a home run to the HBC for each terminal unit.

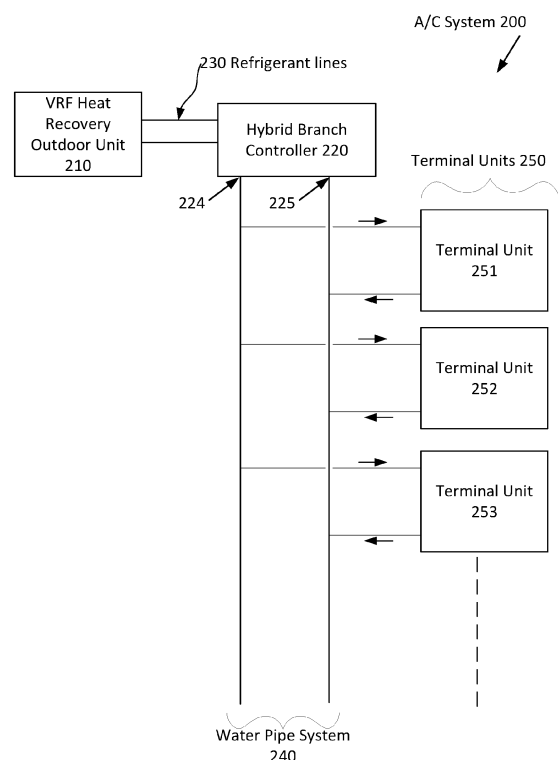


FIG. 2

Description**RELATED APPLICATION**

[0001] This application claims priority under 35 U.S.C. §119(e) to U.S. provisional patent application, U.S. Ser. No. 63/403,855, filed September 5, 2022; U.S. provisional patent application, U.S. Ser. No. 63/340,618, filed May 11, 2022; and U.S. provisional patent application, U.S. Ser. No. 63/298,334, filed January 11, 2022, all of which are herein incorporated by reference in their entirety.

TECHNICAL FIELD

[0002] The present disclosure relates to the field of conditioning of indoor air.

BACKGROUND

[0003] Heating, ventilation, and air conditioning (HVAC) technologies have been developed for conditioning indoor air with the goal of effectively and efficiently providing comfort for occupants and/or satisfactory ambient conditions for property.

[0004] In United States Patent Number 11,054,167 issued July 6, 2021 (hereinafter the '167 patent) which is herein incorporated by reference in its entirety, Inventors Richard Furman and Zachary M. Thomas disclosed, *inter alia*, a control system for controlling liquid flow from a supply into a terminal unit where the control system had a supply input port; a load return port; a recirculation pump for pumping liquid from a pump input port to a pump output port, the pump input port connected to receive a first portion of liquid flowing from the load return port; a junction configured to combine liquid flowing from the pump output port with liquid flowing from the supply input port; a load input port configured to receive such combined liquid from the junction; a supply return port connected to receive a remaining portion of the liquid flowing from the load return port; a control valve to restrict flow of liquid between the supply input port and the supply return port; a sensor; and a control module to control the control valve based at least in part on a measurement from the sensor. FIG. 1 shows a simplified version of the "FlowBridge" control system described in the '167 patent. Specifically, FIG. 1 shows a control system 1 having a water supply input port 8, a water supply return port 9, a coil water input port 10, a coil water return port 11, a control valve 3, a recirculation pump 2, a check valve 7, a sensor 5, junctions 4 and 6, a control module 13, an ambient sensor 12, a power source 14, a user interface 15, and a data port 16. For simplicity, herein embodiments of the control system disclosed in the '167 patent are referred to by the FlowBridge trade name.

[0005] In United States Published Patent Application Number 2022/0154972 published May 19, 2022 (hereinafter the '972 application) which is herein incorporated by reference in its entirety, Inventors Furman and Thomas disclosed, *inter alia*, a control system for managing latent and sensible cooling in a terminal unit by measuring the rates of latent and sensible cooling and controlling them based on set points.

[0006] Products offering a hybrid approach to heating and cooling whereby a combination of refrigerant and water are used have been developed by Mitsubishi and other organizations. A hybrid branch controller is connected with an outdoor unit and circulates refrigerant. Within the hybrid branch controller are two heat exchangers that transfer heat between the primary refrigerant side and the water. The water is then pumped to individual terminal units. Each heat exchanger can operate in either a heating or cooling mode such that both heating and cooling can be provided.

SUMMARY

[0007] A system and terminal unit are provided for efficiently and effectively conditioning indoor air. Some embodiments address temperature control, humidity control, air quality control, while also introducing conditioned outdoor air. One aspect relates to a terminal unit that monitors and controls sensible and latent cooling rates to simultaneously meet temperature and humidity setpoints for the conditioned space. A sensor suite provides measurements for monitoring cooling rates and a control system controls actuators to meet the sensible and latent cooling requirements. The terminal unit may have a secondary recirculation air intake that bypasses the cooling coil to warm supply air prior to exiting the terminal unit. The terminal unit may be part of an air conditioning system where it is connected to a main branch of a hybrid branch controller which avoids having a home run to the HBC for each terminal unit.

[0008] One aspect relates to an air conditioning system comprising a terminal unit having a mixing chamber; a first recirculation air port for receiving first recirculation air and connected to the mixing chamber by a first duct; a cooling coil within the first duct for cooling the first recirculation air; a second recirculation air port for receiving second recirculation air and connected to the mixing chamber; a conditioned air port for receiving conditioned air and connected to the mixing chamber; and a supply air port for providing supply air and connected to the mixing chamber. The mixing chamber

combines the first recirculation air, the second recirculation air, and the conditioned air to produce the supply air which is provided to the conditioned space.

[0009] In some embodiments the terminal unit is among a plurality of terminal units which are part of the air conditioning system. The air conditioning system may further include a hybrid branch controller having a pair of refrigerant pipe ports for receiving and returning refrigerant; a pair of cold water pipe ports; and a heat exchanger having refrigerant piping connected to the pair of refrigerant pipe ports and water piping connected to the pair of cold water pipe ports; and piping connecting the plurality of terminal units to the pair of cold water ports.

[0010] In some embodiments, the supply air port of the terminal unit is connected to the mixing chamber by a second duct, and the terminal unit has a fan within the second duct to draw air from the mixing chamber and blow the supply air through the supply air port.

[0011] In some embodiments, the terminal unit comprises an actuator to control a flow rate of second recirculation air through the second recirculation air port. In some embodiments the actuator is an electronically controlled damper. The terminal unit may have a temperature sensor to measure a temperature of the supply air and a controller to control the damper based on the temperature of the supply air. For example, the controller may be configured to open the damper to control the flow rate of the second recirculation air, at least in part, in proportion to a difference between a specified threshold temperature and the temperature of the supply air measured by the temperature sensor. That is, as the temperature of the supply air falls further below the threshold temperature, the damper opens more to allow more air in more recirculation air. In some embodiments the controller also uses an integral control component to improve performance.

[0012] Another aspect relates to an air conditioning system having a hybrid branch controller, a plurality of terminal units, and piping. The hybrid branch controller has a pair of refrigerant pipe ports for receiving and returning refrigerant, a pair of cold water pipe ports, and a heat exchanger having refrigerant piping connected to the pair of refrigerant pipe ports and water piping connected to the pair of cold water pipe ports. The piping connects the plurality of terminal units to the pair of cold water ports.

[0013] In some embodiments, at least one of the terminal units comprises a mixing chamber; a first recirculation air port for receiving first recirculation air and connected to the mixing chamber by a first duct; a cooling coil within the first duct for cooling the first recirculation air; a second recirculation air port for receiving second recirculation air and connected to the mixing chamber; a conditioned air port for receiving conditioned air and connected to the mixing chamber; and a supply air port for providing supply air and connected to the mixing chamber. The mixing chamber combines the first recirculation air, the second recirculation air, and the conditioned air.

[0014] Another aspect relates to a terminal unit for conditioning the air of a conditioned space. The terminal unit comprises a recirculation air port; a conditioned air port; a supply air port; a mixing chamber connected to the recirculation air port via a recirculation air duct, the conditioned air port via a conditioned air duct, and the supply air port via a supply air duct; a cooling coil in the recirculation air duct; a first sensor in the supply air duct to measure a property of supply air passing through the supply air port; a second sensor in the recirculation air duct to measure the property of recirculation air passing through the recirculation air port; and a controller configured to determine an amount of cooling being delivered to the conditioned space based at least in part on the property of the supply air and the property of the recirculation air measured by the first and second sensors, respectively, and to control coolant in the cooling coil based at least in part on the amount of cooling. In some embodiments the coolant is water or another suitable liquid.

[0015] In some embodiments, the recirculation air port is a first recirculation air port and the terminal unit further comprises a second recirculation air port connected to the mixing chamber via a second recirculation air duct and a third sensor in the second recirculation air duct. In some embodiments, the first and second sensors are carbon dioxide sensors and the third sensor is an air flow rate sensor.

[0016] In some embodiments, the terminal unit includes a fourth sensor to measure the property of conditioned air passing through the conditioned air port. The controller may be further configured to determine an amount of cooling based at least in part on the property of the conditioned air measured by the fourth sensor.

[0017] In some embodiments, the amount of cooling the controller determines is the amount of sensible cooling performed with the terminal unit. In some embodiments, a fifth sensor in the recirculation air duct on the outlet side of the cooling coil is used to measure temperature of the recirculation air. The controller may determine a recirculation air flow rate based at least in part from measurements from the first and second sensors and the amount of sensible cooling based at least in part on a first amount of sensible cooling delivered by the cooling coil, the first amount of sensible cooling determined by the controller at least in part from measurement of the fifth sensor and the recirculation air flow rate. A sixth sensor in the conditioned air duct may be used to measure temperature of conditioned air passing through the conditioned air port. In determining the amount of sensible cooling the controller may further determine a second amount of sensible cooling delivered by conditioned air passing through the conditioned air port, the second amount of sensible cooling determined by the controller at least in part from measurement of the sixth sensor.

[0018] In some embodiments the property measured by the first and second sensors is carbon dioxide concentration.

[0019] In some embodiments the amount of cooling is an amount of latent cooling. The terminal unit may further

comprise a seventh sensor in the recirculation air duct on the outlet side of the cooling coil to measure humidity of the recirculation air. The controller may determine a recirculation air flow rate based at least in part from measurements from the first and second sensors and the amount of latent cooling based at least in part on a first amount of latent cooling delivered by the cooling coil, the first amount of latent cooling determined by the controller at least in part from measurement of the seventh sensor and the recirculation air flow rate.

[0020] In some embodiments, the terminal unit comprises an eighth sensor in the conditioned air duct to measure humidity of conditioned air passing through the conditioned air port. In determining the amount of latent cooling the controller may determine a second amount of latent cooling delivered by conditioned air passing through the conditioned air port, the second amount of latent cooling determined by the controller at least in part from measurement of the eighth sensor.

[0021] In some embodiments, the controller, in determining the amount of cooling, determines the air flow rate through each of the ports of the mixing chamber.

[0022] In some embodiments, the terminal unit further comprises a control valve operably connected to the cooling coil, wherein the controller controls the coolant in the cooling coil at least in part by modulating the control valve. In some embodiments, the coolant may be water.

[0023] In some embodiments, the controller is further configured to control a flow rate of recirculation air through the recirculation air port based at least in part on the property of the supply air and the property of the recirculation air.

[0024] The foregoing is a non-limiting summary of the invention, which is defined by the attached claims.

BRIEF DESCRIPTION OF DRAWINGS

[0025] The accompanying drawings are not intended to be drawn to scale. In the drawings, each identical or nearly identical component that is illustrated in various figures may be represented by a like numeral. For purposes of clarity, not every component may be labeled in every drawing. In the drawings:

FIG. 1 is a simplified block diagram of an embodiment of the control system disclosed in the '167 patent.

FIG. 2 is a block diagram of an air conditioning system according to some embodiments;

FIG. 3 is a block diagram of another air conditioning system according to some embodiments;

FIG. 4 is a hybrid branch controller according to some embodiments;

FIG. 5 is a control module according to some embodiments;

FIG. 6 is a block diagram of a terminal unit according to some embodiments;

FIG. 7 is a block diagram of another air conditioning system, according to some embodiments;

FIG. 8 shows qualitatively how latent cooling (h_L), sensible cooling (h_S), total cooling ($h = h_L + h_S$), and the sensible heating ratio ($SHR = h_S/h$) may change as a function of the water temperature entering the coil (T_{IN}) and the recirculation air flow rate (Q_r);

FIG. 9 shows a flow diagram for a method 300 for controlling a terminal unit according to some embodiments;

FIG. 10 shows a qualitative plot of the amount of cooling provided by a cooling coil, if the coil water temperature is at the supply water temperature, as a function of the water flow rate in the coil, according to some embodiments;

FIG. 11 shows a qualitative plot of the amount of cooling provided by a cooling coil, if the coil water temperature is between the supply water temperature and the dew point temperature, as a function of the water flow rate in the coil, according to some embodiments;

FIG. 12 shows a qualitative plot of the amount of cooling provided by a cooling coil, if the coil water temperature is at the dew point temperature, as a function of the water flow rate in the coil, according to some embodiments;

FIG. 13 is a plot showing qualitatively the relationship between sensible heat ratio (SHR) and the target water input temperature for the cooling coil, according to some embodiments;

FIG. 14 is a plot showing qualitatively the relationship between total cooling and the water flow rate for the cooling coil, according to some embodiments;

FIG. 15 is a plot showing qualitatively the relationship between the target water input temperature for the cooling coil and total cooling provided by the cooling coil, according to some embodiments; and

FIG. 16 is a block diagram of a terminal unit according to some embodiments.

DETAILED DESCRIPTION

[0026] The inventors have recognized and appreciated that current HVAC technologies have a variety of shortcomings that result in excessive or unnecessary tradeoffs between capital equipment and installation costs, operating efficiency, and comfort. An improved system and method for conditioning indoor air is described with reference to the accompanying figures.

[0027] FIG. 2 shows an air conditioning system 200 according to some embodiments. System 200 has a hybrid branch controller (HBC) 220 to transition from refrigerant to water cooling. Using a hybrid branch controller to avoid the use of refrigerant in occupied spaces may reduce costs by eliminating the need to monitor for refrigerant leaks. Refrigerant is delivered between outdoor unit 210 to HBC 220 via refrigerant lines 230. Water is delivered to a set of terminal units 250 (e.g., terminal unit 251, 252, and 253) via a water pipe system 240. A two-pipe system is shown in FIG. 2. In some embodiments, such as that shown in FIG. 3, system 200 is capable of delivering both heating and cooling simultaneously to different terminal units 250 using four-pipe water system 241. Terminal units 250 each have a coil which acts as a heat exchanger between the water and local air. It should be appreciated that the constituent terminal units of terminal units 250 need not have the same design; that is, for example, terminal unit 251 may have a different design than terminal unit 252. Though in some embodiments, some or all terminal units may be substantially identical.

[0028] In some embodiments, water pipe system 240 is a single loop system which connects via a water supply port 224 and a water return port 225 on HBC 220. Terminal units 250 are each connected to water pipe system 240 via "branches." A flow limiting valve may be incorporated into each branch or terminal unit to prevent excess flow in some terminal units which may result from different branch connection points to the water pipe system 240. Because each terminal unit is connected to the single loop at nominally the closest point on the loop, home runs of piping for each terminal unit going back to HBC 220 are avoided. This significantly reduces the amount of water pipe necessary to connect each of terminal units 250.

[0029] Outdoor unit 210 and/or HBC 220 control(s) the flow of refrigerant and the pressure of the refrigerant. Outdoor unit 210 may include a compressor. In some embodiments additional hardware is included to provide variable refrigerant flow (VRF).

[0030] FIG. 4 shows a diagram of HBC 220 of system 200 (FIG. 2) according to some embodiments. Though, HCB 220 may be used in any suitable system. The refrigerant lines 230 feed into a heat exchanger 221 via ports 223 and 226. Heat is exchanged between the refrigerant and the water which is connected from the water pipe system 240 via ports 224 and 225. A pump 222 may be included within HBC 220 to pump water through water pipe system 240 (and in turn through terminal units 250, as applicable). Though, pump 222 may have any suitable location. In some embodiments, pump 222 is either a fixed speed pump or a variable speed pump. Though any suitable pump may be used. HBC controller 227 may be used to control pump 222. For example, HBC controller 227 may increase if the amount of cooling required by terminal units 250 increases. Likewise the pump speed may be decreased or turned off if the amount of cooling required by terminal units 250 decreases.

[0031] FIG. 6 shows a terminal unit 100 according to some embodiments. Terminal unit 100 may be a terminal unit among the terminal units 250 as part of system 200 (FIG. 2). Though, terminal unit 100 may be used in any suitable air conditioning system. Terminal unit 100 may be installed in an indoor space to be heated and/or cooled (a "conditioned space").

[0032] Terminal unit 100 may have four air ports connected to a mixing chamber 150. A primary recirculation air port 110 draws air from the conditioned space. A conditioned air port 120 is connected to a duct providing conditioned outdoor air. The outdoor air may be conditioned using a dedicated outdoor air system (DOAS), energy recovery ventilator (ERV), or any other equipment for suitably providing outdoor air. In some embodiments, a secondary recirculation air port 130 draws in additional air from the conditioned space. A supply air port 140 delivers the air drawn from the other three ports to the conditioned space.

[0033] Each port may have an air duct which delivers air to a mixing chamber 150. As shown, port 110 has duct 116, port 120 has duct 123, port 130 has duct 133, and port 140 has duct 143.

[0034] Duct 116 associated with the primary recirculation port 110 may have an air filter 112, cooling coil 113 and damper 117. Air filter 112 removes dust and other particulates before the recirculation air is passed over cooling coil 113.

[0035] Coil 113 receives water from water input port 118 at a temperature T_{IN} and returns water via water return port

119 at a temperature T_{OUT} . Ports 118 and 119 are connected to piping system 180 which itself receives and returns water from the water supply system. Ports 118 and 119 may be instrumented with temperature sensors to measure the temperature of water entering the cooling coil (T_{IN}) and the temperature of water leaving the cooling coil (T_{OUT}), respectively. In some embodiments, piping system 180 has four supply side ports as shown supporting both cold and hot water via ports 181, 182, 183, and 184. In some embodiments, piping system 180 may only have two supply side ports for input and return of hot or cold water. Piping system 180 may have various sensor (e.g., temperature) and actuator (e.g., valves) that may be sensed and controlled by control module 160 to achieve the desired input water properties. Such a system controls the In some embodiments, one or more of the temperature of the water entering the coiling coil (T_{IN}), the temperature of the water exiting the coiling coil (T_{OUT}), and the flow rate of the water through the cooling coil is/are controlled by a suitable control system. In some embodiments, the FlowBridge control system is implemented through piping system 180 and control module 160, though any suitable system for controlling the water in the coil may be used.

[0036] Coil 113 may have a condensate drain 115 that drains off condensation accumulated on coil 113. Though, in some embodiments such as a chilled beam configuration, terminal unit 100 may be operated to prevent condensation on the cooling coil such that condensate drain 115 is unnecessary. (Note that air filter 111 may be unnecessary if coil 113 is non-condensing.) Damper 117 may be used to control the amount of air flowing through port 110. Damper 117 may be closed, for example, when the required conditioned air is suitable and sufficient to provide the desired heating and cooling for the conditioned space.

[0037] Air is drawn through port 110, and then through air filter 111 and coil 113, by fan 141 located in duct 143. Fan 141 may be a variable speed fan, such as an electronically commutated motor (ECM) fan, a fixed speed fan, or any suitable type of fan.

[0038] The conditioned outdoor air required for the conditioned space is provided through conditioned air port 120. A damper 121 in duct 122 may be used to control the amount of conditioned outdoor air. As discussed further herein, the amount of outdoor air may be controlled to maintain the carbon dioxide, volatile organic compounds (VOCs), infectious aerosols, or other measures of air quality at or below prescribed levels.

[0039] In some usage scenarios, mixing the air coming off of cooling coil 113 and the conditioned air alone would result in a supply air temperature exiting port 140 below a desired temperature. Such a desired temperature may be defined to ensure that the supply air is not uncomfortably or unreasonably cold. Conventionally a reheat coil would be used under such a scenario, but this requires heating energy for a conditioned space being cooled. The inventors have recognized and appreciated that mixing a suitable amount of additional recirculation air will raise the temperature such that the minimum temperature requirement for the supply air is met. This additional recirculation air is drawn from the secondary recirculation air port 130. In some embodiments a damper 131 in duct 133 controls the amount of secondary recirculation air. Some other embodiments, do not utilize a damper 131 and always permit a sufficient amount of secondary recirculation air such that the supply air minimum temperature requirement is not violated. One advantage of utilizing a damper is that it may reduce the amount of fan energy required to condition the room under certain circumstances.

[0040] In still other embodiments, terminal unit 100 does not include secondary recirculation air port 130 (a three port embodiment). Such a three port embodiment of terminal unit 100 is equivalent to requiring damper 131 to be closed at all times.

[0041] Cooling coil 113, damper 121, damper 131, and fan 141 may be controlled by control module 160. Control module 160 may operate to condition the conditioned space to meet one or more target conditions such as air temperature, air humidity, and air quality. In some embodiments, one or more of the set points may be set by a user through user interface 170. User interface 170 may include an end user accessible portion in the conditioned space (e.g., a wall mount "thermostat") and/or may be accessible through a computer terminal as part of a building management system (BMS). For example, in a commercial use scenario the humidity and air quality requirements may be set the a building manager through the BMS while the room temperature may be set by a room occupant. In some embodiments a set point range is specified for one more more of the control variable, thus defining an acceptable range of the controlled variable. For example, the humidity set point range may be defined as 35% to 55% relative humidity (RH). As another example, if the air quality metric is carbon dioxide, the set point range may be 0 to 800 ppm. The set point range is similar or equivalent to the concept of a dead band. By specifying a large set point range the system may be able to operate more efficiently than using a single set point. In some embodiments where only a single set point is used for a control variable a dead band may be used to improve operational performance. For air quality measures the set point value may be interpreted as "at or below" the set point value.

[0042] Terminal unit 100 may be instrumented with sensor suites 112, 114, 122, 132, and 142. Each sensor suite may include sensors such as a temperature sensor ("T"), a humidity sensor ("H"), an air quality sensor ("A"), and an air flow rate sensor ("Q"). Though, these sensors are exemplary, and each sensor suite may include any suitable sensor or combination of sensors. The location of sensor suites 112, 114, 122, 132, and 142 are exemplary, and other suitable positions may be used. Also, not all sensor suites may be present in all embodiments, and other sensor suites may be present in some embodiments. For example, as cooling coil 113 may not be expected to affect the air flow rate or the air quality, such sensors may not be needed on both sides of cooling coil 113 within duct 116.

[0043] Control module 160 may be used to control the temperature, humidity, and air quality in the conditioned space. The term "air quality" is used to refer to one or more measures of air quality such as the amount of carbon dioxide, VOCs, infectious aerosols, and other components in the air that may reduce its quality for human or other purposes.

[0044] In some embodiments, air quality is controlled by feedback control of damper 121 based on an air quality sensor measurement. For example, a carbon dioxide sensor located in the conditioned space (e.g., near the user interface) or in sensor suite 112, 114, and/or 132 may be used to measure the amount of carbon dioxide in the room / recirculation air. Damper 121 may be controlled using a PID (proportional-integral-differential) controller or other suitable controller to maintain the carbon dioxide level in the room at or below the set point (e.g., 800 ppm). This operation works because the conditioned air, which is sourced from air outside the building, is expected to have acceptable air quality. In some embodiments, a minimum amount of outdoor air may be required at all times, thus requiring damper 121 to be at least slightly opened (and not completely closed) at all times during normal operation.

[0045] The temperature and humidity in the conditioned space may be controlled with the goal of achieving the specified set points, or set point range, for the conditioned space. Control module 160 may control the amount of sensible cooling/heating and latent cooling by controlling fan 141, the liquid flowing through cooling coil 113, and dampers 117, 131, and 121. Though, not all such control actuators may be present or used in all embodiments, and suitable alternatives may be used in some embodiments. For example, damper 121 may be used exclusively to meet outdoor air / air quality requirements and, while its position affects the supply air temperature and humidity, its position is simply an input to the control of temperature and humidity.

[0046] An embodiment of control module 160 is shown in FIG. 5. Control module 160 may receive input signals from the various sensors and sensor suites in terminal unit 100 (e.g., sensor suite 112), user interface 170 and a suitable data interface. Control module 160 may be configured to send control signals to various actuators in terminal unit 100 such as in piping system 180 (e.g., pump and valve control signals); to dampers 117, 121, and 131; and to fan 141. Control module 160 may also send information such as the input signals, control signals, and status of terminal unit 100 to other devices via a suitable data interface (e.g., BACnet, Ethernet). Control module 160 may also provide power to the sensors and actuators of terminal unit 100. Though, in some embodiments, power is provided directly from a power source to a sensor or actuator.

[0047] Control module 160 may include a plurality of modules such as memory 161, processor 162, power supply 163, communications module 164, and input/output (I/O) modules 165.

[0048] Processor 162 may be configured to implement control algorithms in response to input signals received by control module 160. Processor 162 may be operatively connected to memory 161 and other modules of control module 160. Processor 162 may be any suitable processing device such as for example and not limitation, a central processing unit (CPU), digital signal processor (DSP), field programmable gate array (FPGA), application specific integrated circuit (ASIC), or any suitable processing device. In some embodiments, processor 162 comprises one or more processors, for example, processor 162 may have multiple cores and/or multiple microchips.

[0049] Memory 161 may be integrated into processor 162 and/or may include "off-chip" memory that may be accessible to processor 162, for example, via a memory bus (not shown). In some embodiments, memory 161 stores software modules that when executed by processor 162 perform desired functions; in some embodiments memory 161 stores an FPGA configuration file for configuring processor 162. Memory 161 may be any suitable type of non-transient, computer-readable storage medium such as, for example and not limitation, RAM, ROM, EEPROM, PROM, volatile and non-volatile memory devices, flash memories, or other tangible, non-transient computer storage medium.

[0050] Power supply 163 provides the power signals for the operation of control module 160 and other electrical devices in terminal unit 100. Power supply 163 may use battery and/or utility ("wall") power to facilitate generation of such power signals, though other sources of power may be used. For example, power supply 163 may provide a 120V AC power signal to terminal unit 100. Power supply 163 may convert source power into various voltage levels or any other signals based on the requirements of a particular embodiment.

[0051] Communications module 164 may be any suitable combination of hardware and software configured to generate and receive communication signals over a data interface such as a wired data interface, a wireless data interface, or both. Communications module 164 may provide a connection to a network such as a LAN, WAN, the internet, and/or another device using any suitable communications protocol. Communications module 164 may be configured to communicate with other control systems, a centralized control and monitoring center, or any other device. For example, multiple terminal units may be connected together and to a control and monitoring center to facilitate data logging, reconfiguration of the connected control systems and the like. In some embodiments, multiple terminal units are daisy chained together; to facilitate this communications module 164 may include two or more physical connectors to allow each control system to be connected by cable into the next. Other suitable network topologies may also be used.

[0052] I/O 165 may include digital I/O, analog-to-digital converter (ADC), digital-to-analog converter (DAC), and other suitable input/output capabilities. I/O 165 permits signaling with other devices and sensors connected to control module 160. I/O 165 is not limited to these types of input and output, and the discussion of the use of I/O 165 is exemplary and other input/output mechanisms may be used in other embodiments.

[0053] FIG. 7 shows terminal unit 100 as part of an air conditioning system 400 for a building 460. Building 460 has a number of conditioned spaces such as exemplary conditioned spaces 410, 440, and 450. Conditioned space 410 has a terminal unit 100. Terminal unit 100 is connected via piping system 180 to supply water system 420. Cold Water Plant 423 may be any suitable equipment for providing suitable cold water to supply water system 420. For example, a chiller or the HBC / Outdoor Unit combination in system 200 shown in FIG. 2. For simplicity, supply water system 420 is shown as only providing cold water, but it should be appreciated that both cold and hot water may be supported (e.g., using a four-pipe system and a boiler).

[0054] Conditioned space 410 utilizes a terminal unit 100 to condition room air 413. Arrows with dashed lines suggest the general flow of air within conditioned space 410 (e.g., into air ports 110, 130, and 412; and out of supply air port 140). Terminal unit 100 may be similar to that described in connection with FIG. 6. Conditioned spaces 440 and 450 have terminal units 441 and 451, respectively, which may be the same or different design as terminal unit 100.

[0055] System 400 has an outdoor air unit 430 that conditions outdoor air and provides conditioned air 433 to the terminal units. Outdoor air unit 430 may be, for example, an energy recovery ventilator (ERV), a dedicated outdoor air system (DOAS), or any other suitable equipment for conditioning outdoor air. Outdoor air unit 430 may condition the outdoor air by filtering, heating/cooling, and/or drying/humidifying the outdoor air depending on the operating needs of the building. Conditioned space 410 may have an exhaust/return air port 412 that returns a portion of room air 413 to outdoor air unit 430. Outdoor air unit 430 may utilize exhausted room air 413 to condition outdoor air 431 before the exhaust air exits building 460 as waste air 432.

[0056] FIG. 8 shows qualitatively how latent cooling (h_L), sensible cooling (h_S), total cooling ($h = h_L + h_S$), and the sensible heating ratio ($SHR = h_S/h$) may change as a function of the water temperature entering the coil (T_{IN}) and the primary recirculation air flow rate (Q_r). In these illustrations the flow rate through the coil is assumed to be constant. In each plot the coil water temperature varies between the minimum temperature of the supply water, T_{supply} (e.g., from a chiller), to a maximum water temperature of the recirculation air (T_r). The dew point temperature, T_{dew} , is also noted as this is an inflection point of the behavior above which all cooling is sensible. (Note that this is a simplifying assumption since there will be a temperature gradient through the coil pipe wall which will result in the exterior surface temperature of the coil pipe wall being warmer than the interior surface of the coil pipe wall.) The air flow rate through the primary recirculation air port 110 is varied between a minimum value (Q_{r_min}) and a maximum value (Q_{r_max}).

[0057] At upper-left, FIG. 8 shows qualitatively how the amount of latent cooling changes as a function of T_{IN} and Q_r for one example embodiment. At $T_{IN} = T_{SUPPLY}$ the rate of latent cooling decreases as air flow through the coil increases from the minimum air flow rate (Q_{r_min}) to the maximum air flow rate (Q_{r_max}). For water temperatures above the dewpoint (i.e., for $T_{IN} \geq T_{dew}$) the rate of latent cooling is zero.

[0058] At lower-left, FIG. 8 shows qualitatively how sensible cooling changes as a function of T_{IN} and Q_r for the example embodiment. At $T_{IN} = T_{SUPPLY}$ the rate of sensible cooling increases as air flow through the coil increases from Q_{r_min} to Q_{r_max} . The rate of sensible cooling goes to zero when the water temperature entering the coil equals the recirculation air temperature (i.e., for $T_{IN} = T_r$).

[0059] At upper-right, FIG. 8 shows qualitatively the total cooling, which is simply the sum of the latent cooling and the sensible cooling. At lower-right, FIG. 8 shows the sensible heating ratio (SHR), which is simply the ratio of the amount of sensible cooling to the total cooling expressed as a percent. Notably, SHR is 100% for all coil input water temperatures above the dew point.

[0060] The plots in FIG. 8 are intended to illustrate that given desired amounts of sensible and latent cooling (or equivalently a desired amount of total cooling and a SHR) an air flow rate and water temperature that best match that requirement can be determined using an appropriate control system. These plots represent a simple model and may not realistically reflect the performance of an actual system. It should be appreciated that these surfaces could be determined quantitatively using an analytical model of the system or through empirical measurements. It should also be appreciated that the relationship between (T_{IN} , Q_r) and (h_S , h_L) is also dependent upon the temperature and humidity of the recirculation air.

[0061] FIG. 9 shows a flow diagram for a method 300 for controlling a terminal unit such as terminal unit 100 shown in FIG. 6. In the description of method 300, reference numbers are with respect to terminal unit 100, though it should be appreciated that method 300 may be used in connection with any suitable terminal unit. In some embodiments, method 300 is implemented in part by control module 160. Method 300 may be used to control the temperature, humidity, and/or air quality in a conditioned space associated with the terminal unit. The following discussion is with respect to cooling, but it should be appreciated that a similar approach may be taken for heating.

[0062] At step 310 set point conditions are received. The set points specify the target value of the temperature, humidity, and air quality in the conditioned space. In some embodiments, the set point conditions are specified as a range.

[0063] At step 320 sensor measurements are collected from at least a subset of the sensors on the terminal unit. These may include temperature, humidity, air flow rate, water flow rate, air quality, and other suitable sensors.

[0064] At step 330 the target sensible and latent cooling rates are determined. These are determined from the measured room air properties and the temperature and humidity set points. For example, a proportional-integral controller may be

used which has the form:

$$h_s = H_{sp} + H_{si}$$

$$H_{sp} = K_{sp} (T_{AIR} - T_{setpoint})$$

$$H_{si} = K_{si} (T_{AIR} - T_{setpoint})(t_{elapse}) + H_{si_prior}$$

where T_{AIR} and $T_{setpoint}$ are the measured air temperature and setpoint air temperature, respectively; each K is a calibration constant; t_{elapse} is the elapsed time since the prior iteration and H_{si_prior} is the value of H_{si} in the prior computational loop.

[0065] Similarly for the rate of latent cooling:

$$h_L = H_{Lp} + H_{Li}$$

$$H_{Lp} = K_{Lp} (\omega_{AIR} - \omega_{setpoint})$$

$$H_{Li} = K_{Li} (\omega_{AIR} - \omega_{setpoint})(t_{elapse}) + H_{Li_prior}$$

where the variables have analogous meanings (e.g., ω_{AIR} and $\omega_{setpoint}$ are the humidity ratio of the air and set point humidity ratio, respectively). Each K used to calculate sensible and latent cooling may be determined empirically, analytically, numerically, a suitable combination thereof, or using any suitable method.

[0066] Other suitable methods may be used to set target rates of latent cooling and heating. For example, a PID controller, a machine learning algorithm, a look-up table, or any other suitable method or combination of methods may be used.

[0067] Once the target rates of latent cooling are determined, the total cooling equals:

$$h = h_L + h_s$$

and the sensible heating ratio (SHR) can be calculated as:

$$SHR = h_s / h$$

[0068] At step 340 a target input water temperature for coil 113, T_{IN} , and air flow rate, Q_r , are determined, based on h_s and h_L (or equivalently based on h and SHR). Any suitable method such as those discussed above may be used to determine the target values for T_{IN} and Q_r . For example, model similar to that shown in FIG. 8 may be used to translate h and SHR into target water temperature and air flow rate. For example, a line of constant SHR on the surface of the SHR plot in FIG. 8 (lower-right) may be determined for the target SHR. Such a line defines the combinations of target water temperature and air flow rates that provide the target SHR. A corresponding line for target total cooling may be determined from the plot of total cooling (FIG. 8, upper-right). Any intersection of the two lines in the (T_{IN}, Q_r) plane represents a solution. If no solution exists (i.e., the target SHR and target total cooling cannot be achieved simultaneously) a solution case may be chosen using suitable criteria. For example, a minimum error criteria may be used, or achieving one variable (e.g., SHR) may be prioritized over the other (e.g., total cooling).

[0069] At step 350 a control system is used to control actuators to achieve the desired coil water temperature and air flow rate. The desired coil water temperature may be achieved by controlling actuators (e.g., valves, pumps) in piping system 180 to achieve the target temperature. In some embodiments, the temperature of the water entering the coil is controlled using the FlowBridge. Though, any suitable piping system may be used to achieve the target water temperature. The desired air flow rate may be achieved by controlling one or more dampers and/or fans. For example, a suitable combination of the position of damper 117, damper 121, and damper 131, as well as the speed of fan 141 may be used to achieve the desired air flow rate, Q_r . Feedback control systems may be used to maintain the water temperature and

air flow rate at the target values.

[0070] In some embodiments, damper 121 is controlled strictly to meet the air quality and outdoor air requirements and damper 131 is used to ensure the supply air temperature T_s meets minimum temperature requirements. Thus, neither damper 121 or damper 131 is used to control Q_r . In some embodiments, fan 141 is not dedicated to control of Q , and thus the only available control of Q_r is damper 117. In some embodiments, fan 141 is used primarily to achieve the desired Q_r and damper 117 is preferentially 100% open except under special circumstances that require fan 141 to be run at a higher speed than is necessary to achieve the desired Q_r . For example, if the minimum outside air requirement is not being met when the conditioned air damper 121 is 100% open, fan 141 may be required to run at a higher speed to further increase the flow rate of conditioned air, Q_c . This higher fan speed may otherwise result in a higher Q_r than desired unless damper 117 is less than 100% open.

[0071] At step 360 sensors are used to measure the actual sensible cooling and latent cooling achieved in the system (or equivalently the total cooling and SHR). Step 360 may be used to provide feedback to the system that the intended cooling rates are being achieved. It should be appreciated in performing step 360 that a delay is expected between when the target input conditions are met (e.g., when the water input temperature and air flow rates are at target) and when the corresponding cooling rates are realized. This is primarily because it takes time for the water to pass through the cooling coil and for associated transients to substantially subside.

[0072] The sensible cooling and latent cooling calculation may take into account not only the cooling performed by coil 113 but also the cooling provided by the conditioned air which replaces air exhausted from the conditioned space (whether through a return duct or other leakage from the conditioned space). Here the sensible and latent cooling performed by the coil are first presented followed by the cooling resulting from the conditioned air from conditioned air port 120.

[0073] In general, the sensible heating rate of air for a two-port device is

$$h_s = c_p \rho Q \Delta T$$

where h_s is the sensible heat (energy per unit time), c_p is the specific heat of air, ρ is the density of air, Q is the air flow volume and ΔT is the temperature difference between the two ports. Q and ΔT are measured in the same direction. In heating the air passing through the two-port device gets warmer and h_s is positive. In cooling the passing through the two-port device gets colder and h_s is negative. Since we are primarily concerned with cooling, we will refer to the "sensible cooling rate" which simply flips the sign of h_s (i.e., positive value in cooling).

[0074] In general, the latent heat rate of air for a two-port device is

$$h_L = \rho h_{we} Q \Delta w$$

where h_L is the latent heat (energy per unit time), ρ is the density of air, h_{we} is the enthalpy of evaporation of water, and Δw is the humidity ratio difference between the two ports. Q and Δw are measured in the same direction. As with sensible cooling, for cooling we will generally flip the sign and refer to the "latent cooling rate".

[0075] In some embodiments, only ΔT , Δw and Q are treated as unknowns on the right hand side of the sensible and latent cooling equations. The temperature of the air can be measured before entering the coil, for example, by a temperature sensor such as in sensor suite 112, and after the air passes through the coil by a temperature sensor in sensor suite 114. The humidity ratio can similarly be determined using temperature and relative humidity measurements from sensor suites 112 and 114.

[0076] The air flow rate may be measured directly by an air flow rate sensor in either sensor suite 112 or 114, or the air flow rate can be measured indirectly based on conservation principles. Consider an n -port device (n an integer) where each of the n ports exchanges air at a flow rate (volume per unit time) of Q_j and a carbon dioxide content (e.g., ppm) of C_j . Assuming the device cannot sink or source air or carbon dioxide, conservation requires that:

$$\sum_{j=1}^n Q_j C_j = 0$$

[0077] An example terminal unit may have three ports ($n = 3$) referred to as the conditioned-air port (which receives outside air), a recirculation-air port (which receives air from the room being air-conditioned), and a supply-air port (which returns air back to the room). Let Q_c and C_c be the conditioned-air port flow rate and carbon dioxide content, respectively; let Q_r and C_r be the recirculation-air port flow rate and carbon dioxide content, respectively; and let Q_s and C_s be the

supply-air port. Each port may be equipped with a carbon dioxide sensor such that C_c , C_r and C_s are known. In some embodiments, the conditioned-air port may have an air source with a known carbon dioxide content so that the need for a carbon dioxide sensor is obviated. For HVAC cooling applications it is reasonable to assume that:

$$Q_c + Q_r = Q_s$$

[0078] Note that we have assumed Q_s is in the opposite direction of Q_c and Q_r (e.g., Q_s flows out, while Q_c and Q_r flow "in"). Applying the same convention to the conservation equation we have:

$$Q_c C_c + Q_r C_r = Q_s C_s$$

[0079] Assuming Q_c is known (e.g., it is fixed or measured by an air flow meter), the other two flow rates can be solved for using the carbon dioxide measurements

$$Q_r = Q_c \frac{C_c - C_s}{C_s - C_r}$$

and

$$Q_s = Q_c \frac{C_c - C_r}{C_s - C_r}$$

[0080] Advantageously, a cooling coil should have no effect on the carbon dioxide content. Accordingly, it is not critical that the carbon dioxide sensor at the recirculation air port be located before or after the cooling coil. In some embodiments, a carbon dioxide sensor at the thermostat is used as the recirculation air port carbon dioxide measurement.

[0081] Another advantage is that during normal operation C_s and C_r should be measurably different, such that the denominator of the above equations should be substantially non-zero providing reasonably accurate flow rate estimates.

[0082] A similar analysis can be applied in the case of a 4 port terminal unit such as terminal unit 100 in FIG. 6, however, a second flow rate meter may be used on one of the ports to provide a sufficient number of known values.

They key equations are:

$$Q_c + Q_r + Q_{r2} = Q_s$$

where Q_{r2} is the air flow rate through the secondary recirculation air port, and

$$Q_c C_c + Q_r C_r + Q_{r2} C_r = Q_s C_s$$

[0083] Note that it is assumed the carbon dioxide levels entering the primary and secondary recirculation air ports are the same. Taking Q_c and Q_{r2} as known (e.g., through air flow meter measurement) we find Q_r and Q_s as follows:

$$Q_r = Q_c \frac{C_c - C_s}{C_s - C_r} + Q_{r2} \frac{C_r - C_s}{C_s - C_r}$$

and

$$Q_s = Q_c \frac{C_c - C_r}{C_s - C_r}$$

[0084] Other conservation principles such as conservation of energy and conservation of moisture can similarly be applied to compute air flow. Notably, because coil 113 may result in a change in temperature and or humidity, such conservation equations require the internal air port 190 to be considered for conservation calculations rather than primary recirculation air port 110. The '972 application provides further discussion on the use of conservation equations to determine air flow rates.

[0085] Thus ΔT , Δw and Q_r can be measured and used to determine the amount of sensible and latent cooling achieved by the cooling coil.

[0086] The latent and sensible cooling resulting from the conditioned air replacing the exhaust air can be similarly calculated. The temperature and humidity ratio of the exhaust air may be assumed to be the same as the room/recirculation air measured by sensor suite 112 or at another location in the conditioned space. The temperature and humidity ratio of the conditioned air can be measured by sensor suite 122. The air flow rate is that of the conditioned air, Q_c , which can be determined from measurement (e.g., from an air flow rate sensor in sensor suite 122), or indirectly based on conservation principles. Note that under some operating the conditioned air may be above room neutral conditions (i.e., adding heat or humidity to the conditioned space) and thus attention should be paid to ensure the consistent use of cooling or heating rates. With the latent and sensible cooling rates calculated from both the coil and from the conditioned air, the net sensible and latent cooling can be calculated.

[0087] At step 370, differences in the latent and sensible cooling rates calculated at step 360 from the target values determined at step 330 are used to tweak the target values of coil water temperature and air flow rate. When determining if such differences exist and their extent, appropriate consideration should be taken for system transients. In some embodiments when the error is small the tweak is a simple proportional control. Though, more sophisticated tweaks may be used. In some embodiments, the model used to determine T_{IN} and Q , from h and SHR is updated based on the measured conditions. In this way an empirical database can be built up to refine the model.

[0088] After step 370 Method 300 returns to step 310 and repeats the process steps. The process can continue indefinitely until an interrupt (step 380) indicates the method is to stop.

[0089] It should be appreciated that other embodiments of method 300 may use alternative control variables to achieve the desired sensible and latent cooling. In addition to the water temperature entering the coil (T_{IN}) and the air flow rate (Q_r) such variables may include, for example, the coil water exit temperature (T_{OUT}), the change in water temperature across the coil ($\Delta T_{coil} = T_{IN} - T_{OUT}$), and the coil water flow rate (F_{coil}). For example, in one embodiment, method 300 uses F_{coil} and Q_r to control h_L and h_S . In another embodiment, method 300 uses F_{coil} and T_{IN} for control. Also, it should be appreciated that in some embodiments, some steps of method 300 are omitted, additional steps are added, the sequence of steps is changed (including performance of some steps simultaneously).

[0090] As further discussion of conditioning the temperature of an indoor space control using a terminal unit such as terminal unit 100, attention is now directed to FIG. 10 which is a qualitative plot showing a relationship between total cooling and the water flow rate through the coil (F_{coil}). Observe in FIG. 10 the relationship between cooling and flow rate for a $T_{IN} = T_{SUPPLY}$ (i.e., the input water temperature to the cooling coil is the water temperature of the chilled water supply). Maximum cooling (h_{max}) is achieved when the flow rate of water through the coil (F_{coil}) is maximum (F_{max}), but there are diminishing returns. At very low flow rates the water reaches the air temperature before it reaches the end of the coil and ΔT is maximum, however, this corresponds with relatively low Total Cooling (h). In between there is a useful range where Total Cooling is substantial yet we are not wasting energy with an excessive flow rate (i.e., excessive pumping energy). FIG. 10 represents the lowest SHR that can be achieved (SHR_{min}).

[0091] FIG. 11 shows the same plot for $T_{IN} = T_{DEW}$. Notably there is not any latent cooling ($SHR = 100\%$). Also the maximum cooling that can be achieved at high flow rate is substantially lower than h_{max} achieved when $T_{IN} = T_{SUPPLY}$. Of course, any T_{IN} above T_{DEW} will also have an SHR of 100%, and the maximum total cooling will continue to go down.

[0092] The regime in between where $T_{SUPPLY} < T_{IN} \leq T_{DEW}$ is where we will usually be operating. Generally speaking the higher T_{IN} the higher the SHR. FIG. 12 shows qualitatively the regime where $T_{SUPPLY} \leq T_{IN} \leq T_{DEW}$. Thus we come to the conclusion that if we know the desired SHR we can determine the desired T_{IN} and then control F_{coil} the flow rate through the coil to achieve the desired Total Cooling, h .

[0093] Once target values are calculated for a suitable combination of h , h_L , h_S , and SHR, the target T_{IN} can be determined as follows. If the target SHR is less than the minimum SHR achievable we use $T_{IN_TARGET} = T_{SUPPLY}$. The flow rate, F_{coil} , is controlled to achieve the desired total cooling. This could be controlled by measuring the total cooling from the air side sensors or measuring the total cooling from the flow rate and ΔT on the cooling coil. If the target SHR is 100% a control methodology that avoids condensation can be used. For example, if the FlowBridge is the piping system, the methodology disclosed in the '167 patent that avoids condensation may be used. If the target SHR is greater than the minimum SHR but less than 100% we may determine T_{IN} based on FIG. 13 where we assume SHR varies linearly between T_{SUPPLY} and T_{DEW} . In summary, if $SHR_{min} < SHR < 100\%$, then

$$T_{IN_TARGET} = (T_{DEW} - T_{SUPPLY}) / (1 - SHR_{min}) \times (SHR - SHR_{min}) + T_{SUPPLY}.$$

If $SHR < SHR_{min}$, then

$$T_{IN_TARGET} = T_{SUPPLY}.$$

And, if $SHR = 100\%$

$$T_{IN_TARGET} = T_{SETPOINT} - ([P-I \text{ value}] \times (T_{SETPOINT} - T_{DEW}))$$

subject to the requirement that $T_{DEW} \leq T_{IN_TARGET} \leq T_{AIR}$, and where P-I Value is the proportional integral value calculated by a proportional-integral controller based on the air temperature and air setpoint.

[0094] Note that the water flow rate may be selected to be the optimum rate when $SHR = 100\%$; since we are only controlling the sensible cooling rate ($h_L = 0$) we can do so totally through water temperature. When $SHR < SHR_{min}$ we cannot match the load (by definition). We could be in this predicament because the room air temperature is close to setpoint (low or zero target for h_S) and RH is far away (high h_L) or because the room air temperature is at or below setpoint (target for h_S is 0). Because we cannot meet the load, there is no perfect solution for addressing this case. Under such conditions in one embodiment the system is run with $T_{IN} = T_{SUPPLY}$ to match the sensible load and tolerating the unaddressable latent load. In essence F_{coil_target} is controlled based on the h_S curve.

$$F_{coil_target} = (F_{max} / h_{max_for_Tin}) \times (h_S / SHR_{min})$$

[0095] Dividing by SHR_{min} insures we get the correct total amount of h_S and as much h_L as possible.

[0096] When $SHR_{min} < SHR < 100\%$, F_{coil_target} is determined as follows (see FIG. 14):

$$F_{coil_target} = (F_{max} / h_{max_for_Tin}) \times h$$

[0097] The "max" cooling ($h_{max_for_Tin}$) is dependent upon the specific T_{IN} according to FIG. 15 which plots the maximum total cooling that can be achieved for the maximum permissible flow rate in the coil for each T_{IN} .

[0098] Having determined the desired T_{IN} and the desired water flow rate, F_{coil} , we must control the piping system 180 appropriately. In the case of the FlowBridge, a variable speed pump may be used in combination with a control valve. The pump speed could be used to control F_{coil} and the valve could be used to control T_{IN} . T_{IN} is readily measured using an inexpensive sensor. The flow rate could be measured directly using a flow rate meter. Though, to avoid the cost of such a meter, one alternative is to use ΔT across the coil (i.e., $T_{IN} - T_{OUT}$) to estimate the flow rate (e.g., using a mapping), however, the response would be delayed relative to the reading of T_{IN} due to the response lag of T_{OUT} . Total cooling measured from the air flow could also be used. Of course increasing the pump speed will generally cause T_{IN} to go down which will cause the control valve to open allowing more supply water which will result in increased flow rate, which will cause the pump to slow down. This creates a negative feedback loop which can be stably controlled. If operating at $T_{IN} = T_{SUPPLY}$, the FlowBridge recirculation pump is turned off and the flow rate can be controlled by the control valve alone.

[0099] Attention is now turned to FIG. 16, which shows a terminal unit 190. Terminal unit 190 may be similar to terminal unit 100 described, for example, in connection with FIG. 6.

[0100] Terminal unit 190 has sensor suite 112 which includes sensors to measure the temperature, humidity, and air quality of room air. Sensor suite 112 is shown before the cooling coil in primary recirculation air duct 116, though the room air properties may be measured at any suitable location. In some embodiments, sensor suite is located with user interface 170 and may be, for example, mounted on the wall of the conditioned space being served by terminal unit 190. It should also be appreciated that in some embodiments, different sensors in sensor suite 112 are located at different locations to measure the room air properties. For example, preferred sensor locations may be chosen based on the property each sensor measures.

[0101] Sensor suite 114 is located within duct 116 and measures the temperature and humidity of the air on the outlet side of coil 113 prior to entering mixing chamber 150.

[0102] Sensor suite 122 is located in conditioned air duct 123 and includes temperature, humidity, air quality, and air flow rate sensors to measure the respective properties of the conditioned air.

[0103] Sensor suite 142 is located in supply air duct 143 and includes temperature, humidity, and air quality sensors.

[0104] Sensor suite 132 is located in secondary recirculation air duct 133 and includes an air flow rate sensor.

[0105] This configuration of sensors illustrates one configuration of sensors sufficient to determine the air flow rates

through each port and the amount of sensible and latent cooling provided by terminal unit 190.

[0106] Having thus described several aspects of at least one embodiment of this invention, it is to be appreciated that various alterations, modifications, and improvements will readily occur to those skilled in the art. Such alterations, modifications, and improvements are intended to be part of this disclosure and are intended to be within the spirit and scope of the invention. Accordingly, the foregoing description and drawings are by way of example only.

[0107] It should be appreciated that the connections between the hydraulic components shown in the drawings and described with reference to embodiments of control systems, liquid supply systems, conditioning systems, and the like may be achieved by any suitable pipe, hose, tube, conduit, or other mechanism for conveying liquid under pressure. Where such connections have been described as a specific hydraulic conveyance it should be appreciated that other embodiments may use hose, tube, conduit, or any other suitable hydraulic conveyance.

[0108] It should be appreciated that while the liquid coolant has frequently been described as water, any suitable liquid or combination of liquids may also be used. In some embodiments, water contains additives such as glycol to improve certain aspects of performance.

[0109] It should be appreciated that while some embodiments were described with respect to cooling a conditioned space, the embodiments may be applicable to heating a conditioned space. Those of skill in the art will appreciate that some embodiments may be used for heating without modification or with only minor modifications.

[0110] It should be appreciated that all mechanical and end electrical equipment will have functional limitations. Generally, the ideal behavior has been described so as to not unnecessarily distract from the general operation and description of the embodiments. Those of skill in the art will recognize and appreciate the need to consider both ideal and non-ideal behavior in designing specific embodiments just as with any electrical or mechanical device.

[0111] It should also be appreciated that in describing the operation of valves, variations of "close" and "open" (e.g., closed, closing, opened, opening) generally refer to the change in the control valve's resistance to flow relative to its current position and do not mean "completely closed" (whereby flow is prevented) or "completely open" (allowing maximum flow) unless it is clear from the context that that is the intended meaning.

[0112] It should also be appreciated that the descriptions of components having the same name or same reference number appear in multiple drawings so as to avoid having to describe the common aspects of a component multiple times. It should be clear to those of skill in the art whether such descriptions made with reference to one embodiment are applicable to another embodiment.

[0113] Various aspects of the present invention may be used alone, in combination, or in a variety of arrangements not specifically discussed in the embodiments described in the foregoing and is therefore not limited in its application to the details and arrangement of components set forth in the foregoing description or illustrated in the drawings. For example, aspects described in one embodiment may be combined in any manner with aspects described in other embodiments. The above-described embodiments of the present invention can be implemented in any of numerous ways. For example, the embodiments may be implemented using hardware, software or a combination thereof. When implemented in software, the software code can be executed on any suitable processor or collection of processors, whether provided in a single computer or distributed among multiple computers.

[0114] Further, it should be appreciated that a computer may be embodied in any of a number of forms, such as a rack-mounted computer, a desktop computer, a laptop computer, or a tablet computer. Additionally, a computer may be embedded in a device not generally regarded as a computer but with suitable processing capabilities, including a Personal Digital Assistant (PDA), a smart phone or any other suitable portable or fixed electronic device.

[0115] Also, a computer may have one or more input and output devices. These devices can be used, among other things, to present a user interface. Examples of output devices that can be used to provide a user interface include printers or display screens for visual presentation of output and speakers or other sound generating devices for audible presentation of output. Examples of input devices that can be used for a user interface include keyboards, and pointing devices, such as mice, touch pads, and digitizing tablets. As another example, a computer may receive input information through speech recognition or in other audible format.

[0116] Such computers may be interconnected by one or more networks in any suitable form, including as a local area network or a wide area network, such as an enterprise network or the Internet. Such networks may be based on any suitable technology and may operate according to any suitable protocol and may include wireless networks, wired networks or fiber optic networks.

[0117] Also, the various methods or processes outlined herein may be coded as software that is executable on one or more processors that employ any one of a variety of operating systems or platforms. Additionally, such software may be written using any of a number of suitable programming languages and/or programming or scripting tools, and also may be compiled as executable machine language code or intermediate code that is executed on a framework or virtual machine.

[0118] In this respect, the invention may be embodied as a computer readable medium (or multiple computer readable media) (e.g., a computer memory, one or more floppy discs, compact discs, optical discs, magnetic tapes, flash memories, circuit configurations in Field Programmable Gate Arrays or other semiconductor devices, or other tangible computer

storage medium) encoded with one or more programs that, when executed on one or more computers or other processors, perform methods that implement the various embodiments of the invention discussed above. The computer readable medium or media can be transportable, such that the program or programs stored thereon can be loaded onto one or more different computers or other processors to implement various aspects of the present invention as discussed above.

[0119] In this respect, it should be appreciated that one implementation of the above-described embodiments comprises at least one computer-readable medium encoded with a computer program (e.g., a plurality of instructions), which, when executed on a processor, performs some or all of the above-discussed functions of these embodiments. As used herein, the term "computer-readable medium" encompasses only a computer-readable medium that can be considered to be a machine or a manufacture (i.e., article of manufacture). A computer-readable medium may be, for example, a tangible medium on which computer-readable information may be encoded or stored, a storage medium on which computer-readable information may be encoded or stored, and/or a non-transitory medium on which computer-readable information may be encoded or stored. Other non-exhaustive examples of computer-readable media include a computer memory (e.g., a ROM, a RAM, a flash memory, or other type of computer memory), a magnetic disc or tape, an optical disc, and/or other types of computer-readable media that can be considered to be a machine or a manufacture.

[0120] The terms "program" or "software" are used herein in a generic sense to refer to any type of computer code or set of computer-executable instructions that can be employed to program a computer or other processor to implement various aspects of the present invention as discussed above. Additionally, it should be appreciated that according to one aspect of this embodiment, one or more computer programs that when executed perform methods of the present invention need not reside on a single computer or processor, but may be distributed in a modular fashion amongst a number of different computers or processors to implement various aspects of the present invention.

[0121] Computer-executable instructions may be in many forms, such as program modules, executed by one or more computers or other devices. Generally, program modules include routines, programs, objects, components, data structures, etc. that perform particular tasks or implement particular abstract data types. Typically, the functionality of the program modules may be combined or distributed as desired in various embodiments.

[0122] Also, data structures may be stored in computer-readable media in any suitable form. For simplicity of illustration, data structures may be shown to have fields that are related through location in the data structure. Such relationships may likewise be achieved by assigning storage for the fields with locations in a computer-readable medium that conveys relationship between the fields. However, any suitable mechanism may be used to establish a relationship between information in fields of a data structure, including through the use of pointers, tags or other mechanisms that establish relationship between data elements.

[0123] Also, the invention may be embodied as a method, of which an example has been provided. The acts performed as part of the method may be ordered in any suitable way. Accordingly, embodiments may be constructed in which acts are performed in an order different than illustrated, which may include performing some acts simultaneously, even though shown as sequential acts in illustrative embodiments.

[0124] For the purposes of describing and defining the present disclosure, it is noted that terms of degree (e.g., "substantially," "slightly," "about," "comparable," etc.) may be utilized herein to represent the inherent degree of uncertainty that may be attributed to any quantitative comparison, value, measurement, or other representation. Such terms of degree may also be utilized herein to represent the degree by which a quantitative representation may vary from a stated reference (e.g., about 10% or less) without resulting in a change in the basic function of the subject matter at issue. Unless otherwise stated herein, any numerical values appearing in this specification may be modified by a term of degree thereby reflecting their intrinsic uncertainty.

[0125] Use of ordinal terms such as "first," "second," "third," etc., in the claims to modify a claim element does not by itself connote any priority, precedence, or order of one claim element over another or the temporal order in which acts of a method are performed, but are used merely as labels to distinguish one claim element having a certain name from another element having a same name (but for use of the ordinal term) to distinguish the claim elements.

[0126] Also, the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of "including," "comprising," or "having," "containing," "involving," and variations thereof herein, is meant to encompass the items listed thereafter and equivalents thereof as well as additional items.

Claims

1. A terminal unit (100) for conditioning the air of a conditioned space (410), the terminal unit comprising:

- a mixing chamber (150);
- a first recirculation air port (110) for receiving first recirculation air and connected to the mixing chamber by a first duct (116);
- a cooling coil (113) within the first duct for cooling the first recirculation air;

a second recirculation air port (130) for receiving second recirculation air and connected to the mixing chamber;
a conditioned air port (120) for receiving conditioned air and connected to the mixing chamber; and
a supply air port (140) for providing supply air and connected to the mixing chamber;

5 wherein the mixing chamber combines the first recirculation air, the second recirculation air, and the conditioned air to produce the supply air.

2. The terminal unit of claim 1, wherein the supply air port is connected to the mixing chamber by a second duct (143),
the terminal unit further comprising:
10 a fan (141) within the second duct to draw air from the mixing chamber and blow the supply air through the supply air port.

3. The terminal unit of claim 1, further comprising an actuator to control a flow rate of second recirculation air through
the second recirculation air port.

15 4. The terminal unit of claim 3, wherein the actuator is a damper (131).

5. The terminal unit of claim 3, further comprising:

20 a temperature sensor (142) to measure a temperature of the supply air; and
a controller (160) to control the actuator based on the temperature of the supply air.

6. The terminal unit of claim 5, wherein the controller is configured to adjust the actuator to control the flow rate of the
second recirculation air, at least in part, in proportion to a difference between a threshold temperature and the
25 temperature of the supply air if the temperature of the supply air is below the threshold temperature.

7. The terminal unit of claim 6, wherein the supply air port is connected to the mixing chamber by a second duct (143),
the terminal unit further comprising:
a fan (141) within the second duct to draw air from the mixing chamber and blow the supply air through the supply
30 air port.

8. The terminal unit of claim 1, further comprising:

a sensor suite having plurality of sensors;
35 a control module (160) configured to determine a rate of cooling being delivered to the conditioned space based
at least in part on a plurality of measurements obtained from the sensor suite, and to control coolant in the
cooling coil based at least in part on the rate of cooling.

9. The terminal unit of claim 8, wherein

40 the sensor suite comprises

at least one first sensor for measuring a flow rate of air through the cooling coil;
a second sensor to measure a humidity of air entering the recirculation air port; and
45 at least one third sensor to measure a humidity of air exiting the cooling coil; and

the control module

determines an actual rate of latent cooling provided by the cooling coil based on the flow rate of air through
50 the coil, the humidity of air entering the recirculation air port, and the humidity of air entering the recirculation
air port;
determines a target rate of latent cooling; and
controls coolant to the coil to at least in part adjust the actual rate of cooling to match the target rate of cooling.

55 10. The terminal unit of claim 9, wherein the at least on first sensors comprises a plurality of carbon dioxide sensors.

11. The terminal unit of claim 10, wherein the plurality of carbon dioxide sensors includes a first carbon dioxide sensor
to measure a carbon dioxide concentration in the supply air, and a second carbon dioxide sensor to measure a

carbon dioxide concentration in the conditioned space.

12. The terminal unit of claim 11, wherein the at least one first sensor further comprises a flow rate meter for measuring an air flow rate of the second recirculation air.

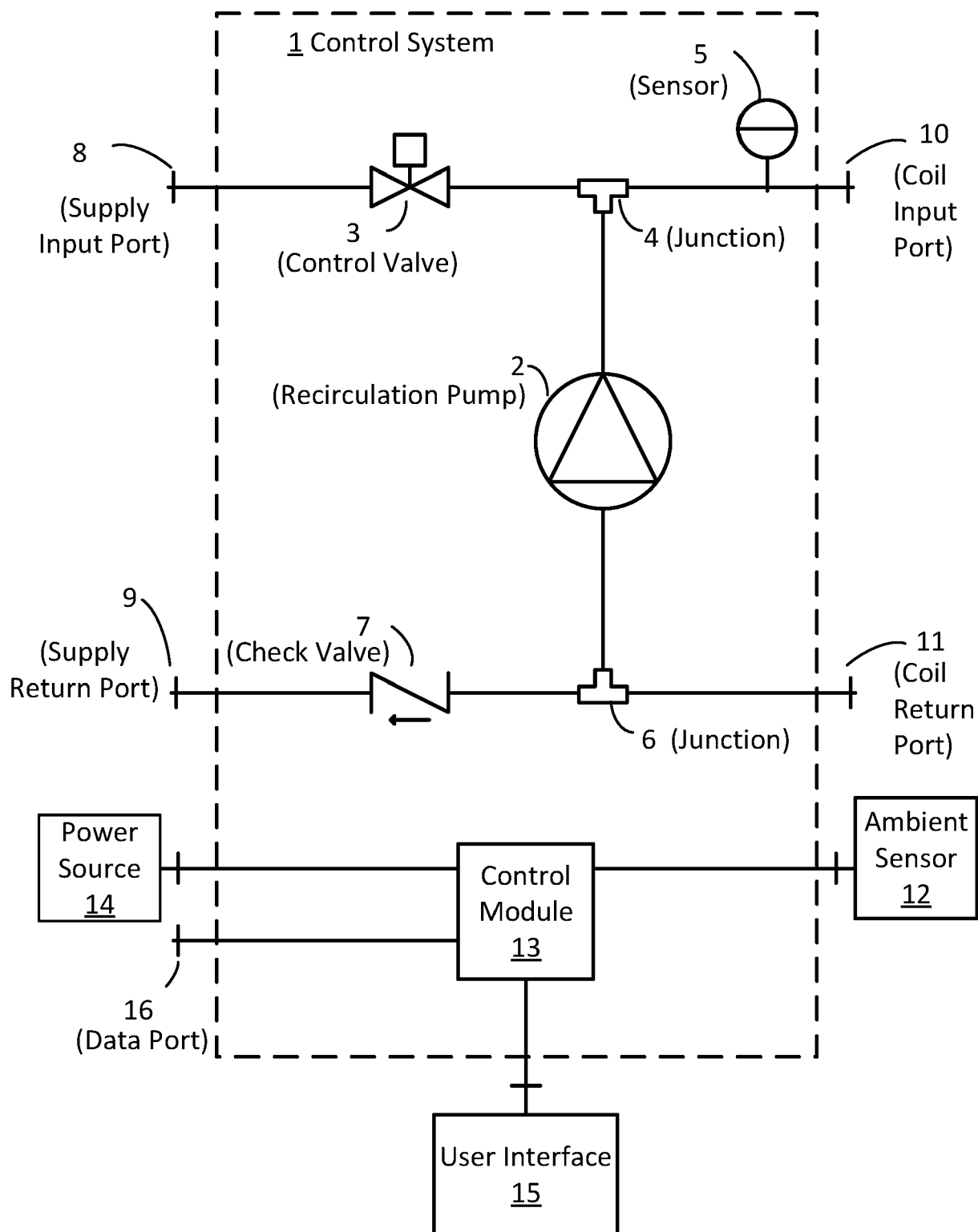
13. The terminal unit of claim 8, wherein

in determining the rate of cooling, the control module determines an actual rate of latent cooling and an actual rate of sensible cooling;
the control module determines a target rate of latent cooling and a target rate of sensible cooling; and
the control module controls a temperature of the coolant in the cooling coil, and at least one of a flow rate of the coolant in the cooling coil and the air flow rate of air through the cooling coil, such that the actual rate of latent cooling and the actual rate of sensible cooling approach the target rate of latent cooling and the target rate of sensible cooling, respectively.

14. The terminal unit of claim 8, wherein

in determining the rate of cooling, the control module determines an actual rate of total cooling and an actual sensible heating ratio;
the control module determines a target rate of total cooling and a target sensible heating ratio; and
the control module controls a temperature of the coolant in the cooling coil, and at least one of a flow rate of the coolant in the cooling coil and the air flow rate of air through the cooling coil, such that the actual rate of total cooling and the actual sensible heating ratio approach the target rate of total cooling and the target sensible heating ratio, respectively.

15. The terminal unit of claim 14, wherein the supply air port is connected to the mixing chamber by a second duct (143), the terminal unit further comprising:
a fan (141) within the second duct to draw air from the mixing chamber and blow the supply air through the supply air port,
wherein the control module controls a speed of the fan to, at least in part, control the air flow rate of air through the cooling coil.

**FIG. 1 (Prior Art)**

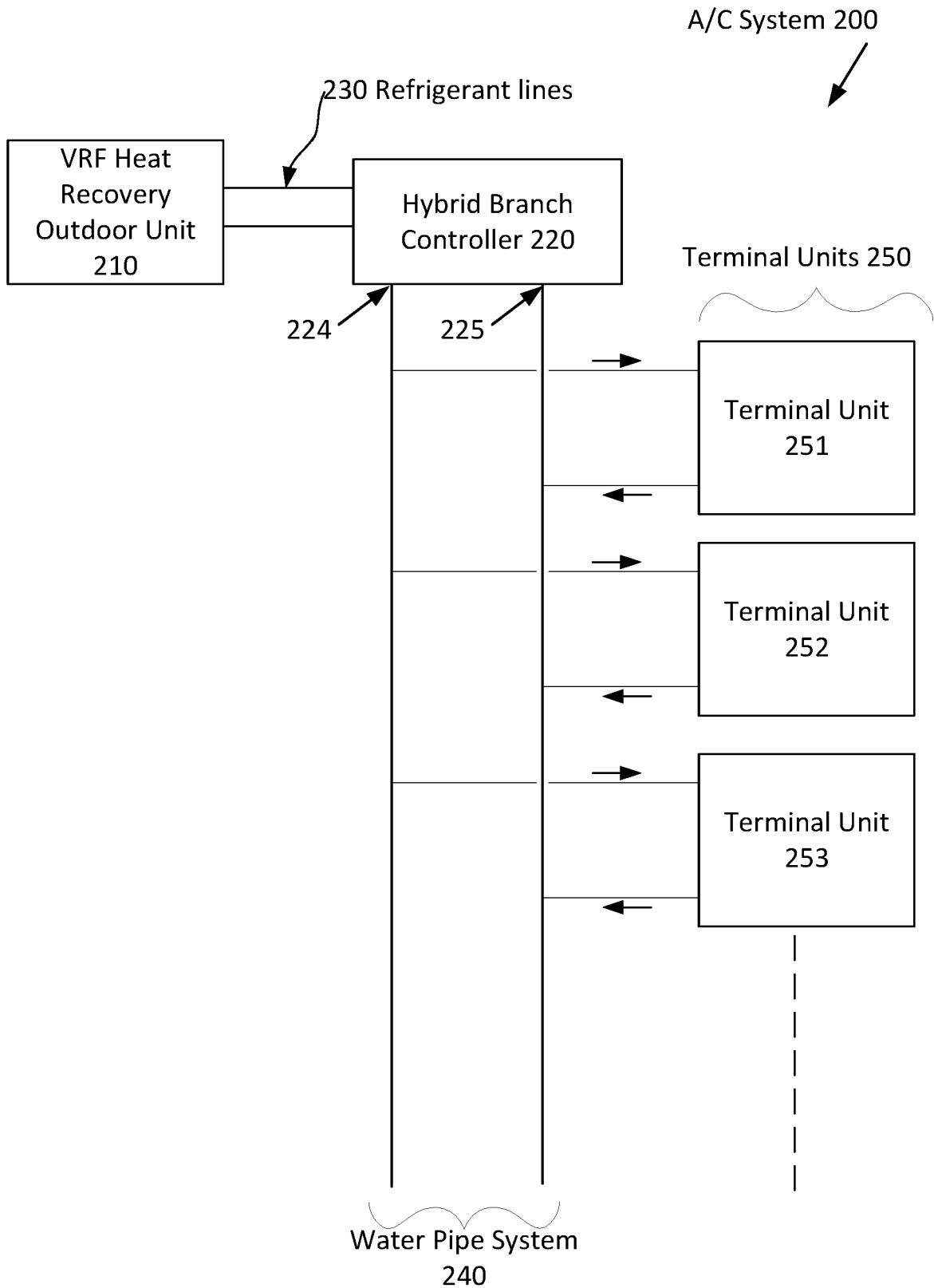


FIG. 2

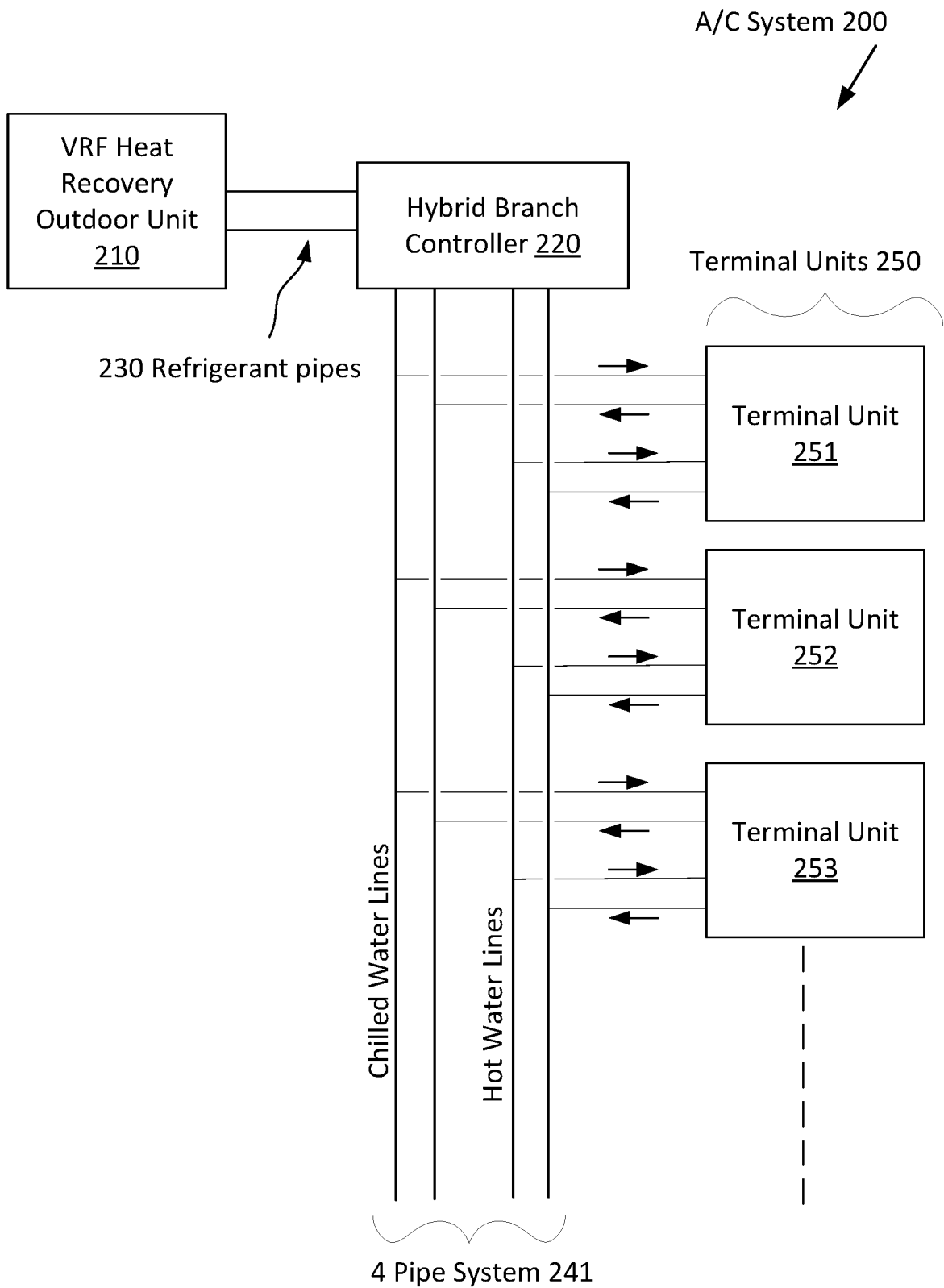


FIG. 3

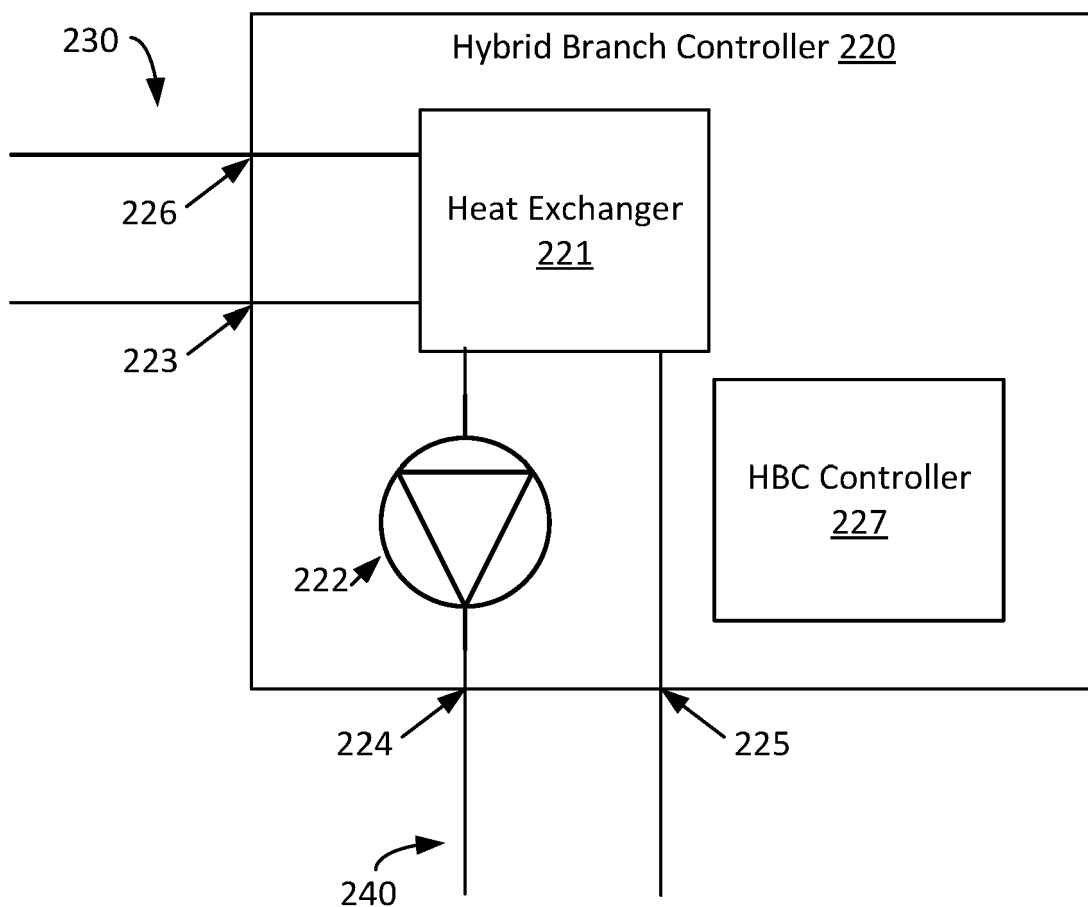


FIG. 4

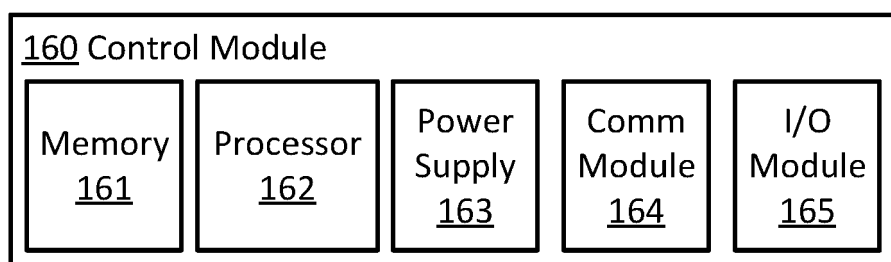


FIG. 5

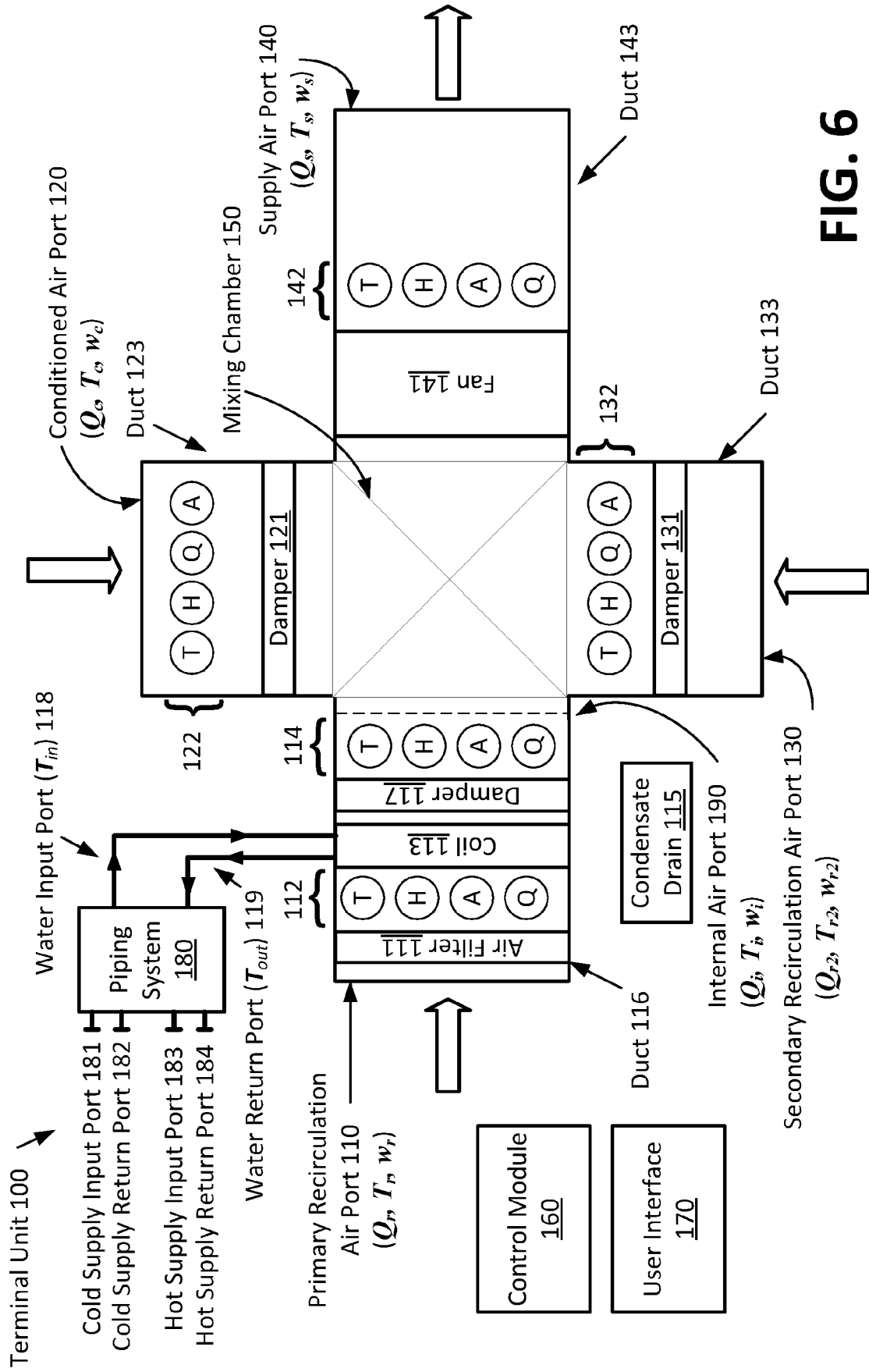


FIG. 6

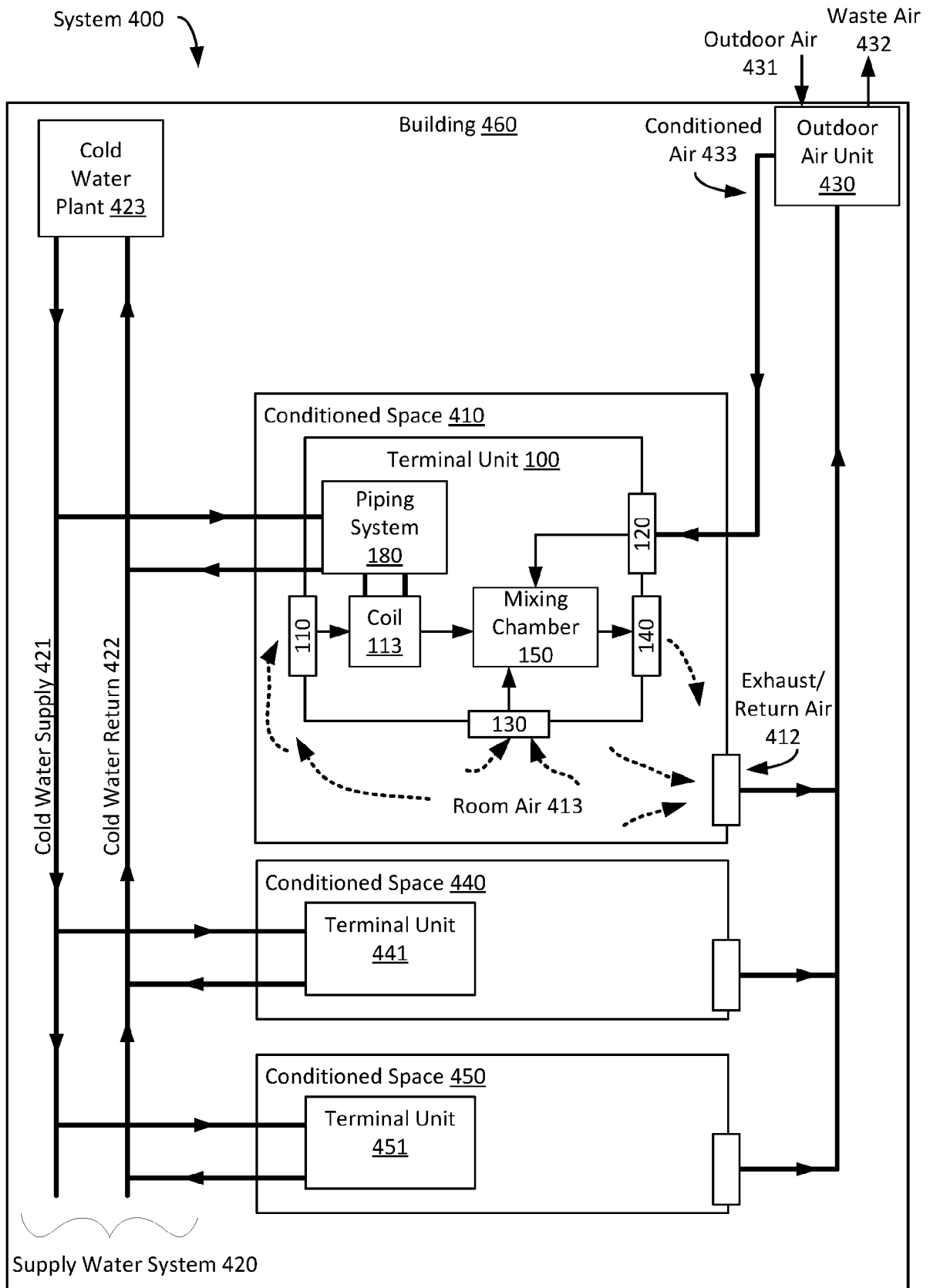


FIG. 7

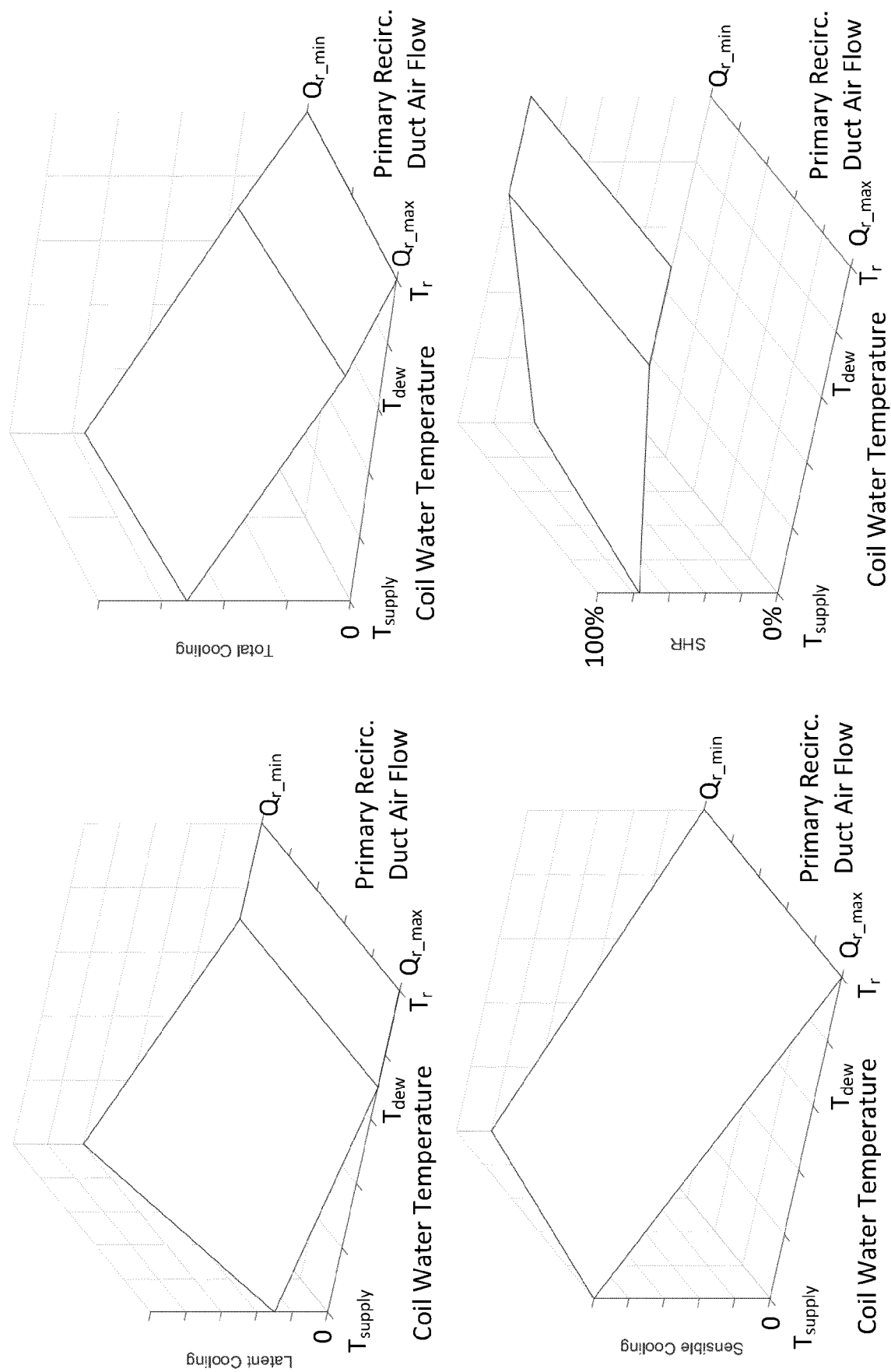
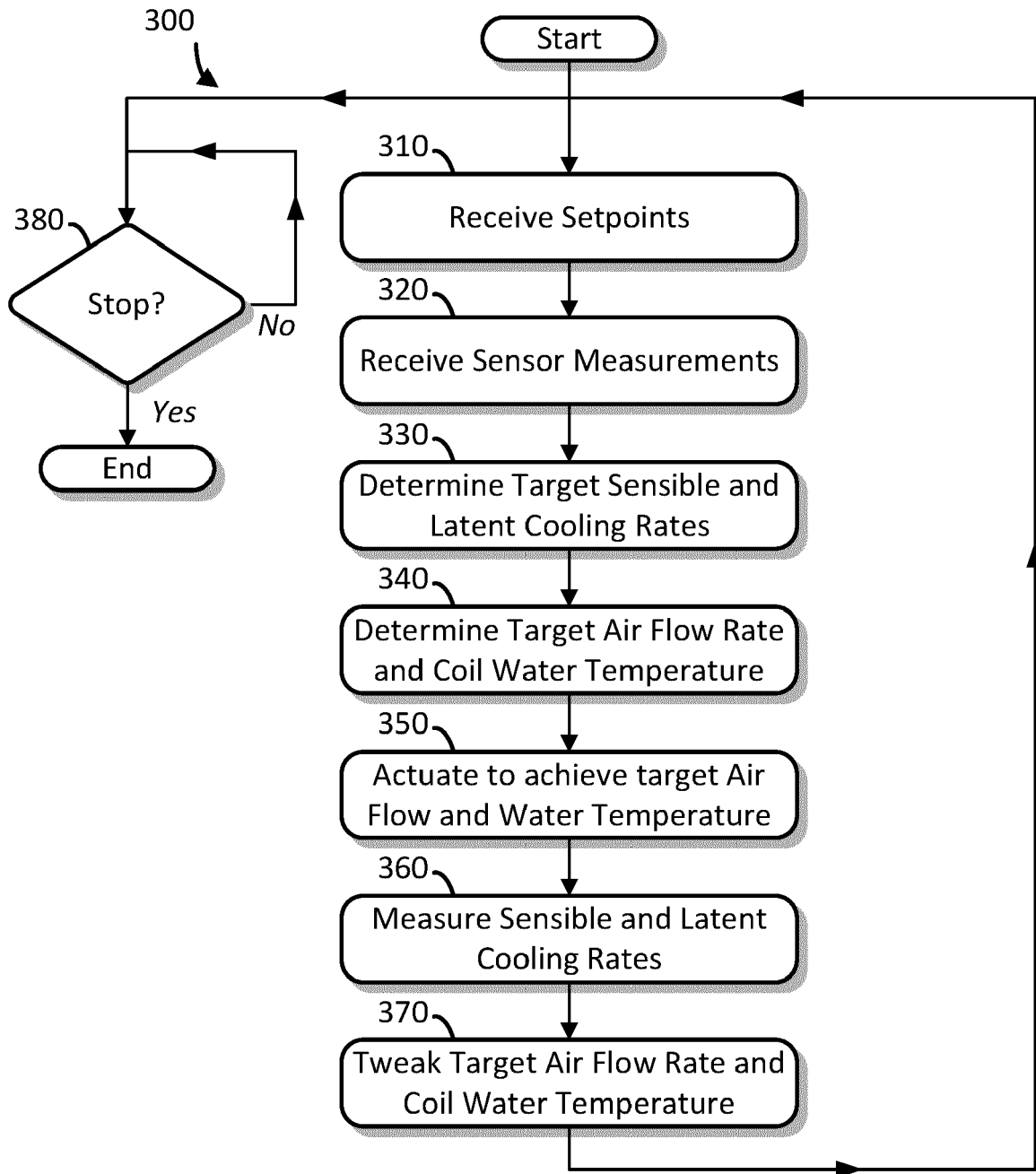


FIG. 8

**FIG. 9**

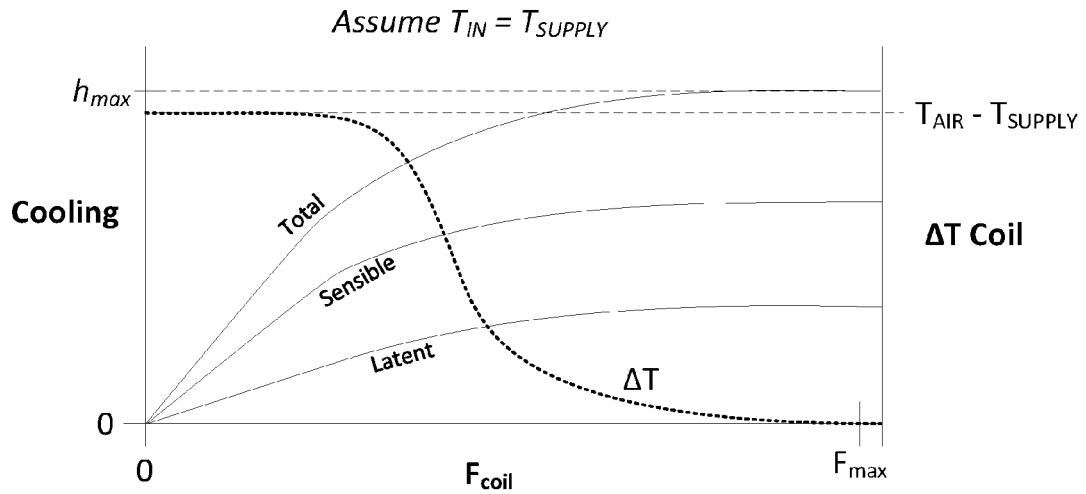


FIG. 10

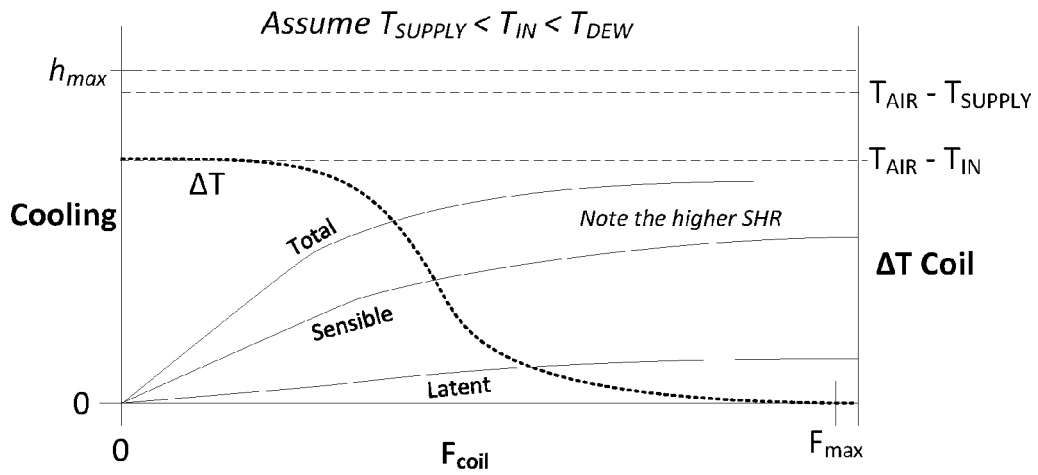


FIG. 11

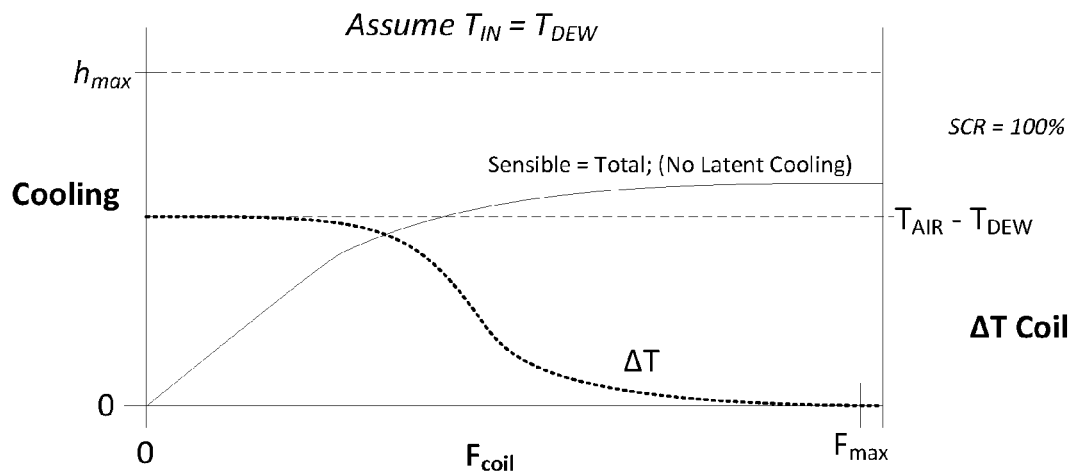


FIG. 12

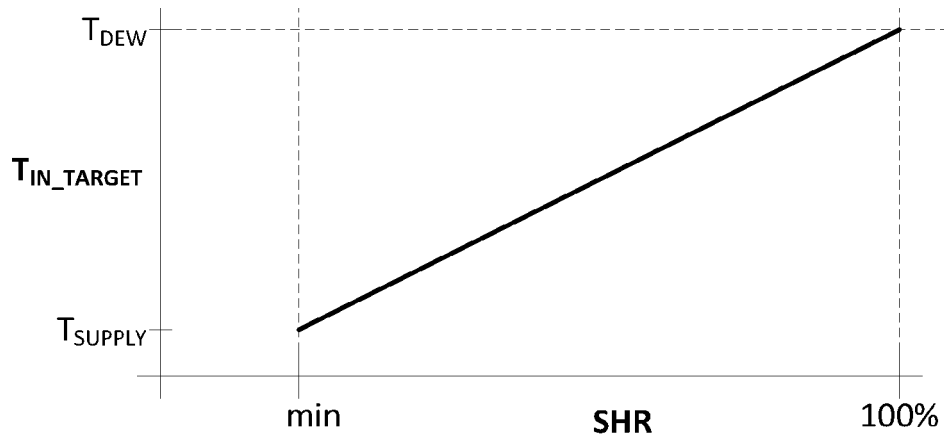


FIG. 13

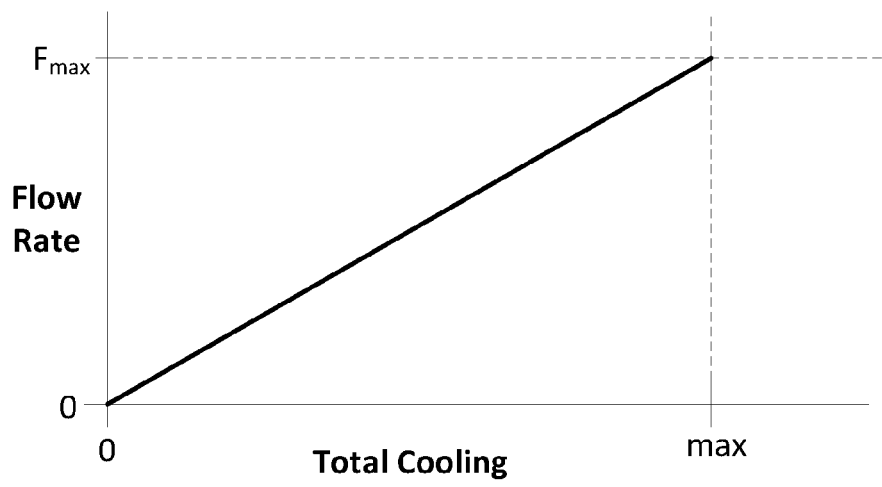


FIG. 14

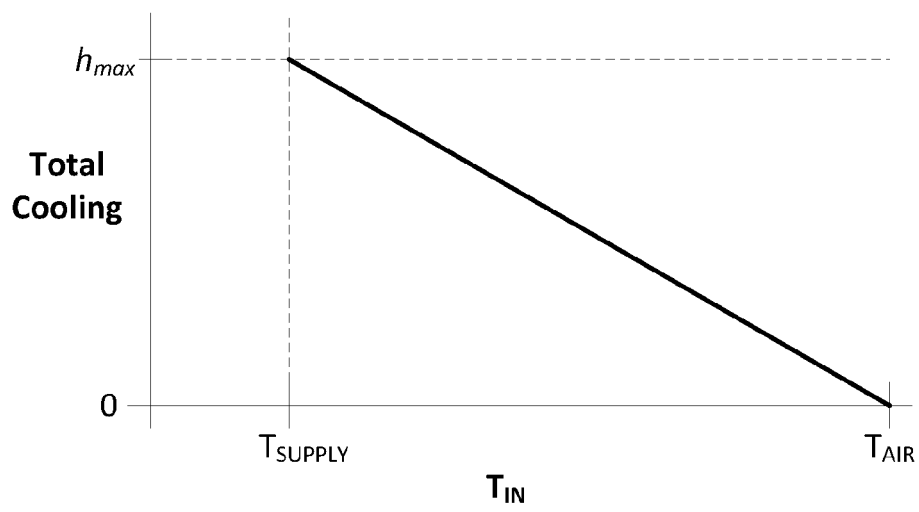


FIG. 15

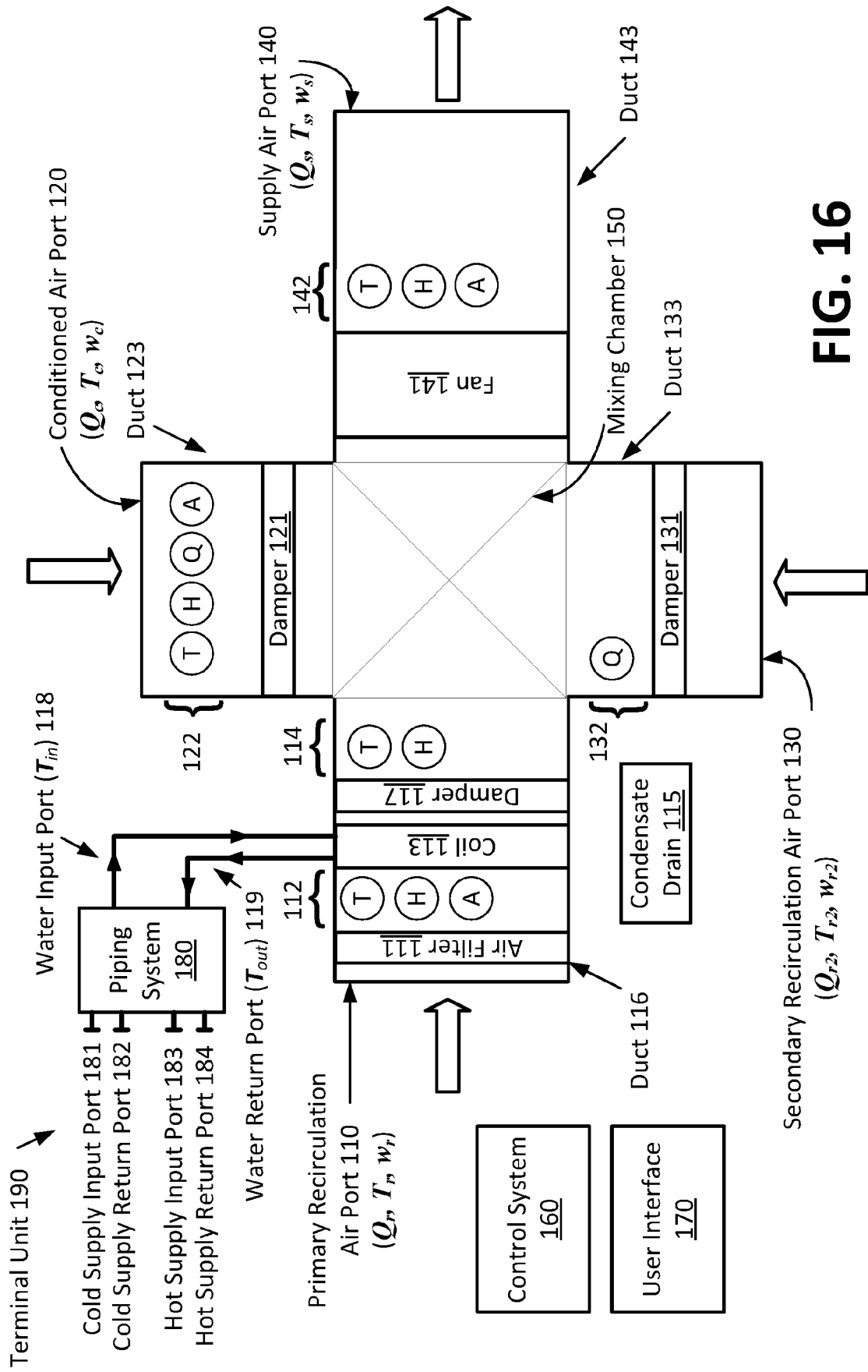


FIG. 16



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Application Number

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A	* column 3 - column 6; figure 1 * -----	9-12	F24F13/04
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A	* paragraph [0047] - paragraph [0123]; figures 1-10 *	9-12	
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A	* column 5 - column 6; figure 5 * -----	9-12	
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A	* page 4 - page 6; figures 1-5 * -----	9-12	
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Place of search Munich		Date of completion of the search 19 September 2023	Examiner Anconetani, Mirco
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document		T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document	

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