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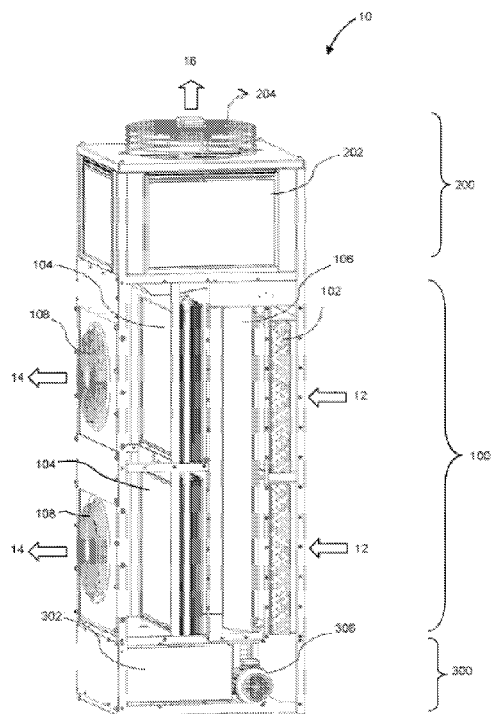


FIG. 2

(57) Abstract: A system for cooling an outdoor space comprises a main cooling module, a heat rejection module, a water management module, and a control module. The main cooling module comprises an indirect evaporative cooling unit for pre-cooling an intake ambient air to a lower temperature by reducing sensible heat, and a direct evaporative cooling unit having a first evaporative medium for cooling the pre-cooled air (or direct ambient air) through vaporization of water thereby generating a conditioned supply air with a much lower wet bulb temperature than the ambient air. The heat rejection module comprises a second evaporative medium for removing heat contained in the excess water from the indirect evaporative cooling unit thereby producing cool water having a temperature almost equivalent to the intake ambient air wet bulb temperature.



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DUAL STAGE EVAPORATIVE COOLING SYSTEM AND CONTROL METHOD THEREOF

FIELD OF THE INVENTION

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The present invention relates to a system and method for cooling an outdoor space, as well as for an indoor space. More particularly, the present invention relates to a dual stage cooling system comprises an indirect evaporative cooling unit which employs cool water for pre-cooling an ambient air by reducing its sensible heat without increasing humidity, and a direct evaporative cooling unit which employs an efficient evaporative medium for cooling the pre-cooled air through vaporization of water thereby achieving a desired comfortable temperature level that goes well below the wet bulb temperature of the ambient air without using a mechanical vapour compression system. Still more particularly, the system of the present invention is compact and suitable for installation at any desired location.

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BACKGROUND OF THE INVENTION

Evaporative cooling is a known method for conditioning air that employs the latent heat of vaporization of water to produce a reduction in temperature and increase in humidity. This method of cooling is far more economical than the conventional mechanical vapour compression systems that are more widely utilized.

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Temperature reduction potential of evaporative cooling systems is typically limited by the pre-treatment psychrometric conditions. For example, temperature reduction for a direct evaporative cooling process is limited by the pre-treatment ambient wet bulb temperature. Alternative methods such as dew point coolers try to overcome this limitation in order to achieve temperature reduction beyond wet bulb. Many of the existing cooling evaporative systems are bulky and not so easy to move around.

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In view of the above, a need exists for an efficient and compact evaporative cooling system that capable of providing a comfortable temperature level that goes well below the pre-treatment wet bulb temperature without using a mechanical vapour compression system.

SUMMARY OF THE INVENTION

The above and other problems are solved and an advance in the art is made by provision of an efficient system and method for cooling ambient air in accordance with this invention. The present invention is capable of providing a comfortable temperature level that goes well below the wet bulb temperature of ambient air. For example, for ambient psychrometric conditions of 32°C and 50%RH, a wet bulb temperature of 23°C can be achieved by the present invention. The system can provide cooling capacity of about 50,000 Btu/hr. Further, the entire system can be fully enclosed within a relatively small casing and thus convenience for installation at any desired locations. For example, the system may be enclosed within a casing having a dimension (height x width x depth) of about 1.8m x 0.8m x 0.85m. Further, side dampers can be manipulated to minimise workload and thus increase energy efficiency of the system. Heat rejection module can efficiently remove heat in the excess water exits from the indirect evaporative cooling unit, thus increasing cooling capacity of the indirect evaporative cooling unit. Several operation modes are provided based on the ambient conditions detected by the system.

According to a first aspect of the invention, there is provided a system for cooling an outdoor space (also suitable for an indoor space). The system comprises a main cooling module, a heat rejection module, a water management module, and a control module. The main cooling module comprises an indirect evaporative cooling unit and a direct evaporative cooling unit. The indirect evaporative cooling unit is supplied with water from a water source for pre-cooling an intake ambient air to a lower temperature by reducing sensible heat of the air without increasing humidity. For example, the indirect evaporative cooling unit is capable of reducing the temperature of the ambient air by at least 60% in wet bulb efficiency. The wet bulb efficiency describes the change of dry bulb temperature as a percentage of the wet bulb depression (i.e. maximum adiabatic temperature change capacity). The direct evaporative cooling unit comprises a direct evaporative cooling unit having a first evaporative medium coated with water from a water source for cooling an input air through vaporization of the water coated the first evaporative medium thereby generating a conditioned supply air with a lower dry bulb temperature than the ambient air, wherein the input air comprises the pre-cooled air directly from the indirect evaporative cooling unit or an intake ambient air that bypasses the indirect evaporative cooling unit. For example, the direct evaporative cooling

unit is capable of reducing the temperature of the input air by at least 80% in wet bulb efficiency.

The heat rejection module comprises a second evaporative medium coated with water exits from the indirect evaporative cooling unit for removing heat contained in the water by running the water through the second evaporative medium thereby producing cool water having a temperature almost equivalent to the intake ambient air wet bulb temperature, wherein the cool water is circulated to the indirect and direct evaporative cooling units for facilitating the pre-cooling and cooling processes respectively. The water management module comprises: a water tank supplied with the water exit from the heat rejection module and the direct evaporative cooling unit; and means for circulating water from the water tank to the indirect and direct evaporative cooling units individually, and from the heat rejection module and the direct evaporative cooling unit back to the water tank. The control module provides a plurality of operation modes for the system. The control module comprises: an input device for sensing ambient conditions; and a control algorithm for selecting one of the plurality of operation modes based on the ambient conditions detected by the input device, and controlling the main cooling module and the heat rejection module to function based on the selected operation mode.

In accordance with some embodiments of this invention, the main cooling module further comprises one or more fans installed adjacent to an inlet of the ambient air before the indirect evaporative cooling unit, or installed adjacent to an outlet of the supply air after the direct evaporative cooling unit, or installed between the indirect and direct evaporative cooling units.

In accordance with some embodiments of this invention, the main cooling module further comprises one or more side dampers installed between the indirect and direct evaporative cooling units and configured to control the intake ambient air into the main cooling unit. The one or more side dampers are open (active) to inhibit the intake ambient air from flowing through the indirect evaporative cooling unit. The one or more side dampers are closed (inactive) to allow the intake ambient air to flow through the indirect evaporative cooling unit.

In accordance with some embodiments of this invention, the main cooling

module further comprises a plurality of nozzles installed at an outlet of the supply air after the direct evaporative cooling unit and configured to provide constriction of airflow of the supply air, thereby enhancing directionality, throw distance, and/or coverage area of the supply air.

5 In accordance with some embodiments of this invention, the heat rejection module is placed above the main cooling module and configured to project an exhaust air from the heat rejection module in an upward direction to avoid recirculation of air.

10 In accordance with some embodiments of this invention, the water management module further comprises a water treatment unit for providing water disinfection, wherein the treated water is supplied to the water tank.

15 In accordance with some embodiments of this invention, the input device of the control module comprises a temperature sensor and a humidity sensor.

20 In accordance with some embodiments of this invention, the system is fully enclosed within a casing having a dimension (height x width x depth) of about 1.8m x 0.8m x 0.85m.

25 In accordance with some embodiments of this invention, the plurality of operation modes comprises a “dry mode” which is selected if the detected ambient conditions having a first temperature level and a first humidity level. In the “dry mode” operation, the indirect evaporative cooling unit and the heat rejection module are active while the direct evaporative cooling unit is inactive.

30 In accordance with some embodiments of this invention, the plurality of operation modes comprises an “eco-cool mode” which is selected if the detected ambient conditions having a first temperature level and a second humidity level wherein the second humidity level is greater than the first humidity level. In the “eco-cool mode” operation, the direct evaporative cooling unit is active while the indirect evaporative cooling unit and the heat rejection module are inactive.

 In accordance with some embodiments of this invention, the plurality of operation modes comprises an “eco-cool plus mode” which is selected if the detected ambient

conditions having a first temperature level and a third humidity level wherein the third humidity level is greater than the second humidity level. In the “eco-cool plus mode” operation, the direct evaporative cooling unit and the heat rejection module are active while the indirect evaporative cooling unit is inactive.

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In accordance with some embodiments of this invention, the plurality of operation modes comprises a “booster mode” which is selected if the detected ambient conditions having a first temperature level and a fourth humidity level wherein the fourth humidity level is greater than the third humidity level. In the “booster mode” operation, the indirect evaporative cooling unit, the direct evaporative cooling unit and the heat rejection module are active.

In accordance with some embodiments of this invention, wherein the plurality of operation modes comprises a “fan mode” which is selected if the detected ambient conditions having a second temperature level or a fifth humidity level, wherein the second temperature is smaller than the first temperature level and the fifth humidity level is greater than the fourth humidity level. In the “fan mode” operation, the indirect evaporative cooling unit, the direct evaporative cooling unit and the heat rejection module are inactive.

According to a second aspect of the invention, there is provided a method for cooling an outdoor space (also suitable for an indoor space). The method comprises the following steps. Firstly, providing a system with a plurality of operation modes, the system comprises: a main cooling module comprises an indirect evaporative cooling unit and a direct evaporative cooling unit having a first evaporative medium; a heat rejection module having a second evaporative medium; and a control module comprises an input device and a control algorithm. Further, operating the control module to select one of the plurality of operation modes based on ambient conditions detected by the input device, and control the main cooling module and the heat rejection module to function based on the selected operation mode. Further, operating the indirect evaporative cooling unit based on the selected operation mode, wherein the operating of the indirect evaporative cooling unit comprises pre-cooling an intake ambient air to a lower temperature by reducing sensible heat of the air without increasing humidity. Further, operating the direct evaporative cooling unit based on the selected operation mode, wherein the operating of the direct evaporative cooling unit comprises cooling an input air through vaporization of water coated the first evaporative

medium thereby generating a conditioned supply air with a lower dry bulb temperature than the ambient air, wherein the input air comprises the pre-cooled air directly from the indirect evaporative cooling unit or an intake ambient air that bypasses the indirect evaporative cooling unit. Further, operating the heat rejection module based on the selected operation mode, wherein operating of the heat rejection module comprises removing heat contained in water exits from the indirect evaporative cooling unit by running the water through the second evaporative medium thereby producing cool water having a temperature almost equivalent to the intake ambient air wet bulb temperature. The cool water is circulated to the indirect and direct evaporative cooling units for facilitating the pre-cooling and cooling processes respectively.

In accordance with some embodiments of this invention, a “dry mode” is selected from the plurality of operation modes if the detected ambient conditions having a first temperature level and a first humidity level. The “dry mode” comprises the operating of the indirect evaporative cooling unit and the heat rejection module.

In accordance with some embodiments of this invention, a “eco-cool mode” is selected from the plurality of operation modes if the detected ambient conditions having a first temperature level and a second humidity level wherein the second humidity level is greater than the first humidity level. The “eco-cool mode” comprises the operating of the direct evaporative cooling unit.

In accordance with some embodiments of this invention, a “eco-cool plus mode” is selected from the plurality of operation modes if the detected ambient conditions having a first temperature level and a third humidity level wherein the third humidity level is greater than the second humidity level. The “eco-cool plus mode” comprises the operating of the direct evaporative cooling unit and the heat rejection module.

In accordance with some embodiments of this invention, a “booster mode” is selected from the plurality of operation modes if the detected ambient conditions having a first temperature level and a fourth humidity level wherein the fourth humidity level is greater than the third humidity level. The “booster mode” comprises the operating of the indirect evaporative cooling unit, the direct evaporative cooling unit and the heat rejection module.

In accordance with some embodiments of this invention, a “fan mode” is selected from the plurality of operation modes if the detected ambient conditions having a second temperature level or a fifth humidity level wherein the second temperature is lower than the first temperature level and the fifth humidity level is greater than the fourth humidity level.

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BRIEF DESCRIPTION OF THE DRAWINGS

The summary above, as well as the following detailed description of illustrative embodiments, is better understood when read in conjunction with the appended drawings.

10 For the purpose of illustrating the present disclosure, exemplary constructions of the disclosure are shown in the drawings. However, the disclosure is not limited to specific methods and instrumentalities disclosed herein. Moreover, those in the art will understand that the drawings are not to scale. Wherever possible, like elements have been indicated by identical numbers.

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FIG. 1 shows a schematic diagram of a system in accordance with an embodiment of the present invention which mainly comprises a main cooling module, a heat rejection module, a water management module and a control module;

20 FIG. 2 shows a perspective view of the system of FIG. 1;

FIG. 3 shows a perspective view of the system of FIG. 1 in the “booster mode” or “dry mode” operation;

25 FIG. 4 shows a perspective view of the system of FIG. 1 in the “eco-cool mode” or “fan mode” operation;

FIG. 5 shows a perspective view of the system of FIG. 1 in the “eco-cool plus mode” operation;

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FIG. 6 shows a flow chart illustrating a method of operating the system of FIG. 1.

DETAILED DESCRIPTION OF THE INVENTION

The present invention relates to a compact and efficient system for cooling ambient air in an outdoor space (also suitable for an indoor space). This invention provides various operation modes to achieve desired comfortable temperature levels based on the ambient conditions detected by the system. The system comprises an indirect evaporative cooling unit (e.g. air-water heat exchanger) which employs cool water for pre-cooling an ambient air by reducing its sensible heat without increasing humidity, and a direct evaporative cooling unit which employs an efficient evaporative medium for cooling the pre-cooled air (or a direct ambient air) through vaporization of water to achieve a desired comfortable temperature level that goes well below the wet bulb temperature of the ambient air without using a mechanical vapour compression system.

FIG. 1 shows a schematic diagram of cooling system 10 in accordance with an embodiment of the present invention. System 10 mainly comprises main cooling module 100, heat rejection module 200, water management module 300, and control module 400. A physical arrangement of the modules of FIG. 1 is illustrated in FIG. 2 in accordance with an embodiment of the present invention.

As main cooling module 100 provides the conditioned supply air, it is preferably positioned in the middle of system 10 between heat rejection module 200 (above main cooling module 100) and water management module 300 (below main cooling module 100). This configuration provides a targeted delivery of supply air to the upper body of a person. Main cooling module 100 comprises an indirect evaporative cooling unit 102 (e.g. air-water heat exchanger), a direct evaporative cooling unit 104, one or more side dampers 106, one or more fans 108.

Indirect evaporative cooling unit 102 may be a commonly used air-water heat exchanger that performs an indirect evaporative cooling. Indirect evaporative cooling unit 102 comprises a cooling tube 103 supplied with water from water tank 302 for pre-cooling ambient air 12 that enters main cooling module 100. Ambient air 12 that enters indirect evaporative cooling unit 102 will be in contact with the surface of cooling tube 103 which has a lower temperature than ambient air 12. The temperature different between the warm ambient air 12 and the cool cooling tube 103 results in the transfer of heat between ambient

air 12 and the water enclosed within cooling tube 103. Consequently, ambient air 12 that enters indirect evaporative cooling unit 102 is cooled sensibly to a lower temperature without increasing its absolute humidity. In order to achieve maximum wet bulb efficiency where both sensible and adiabatic cooling are employed, sensible cooling is performed prior to
5 adiabatic cooling. Accordingly, indirect evaporative cooling unit 102 (for sensible cooling) is positioned before direct evaporative cooling unit 104 (for adiabatic cooling) in the path of the air flow. In certain operation modes, indirect evaporative cooling unit 102 may be bypassed by side dampers 106, i.e. ambient air 12 flows in through side dampers 106 that are open instead of flowing through indirect evaporative cooling unit 102.

10 Direct evaporative cooling unit 104 comprises a first evaporative medium 105 coated with water from water tank 302 for cooling an input air. The input air may be the pre-cooled ambient air directly from indirect evaporative cooling unit 102 or an ambient air that flows in through side dampers 106 that bypasses indirect evaporative cooling unit 102 (i.e.
15 not pre-cooled by indirect evaporative cooling unit 102), based on the operation mode of system 10. First evaporative medium 105 is a highly efficient porous material. The high efficiency of this evaporative medium is achieved through high water absorption and desorption characteristics, which is a result of the material and structural elements of the medium. In brief, the absorption process ensures that water flowing across the medium is
20 stored within the medium effectively, and secondly, the desorption process ensures that water is released readily into the cross-flowing air. The input air passes across the wetted surface of first evaporative medium 105. As warm input air passes across the surface of first evaporative medium 105, the surface water is heated and evaporates, resulting in adiabatic cooling from first evaporative medium 105. Therefore, temperature of the passing air is
25 reduced through an increase in absolute humidity. However, the maximum temperature drop in this process is limited to the wet bulb temperature of the pre-treatment air. In this invention, the first heat removal process (via indirect evaporative cooling unit 102 as described above) changes the psychrometric conditions of the air stream, where the characteristic wet bulb temperature is lowered, thus allowing the direct evaporative cooling
30 unit 104 to achieve a lower supply air temperature. The excess water that passes through first evaporative medium 105 is cooled to about the wet bulb temperature and flows back to water tank 302.

One or more side dampers 106 are installed between indirect evaporative

cooling unit 102 and direct evaporative cooling unit 104 as shown in FIG. 2. Side damper 106 are activated by damper actuators controlled via control module 400. Side dampers 106 will open when activated and thus allows ambient air 12 to flow in directly through side dampers and bypass indirect evaporative cooling unit 102, under certain operation modes in order to achieve most energy efficient operation. In an alternative embodiment, side dampers 106 are not installed in main cooling module 100, i.e. no bypassing of indirect evaporative cooling unit 102 is required. Accordingly, ambient air 12 can flow through indirect evaporative cooling unit 102 regardless the operation mode of system 10. However, no bypassing of direct evaporative cooling unit 104 via side dampers 106.

One or more fans 108 can be installed near an outlet of supply air 14 after direct evaporative cooling unit 104 as shown in FIG. 1 and 2 so as to draw the conditioned supply air (including unconditioned air) out of main cooling module 100. In an alternative embodiment, fans 108 may be installed near an inlet of ambient air 12 before indirect evaporative cooling unit 102. This configuration is useful when nozzle constriction is installed at the outlet of supply air 14 which will be discussed below. In another embodiment, fans 108 can be placed between dampers 106 and direct evaporative cooling unit 104 and this arrangement may reduce the noise level.

Main cooling module 100 may further comprise a plurality of nozzles (not shown) installed at the outlet of supply air 14 of main cooling module 100 after direct evaporative cooling unit 104. These nozzles can be arranged in a variety of array configurations and provide constriction of air. The introduction of nozzle constriction at the outlet of supply air 14 increases the speed of the exit supply air and thus increasing the lengthwise throw distance. These nozzles can also be configured to provide directionality and increase the horizontal or vertical spatial coverage, whereby the nozzles projection angles are configured horizontally or vertically respectively. In an embodiment where nozzles are installed, fans 108 should be placed near the inlet of ambient air 12 so that to allow for homogenous output of air prior to the nozzle constriction at the outlet of supply air 14. Further, side dampers 106 are not required to be installed as they require a negative pressure flow to operate and thus would not be functional in this configuration. In an alternative embodiment, constriction fixtures, such as louvers and blades, may be used instead of nozzles. These fixtures may be installed at the inlet and/or outlet of main cooling module 100. Also, a series of ducts may be attached to the inlet and/or outlet fixtures to facilitate certain air flow regimes. Therefore, a

desired air flow profile, such as a circular swirl, may be induced through the manipulation of the nozzles or the constriction fixtures.

Heat rejection module 200 comprises second evaporative medium 202 and exhaust fan 204. Second evaporative medium 202 is a highly efficient porous material, which is similar to first evaporative medium 105 that contained within main cooling module 100 and thus shared the same efficiency characteristics. The primary function of heat rejection module 200 is to produce cool water via an evaporative cooling process. Similar to first evaporative medium 105, when water is vaporized to a gas, heat is extracted from the unvaporized water streaming down second evaporative medium 202. This results in water temperature to be reduced to about the wet bulb temperature of unconditioned ambient air 12. The resulting cool water flows back to water tank 302. The exhaust fan 204 is installed near the outlet of heat rejection module 200 and adjacent to second evaporative medium 202 so that it can pull air through second evaporative medium 202 to facilitate the evaporative cooling process as described. For an example as shown in FIG 2, exhaust fan 204 is installed at the top part of heat rejection module 200. Heat rejection module 200 is placed above main cooling module 100 so as to ensure that exhaust air 16 is channelled away from system 10 in an upward direction so as to avoid recirculation of air around the system. Heat rejection module 200 acts to expel heat contained in the water exits from indirect evaporative cooling unit 102, and generate cool water to flow back to water tank 302.

Water management module 300 comprises water tank 302, water pipes 304, pumps 306 and 308, and an optional water treatment unit (not shown). The main pump 306 has a higher capacity than the secondary pump 308, which is used to drive water from water tank 302 to cooling tube 103 of indirect evaporative cooling unit 102 and to second evaporative medium 202 of heat rejection module 200. Secondary pump 308 is of lower capacity than main pump 306 which is used to drive water up to first evaporative medium 105 of direct evaporative cooling unit 104. The water after passing through first and second evaporative medium 105 and 202 will flow back to water tank 302 via gravity. This is achieved by positioning water tank 302 at the bottom of system 10, below of main cooling module 100 and heat rejection module 200. Water tank 302 is supplied with cool water from heat rejection module 200 and direct evaporative cooling unit 104. Water tank 302 may also be supplied with water from an external source via water supply pipe 308. The water in water tank 302 can also be drained out via draining pipe 310. The water treatment unit

provides certain disinfection of water to prevent biological contaminations, such as legionella prevention, and thus minimize degradation of first and second evaporative medium 105 and 202, such as to prevent mildew growth. The treatment processes can range from ultraviolet (UV) irradiation, chlorine or ozone dosing, etc. The treated water can then be supplied to
5 water tank 302 via water supply pipe 308.

Control module 400 comprises a control algorithm 402 and input/output device 404. Control module 400 aims to achieve a comfortable temperature level through the most energy efficient operation mode. Input device 404 may include temperature and humidity
10 sensors for sensing ambient conditions. Control module 400 provides several operation modes for system 10 which is selected/determined by control algorithm 402 based on the psychrometric conditions such as temperature and humidity of ambient air 12. The operation modes include, but not limited to, "fan mode", "eco-cool mode", "booster mode", "eco-cool plus mode" and "dry mode". Output device or actuators 404 can be activated by control
15 algorithm 402 to control various modules/units of cooling system 10, including indirect and direct evaporative cooling units 102 and 104, heat rejection module 200, fans 108, side dampers 106, pumps 306 and 308, water treatment unit and etc., depending on the operation mode selected by control algorithm 402.

Input device 404 may include various sensor elements for detecting the psychrometric conditions of temperature and humidity. This psychrometric information is then processed by control algorithm 402 to select the most energy efficient operation mode for system 10 in order to provide a comfortable temperature level, and activate the relevant
20 output device 404 to control the functions of various modules/units of system 10. The control process of control algorithm 402 is illustrated in the flow chart as shown in FIG 6. Control module 400 together with other modules of system 10 may be enclosed within a relatively small casing. Input device 404 (ambient sensors) are preferably placed at locations where
25 they are in direct contact with the ambient air, such as near the inlet of ambient air intakes.

The "dry mode" is selected when the detected psychrometric conditions are such that temperature is at an uncomfortable level (i.e. first temperature level) and humidity is at an extremely low level (i.e. first humidity level). For examples, the first temperature level may be defined as temperatures (T) greater than 27°C ($T > 27^{\circ}\text{C}$), and the first humidity level may be defined as relative humidity (RH) lower than 30% ($\text{RH} < 30\%$). In this mode, air
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conditioning is provided via indirect evaporative cooling unit 102 while direct evaporative cooling unit 104 is inactive. Thus, this mode provides sensible heat removal without added moisture to supply air 12. Heat rejection module 200 is active in order to remove the heat contained in the water exits from indirect evaporative cooling unit 102. Side dampers 106 are closed (inactive) and thus ambient air will flow through indirect evaporative cooling unit 102 (i.e. no bypassing). The airflow through system 10 in the “dry mode” is illustrated in FIG. 3.

The “eco-cool mode” is selected when the detected psychrometric conditions are such that temperature is at an uncomfortable level (i.e. first temperature level) and humidity is at a relatively low level (i.e. second humidity level). The second humidity level is greater than the first humidity level. For examples, the first temperature level may be defined as temperatures (T) greater than 27°C ($T > 27^{\circ}\text{C}$), and the second humidity level may be defined as relative humidity (RH) between 30% and 55% ($30\% \leq \text{RH} < 55\%$). In this mode, air conditioning is provided via direct evaporative cooling unit 104 while indirect evaporative cooling unit 102 is inactive. Side dampers 106 are open (active) to allow ambient air 12 to enter via side dampers 106 and bypass indirect evaporative cooling unit 102. This configuration minimizes workload on fans 108. Heat rejection module 200 is inactive. The airflow through system 10 in the “eco-cool mode” is illustrated in FIG. 4.

The “eco-cool plus mode” is selected when the detected psychrometric conditions are such that temperature is at an uncomfortable level (i.e. first temperature level) and humidity is at a moderate level (i.e. third humidity level). The third humidity level is greater than the second humidity level. For examples, the first temperature level may be defined as temperatures (T) greater than 27°C ($T > 27^{\circ}\text{C}$), and the third humidity level may be defined as relative humidity (RH) between 55% and 75% ($55\% \leq \text{RH} < 75\%$). In this mode, air conditioning is provided via direct evaporative cooling unit 104 while indirect evaporative cooling unit 102 is inactive. Side dampers 106 are open (active) to allow ambient air 12 to enter via side dampers 106 and bypass indirect evaporative cooling unit 102. Heat rejection module 200 is active so as to deliver an added volume of supply airflow. This mode can deliver the same humidification performance as the “eco-cool mode”, and provide at least double the volume of airflow than the “eco-cool mode”. The airflow through system 10 in the “eco-cool plus mode” is illustrated in FIG. 5.

The “booster mode” is selected when the detected psychrometric conditions are such that temperature is at an uncomfortable level (i.e. first temperature level) and humidity is at a relatively high level (i.e. fourth humidity level). The fourth humidity level is greater than the third humidity level. For examples, the first temperature level may be defined as temperatures (T) greater than 27°C ($T > 27^{\circ}\text{C}$), and the fourth humidity level may be defined as relative humidity (RH) between 75% and 90% ($75\% \leq \text{RH} \leq 90\%$). In this mode, both indirect and direct evaporative cooling units 102 and 104 are active to provide air conditioning. Side dampers 106 are closed (inactive) and thus ambient air will flow through indirect evaporative cooling unit 102 (i.e. no bypassing). Heat rejection module 200 is active in order to remove the heat contained in the water exits from indirect evaporative cooling unit 102, thus increases the cooling capacity of the indirect evaporative cooling unit 102. The airflow through system 10 in the “booster mode” is also illustrated in FIG. 3.

The “fan mode” is selected when the detected psychrometric conditions are such that temperature at a comfortable level (i.e. second temperature level) or humidity is at an extremely high level (i.e. fifth humidity level). The second temperature level is smaller than the first temperature level. The fifth humidity level is greater than the fourth humidity level. For examples, the second temperature level may be defined as temperatures (T) smaller than 27°C ($T \leq 27^{\circ}\text{C}$), and the fifth humidity level may be defined as relative humidity (RH) greater than 90% ($\text{RH} > 90\%$). In this mode, no air conditioning is provided as the temperature is comfortable and thus both main cooling module 100 and heat rejection module 200 are inactive. Only fans 108 are in operation to draw in air to create a draft. Side dampers 106 are open (active) to allow ambient air 12 to enter via side dampers 106 and bypass indirect evaporative cooling unit 102. This configuration minimizes the pressure resistance on fans 108 and thus minimizes the workload on fans 108. The “fan mode” is the least energy intensive mode. The airflow through system 10 in the “fan mode” is also illustrated in FIG. 4.

FIG. 6 shows a flow chart illustrating a method 600 of operating system 10 of FIG. 1 in various operation modes in accordance with embodiments of the present invention. In step 601, input device 404 (e.g. sensors) detects psychrometric conditions of temperature and humidity. This information is then processed by control algorithm 402 to select/determine the most energy efficient operation mode that provides a desired comfortable temperature level, and activate the relevant modules/units of system 10 to

perform their functions.

In step 602 where input device 404 detects that the temperature at an uncomfortable level and the humidity at an extremely low level, the “dry mode” will be selected by control algorithm 402, and system 10 proceeds to perform the “dry mode” operation in step 603. In step 603, indirect evaporative cooling unit 102 and heat rejection module 200 will be activated to function; direct evaporative cooling unit 104 will not be activated to function; and side dampers 106 will be closed (not activated).

In step 604 where input device 404 detects that the temperature at an uncomfortable level and the humidity at a relatively low level, the “eco-cool mode” will be selected by control algorithm 402, and system 10 proceeds to perform the “eco-cool mode” operation in step 605. In step 605, direct evaporative cooling unit 104 will be activated to function; indirect evaporative cooling unit 102 and heat rejection module 200 will not be activated to function; and side dampers 106 will be open (activated).

In step 606 where input device 404 detects that the temperature at an uncomfortable level and the humidity at a moderate level, the “eco-cool plus mode” will be selected by control algorithm 402, and system 10 proceeds to perform the “eco-cool plus mode” operation in step 607. In step 607, direct evaporative cooling unit 104 and heat rejection module 200 will be activated to function; indirect evaporative cooling unit 102 will not be activated to function; and side dampers 106 will be open (activated).

In step 608 where input device 404 detects that the temperature at an uncomfortable level and the humidity at a relatively high level, the “booster mode” will be selected by control algorithm 402, and system 10 proceeds to perform the “booster mode” operation in step 609. In step 609, indirect evaporative cooling unit 102, direct evaporative cooling unit 104 and heat rejection module 200 will be activated to function; and side dampers 106 will be closed (not activated).

In step 610 where input device 404 detects that the temperature at a comfortable level or the humidity at an extremely high level, the “fan mode” will be selected by control algorithm 402, and system 10 proceeds to perform the “fan mode” operation in step 611. In step 611, indirect evaporative cooling unit 102, direct evaporative cooling unit 104 and heat

rejection module 200 will not be activated to function; and side dampers 106 will be open (activated).

Thus, the first cooling stage in the operation of system 10 is a sensible heat reduction that does not increase the absolute humidity. The second cooling stage is an adiabatic cooling process whereby sensible heat is converted to latent heat through the vaporization of water. The combination of these two conditioning stages provides for supply air temperature that goes well below the pre-treatment wet bulb temperature without the use of a mechanical vapour compression system.

It will be appreciated that variations of the above disclosed dual stage cooling system and other features and functions, or alternatives thereof, may be desirably combined into many other different systems or applications. Also that various presently unforeseen or unanticipated alternatives, modifications, variations or improvements therein may be subsequently made by those skilled in the art which are also intended to be encompassed by the following claims.

Although embodiments of the current disclosure have been described comprehensively, in considerable detail to cover the possible aspects, those skilled in the art would recognize that other versions of the disclosure are also possible.

CLAIMS

1. A system for cooling an outdoor space comprising:
a main cooling module comprising:
- 5 an indirect evaporative cooling unit supplied with water from a water source for pre-cooling an intake ambient air to a lower temperature by reducing sensible heat of the air without increasing humidity, and
- a direct evaporative cooling unit having a first evaporative medium coated with water from a water source for cooling an input air through vaporization of the water coated the first evaporative medium thereby generating a conditioned supply air with
- 10 a lower dry bulb temperature than the ambient air, wherein the input air comprises the pre-cooled air directly from the indirect evaporative cooling unit or an intake ambient air that bypasses the indirect evaporative cooling unit;
- a heat rejection module comprising:
- 15 a second evaporative medium coated with water exits from the indirect evaporative cooling unit for removing heat contained in the water by running the water through the second evaporative medium thereby producing cool water having a temperature almost equivalent to the intake ambient air wet bulb temperature, wherein the cool water is circulated to the indirect and direct evaporative cooling units
- 20 for facilitating the pre-cooling and cooling processes respectively;
- a water management module comprising:
- a water tank supplied with the water exit from the heat rejection module and the direct evaporative cooling unit, and
- means for circulating water from the water tank to the indirect and direct evaporative cooling units individually, and from the heat rejection module and the direct evaporative cooling unit back to the water tank; and
- 25 a control module that provides a plurality of operation modes for the system, the control module comprising:
- an input device for sensing ambient conditions, and
- 30 a control algorithm for selecting one of the plurality of operation modes based on the ambient conditions detected by the input device, and controlling the main cooling module and the heat rejection module to function based on the selected operation mode.

2. The system of claim 1, wherein the main cooling module further comprising:

one or more fans installed adjacent to an inlet of the ambient air before the indirect evaporative cooling unit, or installed adjacent to an outlet of the supply air after the direct evaporative cooling unit, or installed between the indirect and direct evaporative cooling units.

3. The system of claim 1, wherein the main cooling module further comprising:

one or more side dampers installed between the indirect and direct evaporative cooling units and configured to control the intake ambient air into the main cooling unit, wherein the one or more side dampers are open (active) to inhibit the intake ambient air from flowing through the indirect evaporative cooling unit, wherein the one or more side dampers are closed (inactive) to allow the intake ambient air to flow through the indirect evaporative cooling unit.

4. The system of claim 1, wherein the main cooling module further comprising:

a plurality of nozzles installed at an outlet of the supply air after the direct evaporative cooling unit and configured to provide constriction of airflow of the supply air, thereby enhancing directionality, throw distance, and/or coverage area of the supply air.

5. The system of claim 1, wherein the heat rejection module is placed above the main cooling module and configured to project an exhaust air from the heat rejection module in an upward direction to avoid recirculation of air.

6. The system of claim 1, wherein the water management module further comprising a water treatment unit for providing water disinfection, wherein the treated water is supplied to the water tank.

7. The system of claim 1, wherein the input device of the control module comprising a temperature sensor and a humidity sensor.

8. The system of claim 1, wherein the system is fully enclosed within a casing having a dimension (height x width x depth) of about 1.8m x 0.8m x 0.85m.

9. The system of claim 1, wherein the plurality of operation modes comprising:

a “dry mode” which is selected if the detected ambient conditions having a first temperature level and a first humidity level,

wherein, in the “dry mode” operation, the indirect evaporative cooling unit and the heat rejection module are active while the direct evaporative cooling unit is inactive.

10. The system of claims 1 and 9, wherein the plurality of operation modes comprising:

an “eco-cool mode” which is selected if the detected ambient conditions having a first temperature level and a second humidity level wherein the second humidity level is greater than the first humidity level,

wherein, in the “eco-cool mode” operation, the direct evaporative cooling unit is active while the indirect evaporative cooling unit and the heat rejection module are inactive.

11. The system of claims 1 and 10, wherein the plurality of operation modes comprising:

an “eco-cool plus mode” which is selected if the detected ambient conditions having a first temperature level and a third humidity level wherein the third humidity level is greater than the second humidity level,

wherein, in the “eco-cool plus mode” operation, the direct evaporative cooling unit and the heat rejection module are active while the indirect evaporative cooling unit is inactive.

12. The system of claims 1 and 11, wherein the plurality of operation modes comprising:

a “booster mode” which is selected if the detected ambient conditions having a first temperature level and a fourth humidity level wherein the fourth humidity level is greater than the third humidity level,

wherein, in the “booster mode” operation, the indirect evaporative cooling unit, the direct evaporative cooling unit and the heat rejection module are active.

13. The system of claim 1, 2 and 12, wherein the plurality of operation modes comprising:

a “fan mode” which is selected if the detected ambient conditions having a second temperature level or a fifth humidity level, wherein the second temperature is smaller than the first temperature level and the fifth humidity level is greater than the fourth humidity level,

wherein, in the “fan mode” operation, the indirect evaporative cooling unit, the direct evaporative cooling unit and the heat rejection module are inactive.

14. A method for cooling an outdoor space comprising:

providing a system with a plurality of operation modes, the system comprising:

a main cooling module comprises an indirect evaporative cooling unit and a

direct evaporative cooling unit having a first evaporative medium,

a heat rejection module having a second evaporative medium, and

a control module comprises an input device and a control algorithm for selecting one of a plurality of operation modes based on ambient conditions detected by the input device;

operating the control module to select one of the plurality of operation modes based on ambient conditions detected by the input device, and control the main cooling module and the heat rejection module to function based on the selected operation mode;

operating the indirect evaporative cooling unit based on the selected operation mode, wherein the operating of the indirect evaporative cooling unit comprises pre-cooling an intake ambient air to a lower temperature by reducing sensible heat of the air without increasing humidity;

operating the direct evaporative cooling unit based on the selected operation mode, wherein the operating of the direct evaporative cooling unit comprises cooling an input air through vaporization of water coated the first evaporative medium thereby generating a conditioned supply air with a lower wet dry bulb temperature than the ambient air, wherein the input air comprises the pre-cooled air directly from the indirect evaporative cooling unit or an intake ambient air that bypasses the indirect evaporative cooling unit; and

operating the heat rejection module based on the selected operation mode, wherein operating of the heat rejection module comprises removing heat contained in water exits from the indirect evaporative cooling unit by running the water through the second evaporative medium thereby producing cool water having a temperature almost equivalent to the intake ambient air wet bulb temperature, wherein the cool water is circulated to the indirect and direct evaporative cooling units for facilitating the pre-cooling and cooling processes respectively.

15. The method of claim 14, wherein a "dry mode" is selected from the plurality of operation modes if the detected ambient conditions having a first temperature level and a first humidity level. The "dry mode" comprises the operating of the indirect evaporative cooling unit and the heat rejection module.

16. The method of claims 14 and 15, wherein a “eco-cool mode” is selected from the plurality of operation modes if the detected ambient conditions having a first temperature level and a second humidity level wherein the second humidity level is greater than the first humidity level. The “eco-cool mode” comprises the operating of the direct evaporative cooling unit.

17. The method of claims 14 and 16, wherein a “eco-cool plus mode” is selected from the plurality of operation modes if the detected ambient conditions having a first temperature level and a third humidity level wherein the third humidity level is greater than the second humidity level. The “eco-cool plus mode” comprises the operating of the direct evaporative cooling unit and the heat rejection module.

18. The method of claims 14 and 17, wherein a “booster mode” is selected from the plurality of operation modes if the detected ambient conditions having a first temperature level and a fourth humidity level, wherein the fourth humidity level is greater than the third humidity level. The “booster mode” comprises the operating of the indirect evaporative cooling unit, the direct evaporative cooling unit and the heat rejection module.

19. The method of claims 14 and 18, wherein a “fan mode” is selected from the plurality of operation modes if the detected ambient conditions having a second temperature level or a fifth humidity level, wherein the second temperature is lower than the first temperature level and the fifth humidity level is greater than the fourth humidity level.

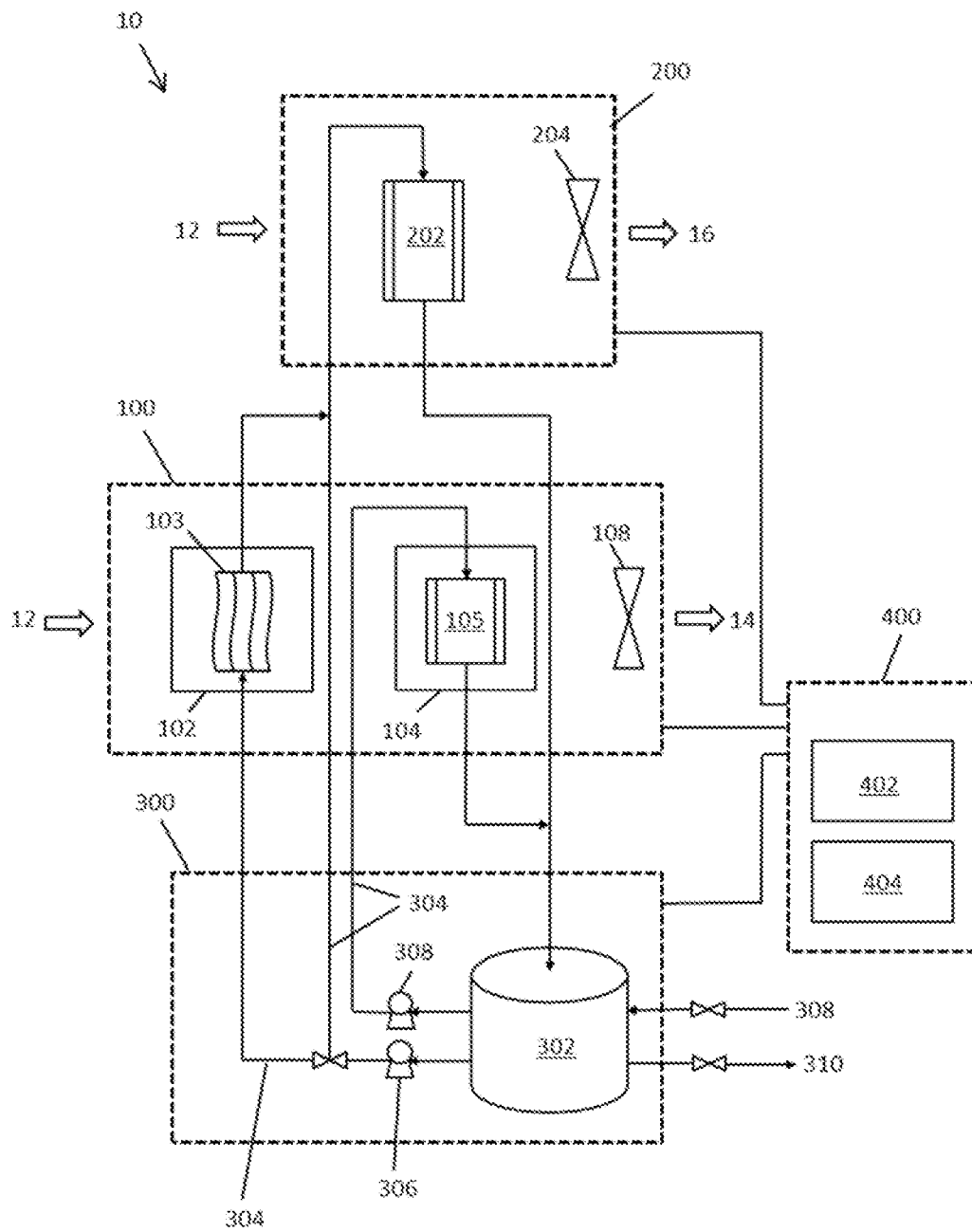


FIG. 1

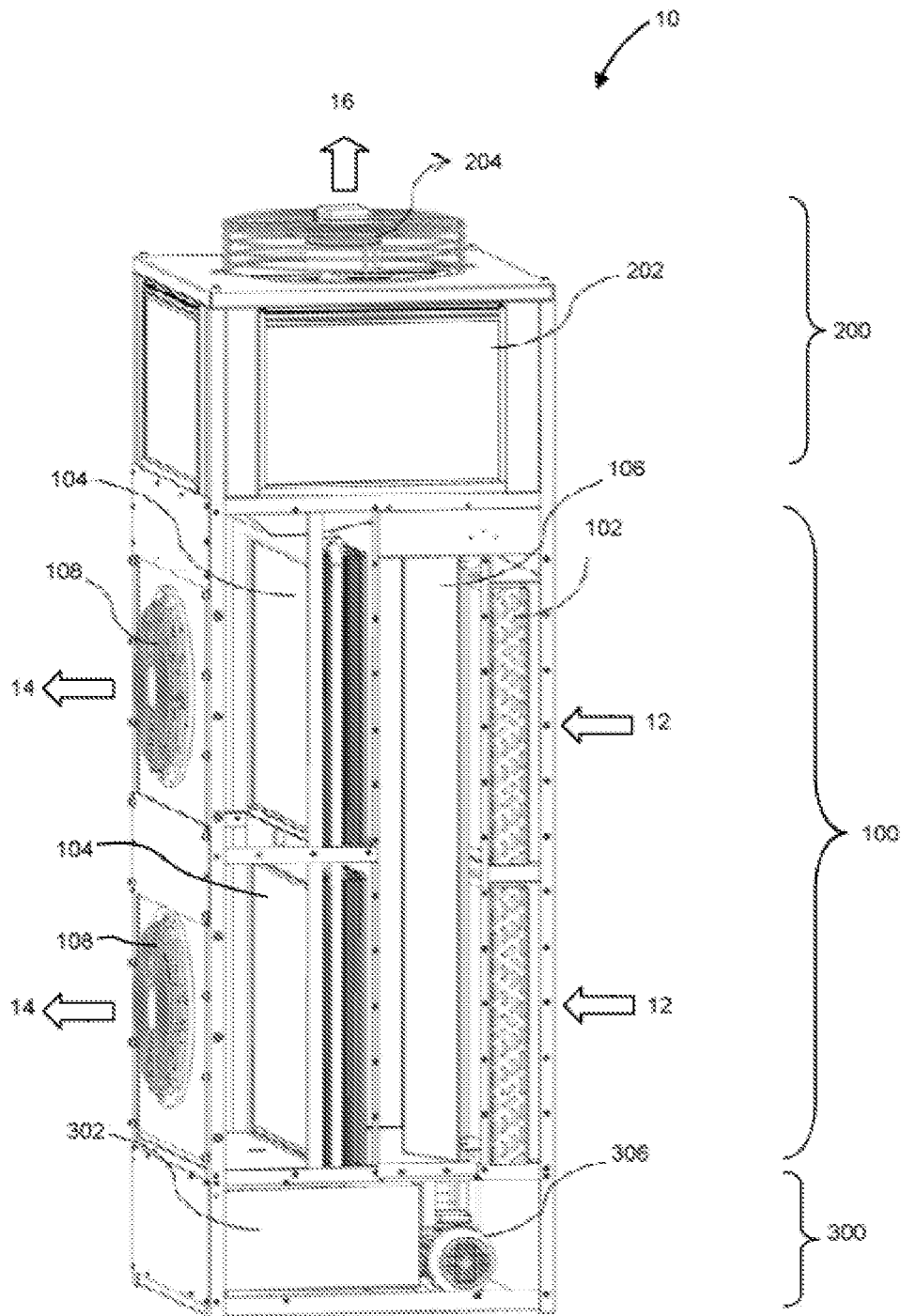


FIG. 2

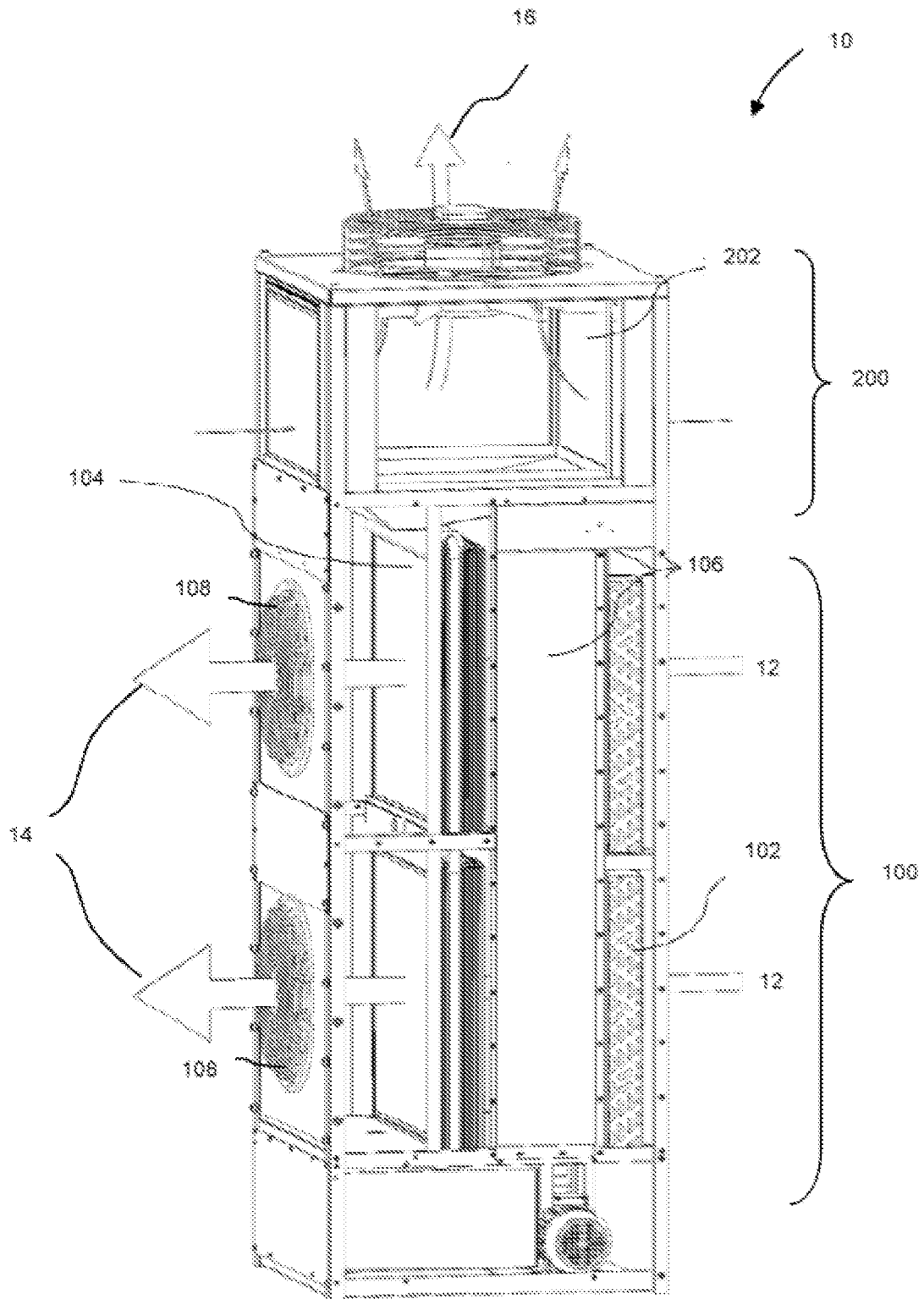


FIG. 3

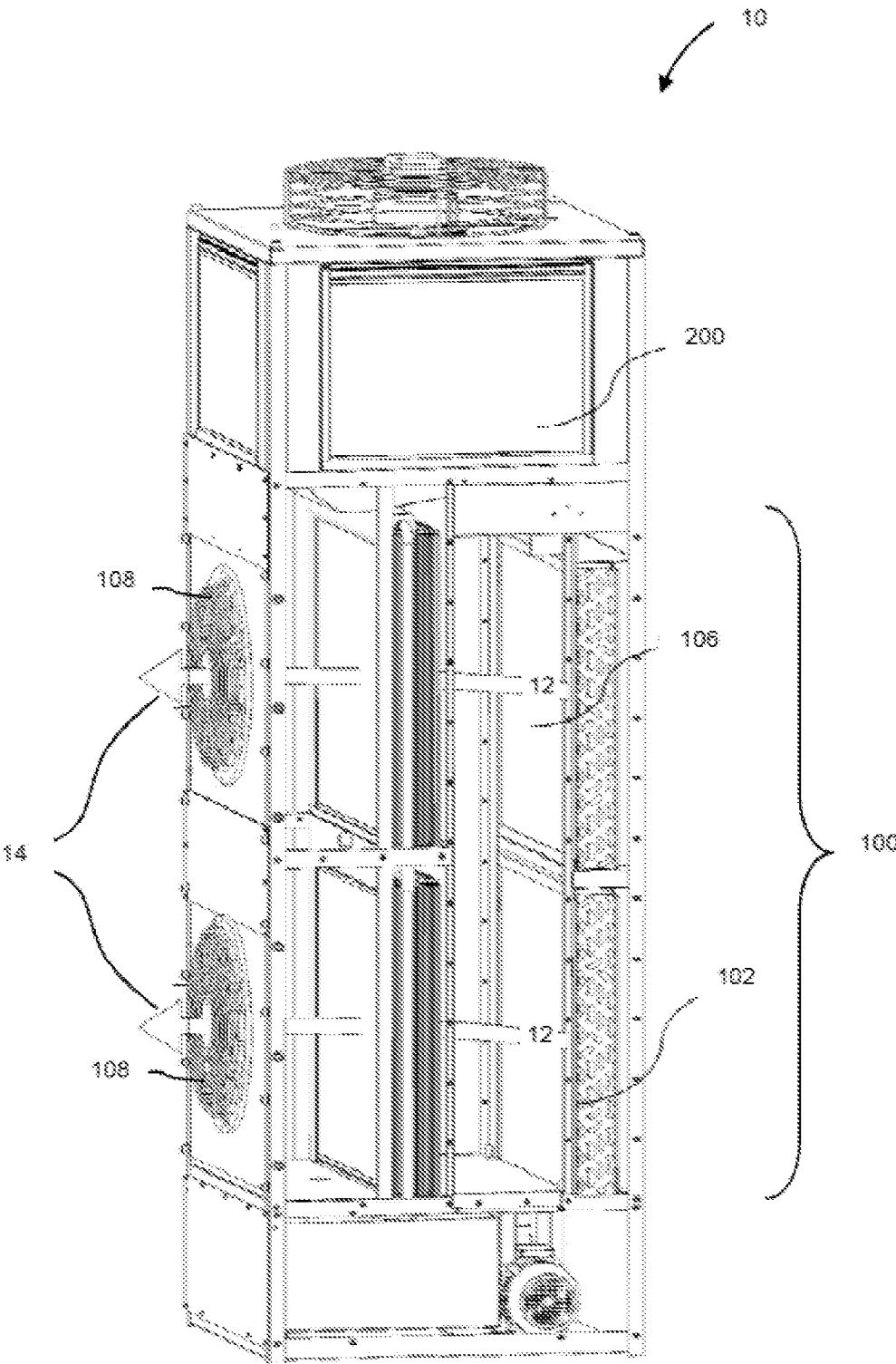


FIG. 4

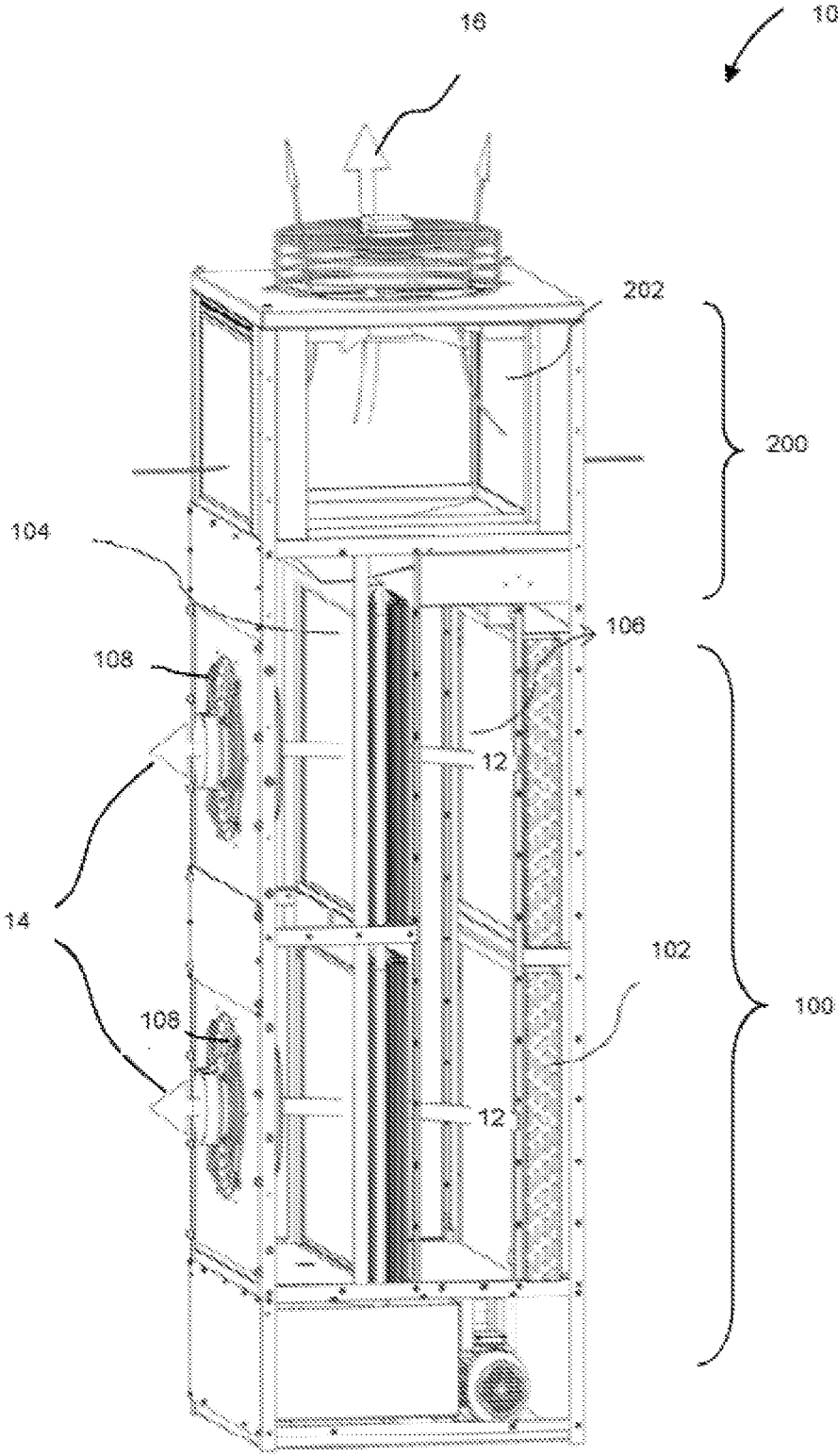


FIG. 5

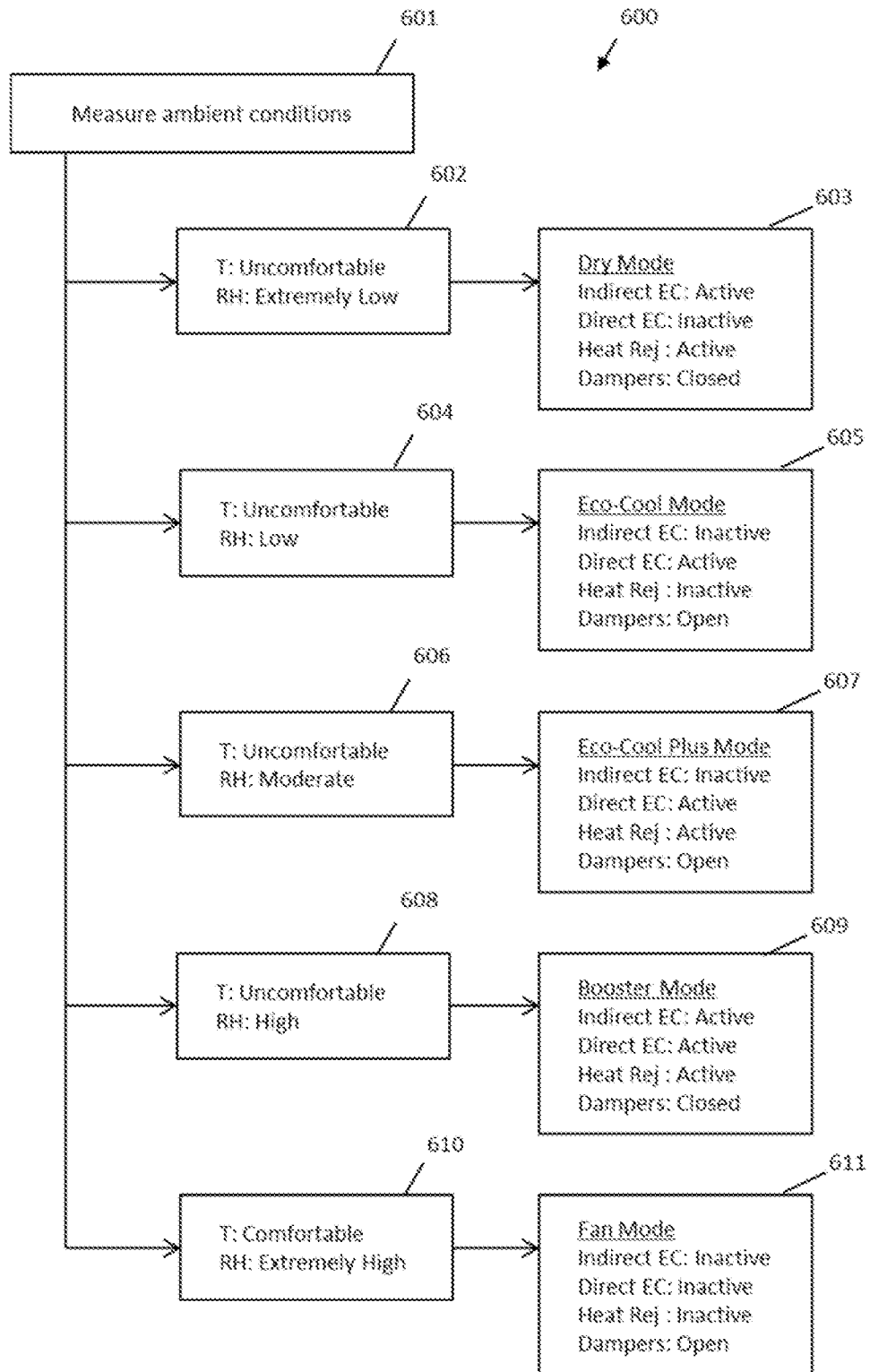


FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.

PCT/SG2017/050062

A. CLASSIFICATION OF SUBJECT MATTER

F24F 5/00 (2006.01)

According to International Patent Classification (IPC)

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F24F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

FAMPAT and WPIAP; synonyms, variations and combinations of: evaporative, cool, sensible, adiabatic, direct, wet bulb, recirculation and outdoor.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3116612 A (PENNINGTON, N A) 7 January 1964 Entire document, particularly: C2 L68-C3 L69, C5 L50-C6 L12, C6 L71-C7 L54 & C9 L25-L39 Figs 1-3 & 5	1-19
A	US 5076065 A (BROGAN, J W) 31 December 1991 Entire document, particularly: C4 L21-C6 L6 Fig 2	
A	US 4926656 A (HICKLEY, P J A ET AL) 22 May 1990 Entire document	
A	US 2010/0154448 A1 (HAY, J D) 24 June 2010 Entire document	

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

*Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

13/03/2017

(day/month/year)

Date of mailing of the international search report

27/03/2017

(day/month/year)

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/SG2017/050062

Note: This Annex lists known patent family members relating to the patent documents cited in this International Search Report. This Authority is in no way liable for these particulars which are merely given for the purpose of information.

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 3116612 (A)	07/07/1964	None	
US 5076065 (A)	31/12/1991	None	
US 4926656 (A)	22/05/1990	ZA 8909249 (B)	26/09/1990
US 2010/0154448 (A1)	24/06/2010	US 8141374 (B2) EP 2368082 (A1) EP 2368082 (A4) SG 172278 (A1) US 2012/0144850 (A1) US 8578726 (B2) US 2012/0144851 (A1) US 8584477 (B2) US 2014/0063730 (A1) WO 2010/075358 (A1)	27/03/2012 28/09/2011 01/01/2014 28/07/2011 14/06/2012 12/11/2013 14/06/2012 19/11/2013 06/03/2014 01/07/2010